Soil Dynamics and Earthquake Engineering 90 (2016) 112–127

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Evaluation of substructuring method for seismic soil-structure interaction analysis of bridges

Amin Rahmani, Mahdi Taiebat*, W.D. Liam Finn, Carlos E. Ventura

Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada

ARTICLE INFO

Article history:
Received 31 January 2016
Received in revised form
1 August 2016
Accepted 9 August 2016

Keywords:
Bridge
Soil-structure interaction
Numerical modeling
Substructure model
Continuum model

ABSTRACT

This paper evaluates the commonly used substructuring method for analysis of bridge systems where the bridge is divided into two sub-systems: the bridge superstructure and the substructure including the pile foundations, abutments, and soil. Modeling of the soil-structure interaction (SSI) in the system is simplified by replacing the pile foundations, abutments, and soil with sets of independent equivalent linear springs and dashpots at the base of the superstructure. The main objective of the paper is to examine how well the substructuring method simulates the seismic response of a bridge system. The baseline data required for the evaluation process is derived from analyzing a fully-coupled continuum bridge model, already validated for the instrumented two-span Meloland Road Overpass. The same bridge system is also simulated using the substructuring method. The results from both approaches are compared, and it is shown that the differences between them can be significant. The substructuring method consistently overestimates the pier base shear forces and bending moments and the pier top deflections. Moreover, the spectral response of the bridge structure is mispredicted. The analyses are repeated for a three-span bridge system subjected to several ground motions, leading to a similar observation as before. Hence, the current state of practice for simulating seismic SSI in bridges using the substructure model is shown to be too simplified to capture the major mechanisms involved in SSI.

1. Introduction

In recent decades a significant effort has been directed towards developing practical methods for the simulation of complex soil-structure interaction (SSI) in bridge systems during earthquake excitations. In bridge engineering, the most common practical approach is the substructuring method which separates the bridge system into two subsystems: the bridge superstructure which typically includes the bridge deck and the piers, and the substructure which includes the soil-pile group and embankment-abutment systems.

The soil-pile group system is analyzed separately to generate 6×6 stiffness and dashpot matrices which represent the lateral, vertical, rocking, torsional, and cross-coupling stiffnesses and damping at the pile cap. These stiffness and damping matrices are incorporated into the structural model of the superstructure representing the soil-pile group system. The methodology for determining this matrix has been explained in GEOSPECTRA [1] and in a MCEER report by Lam et al. [2]. In their methodology, the nonlinear inelastic response of the foundation soil and its interaction with the pile group is approximately represented by using secant stiffness values at peak free-field displacements expected during the earthquake. For soil-pile interaction, the secant stiffnesses are derived from the nonlinear backbone curves recommended by American Petroleum Institute (API) [3]. These backbone curves are widely used in practice, especially in North America, to approximate the nonlinear response of soil and its interaction with pile foundations.

For embankment-abutment interaction the common state of practice is to follow the guidelines of California Department of Transportation (Caltrans) [4]. These guidelines were established partly based on the nonlinear backbone curves proposed by Shamsabadi et al. [5]. These curves were based on the force-deflection measurements from large-scale abutment tests at the University of California, Davis [6] and the University of California, Los Angeles [7]. Although the guidelines of API and Caltrans are based on the results of static or slow cyclic loading tests, they have been also used in practice for analyses of seismic problems.

In several research studies such as those of Zhang and Makris [8], Tongaonkar and Jangid [9], and Shamsabadi et al. [5] the substructuring method was used to investigate the seismic performance of bridge systems. However, there has been limited validation of this method where the results are compared with field measurements or those of fully coupled SSI analyses. Zhang and

---

* Corresponding author.
E-mail address: mtaiebat@civil.ubc.ca (M. Taiebat).

http://dx.doi.org/10.1016/j.soildyn.2016.08.013
0267-7261/

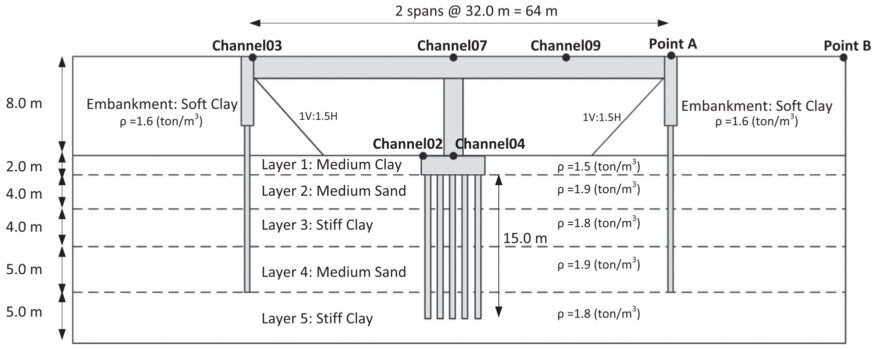

Fig. 1. Schematic of the MRO, soil layers, and channel locations at the site (dimensions are not to scale).

