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Soil-structure interaction effects in analysis of seismic fragility of bridges using an intensity-based ground motion selection procedure

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ABSTRACT

The paper focuses on the effects of Soil-Structure Interaction (SSI) in seismic fragility analysis of reinforced concrete (RC) bridges, considering the vulnerability of multiple critical components of the bridge and different modelling approaches for soil-foundation and bridge-embankment interactions. A two-step procedure, based on the introduction of springs and dashpots at the pier foundations and the abutment to account for inertial and kinematic SSI effects, is incorporated into a component-based methodology for the derivation of bridge-specific fragility curves. The proposed methodology is applied for quantifying the fragility of a typical highway overpass at both the component and system level, while the effect of alternative procedures (of varying complexity) for modelling foundation and abutment boundary conditions is critically assessed. The rigorous SSI modelling method is compared with simpler methods and the results show that consideration of SSI may only slightly affect the probability of system failure, depending on the modelling assumptions made. However, soil-structure interaction may have a notable effect on component fragility, especially for the more critical damage states. This is an observation that is commonly overlooked when assessing the structural performance at the system level and can be particularly important when component fragility is an issue, e.g. when designing a retrofit scheme.

1. Introduction

Field evidence from past earthquakes indicates that soil-structure interaction (SSI) effects can modify the dynamic response and hence affect the seismic performance of bridges [1]. Although SSI effects have long attracted the interest of the scientific community worldwide, and several thorough solutions are currently available, there is still ambiguity regarding the effect of soil-structure interaction on the seismic response of bridges, as documented by the conflicting findings of numerous research studies. Interaction of soil-bridge systems is inherently a case-dependent, multi-parametric problem and its impact (either favourable or unfavourable) on the system performance is uncertain, depending on numerous parameters such as structural characteristics, foundation type, soil stiffness [2], structure-to-soil stiffness [3], as well as frequency content, duration and intensity of the earthquake ground motion [4]. Given the significant epistemic and aleatory uncertainty associated with the aforementioned parameters, a reliable consideration of SSI effects requires detailed analytical models, incorporating all major parameters describing the physical problem and all critical structural components of the system studied.

Different types of *interactions* need to be considered during seismic analysis of bridges, namely soil-foundation-pier [5,6], deck-abutment and abutment-embankment [7–13], while strong coupling between soil conditions and the spatially variable ground motions strongly affect longer bridges [14]. Depending on the system under consideration, soil-foundation-pier interaction may consist in soil-pile or pile-soil-pile (i.e., pile-group) interaction for bridges with deep foundations, while a more simplified approach can typically be adopted for shallow foundations [5], based on wave propagation formulations. Both inertial and kinematic interactions are considered, through closed-form relationships for the evaluation of the foundation dynamic impedance and the calculation of the corresponding, frequency-dependent, spring and dashpot element properties. Interaction between the abutments and the approach embankments of the bridge is also

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considered in some studies [15], its effect being naturally more pronounced in the case of integral abutments. A refined methodology for the consideration of bridge-embankment interaction effects was put forward in [7], involving both analytical solutions and computational procedures, with a view to providing reliable estimates of the dynamic response of the bridge while accounting for the effect of embankments on dynamic response. The pertinent boundary conditions, as well as the soil degradation under increasing shear deformation were thoroughly investigated.

Due to the significant uncertainty associated with the dynamic interplay between the characteristics of ground motion, soil and structure, as well as the constitutive models adopted and the mechanical properties used, *fragility* analysis is widely used for the assessment of seismic performance of structures, on the basis of the probability of reaching distinct damage states under various levels of earthquake intensity. Both *capacity* (in terms of damage threshold values) and (seismic) *demand* are estimated in terms of the selected engineering demand parameter(s), EDP, for critical components and/or the entire system, within a probabilistic framework. The latter entails a holistic quantification of uncertainties in capacity, demand, and damage state definition. Soil-structure interaction strongly affects elastic and inelastic demand, since it accounts for radiation damping due to geometric dissipation of waves and subsequent increase in system damping [16], ground motion filtering, particularly in high frequencies, and elongation of the periods of vibration. Capacity may also be implicitly affected by SSI as the hierarchy of failure depends on the integrity of the foundation and the sequence of soil- and structure-related failure modes. Furthermore, the capacity of piers is also affected by soil compliance due to the elastic boundary conditions.

