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Effect of dynamic soil–bridge interaction modeling assumptions on the calculated seismic response of integral bridges

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ABSTRACT

In this study, the effect of soil–structure modeling assumptions and simplifications on the seismic analyses results of integral bridges (IBs) is investigated. For this purpose, five structural models of IBs are built in decreasing levels of complexity starting from a nonlinear structural model including close numerical simulation of the behavior of the foundation and backfill soil and gradually simplifying the model to a level where the effect of backfill and foundation soil is totally excluded. Nonlinear time history analyses of the modeled IBs are then conducted using a set of ground motions with various intensities representing small, medium and large intensity earthquakes. The analyses results are then used to assess the effect of modeling complexity level on the calculated seismic response of IBs. The nonlinear soil-bridge interaction modeling assumptions are found to have considerable effects on the calculated seismic response of IBs under medium and large intensity earthquakes.

1. Introduction

Integral bridges (IBs) are defined as a class of rigid frame bridges without deck joints where the abutments are cast monolithically with the bridge deck and supported by a single row of steel H-piles to provide the required lateral flexibility to accommodate thermal movements. In IBs, due to the monolithic construction of the bridge deck with the abutments where the lateral movements of the bridge deck together with the abutments is directly reflected on the backfill and foundation soil, soil–bridge interaction becomes important under seismic load effects [1]. The soil–bridge interaction effects in IBs includes; (i) global soil–pile interaction where the relative movement of the surrounding free-field soil over the bedrock with respect to the piles is taken into consideration [2], (ii) local soil–pile interaction that considers the local resistance provided by the surrounding soil to the pile movement (*P–Y* effects) as well as (iii) abutment–backfill interaction where the passive resistance of the backfill to the movement of the abutment is taken into consideration [3]. In the case of global soil–pile interaction, the free field effects become especially important in softer soils where the relative movement of the free field soil over the bedrock with respect to the piles (where the pile ends are embedded into the bedrock to the point of refusal) may become considerable. In this free field movement of the soil, the interaction between the pile and the soil creates a phenomenon called radiation damping where energy is dissipated through impact waves radiating through the surrounding soil medium. Especially, if the free-field soil moves in the opposite direction of that of the bridge under seismic effects, the piles may experience considerable lateral forces exerted by the free field soil and associated damage or even failure. In the case of local soil–pile interaction, the surrounding soil provides resistance to pile movement due to local nonlinear *p–y* effects where energy may be dissipated due to the hysteretic behavior of the yielding soil. In the case of abutment-backfill interaction, the backfill, which is compressed by the abutment, yields and dissipates energy. Additional energy is dissipated due to radiation damping upon the abutment impacting the backfill. As the abutment moves away from the backfill under seismic displacement reversals, the already compressed and yielded backfill experiences permanent deformation and hence, a gap is formed between the abutment and the backfill.

Modeling such a complex soil–bridge interaction behavior described above requires a broad knowledge of the behavior and associated nonlinear modeling techniques. Therefore, bridge design engineers generally use a simplified soil–bridge interaction modeling approach in the analyses of IBs under seismic loads. The much longer run time as well as convergence problems associated with such complicated nonlinear models are additional factors that deter design engineers from using them. However, the effects of such modeling simplifications on the seismic response of IBs

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have not been investigated yet. Most research studies in the field are concentrated on the effect of backfill and foundation soil properties on the performance of IBs under thermal and live load effects [4–7]. Therefore, a research study investigating the effect of soil–bridge interaction modeling simplification on the seismic response of IBs is urgently needed. The results from such a research study may be used by the bridge engineering community at large to decide on the complexity of the modeling techniques required in design.

2. Research scope and outline

The scope of this research study is limited to straight slab-on-prestressed-concrete girder IBs with no skew. The abutments at both ends of the bridge are assumed to be identical and supported by end bearing steel H-piles. Bridges with reinforced concrete piles at the abutments are out of the scope of this research study. In addition, for the IB used in this study, pile spacings are too large to exhibit any group effects. Therefore, group effect is not considered in the structural model. Moreover, for the bridge under consideration, the steel H-piles do not experience any inelastic displacements under thermal variations. The thermal induced displacements in the piles are far smaller than the maximum inelastic seismic displacements. Therefore, they have not been included in the analyses. Typical granular backfill used in bridge construction is assumed behind the abutments. The abutments are assumed to be in full contact with the backfill. Furthermore, medium sand resting on bedrock is assumed for the simulation of free-field effects of the foundation soil as well as dynamic soil–pile interaction.

