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Sensitivity analysis and its role in pseudo-static design of pile foundations

Jennifer J.M. Haskell [a,*], Misko Cubrinovski [b], Brendon A. Bradley [b]

[a] Schofield Centre, High Cross, Madingley Road, University of Cambridge, Cambridge CB3 0EL, United Kingdom
[b] University of Canterbury, Christchurch, New Zealand

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ABSTRACT

Lateral spreading, a phenomenon associated with earthquake-induced soil liquefaction, can impose large lateral demands on piles and has been responsible for the failure of many foundations. One of the key issues in the simplified analysis of piles using the pseudo-static approach is how to deal with the uncertainties associated with soil liquefaction and lateral spreading, an understanding of which is necessary for the consistent and reliable use of these methods in practice. In this paper a comprehensive series of analyses is used to examine the parametric sensitivity of the pile response for a broad range of soil-pile systems and magnitudes of lateral spreading displacement. The parametric sensitivity results clearly demonstrate the fundamental link between the relative importance of the various model parameters and the mechanism of soil-pile interaction, with soil strength-related parameters most important in the case of 'stiff' pile behaviour, and soil stiffness-related parameters in the case of 'flexible' pile behaviour. The SPT blowcount, *N*, in particular was arguably the most influential parameter given the magnitude of its uncertainty, and its use in determination of the stiffness and strength of soil.

1. Introduction

Widespread damage to pile foundations has been observed after many strong earthquakes in areas where extensive soil liquefaction and lateral spreading have occurred [1–3]. In response to this, numerous methods for pile design and analysis have been developed, ranging from simplified pseudo-static procedures to advanced dynamic effective stress techniques. The most commonly adopted simplified procedure is the pseudo-static method, in which kinematic and inertial loads on the pile are imposed via free-field ground displacements and forces, respectively. Despite its commonality, there are numerous different implementations of the pseudo-static method, which primarily reflect different parameterisations for the ground displacement, inertial forces, soil force-displacement and pile moment-curvature relationships (e.g., [4–6]). The interaction between piles and liquefying soils is a complex and intense dynamic process, and it is very difficult to predict the magnitude and distribution of lateral spreading displacements and the mechanical properties of the liquefied soil. When undertaking a simplified pseudo-static analysis for a particular scenario, it is important to recognise that key parameters affecting the predicted pile response may take values over a very wide range, due to the limitations of a simplified static analysis for representation of a complex dynamic problem.

In this paper, a simplified, pseudo-static analysis method developed by Cubrinovski and others [7,8] has been used to explore the effects of variation of the model parameters on the predicted pile response by means of sensitivity analyses. The analyses focus solely on the response of single piles in order to first identify key mechanism-driven sensitivities in the pile response for the simpler single-pile case, while sensitivity analyses covering more complex pile-group effects are addressed in subsequent studies [9].We first introduce the adopted simplified analysis method, before outlining a procedure for undertaking a deterministic parametric sensitivity study. The interpretation of parametric sensitivity results is then explored by means of a large series of systematic pseudo-static analyses.

2. Simplified pseudo-static analysis method adopted for this study

The behaviour of piles in laterally spreading soils is inherently complex. The essence of the problem is the interaction between the soil, piles, and superstructure both during and after the strong earthquake shaking. Case studies of past lateral spreading events [10], along with physical model and analytical studies (for example [11–13]), highlight the need to identify and understand the mechanisms of soil-pile interaction, as these control the nature of the loads on the foundation and the subsequent pile performance.

The simplified, pseudo-static analysis method developed and validated by Cubrinovski and others [7,8,14] is adopted in this

* Corresponding author. Tel.: +44 1223 768041; fax: +44 1223 760777.
E-mail address: jjmh2@cam.ac.uk (J.J.M. Haskell).

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paper. The method has been developed to provide accurate predictions of the maximum bending moment in the pile and the peak pile displacement induced by the lateral spreading demands, so is suitable for tracking the change in pile response as individual parameters are varied. Fig. 1 illustrates the soil-pile system is modelled as a series of springs and beam elements, the properties of which are based on conventional, and physically-meaningful, parameters and soil properties. Static soil displacements (here representing the lateral spreading of the soil) are applied at the ends of the soil springs, as well as external forces on the pile (representing inertial forces from the superstructure and pile cap).

Most importantly, nonlinear behaviour of both the soil and the pile is accommodated, allowing the pattern of damage to the pile and the stresses mobilised in the soil to be reasonably simulated [7]. This method is thus able to capture the mechanism of interaction between the soil and the pile, as the forces developed in the soil springs are compatible with the displacement of the pile.

