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A simplified Nonlinear Sway-Rocking model for evaluation of seismic response of structures on shallow foundations

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ABSTRACT

This paper presents a simplified Nonlinear Sway-Rocking model as a preliminary design tool for seismic soil-structure interaction analysis. The proposed model is intended to capture the nonlinear load-displacement response of shallow foundations during strong earthquake events where foundation bearing capacity is fully mobilised. Emphasis is given to heavily-loaded structures resting on a saturated clay half-space. The variation of soil stiffness and strength with depth, referred to as soil non-homogeneity, is considered in the model. Although independent springs are utilised for each of the swaying and rocking motions, coupling between these motions is taken into account by expressing the load-displacement relations as functions of the factor of safety against vertical bearing capacity failure (FSv) and the moment-to-shear ratio (M/H). The simplified model has been calibrated and validated against results from a series of static push-over and dynamic analyses performed using a more rigorous finite-difference numerical model. Despite some limitations of the current implementation, the concept of this model gives engineers more degrees of freedom in defining their own model components, providing a good balance between simplicity, flexibility and accuracy.

1. Introduction

During the past decade, the interest in the topic of seismic Soil-Structure Interaction (SSI) has seen a gradual shift from the superstructure to the foundation soil. Recent research studies on SSI have shown reduced seismic ductility demands of structures due to nonlinearity that arises mainly from the mobilisation of the ultimate capacity and the uplifting response of shallow foundations. These studies have mainly focused on stiff slender structures on small foundations, such as shear walls [1], bridge piers [2,3], and framed structures [4,5] supported by spread footings. It has been found that the lifting off of one side of the footing not only results in geometric nonlinearity at the soil-footing interface, but causes yielding of soil on the other side, which in turn increases the uplift. Allowing mobilisation of the foundation bearing capacity through soil yielding and foundation uplifting limits the maximum loads that can act on the superstructure, and also leads to a considerable amount of energy dissipation due to the hysteretic damping in the soil [6].

On the other hand, structures supported on spread footings may experience unexpectedly high differential settlements during strong shaking. This phenomenon, induced by either heavy structural loads that are unevenly distributed across the footing, poor soil conditions, or the combination of both, can lead to failure of structural components and hence, non-repairable damage or collapse of structures [7]. Mat (or Raft) foundations, in these cases, are more suitable to spread the loads from the structure to the ground. Unlike the shear walls or bridge piers, structures supported on mat foundations are usually designed with a medium slenderness ratio. This leads to a strong interaction between the sway and rocking motions of the foundation when subjected to the horizontal component of strong ground motion.

It has been shown that nonlinearities in the soil (corresponding to large strains) and at the soil-foundation interface are almost unavoidable in strong seismic events [8]. Performance-based seismic design methodology embraces these nonlinearities, provided that the responses of both structural and geotechnical components satisfy the performance targets. The role of nonlinear seismic soil-structure interaction on dynamic response of buildings has recently been emphasised by Pecker et al. [9] and Gazetas [10]. In this context, it is important to develop reliable design tools that provide sufficient accuracy to assess the seismic performance of SSI while maintaining simplicity so as to be easily understood and accepted by engineers.

In recent years, the concept of a macro-element, which simplifies the dynamic interaction between soil and foundation by