To assess the effect of dynamic soil–bridge interaction modeling simplifications on the calculated seismic response of IBs, a two span IB is considered. Then, five structural models of the IB are built in decreasing levels of complexity starting from the most complicated, full nonlinear structural model. In the most complicated nonlinear structural model (Model 1), the foundation soil is modeled in two parts; (i) as a shear column with dashpots to simulate free field motion and (ii) nonlinear *p*–*y* springs and dashpots connected between the piles and the shear column to simulate local soil–pile interaction effects and radiation damping. Moreover, the nonlinear dynamic interaction between the backfill and abutment is modeled using nonlinear springs and dashpots. In the structural model, the nonlinear hysteretic behavior of the reinforced concrete (RC) piers and steel H-piles at the abutments are also considered. The nonlinear soil–bridge interaction parts of the most complicated structural model are gradually simplified where four additional models are built. First, the shear column is removed from the structural model (Model 2) neglecting the free field effect of the foundation soil. Then, the dashpots which are used to simulate radiation damping at the piles are excluded from the structural model (Model 3). Next, the soil–pile interaction is modeled using simple linear springs (Model 4). Finally, the piles are modeled without springs using an equivalent pile length concept where the piles are idealized as simple cantilever beam members fixed at some depth below the soil surface (Model 5). The summary of details of the five structural models considered in this study is tabulated in Table 1. For all five structural models, the abutment–backfill interaction is included (as described in Model 1) and excluded (the backfill is totally neglected) from the structural models. This resulted in overall 10 different structural models. The nonlinear time history analyses (NLTHA) of the structural models are then conducted using seven ground motions recorded on rock and scaled to various peak ground accelerations. The effect of dynamic soil–bridge interaction modeling simplifications on the calculated seismic response of IBs are then studied in terms of deck and bearing displacements, pier, pile and abutment drifts and rotations, backfill pressure intensity and distribution as well as pile axial forces.

3. Properties of the integral bridge used in this study

A two span slab-on-girder IB is considered in the analyses (Fig. 1). The total length of the bridge is 82 m (each span is 41 m long) and the width is 16 m. The deck is composed of a 225 mm thick reinforced concrete slab supported by seven AASHTO type VI girders spaced at 2.4 m. A 75 mm thick asphalt pavement is provided on the deck surface. The bridge pier is composed of three reinforced concrete columns supporting a cap beam (Fig. 1(c)). The abutments of the IB considered in this study are assumed to be 4 m tall and supported by 15 m long end-bearing steel HP310 × 174 piles. The strength of the concrete used for the prestressed concrete girders is assumed to be 50 MPa while those of the slab and abutments are assumed to be 30 MPa. The granular backfill behind the abutments is assumed to have a unit weight of 20 kN/m^3. The foundation soil surrounding the piles is assumed to be medium sand.

4. Selected ground motions

For the nonlinear time history analyses of the IB considered in this study, seven earthquake ground motions whose response spectra are compatible with the AASHTO spectrum for soil type I (Rock) are selected from the PEER (Pacific Earthquake Engineering Research) strong motion database of the University of California, Berkeley. The main reason for considering soil type I (Rock) in the analyses is that the ground motions are applied at the base of the piles at the bedrock level and the free-field effect of the foundation soil above the bedrock is considered separately in the structural model using an equivalent soil column. Details of the selected ground motions are given in Table 2.

5. Nonlinear structural modeling of the integral bridge

In this section, the five structural models considered in this study are described. First, the most complicated structural model, Model 1, is

Table 1
The details of structural models considered in the analyses.

Model case	Properties
Model 1	Foundation soil is modeled as a shear column to simulate free field effects and dynamic *p*–*y* curves and dashpots connected between the piles and the shear column are used to simulate local soil-pile interaction effects and radiation damping.
Model 2	The shear column is excluded from the structural model neglecting the free field effects.
Model 3	The dashpots which are used to simulate radiation damping are excluded from the structural model.
Model 4	The soil–pile interaction is modeled using linear springs.
Model 5	The piles are modeled without springs using an equivalent cantilever pile length concept.