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A FREQUENCY- AND INTENSITY-DEPENDENT, LUMPED PARAMETER MODEL FOR CONSIDERING SSI EFFECTS ON SEISMIC BRIDGE DESIGN AND ASSESSMENT

N. Lesgidis[1], A. Sextos[2] and O.-S. Kwon[3]

ABSTRACT

The computational demand of soil-structure interaction analysis in seismic risk assessment of a structure has led the civil engineering community to the development of a variety of methods towards the model order reduction of the soil-structure dynamic system. Different approaches have been proposed in the past as computationally viable alternatives to the FEM simulation of the complete structure-soil domain, such as the nonlinear lumped spring, the macro-element method and the substructure partition method. Yet, with few exceptions, no approach was capable of capturing simultaneously the frequency-dependent dynamic properties along with the nonlinear behavior of the condensed segment of the overall soil-structure system, an essential step for the accurate assessment of a structure's performance under a seismic hazard. To this end, a dual frequency- and intensity-dependent expansion of the lumped parameter modeling method is proposed in the current paper, materialized through a multi-objective algorithm, capable of fully capturing the behavior of the nonlinear dynamic system of the condensed segment. The efficiency of the proposed approach is validated for the case of an existing bridge, wherein the seismic response is comparatively assessed for both the proposed method and the detailed finite element model.

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A frequency- and intensity-dependent, Lumped Parameter Model for considering SSI effects on seismic bridge design and assessment

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The computational demand of soil-structure interaction analysis in seismic risk assessment of a structure has led the civil engineering community to the development of a variety of methods towards the model order reduction of the soil-structure dynamic system. Different approaches have been proposed in the past as computationally viable alternatives to the FEM simulation of the complete structure-soil domain, such as the nonlinear lumped spring, the macro-element method and the substructure partition method. Yet, with few exceptions, no approach was capable of capturing simultaneously the frequency-dependent dynamic properties along with the nonlinear behavior of the condensed segment of the overall soil-structure system, an essential step for the accurate assessment of a structure's performance under a seismic hazard. To this end, a dual frequency- and intensity-dependent expansion of the lumped parameter modeling method is proposed in the current paper, materialized through a multi-objective algorithm, capable of fully capturing the behavior of the nonlinear dynamic system of the condensed segment. The efficiency of the proposed approach is validated for the case of an existing bridge, wherein the seismic response is comparatively assessed for both the proposed method and the detailed finite element model.

Introduction

Simulation of soil-structure interaction can be a computationally demanding approach. As a result, a number of order reduction methods have been developed in the past capable of significantly reducing the SSI problem computational cost. The macroelement approach, a concept initially introduced by Montrasio et al [1] and further developed by a number of different research groups [2–4], has successfully provided with an accurate, yet low in computational effort, representation of the inelastic behavior of the soil-foundation domain. Although the macroelement approach emulates with great detail the different mechanisms triggered during a quasi-static excited simulation, it is common in the literature that it either completely neglects or oversimplifies the dynamic traits of the foundation-soil domain through the use of complementary Kelvin –Voigt components. As such components are only limited to accuracy along a specific frequency, their use can lead to significant error in predicting the behavior of the structure under dynamic excitation as illustrated in [5]. On the other hand, the lumped parameter (LP) modeling method has provided with an effective order reduction approach targeting the viscoelastic dynamic properties of the soil foundation domain along a broad frequency as reported in the literature [6–9]. Despite the above advantage, the LP modeling method is limited to the reduction of only viscous elastic dynamic systems.

In order to eliminate the drawbacks of the aforementioned approaches, a frequency-dependent macroelement is presented herein, capable of significantly reducing the order of inelastic dynamic SSI systems without compromising the accuracy of nonlinear dynamic SSI analysis.

Inelastic Lumped Parameter Model

Two individual methods are developed for the frequency- and intensity-dependent reduction of the SSI problem as observed in the model assembly of Figure 1. In both methods the inelastic behavior of the system is emulated by the selection of an appropriate macroelement as the base component. On the proposed method (M.1), externally controlled springs are incorporated and the overall complementary mass, spring and dashpot components of the assembly are calibrated targeting the impedance functions of the system for different intensity levels. On the simplified approach (M.2) the conventional complementary components are calibrated targeting the elastic impedance function of the system. The calibration approach is accomplished through the reformulation of a multi-objective optimization problem solved by a trust region nonlinear programming algorithm.

