# Numerical Models for the Analysis and Performance-Based Design of Shallow Foundations Subjected to Seismic Loading


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# ABSTRACT

For stiff structural systems such as shear walls and braced frames, deformations that occur at the soil-foundation interface can represent a significant component of the overall soil-foundation-structure system flexibility. Practical guidelines have been available for many years to characterize these soil-structure interaction (SSI) effects when structural analyses are performed using simplified pseudo-static force-based or pushover type procedures. Those guidelines are typically based in large part on representing the soil-foundation interaction in terms of elastic impedance functions that describe stiffness and damping characteristics. Such approaches are not able to capture nonlinear behavior at the foundation level, which may involve temporary gap formation between the footing and soil, settlement of the foundation, sliding, or energy dissipation from hysteretic effects.

Due to the importance of these effects, reliable characterization of structural system response within a performance-based design framework requires improved tools for modeling of soil-foundation interaction. In this work, two such tools have been developed. The first, which is referred to as the Beam-on-Nonlinear-Winkler-Foundation (BNWF) model, consists of a system of closely spaced independent nonlinear inelastic springs that are capable of capturing gapping and radiation damping. Vertical springs distributed along the base of the footing are used to capture the rocking, uplift and settlement, while horizontal springs attached to the sides of the footing capture the resistance to sliding. The second tool is referred to as the Contact Interface Model (CIM). The CIM provides nonlinear constitutive relations between cyclic loads and displacements at the footing-soil interface of a shallow rigid foundation that is subjected to combined moment, shear, and axial loading.

Major distinguishing characteristics of the two models are (1) the BNWF model directly captures the behavior of structural footing elements with user-specified levels of stiffness and strength, whereas the CIM assumes a rigid footing; (2) the BNWF model does not couple foundation response in the vertical direction (in response to vertical loads and moments) with horizontal response whereas the CIM does couple those responses. Accordingly, the BNWF model is preferred when simulation results are to be used to design footing elements and for complex foundation systems consisting of variable-stiffness elements (such as wall footings and columns footings). Conversely, the CIM is preferred when moment and shear response are

highly coupled. Some applications may involve a combination of CIM elements beneath wall footings and BNWF elements beneath other foundation components of a given structure.

Both models are described by a series of parameters that are categorized as being "user-defined" or "hard-wired". User-defined parameters include those that are directly defined by foundation geometry or by conventional material properties such as shear strength, and soil stiffness. Hard-wired parameters describe details of the cyclic or monotonic response and are coded into the computer codes. Both sets of parameters are fully described in this report and a consistent set of parameter selection protocols is provided. These protocols are intended to facilitate straightforward application of these codes in OpenSees.

The models are applied with the parameter selection protocols to a hypothetical shear wall building resting on clayey foundation soils and to shear wall and column systems supported on clean, dry sand foundation soils tested in the centrifuge. Both models are shown to capture relatively complex moment-rotation behavior that occurs coincident with shear-sliding and settlement. Moment-rotation behaviors predicted by the two models are generally consistent with each other and the available experimental data. Shear-sliding behaviors can deviate depending on the degree of foundation uplift with coincident loss of foundation shear capacity. This can significantly affect isolated footings for shear walls or braced frames, but is less significant for multi-component, inter-connected foundation systems such as are commonly used in buildings. Settlement response of footings tends to increase with the overall level of nonlinearity. Accordingly, in the absence of significant sliding, settlement responses tend to be consistent between the two models and with experimental data. However, conditions leading to sliding cause different settlement responses. For conditions giving rise to significant coupling between moment and shear responses (resulting in shear-sliding), CIM elements provide improved comparisons to data and their use is preferred.

This work has advanced the BNWF model and CIM from research tools used principally by the PhD students that wrote the codes to working OpenSees models with well-defined (and at least partially validated) parameter selection protocols. We recognize that further validation against full-scale field performance data would be valuable to gain additional insights and confidence in the models. In the meantime, we encourage the application of these models, in parallel with more conventional methods of analysis, with the recognition that the simulation results from both established and new procedures should be interpreted with appropriate engineering judgment as part of the design process.

At present, many building engineers are reluctant to allow significant rocking rotations and soil nonlinearity at the soil-foundation interface. It is hoped that the availability of procedures that are able to reliably predict displacements caused by cyclic moment, shear, and axial loading will empower engineers to consider rocking of shallow foundations as an acceptable mechanism of yielding and energy dissipation in a soil-foundation-structure system. In some cases, the allowance of foundation nonlinearity may lead to economies in construction and improvements in performance.