2.1. Input soil parameters for a typical simplified model

The input parameters that must be defined for a three-layer soil profile (assuming in this example to comprise a non-liquefiable base layer, a uniform liquefiable layer, and a permeable sand crust), are illustrated in Fig. 2 and summarised in Table 1. In particular, it should be noted that bi-linear force-displacement springs are adopted for the soil, and a tri-linear M–κ relationship for the pile. The bi-linear soil relationships are intended to reflect a representative combination of gross mobilisation of demand and resistance from the soil for the *duration* of the response covered by the analysis (as opposed to the dynamic τ–γ response of the soil over a single cycle of shaking). While the bi-linear model is clearly a simplified representation of the complex dynamic stress-strain response of the soil, it permits the influence of soil strength and stiffness to be independently scrutinised, and can account for excess pore water pressure development through the reduction of strength and stiffness, just as for other nonlinear force displacement (or so-called 'p–y') models. Given the magnitude of uncertainties subsequently examined, and likely quality and availability of site and soil data typical of pseudo-static analyses, it is argued that a more complicated soil force-displacement relation would violate the principal of consistent crudeness [15], and only marginally influence the accuracy of the prediction.

Here, various established relationships are presented to determine values for the input parameters of the adopted model. It should be noted that both different relationships and

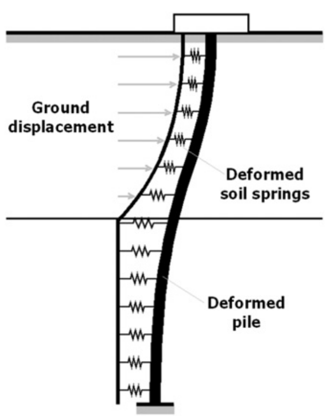

Fig. 1. Conceptual illustration of the displacement-based beam-spring model of the soil-pile system.

Table 1
Summary of the uncertainties considered in the parametric analyses and the soil spring properties each affects.

Uncertainty	Parameter(s) affected
β_C	K_C
α_C	$P_{C\ max}$
ϕ_C	$P_{C\ max}$
$k_{C,L}$	K_C, K_L
$N_{C,L}$	K_C, K_L, $P_{C\ max}$, $P_{L\ max}$
β_L	K_L
α_L	$P_{L\ max}$
S_{rL}	$P_{L\ max}$
β_B	K_B
k_B	K_B
α_B	$P_{B\ max}$
S_{uB}	$P_{B\ max}$
N_B	K_B, $P_{B\ max}$

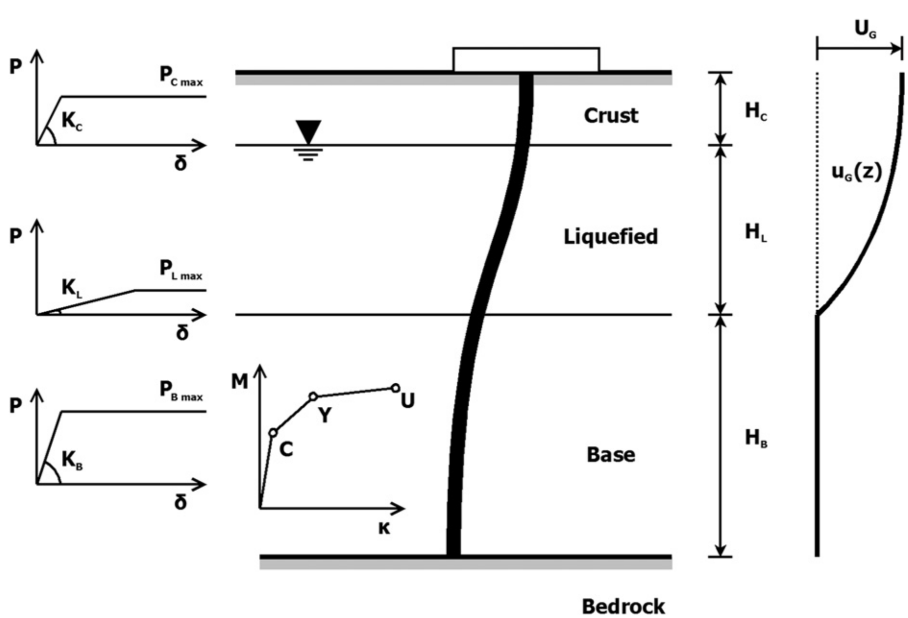

Fig. 2. Illustration of the various beam and spring properties of the adopted pseudo-static model.