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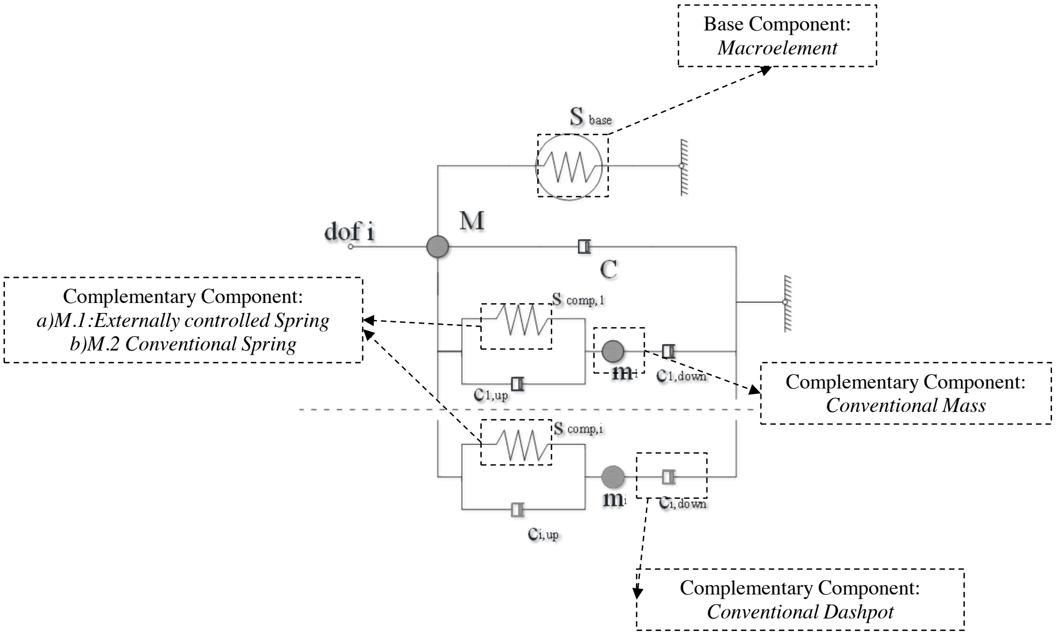

Figure 1. Physical representation of the proposed frequency- and intensity-dependent Lumped Parameter Model.

Numerical Verification of the proposed Method

The methods proposed follow a verification procedure for the case study of a bridge pier system excited from an earthquake ground motion. The proposed methods M.1 and M.2 along with the targeted FEM model and the static macroelement are all subjected to the acceleration time history recorded in the Earthquake of the Imperial Valley at the El Centro Array station rescaled to a PGA=0.1g. The time history response of the superstructure and the foundation interface DOFs are compared for the complete FEM simulation and the proposed inelastic LP method. The vertical component of the earthquake motion is neglected. The time history results are depicted in Figures 2 and 3 for the two proposed methods M.1 and M.2, the holistic FEM solution and the conventional static macroelement approach.