Several studies have addressed the effect of SSI on fragility analysis of buildings [17,18], and bridges [2,16,19–21]. These effects are more pronounced in the case of stiff structures located on soft soils [3], as well as in the case of bridges having relatively light superstructure and heavy substructure, regardless of the soil stiffness. Consideration of SSI effects was also found to be important for seismically isolated bridges [21] and for bridge foundations with small rotational stiffness around their transverse axis. The importance of SSI consideration was further related to ratio of the period of the structure to the predominant period of the ground motion [3], as well as its frequency content [4,23,24].

A breadth of different modelling approaches for SSI effects have also been explored, varying from simple equivalent force-deformation (P-y) soil springs [24,25], to detailed 3D finite elements [16], involving (a) linear or nonlinear, static or dynamic lumped springs estimated either from conventional, analytical, pile analysis, experimental investigations or 2D/3D finite element analysis of foundations or, (b) detailed 3D finite element models of the entire soil-foundation-bridge system [4,20,22,26]. In general, consideration of SSI effects in fragility analysis of bridges resulted in reduction of component and system probability of failure [4,22] due to reduced structural demand, with the exception of isolated bridges [27].

The motivation for the study present herein is to challenge the perception that consideration of soil-structure interaction effects reduce the probability of failure of a bridge under earthquake loading as this effectively implies that SSI effects are probabilistically beneficial and contradicts the outcome of numerous deterministic studies that have revealed cases wherein not only the interaction between soil-foundation and superstructure was critical, but also led to extensive bridge damage and even collapse [28].

This study aims to revisit the problem through a detailed SSI modelling approach, based on a two-step procedure for the definition of equivalent springs and dashpots at the foundations and the abutment-backfill interface, which can be incorporated in a component-based methodology for the derivation of bridge-specific fragility curves. Notably, equal emphasis is given to the (local) component and the (global) system probability of failure. The rigorous procedure is compared with different simplified ones commonly adopted in bridge assessment, and the effect of simple and complex modelling on the estimated seismic demand, and eventually the fragility, is evaluated. The methodology is applied to an actual concrete bridge, to investigate the effect of considering and/or ignoring SSI in seismic fragility analysis of the bridge, and to comparatively assess alternative modelling approaches. Based on the obtained results, it can be concluded that SSI effects can modify the dynamic response, as well as the seismic performance at both component and system level.

2. Methodology for assessing the fragility of bridges considering nonlinear SSI effects

2.1. Overview

The general principles for the consideration of SSI effects are common for both foundation-soil and abutment-embankment interactions. In this regard, two different types of interaction are mainly identified [13,29,30]: (a) Kinematic interaction, related to deformations imposed by the soil to the structural elements of the substructure, (b) Dynamic (inertial) interaction, related to the effect of the superstructure inertial forces on the substructure elements. These definitions are also valid in the case of bridge-embankment interaction effects, as both kinematic and inertial interaction may also be identified in a similar way, with due consideration of the embankment mass mobilization as well as the soil flexibility under increasing shear strain [7].

Soil-foundation interaction effects (inertial and kinematic) in shallow foundations were studied in [31,32], among other studies, for a broad range of geometric configurations and soil characteristics. Based on a simplified foundation modelling approach involving springs and dashpots, modification factors were proposed to relate dynamic and static stiffness, along with frequency-dependent parameters to define the complex dynamic impedance matrix.

The methodology proposed herein to assess the vulnerability of bridges utilises the model for bridge-embankment interaction effects in [7,15] developed for typical US highway overcrossings with integral abutments (monolithic connection of the abutment to the deck). According to this method, the embankment is analysed using first principles, based on soil constitutive properties, imposed boundary conditions, and ground motion characteristics. From the results of such analyses, specific elements for SSI (masses, springs, dashpots) are developed, which can be directly introduced in the finite element model of the bridge. For the derivation of bridge-specific fragility curves the component-based methodology introduced in [33] is utilised herein; it is outlined in Fig. 1. The successive steps consist in: (a) defining case-dependent component capacity and threshold limit state values for the quantification of damage at component level, (b) ad-hoc selection of earthquake ground motion, (c) refined modelling of nonlinear effects in both the soil and the superstructure and (d) uncertainty treatment in the frame of fragility analysis.

2.2. Bridge component capacity and associated uncertainties

Bridge piers, abutments, and bearings (Fig. 2) are considered as the critical components for the system's seismic performance. The prestressed concrete deck is assumed to remain elastic and the pier-foundation system is considered capacity-designed, so that plastic hinges are not expected to form at the foundation level. Capacity is defined at component level, accounting for the effect