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Nomenclature

A	Area of the mat foundation
c	Shape parameter of the backbone curve used in NSR model
C_r	Initial elastic range of the backbone curve used in NSR model
D	Diameter of the mat foundation
E_f	Young's modulus of the foundation material
F_0	Force at the start of the current plastic loading cycle
F_c	Bearing capacity of foundation under combined loading
F_{in}	Force when first entering the plastic cycle
FSv	Factor of safety of foundation against pure static vertical load
G	Soil shear modulus
G_0	Soil shear modulus at ground level
H	Foundation shear force
H_c	Foundation shear capacity under combined loading
H_u	Foundation shear capacity under pure sliding
h_{eff}	Effective height of the superstructure
h_i	Height of superstructure from base to the ith level
h_{tot}	Total height of the superstructure
K	Bulk modulus
k_h	Foundation swaying stiffness
k_{hr} (k_{rh})	Coupled term in foundation stiffness matrix
k_{in}	Initial foundation stiffness after vertical load is fully developed
k_n	Normal stiffness of the interface
k_r	Foundation Rocking stiffness
k_s	Tangential stiffness of the interface
M	Foundation rocking moment
M_c	Foundation moment capacity under combined loading
M_u	Foundation moment capacity under pure rocking
m	Mass of the superstructure
N	Number of storeys
N_{cM}	Foundation ultimate moment capacity coefficient
R	Radius of the mat foundation
s_u	Soil undrained shear strength
s_{u0}	Soil undrained shear strength at ground level
u	Foundation sliding displacement
u_{50}	Total foundation displacement at which 50% of capacity is mobilised
u_e	Elastic component of foundation displacement
u_p	Plastic component of foundation displacement
u_{p0}	Plastic component of foundation displacement at the start of the current plastic loading cycle
V	Foundation vertical force
V_u	Foundation bearing capacity under pure vertical load
w	Foundation settlement
ρ	Mass density
α_h	Stiffness loss factor for foundation swaying response
α_r	Stiffness loss factor for foundation rocking response
β	Gradient defining the stiffness and strength profile of the foundation soil
χ	Influence factor for foundation stiffness taking into account soil heterogeneity
φ_{i1}	Amplitude at the ith storey corresponding to the fundamental mode of vibration of the superstructure
λ	Soil non-homogeneity index
ν	Poisson's ratio
ν_f	Poisson's ratio of the foundation material
θ	Foundation rotation

integrating the nonlinearities (in the soil and/or at the soil-foundation interface) into a single plasticity-based element, has attracted considerable attention (e.g. [11–13]). However, this macro element for practical engineers remains a "black box" where the multi-yield (and sometimes multi-mechanism) complexity makes it difficult to be implemented into computer codes [14].

On the other hand, using spring-type models to simulate the dynamic response of soil-structure systems is popular in design practice because of their ease of use and clear physical meaning. Examples include (1) the linear dynamic impedance models (e.g. cone model [15]) used in the analysis of foundation vibrations on an elastic soil medium, (2) Winkler-based linear/nonlinear spring-bed models (e.g. [16,17]), and (3) the nonlinear rotational spring model [18] for the analysis of rocking-dominant nonlinear foundation behaviour. These models usually assume that the foundation soil is homogeneous, whereas in most cases the soil stiffness and strength increase with depth due to the effects of overburden stress. There is a lack of an effective and efficient spring-type model which is able to capture both Nonlinear Sway-Rocking response of shallow foundations and soil non-homogeneity.

This paper presents a simplified Nonlinear Sway-Rocking (NSR) model that is capable of simulating the load-displacement response of mat foundations subjected to seismic excitations. Compared with the linear/nonlinear spring-type models in the literature, the present model in this study is able to simulate the nonlinear foundation sway-rocking response which can be significantly affected by the load path of the seismically-excited SSI system. The effect of soil non-homogeneity is also considered. The model is developed using the OpenSees platform [23] and verified using data obtained from more rigorous Finite Difference (FD) analyses conducted using FLAC^{3D}. The simplified model is well suited for heavily-loaded structures with a moderate slenderness ratio for which the nonlinear sway response is strongly coupled with the rocking response.

The paper is organised into six main sections. First, an overview of the problem is provided, followed by a description of a FLAC^{3D} numerical model and static analyses conducted to identify the foundation load-displacement relations and bearing capacities. The NSR model is then developed based on calibration of analytical foundation backbone curves with load-displacement relations obtained from the FLAC^{3D} static push-over tests. The process by which the coupling between swaying and rocking motions is taken into account in the proposed model is also described. The efficiency of the NSR model to predict load-displacement and moment-rotation responses of shallow foundations to dynamic loading is demonstrated using results obtained from additional dynamic FLAC^{3D} numerical simulations. Finally, the limitations of the model are discussed and conclusions are provided.

2. Problem definition

The problem investigated in this study (Fig. 1) is a seismically-excited building founded on a half-space consisting of saturated soft clay layers, where undrained shear strength s_u and stiffness G increase linearly with depth (Poisson's ratio ν and density ρ remain constant). The foundation is assumed to be rigid, which is appropriate for a mat foundation that is much stiffer than the soil. Foundation movements are described by the translations w