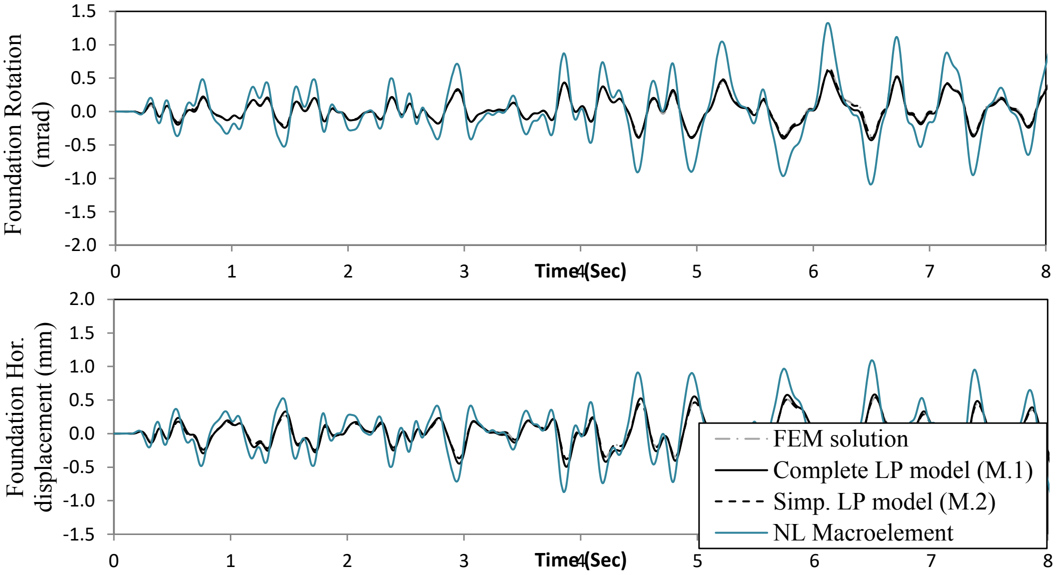

Figure 2. Time history results of the (a) foundation rotation (b) foundation horizontal displacement for the FEM and the reduced model approaches.

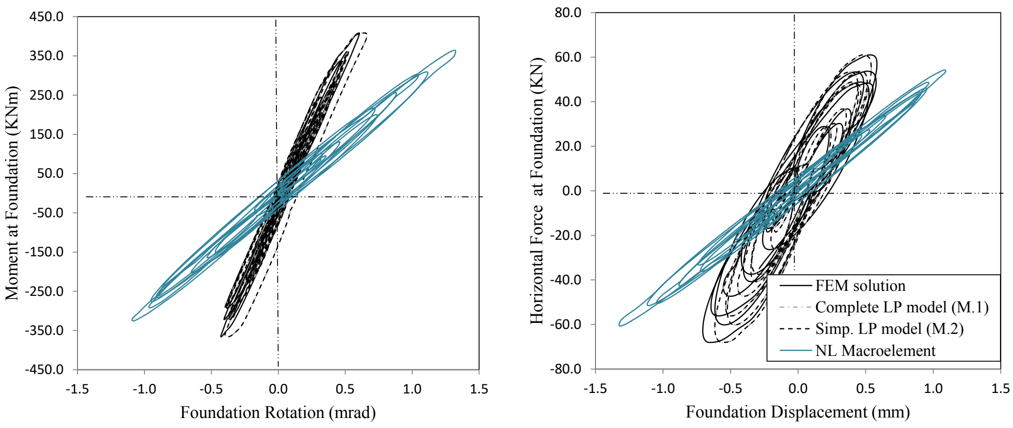

Figure 3. (a) foundation rotation to moment relation (b) foundation horizontal displacement to force relation for the FEM and the reduced model approaches.

From the comparison of the foundation response on the three different approaches (i.e., FEM, M.1 and M.2), it can be observed that both proposed methods M.1 and M.2 are adequately emulating the targeted system behavior. The efficiency of the M.2 method can be explained by the fact that the higher frequency content of the earthquake excitation is filtered out by the superstructure's transfer function. This also practically implies that the simplified method M.2 is adequately accurate mainly for excitations with low predominant frequencies. The static macroelement on the other hand, is observed to misrepresent the foundation behavior on both rotation and horizontal displacement.

Conclusions

A lumped parameter modelling method has been proposed in the current paper, capable of accurately emulating the dynamic behaviour of the soil foundation system. In contrast to methods presented in the past literature, the proposed method copes with the frequency depended properties of the soil-foundation system in different intensity regions through the expansion of the lumped parameter model framework to inelastic dynamic systems. The procedure is numerically verified through the comparison with the FE model, the complete and the simplified version of the proposed approach. The results are limited to three interface DOF representations of simplified bridge model-soil foundation systems and thus future work is essential to the expansion of the proposed method to more realistic soil foundation systems.

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