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A macro-element for the modelling of shallow foundation deformations under seismic load

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ABSTRACT

This paper presents a new soil-foundation macro-element model to allow efficient and sufficiently accurate consideration of soil-foundation-structure interaction in structural analysis. The model makes use of two constitutive models, a plasticity model which models the soil inelastic deformation, and an elastic uplift model, which captures the geometric non-linearity during uplift of the foundation. Further considerations are made to allow the macro-element to be efficiently implemented in a particular non-linear finite element software (Ruaumoko3D). Two experimental centrifuge tests are simulated using the proposed macro-element: one of a bridge pier and one of a one-bay, one-storey frame structure. The simulated results are compared to the experimental behaviour to demonstrate the accuracy of the numerical model.

1. Introduction

The consideration of soil deformations and soil-foundation-structure interaction (SFSI) in building design and analysis is becoming common place for structural engineers. This is largely motivated by a performance-based design philosophy where there is a need to understand and quantify the transient and residual deformations of the foundation and their influence on the overall behaviour of the soil-foundation-structure system.

The practicing engineering community is often constrained to considering the soil-foundation interface through a series of linear uncoupled springs and dashpots, which can miss some of the most beneficial effects of SFSI [32] as well as the potentially detrimental consequences [26]. An alternative approach is direct mesh finite-element modelling of the soil and structure can capture the non-linear effects, it requires a detailed understanding of soil and structural mechanics and behaviour of soil-foundation-structure systems under earthquake loading, as well as experience in finite element modelling. The need for a simple, reliable and sufficiently accurate numerical tool to predict the non-linear soil-foundation interface has prompted considerable development in lumped parameter approaches to consider soil-foundation-structure-interaction. SFSI is a branch of the widely discussed soil-structure interaction (SSI), which covers the behaviour of many different structures (e.g. pipelines, embankments, buildings). Many of the phenomenon and numerical issues that exist for SFSI are also apparent for many other SSI problems, however, SFSI deals directly with foundation uplift and nonlinear soil behaviour, whereas typical SSI analyses make use of equivalent linear properties and such non-linearities are beyond their scope.

Two different numerical approaches dominate this type of analysis, the conventional Winkler-beam and the macro-element approach. The Winkler-beam uses a series of independent translational springs that can yield and detach (eg. [13,21]) The combination of the springs provides the rotational and vertical stiffness of the footing, while an additional uncoupled translational spring models horizontal stiffness. On the other hand, the macro-element models the rotational, horizontal and vertical stiffness of the foundation directly using coupled translational and rotational springs. The condensation down to only one spring for each degree-of-freedom or mode of deformation (axial, shear and moment) is possible by assuming that the footing itself acts as a rigid body. The non-linear effects, such as uplifting and soil yielding, are captured by considering the coupling of the forces through a coupled hysteretic model. Dashpot elements can be added in parallel to the macro-element to model the radiation damping in each degree-of-freedom.

One of the difficulties with the Winkler-beam approach is that the rotational and vertical stiffnesses are determined from the same springs, which limits its ability to accurately model behaviour in the non-linear range. The macro-element is less limited since it uses separate springs that are coupled through constitutive equations to capture non-linear behaviour and for this reason the authors have chosen to continue to develop and validate it within this paper.

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Nomenclature

h	Magnitude of plastic modulus
h_0	Plastic modulus parameter
K	Stiffness matrix
L	Length of foundation in the plane of loading
M	Applied foundation moment
N	Applied foundation axial load
N_{max}	Ultimate bearing capacity of the foundation
p_1	Ratio of axial stiffness used in the plasticity modulus
p_2	Parameter to control stiffness of reload behaviour
Q	Normalised foundation loads
$Q_{M,max}$	Normalised ultimate capacity of foundation under eccentric load
$Q_{V,max}$	Normalised pseudo shear capacity of soil-foundation interface
$q_{m,uplift}$	Pseudo uplift angle
q	Normalised foundation displacement
V	Applied foundation shear load
α	Uplift parameter
χ	Plasticity surface normalised shear parameter
δ	Uplift parameter
δ_N	Vertical foundation displacement
δ_V	Horizontal foundation displacement
ϵ	Uplift parameter
γ	Uplift parameter
κ	Normalised stiffness
Λ	Normalised distance to bounding surface
λ	Plasticity surface normalised moment parameter
θ	Foundation rotation
ξ	Bounding surface parameter to control the normalised axial load
ζ	Uplift-plasticity coupling parameter

