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Numerical modelling method for inelastic and frequency-dependent behavior of shallow foundations

Seok hyeon Chai, Amir Reza Ghaemmaghami, Oh-Sung Kwon*

Department of Civil Engineering, University of Toronto, Canada

A R T I C L E I N F O

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A B S T R A C T

This paper presents a novel framework with which the inelastic behavior and the frequency-dependent dynamic characteristics of soil-foundation system can be represented with a computationally efficient numerical model. The inelastic behavior of soil in the vicinity of a shallow foundation is represented with a macro-element which is based on the classical plasticity theory. The frequency-dependent property of soil-foundation system is represented with a recursive parameter model. The framework allows integration of both models such that both the inelastic behavior and the frequency-dependent characteristics can be captured. The proposed method is verified against FE analysis of a shallow foundation in the two dimensional parametric space of frequency and inelasticity. The verification shows that the model using the proposed framework can fully represent the inelastic cyclic behavior at low frequency excitation and the dynamic response at high frequency excitation. The method provides an approximate solution for the cases in-between, e.g. a foundation subjected large amplitude high-frequency excitation. As an application example, the method is applied to an analysis of a bridge pier subjected to earthquake loading.

1. Introduction

Performance-Based Seismic Design (PBSD) approach embraces explicit assessment of the response of structural components with target building performance objectives. As shallow foundation exhibits inelastic behavior at the interface of the soil-foundation system upon excessive load, realistic assessment of cyclic inelastic rocking response of foundation is recommended [1,2]. Two mechanisms of nonlinearity take place between the soil and foundation; geometric nonlinearity (i.e. rocking response) and material nonlinearity (i.e. yielding of soil).

The rocking response of shallow foundations has been one of the key research areas that has gained interest in recent years. Various experimental studies, such as a large-scale shaking table test of a bridge column [3], a small-scale shaking table test of a 3-storey building [4] and a centrifuge modelling of rocking-isolated inelastic RC bridge piers [5], have captured the rocking of the shallow foundation and found that this behavior reduces the residual drift and seismic demand of the structure. However, rocking shallow foundation may also experience large differential settlement during excessive cyclic loads which mainly result from yielding of near-field soil. On this basis, rocking of the foundation and yielding of soil should be carefully analyzed in the PBSD of shallow foundations [4,5].

There exists literature which provides guideline on modelling of shallow foundations. For example, ASCE 41-13 [6] provides a component action table with modelling parameters and acceptance criteria for nonlinear and linear analysis of shallow foundations. The values in the component action tables for nonlinear analysis procedures are based on the analysis of rocking shallow foundation, which was observed from experimental model tests. For the linear analysis procedure, the empirical coefficient, *m*-factor, is revised to reflect the allowable rotation of the rocking foundation from the nonlinear analysis procedure [7]. Unlike ASCE 41-06 [8] where rocking foundation and yielding at the soil-foundation interface are uncoupled and checked separately, ASCE 41-13 [6] considers the coupled behavior of foundation rocking and yielding of the soil. This approach is more realistic as the failure of the foundation is governed by stiffness degradation and yielding of the soil [9]. Kutter et al. [7] provided a rationale for the revisions made in ASCE 41-13 for rocking shallow foundation and validated these revisions with extensive experimental results [7,10].

The numerical modelling of dynamic soil-structure interaction (SSI) between an inelastic soil domain and a structural model for shallow foundation is a complicated task. The model entails an infinite soil domain, interface property between the structural foundation and soil, and verification and benchmark analysis. The Finite Element (FE) analysis is a rigorous method which is able to model the infinite soil domain with an arbitrary geometry and diverse soil layers. However,

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* Corresponding author.
E-mail address: os.kwon@utoronto.ca (O.-S. Kwon).

