Critical uncertainties in the analysis of piles in liquefying soils

Incertitudes critiques dans l'analyse de piles dans les sols liquéfiés

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ABSTRACT
The simplified analysis of piles in liquefying and laterally spreading soils is burdened by uncertainties. Key parameters affecting the pile response, such as the stiffness degradation and lateral displacement of the soil, cannot be uniquely defined, but rather vary over a wide range. In this paper a simplified, pseudo-static analysis method is used to model the soil-pile system and explore the effect of uncertainties on the predicted pile response. The strength and stiffness of the liquefied soil, and the load from any overlying non-liquefied crust are found to govern the pile response, and their relative importance reflects the mechanism of soil-pile interaction.

RÉSUMÉ
L'analyse simplifiée de piles dans la liquéfaction et l'étalement latéral de sols est rendu difficile par des incertitudes. Des paramètres clefs affectant la réponse de pile, comme la dégradation de rigidité et le déplacement latéral du sol ne peuvent pas être uniquement définis, mais varient plutôt sur une vaste gamme. Dans cet article une méthode d'analyse simplifiée, pseudo-statique est utilisée pour modèler le système de pile-sol et pour explorer l'effet d'incertitudes sur la réponse de pile prévue. On trouve que la capacité et la rigidité du sol liquéfié et la force de la croûte non-liquéfiée dominent la réponse de pile.

Keywords : pile, liquefaction, lateral spreading, pseudo-static analysis

1 INTRODUCTION

Widespread damage to pile foundations has been observed after many strong earthquakes in areas where extensive soil liquefaction and lateral spreading occurred. The gross horizontal movement of liquefied soil represents a potentially very large demand on piles that has only recently been acknowledged and specifically considered in seismic design codes. The interaction between piles and liquefying soils during an earthquake is a complex and intense dynamic process. Numerous simplified methods intended for preliminary pile design and analysis have been developed (e.g. Architectural Institute of Japan, 2001), however no method is universally accepted and all are burdened by uncertainties associated with seismic liquefaction.

Case studies and past research (e.g. Cubrinovski et al., 2006b; Abdoun & Dobry, 2002) confirm that the properties of the soil and pile, the soil profile, and the magnitude of the lateral spreading displacement influence the fundamental mechanism of interaction between the pile and the displacing soil. Without a quantitative understanding of the effects of uncertainties in these agents on the pile response, the consistent and reliable use of simplified design methods can not be expected.

In this study, a simplified pseudo-static analysis method developed by Cubrinovski and others (Cubrinovski & Ishihara, 2004; Cubrinovski et al. 2006a) was used to explore the effects of uncertainties on pile response by means of a deterministic sensitivity study. In this paper we define a range ofrelevant values for the parameters in the model, before identifying the critical uncertainties and the relationship between their relative importance and the mechanism of soil-pile interaction.

For piles in liquefying, laterally spreading soils it is convenient to distinguish two phases of loading (Tokimatsu & Asaka, 1998; Cubrinovski & Ishihara, 2004), the first during strong shaking when the cyclic ground displacements and inertia of the superstructure dominate the pile response, and the second after the strong shaking has ceased and the kinematic forces from the laterally spreading soil dominate. This paper considers only the latter phase. Furthermore, only single piles are considered, as extension of the scope to pile groups introduces additional complexities and would be premature, given the present lack of guidance for the simpler single-pile case.

Following is an outline of Cubrinovski's simplified method (Cubrinovski et al. 2006a) and an overview of the approach adopted for the sensitivity study. The results of the analyses are then presented in the form of 'tornado' charts, from which the critical uncertainties are identified and explored.

2 SIMPLIFIED MODEL

The adopted pseudo-static analysis method has been developed to provide accurate predictions of the maximum bending moment in the pile and the peak pile head displacement induced by lateral spreading (Cubrinovski & Ishihara, 2004). The soil-pile system is modelled as a series of spring and beam elements, allowing static soil displacements (here representing the lateral spreading of the soil) to be applied via movement of the soil springs. The 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. Furthermore, this method accommodates non-linear soil and pile behaviour, allowing the pattern of damage to the pile and the stresses mobilised in the soil to be reasonably predicted. The model parameters required for a three-layer soil profile (which uses bi-linear soil and tri-linear pile elements) are summarised in Figure 1 (Cubrinovski et al., 2006a).