Makris [8] studied the seismic responses of Meloland Road and Painter Street Overpasses in California using the substructuring method. They showed that the substructuring method adequately captured the recorded time history of acceleration at the middle of the deck of the Meloland Road Overpass in the transverse direction. More recently, Shamsabadi et al. [10] developed full-scale semi-coupled model of Meloland Road Overpass, Painter Street Overpass, and Samoa Channel Bridge. In their models the soil-pile and embankment-abutment interactions were simulated using sets of nonlinear springs. They showed that the bridge models were capable of capturing the recorded time history of displacements at two different locations on the bridge deck. This paper aims to comprehensively test how the substructuring method compares with more representative simulation approaches such as continuum modeling.

The continuum modeling method potentially provides a more powerful means for obtaining realistic estimates of kinematic and inertial interactions. The adequacy of the continuum modeling method for dynamic analysis of bridge systems has been demonstrated in several studies such as Finn [11], Thavaraj et al. [12], Kwon and Elnashai [13], Jeremić et al. [14], Lu et al. [15], Rahmani et al. [16] and Rahmani [17]. In this paper, the continuum modeling method is used to generate the baseline data required for the evaluation of the substructuring method. Two bridge models are simulated and analyzed: the two-span Meloland Road Overpass (MRO) and a prototype three-span bridge. The simulation involves detailed continuum modeling of the foundation soil, pile foundations, abutment structure, and the bridge superstructure. In both models, nonlinear hysteretic response of the foundation soil and the bridge piers are accounted for in the analyses using advanced constitutive models. The continuum model is validated in the recent study of the authors [16] by simulating the seismic responses of the instrumented MRO during the 1979 Imperial Valley and the 2010 El Mayor-Cucapah earthquakes. In that study, acceleration response spectra of the computed motions were compared against the measured ones, and it was shown that the continuum model was capable of adequately simulating the longitudinal and transverse seismic response of the MRO. Based on the validated continuum model, detailed baseline data is generated using both bridge models. Each one of the two bridge systems is also simulated using the substructuring method. The simulation method is similar to the latest state of engineering practice in Caltrans [18]. The dynamic analyses of the continuum and substructure models are all conducted using OpenSees finite element program [19]. In the following sections, the continuum and substructure models of each bridge system are first described, and then the substructure models are evaluated by comparing the results with those obtained from the continuum models.

2. Two-span bridge (Meloland Road Overpass)

The MRO is a two-span integral abutment bridge built in 1971 near El Centro, California, US, as part of Highway 8. The bridge deck has a length of 64.0 m, width of 10.0 m, and depth of 1.73 m. The pier at the center of the deck is 5.0 m in height above the ground surface with a diameter of 1.52 m [13]. The embankment soil material is composed of one layer of medium clay for which the cohesion is 20.0 kPa and the density is 1.6 ton/m^3. The underlying soil is composed of five layers of clays and silty sands. The clayey layers are located at 0–2.7, 6.0–10.7, and more than 15.0 m below the ground surface with cohesion values of 35.9, 76.6, and 86.2 kPa, and densities of 1.5, 1.8, and 1.8 ton/m^3, respectively. The in-between layers are silty sands with friction angle of 33° and density of 1.9 ton/m^3 [13]. The bridge is instrumented with 29 accelerometers on the structure and 3 accelerometers at a free-field site [20]. Fig. 1 presents the schematic of the bridge and the location of five sensors on the bridge structure.

2.1. Continuum model of the bridge

In the following the finite element model is briefly described. Complete details of the MRO continuum model can be found in authors' previous paper [16].

All components of the MRO including the 5×5 pile group underneath the pier, the 7×1 pile groups underneath the abutment structures, the pier, the deck, the back walls, the wing walls, and the supporting soil domain are simulated in a unified continuum model. Solid eight-node brick elements are used to model the soil domain and the pile cap. Each node of the solid elements has three translational degrees of freedom. Four-node shell elements with three translational and three rotational degrees of freedom at each node are used to model the back walls, wing walls, and bridge deck. Fig. 2 presents 3D continuum model of the MRO. The continuum model includes a total of 41,177 nodes, 3996 beam-column elements, 1931 shell elements, and 31,844 solid elements representing a soil domain of 99.0 m long (in direction x), 50.0 m wide (in direction y), and 20.0 m deep (in direction z). The soil domain depth becomes 27.0 m with side slope of 1V:2H at the location of abutment embankments. 3D fiber beam-column elements with six degrees of freedom are used to model the bridge pier and the piles. To connect pile elements to the surrounding soil elements, solid elements in the region physically occupied by the piles are removed, and at each elevation the pile nodes are horizontally connected to the soil nodes using eight rigid beam–column elements.

Advanced nonlinear hysteretic models are used for constitutive modeling of the foundation soil. The pressure dependent multi-yield model (PDMY) [21] and the pressure independent multi-yield model (PIMY) [22], based on nested surface plasticity, were used to simulate the nonlinear hysteretic behavior of sandy and