# Contact Interface Model for Shallow Foundations Subjected to Combined Cyclic Loading

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**Abstract:** It has been recognized that the ductility demands on a superstructure might be reduced by allowing rocking behavior and mobilization of the ultimate capacity of shallow foundations during seismic loading. However, the absence of practical reliable foundation modeling techniques to accurately design foundations with the desired capacity and energy dissipation characteristics and concerns about permanent deformations have hindered the use of nonlinear soil–foundation–structure interaction as a designed mechanism for improving performance of structural systems. This paper presents a new "contact interface model" that has been developed to provide nonlinear relations between cyclic loads and displacements of the footing–soil system during combined cyclic loading (vertical, shear, and moment). The rigid footing and the soil beneath the footing in the zone of influence, considered as a macroelement, are modeled by keeping track of the geometry of the soil surface beneath the footing, along with the kinematics of the footing–soil system, interaction diagrams in vertical, shear, and moment space, and the introduction of a parameter, critical contact area ratio $(A/A_c)$; the ratio of footing area $(A)$ to the footing contact area required to support vertical and shear loads $(A_c)$. Several contact interface model simulations were carried out and the model simulations are compared with centrifuge model test results. Using only six user-defined model input parameters, the contact interface model is capable of capturing the essential features (load capacities, stiffness degradation, energy dissipation, and deformations) of shallow foundations subjected to combined cyclic loading.

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## Introduction

Soil–foundation interaction associated with heavily loaded structures supported by shallow foundations during large seismic events may produce highly nonlinear load–displacement behavior. Geotechnical components of the foundation are known to have a significant effect on the structural response to seismic shaking (Taylor et al. 1981; Faccioli et al. 2001; Gajan et al. 2005; Mergos and Kawashima 2005; Paolucci et al. 2007). The nonlinearity of the soil may provide energy dissipation and serve as a fuse mechanism, potentially reducing shaking demands exerted on the structure. Performance-based earthquake engineering design methods emphasize the importance of incorporating the nonlinear soil–foundation–structure interaction in design. The Federal Emergency Management Agency's (FEMA) "Prestandard and Commentary for the Seismic Rehabilitation of Buildings" document, prepared by ASCE, indicates that buildings may rock on their foundations in an acceptable manner provided the structural components can accommodate the resulting displacements and deformations (FEMA 2000). However, a lack of confidence in our ability to accurately design foundations with the desired capacity and energy dissipation characteristics, as well as concerns about permanent and cyclic deformations and the perceived lack of certainty in material properties, have hindered the adoption of foundation rocking as a primary energy dissipation mechanism.

In order for structural and geotechnical engineers to make use of the advantages of nonlinear soil–foundation–structure interaction and to use optimum energy dissipation mechanisms in structural elements and foundation soil, reliable structural and foundation constitutive models are necessary. As the rocking of footing and soil yielding may result in permanent deformations at foundation level (settlement, sliding, and rotation), it is important to have footing–soil interface models that are capable of predicting the load capacities, stiffness degradation, energy dissipation, and the resulting permanent and cyclic deformations at the foundation.

This paper presents a "contact interface model" that provides nonlinear relations between cyclic loads and displacements at the footing–soil interface. The rigid footing and the soil beneath the footing in the zone of influence, considered as a single macroelement, were modeled by keeping track of the geometry of the soil surface beneath the footing, along with the kinematics of the footing–soil system, aided by the introduction of a new parameter, critical contact area ratio, $A/A_c$, where $A$=actual area of the footing and $A_c$=minimum area of the footing required to have contact with the soil to support the vertical and shear loads. The contact interface model accounts for coupling between forces and displacements when the foundation is subjected to combined loading that causes soil yielding and footing uplift simultaneously. The coupling between vertical load and moment and associated deformations are natural outcomes of tracking the geometry of the contact between a rigid footing and deformed soil. The coupling between vertical load and shear, and shear and moment are accounted for using interaction diagram concepts. The

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