3 SENSITIVITY STUDY

In reality the possible combinations of soil types, layering, and piles used seem almost limitless. It is necessary therefore to

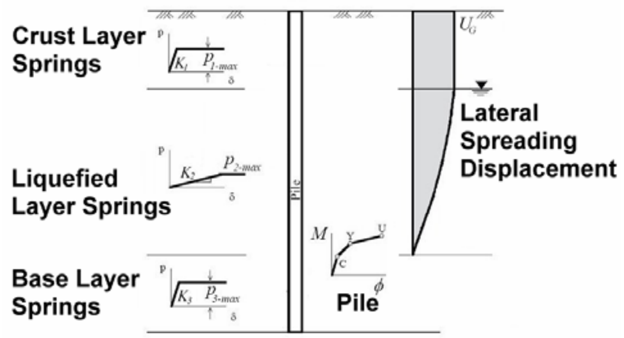

Figure 1. Parameters needed for the simplified analysis of pile response.

distinguish between 'uncertainties' in soil properties and 'gross differences' in the soil profile, pile type and the like. The variation in possible profiles referred to here is not considered to be an uncertainty as, in practice, the soil profile can be determined with some confidence through a standard site investigation. To isolate the effect of differences in the soil profile or pile properties, a 'reference scenario' approach was used for this study. A series of 'reference models' representing a wide (but realistic) range of soil profiles and pile types were first defined. Then, for each reference model, the input parameters and soil properties were varied about their 'expected' or 'reference' values to determine their influence on pile response.

As noted by Cubrinovski et al. (2006a), the most common soil profile for lateral spreading consists of three distinct layers, where a liquefiable layer is 'sandwiched' between a non-liquefiable crust at the ground surface and a non-liquefiable layer of soil at depth. Furthermore, case histories (e.g. Finn & Fujita, 2002; Abdoun & Dobry, 2002) suggest that this configuration generally results in the greatest demand on piles due to the potentially large forces applied at the pile head by the crust layer. On this basis, three-layer soil profiles were used for this study (where the non-liquefiable crust was due to a groundwater table below the surface).

The ultimate goal of the engineer in using simplified methods is to capture the essential features of the performance of piles used to support structures in specific locations. This requires a 'translation' of the complex soil-pile system that exists in reality into an equivalent simplified model that exhibits the same fundamental behaviour. Aside from the properties of the pile, which are the choice of the engineer, the model parameters must be determined indirectly as functions of other soil (and pile) properties. These, in turn, would typically be determined from site investigation data via established empirical relationships. To simulate this, the reference models have been specified as gross soil profiles accompanied only by 'representative' SPT blowcounts for the different layers. The four soil profiles (P1-P4) that were adopted are illustrated in Figure 2. They provide combinations of loose or medium-dense liquefiable soil overlying a base layer of soft clay or dense sand. Three different piles (stiff, medium, and flexible of diameter 1200mm, 800mm, and 400mm, respectively) were embedded in these four profiles, forming the twelve reference models considered in this study. This paper covers only the stiff (1200mm diameter pile) reference models, the detals of which are summarised in Table 1. For example, reference model S3 comprises a 1200mm diameter pile embedded in a medium-dens liquefiable layer (N=15), overlying a base layer of soft clay (N=5).

3.1 *Uncertainties*

Before proceeding to identify all the uncertainties affecting the simplified analysis of piles in laterally spreading soils, it is helpful to define fundamental 'types' of uncertainty so that their physical meaning is clear.

Inherent uncertainties affect quantities that, by their nature, can not be uniquely defined or exactly predicted, such as the degradation of soil stiffness due to liquefaction, β_i, or the shape factor, α_i, which relates the lateral resistance of the pile to that of an infinitely long wall.

Empirical uncertainties arise from the use of inexact or empirical relationships to estimate the values of model parameters, and are usually well defined by the proponents of these relationships. For example, Seed and Harder (1990) provide upper and lower-bounds for the shear strength of the liquefied soil, s_{u2}, as a function of SPT blowcount. Table 2 summarises the empirical relationships used in this study to determine the model parameters.