The first macro-element for modelling soil behaviour was suggested as early as Roscoe and Schofield [34], while the full development of a plasticity framework for monotonic loading was achieved by Nova and Montrasio [29] with a non-associative flow rule for a foundation on sand. Additional developments of this model include (eg. [22,12,2]). Paolucci [30] was the first to implement a macro-element into dynamic seismic analysis using an elastic-perfectly plastic formulation. Cremer et al. [8,9] included a distinct uplift mechanism which was combined with the plasticity model to give the overall response for strip footings on cohesive soils. The Paolucci et al. [31] model introduced a degradation factor to account for softening of the response due to the rounding of the soil contact surface from irrecoverable deformations. Chatzigogos et al. [6] developed a model with coupled plasticity and uplift mechanisms for undrained soil conditions. Chatzigogos et al. [5] extended the Chatzigogos et al. [6] model to capture frictional soils and frictional sliding with a non-associative flow rule. Figini et al. [15] used the bounding surface suggested by the failure envelope from Nova and Montrasio [29] to model foundations on sand and used a vertical mapping rule to define the image point resulting in improved simulation of settlement under small cycles. Figini et al. [15] adopted the degradation model used by Paolucci et al. [31] and the uplift formulation was based on works by Wolf [39]. The experimentally validated macro-element model developed by Figini et al. [15] gives good approximations to base moment, base shear, rotation, translation and settlement, with validations against experimental single and multiple degree-of-freedom experimental shake table tests from Negro et al. [28], Combescure and Chaudat [7] and Shirato et al. [36].

The macro-element formulation presented in this paper uses the uplift model from Chatzigogos et al. [6], and the plasticity formulation from Figini et al. [15]. Additional modifications have been made to allow the model to be implemented into the time history based structural analysis software, Ruaumoko3D [4]. The formal validation of the new macro-element formulation was performed as part of a larger study into the performance-based design of building-foundation systems [24,25].

2. Characteristics of the macro-element

Most structural time-history analysis software solves the equations of motion in the force, displacement and time domain, while to provide a generalised macro-element model the displacements and forces in the macro-element formulation must be normalised using Eqs. (1)–(3).

The forces (N - axial load, V - shear load, M - moment load), displacements (δ_N - axial displacement, δ_V - shear displacement, θ_M - rotation) and stiffnesses (K_{glob}) have been normalised by the static ultimate axial capacity of the footing (N_{max}) and the footing length (L) respectively. The use of Q for normalised forces and lowercase q for normalised forces is consistent with previous formulations of macro-elements (eg. [15]).

$$Q = [Q_N, Q_V, Q_M] \quad = \left[\frac{N}{N_{max}}, \frac{V}{N_{max}}, \frac{M}{N_{max}L}\right] \tag{1}$$

$$q = [q_N, q_V, q_M] \quad = \left[\frac{\delta_N}{L}, \frac{\delta_V}{L}, \theta_M\right] \tag{2}$$

$$\kappa = \begin{bmatrix} \kappa_{NN} & \kappa_{VN} & \kappa_{MN} \\ \kappa_{NV} & \kappa_{VV} & \kappa_{MV} \\ \kappa_{NM} & \kappa_{VM} & \kappa_{MM} \end{bmatrix} \quad = \frac{K_{glob}}{N_{max}} \begin{bmatrix} L & L & 1 \\ L & L & 1 \\ 1 & 1 & 1/L \end{bmatrix} \tag{3}$$

The stiffness matrix (κ) is composed of two components connected in series, the 'elastic' stiffness and the plastic stiffness, which result in elastic and plastic displacements (Eqs. (4) and (5)). The elastic stiffness accounts for the elastic impedance of the soil based on the foundation geometry and soil stiffness, as well as effects of the geometric nonlinearity associated with uplift behaviour. The 'plastic' stiffness captures the plastic deformation associated with the yielding of the soil.

$$\frac{1}{\kappa} = \frac{1}{\kappa^{elastic}} + \frac{1}{\kappa^{plastic}} \tag{4}$$

$$q = q^{elastic} + q^{plastic} \tag{5}$$

2.1. Linear-elastic stiffness

For the purely linear-elastic case with minimal embedment, the off diagonal stiffness terms are negligible, therefore the elastic stiffness matrix consists of only the following impedance terms.

$$\kappa_{elastic} = \begin{bmatrix} \kappa_{NN} & 0 & 0 \\ 0 & \kappa_{VV} & 0 \\ 0 & 0 & \kappa_{MM} \end{bmatrix} \tag{6}$$

The diagonal terms can be approximated based on the foundation impedances and fitted over a frequency range of interest (eg. [27]).

2.2. Uplift formulation

Uplift of a footing results in a reduction in the elastic stiffness due to a reduction in the soil-footing contact area.

As the footing rotates the displacements must be represented by the macro-element at a single point (Fig. 1). The formulation implemented in Figini et al. [15], which captures the displacements at the centre of the compliant part of the footing is not compatible for complex structures modelled using finite element software where the geometry must