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Nomenclature

c	cohesive strength of soil
$\mathbf{c}$	damping matrix of foundation-soil system
$\mathbf{C_j}$	recursive damping matrix at $t=t-t_j$
$\mathbf{C}_0$	instantaneous damping matrix of soil
D	characteristic dimension of strip or circular footing (i.e. width of strip or diameter of circular footing)
E_d	dissipated energy
E_{So}	elastic restoring energy
$\boldsymbol{F}$	force vector of foundation-soil system
$\boldsymbol{F}_i$	force vector of foundation DOF ($i=f$) or soil DOF ($i = s$)
h_0	Initial plasticity parameter in macro-element
$\mathbf{k}$	static stiffness matrix of foundation- soil system
$\mathbf{k}_{ij}$	static stiffness matrix corresponding to foundation DOF(f) or soil DOF(s)
$\mathbf{K}_{\mathrm{el,uplift}}$	stiffness parameter with uplift coefficient of the foundation
$\mathbf{K}_{ij}$	dynamic stiffness matrix corresponding to foundation DOF (f) or soil DOF (s)
K_{ij}	ij= N, V, M , normalized elements of the stiffness parameters for macro-element
$\mathbf{K_j}$	recursive stiffness matrix at $t=t-t_j$
$\mathbf{K}_0$	instantaneous stiffness of soil
$\mathbf{K}_{\mathrm{pl}}$	the plastic stiffness calculated using mapping rule
N	vertical force on the footing
N_{max}	maximum bearing capacity of footing
$\boldsymbol{m}$	mass matrix of foundation-soil system
M	moment applied on the footing
$\mathbf{M}_0$	instantaneous mass matrix of the soil
p_1	plasticity parameter in macro-element
$\boldsymbol{q}_{\mathrm{el}}$	elastic response of macro-element
$\boldsymbol{q}_{\mathrm{pl}}$	plastic response of macro-element
$q_i,\ i = N, V, M$	normalized displacement parameter
$Q_i,\ i = N, V, M$	normalized force parameter
$Q_{M,O}$	Uplift moment initiation for macro-element
$\boldsymbol{r}_D$	restoring force vector from dynamic response of soil-foundation system
$\boldsymbol{r}_f$	restoring force vector from the overall response of soil-foundation system
$\boldsymbol{r}_S$	restoring force vector from quasi-static response of soil-foundation system
t_j	occurrence time (time delay) of the reflection reaction
$\boldsymbol{u}$	displacement vector of foundation-soil system
$\boldsymbol{u}_i$	displacement vector of foundation DOF ($i=f$) or soil DOF ($i = s$)
u_x	horizontal displacement of the footing
u_z	vertical displacement of the footing
V	horizontal force on the footing
x, y, z	cartesian coordinates
Greek	
ν	Poisson's ratio
θ_y	rotation angle
ω	frequency
ζ	equivalent damping ratio

special measures should be taken to accurately model the boundaries of the numerical model. The scattered waves from a structure should be dissipated or absorbed at the boundaries in order to avoid the wave reflection. This means that the numerical domain should be large enough to avoid the negative effects of the reflected wave to the structural responses. If the inelastic dynamic behavior of the foundation is of interest, it is necessary to model soil as a nonlinear material and include the soil-foundation interface. This type of analysis, however, takes enormous computing time as presented in Kabanda et al. [11] where a large inelastic soil domain and a structure were modelled with FE method. Due to these challenges, shallow foundations have been modelled using simplified methods. There are mainly four categories of simplified modelling techniques commonly used in the research and engineering practice; the uncoupled lumped spring approach as presented in ASCE 41-13 [7,10,12]; beam-on-a-nonlinear Winkler foundation (BNWF) [1,13]; simplified nonlinear model with springs and dashpots [2,14]; and a macro-element method with plasticity formulation [15–17].

These simplified models have their own strengths and drawbacks in simulating inelastic behavior of shallow foundations. One major drawback of these methods is the replacement of a dynamic soil-foundation system with an equivalent static or lumped element which ignores the frequency-dependent properties of soil domain. As the simplified model replaces the soil model with equivalent linear or nonlinear springs, the frequency-dependent stiffness and damping components of the soil-foundation system are ignored. This leads to inaccurate representation of wave propagation from structure to soil domain as the inertia and energy dissipation from radiation damping of soil is neglected. It has been well documented that the nature of soil-structure interaction is frequency-dependent [12,18,19]. Mylonakis et al. [12] have compiled studies on frequency-dependent stiffness and damping of soil-foundation system and provided a guideline for engineers to include frequency-independent properties of soil. In their study, it has concluded that soil foundation system exhibits frequency-dependent behavior even for low magnitude cyclic load. Also, Lesgidis et al. [19] have investigated the influence of frequency-dependent characteristics of soil-foundation system on the fragility curves established for RC bridges. It was found that there is a meaningful correlation between the frequency content of the earthquake and the numerical error introduced with the use of frequency-independent approach in establishing the fragility curves.

The objective of this paper is to propose a framework, which can couple a frequency-dependent model of soil-foundation system with a frequency-independent inelastic model. The framework aims to provide a practically accurate modelling approach which can capture the behavior of nonlinear soil-structure interaction problem subjected to dynamic load. The proposed framework is a generalized approach such that it can be used to couple any frequency-dependent model with any inelastic model. As an implementation example, the recursive parameter model by Nakamura [20,21] and the macro-element by Chatzigogos et al. [17] are adopted to model frequency-dependent and inelastic behavior, respectively.

The overall framework is presented in Section 2.1. This framework is used to integrate macro-element and a recursive parameter model, which are introduced in Section 2.2 and Section 2.3, respectively.

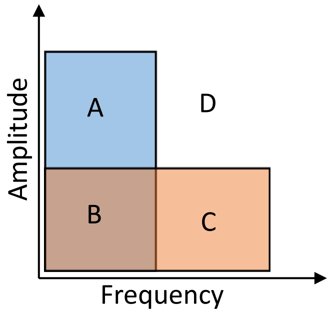

Fig. 1. Domain of dynamic loads.