Characteristic uncertainties are similar to inherent uncertainties in that they reflect the variability introduced when defining parameter values indirectly, on the basis of other soil properties of test data. For example, the selection of a representative SPT blowcount for a soil layer, based on site investigation data. The range of variation to be considered here is not well defined, and the tendency to use lower SPT values may not be conservative, as the pressure the displacing soil applies to the pile could be underestimated.

Table 3 summarises the variations of the input soil properties used to simulate these uncertainties, for all of the reference models. The model parameter(s) affected by each uncertainty are identified along with the uncertainty type. Haskell (2008) gives a full account of the selection of these ranges.

3.2 *Analysis Procedure*

The parametric analyses for each of the four reference models considered here were conducted as follows. For a given lateral spreading displacement and reference model, a reference response (where all parameters were held at their 'expected' or 'reference' values) was first determined. Then (for the same lateral spreading displacement), the analysis was repeated, with each parameter in Table 3 varied, in turn, between its upper and lower bounds while the others were held at their reference values. This process was undertaken incrementally for lateral spreading displacments ranging from 0.1-2.0m for all reference models. The effects of each uncertainty on the prediceted pile performance were thus evaluated across the entire range of relevant response, from elastic pile behaviour to pile failure.

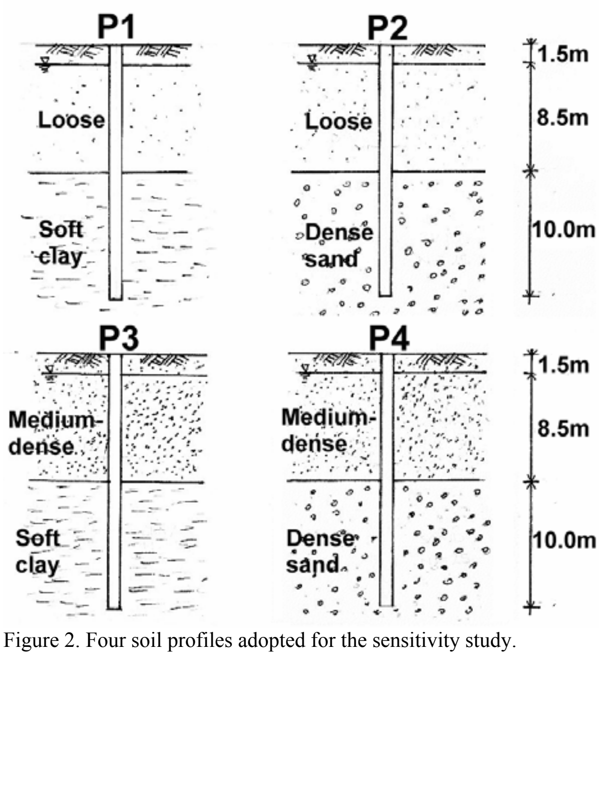

Figure 2. Four soil profiles adopted for the sensitivity study.

Table 1. Details of the four 'stiff' reference models.

Reference Model	S1	S2	S3	S4
Pile Diameter [mm]	1200			
Liquefiable Soil	Loose		Medium-Dense	
	N = 5		N = 15	
Base Soil	Soft Clay	Dense Sand	Soft Clay	Dense Sand
	N = 5	N = 25	N = 5	N = 25

Table 2. Empirical relationships for determining the model parameters.

Stiffness (All Layers)	Strength (Crust and Dense Base Layers)	Strength (Clay Base Layer)	Strength (Liquefied Layer)
$k_i = 56 N_i D^{\frac{-3}{4}}$	$\phi_i' = 20 + 20(N_i)^{0.5}$	$s_{ui} = 12.5 N_i$	$s_{ui} = f_n(N_i)$ (graphical)
(AIJ, 2001)	(Hatanaka & Uchida, 1996)		(Seed & Harder, 1990)
$K_i = \beta_i k_i l D$	$P_{\max i} = \alpha_i \sigma_{pi}' l D$	$P_{\max i} = \alpha_i s_{ui} l D$	

Where D = pile diameter, l = pile element length, σ'$_p$ = passive pressure

Table 3. Uncertainties affecting the simplified analysis of pile response.

Uncertainty	Parameter(s) Affected	Uncertainty Type	Range of Variation
β_1	K_1	Inherent	0.3 - 1.0
α_1	$P_{1\text{-max}}$	Inherent	3.0 - 5.0
Φ_1	$P_{1\text{-max}}$	Empirical	±3°
$k_{1,2}$	K_1, K_2	Empirical	±40%
$N_{1,2}$	K_1, K_2, $P_{1\text{-max}}$, $P_{2\text{-max}}$	Characteristic	±3 (loose) ±4 (med-dense)
β_2	K_2	Inherent	0.001 - 0.02
α_2	$P_{2\text{-max}}$	Inherent	1.0 - 6.0
su_2	$P_{2\text{-max}}$	Empirical	su_{LB} - su_{UB}
β_3	K_3	Inherent	0.3 - 1.0
k_3	K_3	Empirical	±40%
α_3	$P_{3\text{-max}}$	Inherent	3.0 - 5.0 5.0 - 9.0
su_3	$P_{3\text{-max}}$	Empirical	±8 kPa (clay) ±70 kPa (sand)
N_3	K_3, $P_{3\text{-max}}$	Characteristic	±3 (clay) ±4 (sand)

4 INTERPRETATION OF SENSITIVITY RESULTS

The effect of each parametric variation was gauged in terms of the change in the predicted pile head displacement, U_P, and the peak curvature of the pile, $\varphi_{max,}$, which serve as indices of pile performance. Figure 3 shows the effect of uncertainties on the predicted peak pile curvature for the model S1 (which comprises a loose liquefiable layer above a soft clay base, and a 1200mm diameter pile), subjected to lateral spreading displacements of 0.1m, 0.5m, and 1.0m, respectively. Each bar of the tornado charts corresponds to one of the uncertainties listed in Table 3, with the upper and lower bounds of the relevant parameter shown at the ends of the bar. The dashed line indicates the reference peak pile curvature, where all model parameters take their reference values. Additional lines on the curvature tornado charts indicate the cracking, yielding, and ultimate curvatures of the pile, allowing the damage to the pile to be readily assessed. Associated with each tornado chart is a plot of the relative soil-pile displacement throughout the depth of the deposit for the reference response (Figure 4).

Focusing first on the interpretation of individual tornado charts and yield plots, taking the case with a lateral spreading displacement of 1.0m as an example, it can be seen that:

- The reference pile head displacement is 0.2m (inferred from Figure 4c, which shows a relative soil-pile displacement of approximately 0.8m at the ground surface). This is considerably less than the lateral spreading displacement at the ground surface, hence the pile is behaving in a stiff manner (the pile is resisting the soil movement).
- The crust soil has fully yielded, and changes to its stiffness (via β_1) have no effect on the pile response. The crust force is thus controlled by the limiting pressure from the soil (via parameters α_1 and φ'_1).
- Similarly, the pile response is much more sensitive to the parameters α_2 and s_{u2} than to β_2. Indicating that the liquefied soil is yielding throughout much of its depth.
- The selection of certain parameter values can roughly double (or halve) the predicted peak pile curvature and, in this case, will determine whether or not the ultimate curvature capacity of the pile is reached.

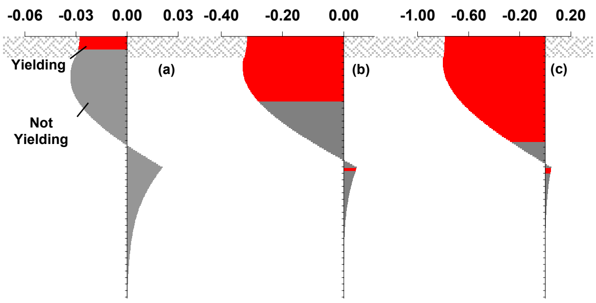

Figure 4. Relative soil-pile displacement for the reference response of model S1 at (a) 0.1m, (b) 0.5m, and (c) 1.0m ground displacement.

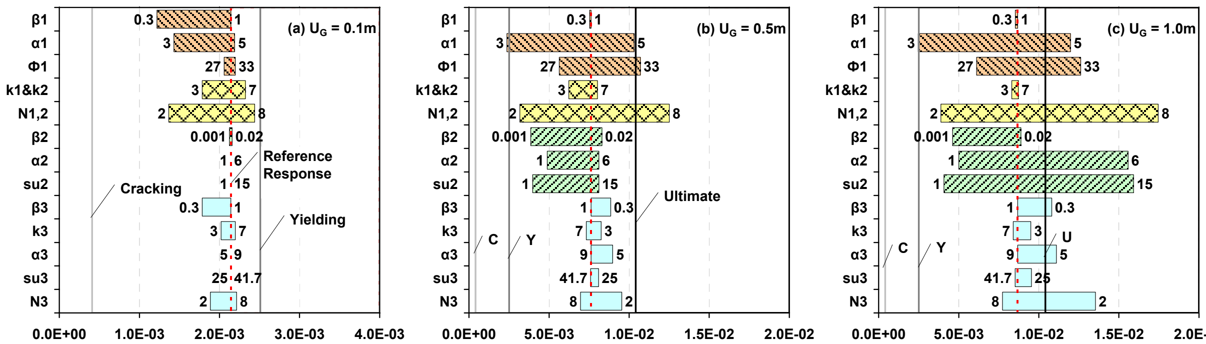

Figure 3. Tornado charts showing the effect of uncertainties on the peak pile curvature (m^{-1}) for (a) 0.1m, (b) 0.5m, and (c) 1.0m ground displacement.

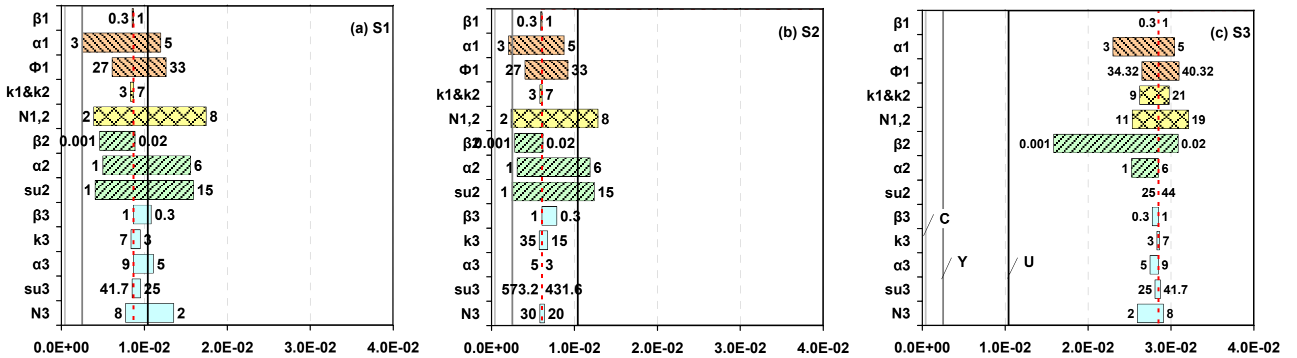

Figure 5. Tornado charts showing the effect of uncertainties on the peak pile curvature (m-1) for reference models (a) S1, (b) S2, and (c) S3.

Essentially, the change in response due to the variation of each parameter can be attributed to either an increase (or decrease) of the load on the pile from the displacing soil, or an increase (or decrease) in the relative stiffness of the soil and the pile.

Comparing the tornado charts for different lateral spreading displacements allows the parametric sensitivities to be related to the mechanism of interaction between the soil and the pile. For small ground displacements, Figure 3a shows that the pile response is most sensitive to uncertainties in the parameters affecting soil stiffness. At larger lateral spreading displacements (Figure 3c), the relative soil-pile displacement is greater and yielding of the soil occurs, limiting the pressure from the soil on the pile. The response thus becomes sensitive to the parameters affecting the soil strength.

A comparison between reference models can also be made to assess the effect of gross differences of the soil profile on the pile response. Figure 5 shows the peak pile curvature for models S1–S3 at a lateral spreading displacement of 1.0m. The greatest differences between the three models reflect the density of the liquefied (and crust) soil. Where this soil is medium-dense (models S3 and S4 (not shown)), the pile behaves in a much more flexible manner and has greater peak curvatures. In terms of parametric sensitivities, the lesser relative soil-pile displacement for models S3 and S4 means there is reduced yielding of the liquefied soil and the transition of the soil-pile mechanism from stiffness to strength-controlled requires a larger ground displacement. Figure 6 summarises how the transition in mechanism affects the sensitivity of the pile response to stiffness and strength parameters (the size of each horizontal bar indicates the degree of sensitivity).

5 SUMMARY AND CONCLUSIONS

The purpose of identifying critical uncertainties is primarily to highlight the modelling decisions that are likely to have the greatest effect on the predicted pile performance. Pile response is particularly sensitive to $N_{1,2}$, reflecting the concurrent influence of the SPT blowcount on both the strength and the stiffness of the soil. Representative blowcounts must clearly be chosen with care, and particular attention should be paid to the role of each layer in the interaction (i.e. whether it provides a driving or resisting force). The pile response is relatively insensitive to the properties of the base layer. Any variation in response these uncertainties cause is primarily the result of a change in the ‘fixity’ of the pile, rather than a fundamental change in the mechanism of interaction.

Yielding of the crust soil occurs at very small lateral spreading displacements. Uncertainties affecting the strength of the crust are therefore critical, while those affecting its stiffness are not. Both the stiffness and the strength of the liquefied soil can have a significant effect on the predicted pile performance. The stiffness degradation, β_2, and the shape factor, α_2, are thus critical uncertainties, as is the liquefied shear strength, s_{u2}. The relative importance of these parameters however depends on the induced pile response and whether or not yielding of the soil springs occurs.

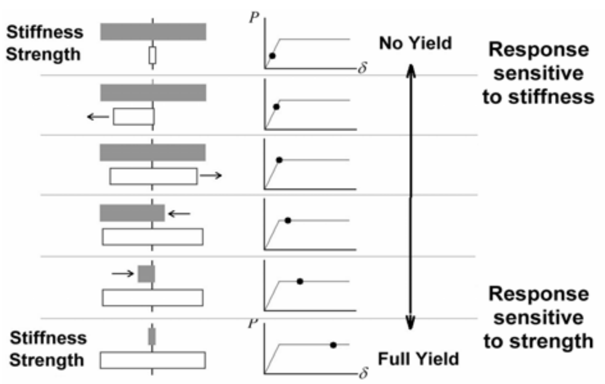

Figure 6. Change in importance of stiffness and strength uncertainties as the response mechanism changes.

REFERENCES

Architectural Institute of Japan (AIJ) (2001). Recommendations for design of building foundations. (in Japanese).

Abdoun, T. and Dobry, R. (2002) Evaluation of pile foundation response to lateral spreading. *Soil Dynamics and Earthquake Engineering*, 22 (9-12), 1051-1058.

Cubrinovski, M. and Ishihara, K. (2004) Simplified method for analysis of piles undergoing lateral spreading in liquefied soils. *Soils and Foundations*, 44 (5), 119-133.

Cubrinovski, M., Ishihara, K. and Poulos, H. (2006a) Pseudo-static analysis of piles subjected to lateral spreading. Proc. New Zealand Workshop on Geotechnical Earthquake Engineering (Christchurch, New Zealand), 20-21 Nov.

Cubrinovski, M., Kokusho, T. and Ishihara, K. (2006) Interpretation from large-scale shake table tests on piles undergoing lateral spreading in liquefied soils. *Soil Dynamics and Earthquake Engineering*, 26 (2-4), 275-286.

Finn, W.D.L. and Fujita, N. (2002) Piles in liquefiable soils: seismic analysis and design issues. *Soil Dynamics and Earthquake Engineering*, 22 (9-12), 731-742.

Haskell, J.J.M. (2008) Assessment of the Performance of Pile Foundations in Laterally Spreading Soils. Third Professional Year Project Report, University of Canterbury, Christchurch.

Hatanaka, M. and Uchida, A. (1996) Empirical correlation between penetration resistance and internal friction angle of sandy soils. *Soils and Foundations*, 36 (4), 1-9.

Seed, R.B. and Harder, L.F. (1990) SPT based analysis of cyclic pore pressure generation and undrained residual strength. Proc. H. Bolton Seed Memorial Symposium (Vancouver), 2, 351-376.

Tokimatsu, K. and Asaka, Y. (1998) Effects of liquefaction-induced ground displacements on pile performance in the 1995 Hyogoken-Nambu earthquake, *Special Issue of Soils and Foundations*, 163-177.