Sensitivity analysis of simplified methods for the design of piles in laterally spreading soils

J.J.M. Haskell, M. Cubrinovski & B.A. Bradley

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch.

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ABSTRACT: The simplified analysis of piles in laterally spreading soils is burdened by uncertainties. Key parameters affecting the pile response, such as the stiffness degradation and lateral displacement of the liquefied soil, cannot be uniquely defined, but rather vary over a wide range. In this paper we explore the effect of variations of model parameters on the pile response by means of a deterministic sensitivity analysis, and demonstrate that the relative importance of the most critical parameters depends on the mechanism of soil-pile interaction. It is clear that without an understanding of the scale of variation of the model parameters and the effect of parametric variations on the predicted pile response, the consistent and reliable use of simplified pile design and analysis methods cannot be expected.

1 INTRODUCTION

Pile foundations are typically used to support engineering structures where the surface soil is of poor quality. Their principal function is usually to transmit vertical loads to stronger, stiffer soil at depth. There are times however, when these foundations must also resist significant lateral loads. Lateral spreading, a phenomenon associated with earthquake-induced soil liquefaction, in particular can impose large lateral loads on pile foundations through the gross horizontal movement of liquefied ,and any overlying ‘crust’ of non-liquefied, soil. These soil movements can be of the order of several metres.

Widespread damage to pile foundations has been observed after many strong earthquakes in areas where extensive soil liquefaction and lateral spreading occurred. In response to this, numerous simplified methods for preliminary pile design and analysis have been developed and adopted in seismic design codes (e.g. Architectural Institute of Japan 2001). However, 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 applying a simplified method to a given scenario, key parameters affecting the predicted pile response are likely to vary within a relatively wide range of values. In spite of this, most of these methods take a deterministic approach, attempting to *uniquely* define all of the model parameters. In this paper, the term ‘uncertainty’ is used not in a probabilistic or statistical sense, but rather to refer to our inability to know ‘for sure’ what the most appropriate values of the model parameters are and what the response of the piles might be.

In this study (which focused on a simplified method developed by Cubrinovski and others (Cubrinovski & Ishihara 2004; Cubrinovski et al. 2006a)), the effects of variation of the model parameters on the predicted pile response were explored via a deterministic sensitivity analysis. The analysis demonstrated that the predicted pile performance is largely controlled by a few critical parameters. The results indicate that an understanding of the effects of parameter variations on the predicted pile response is essential for the consistent and reliable use of simplified design methods. Without parametric evaluation, deterministic pile analysis and design methods cannot be used with confidence.

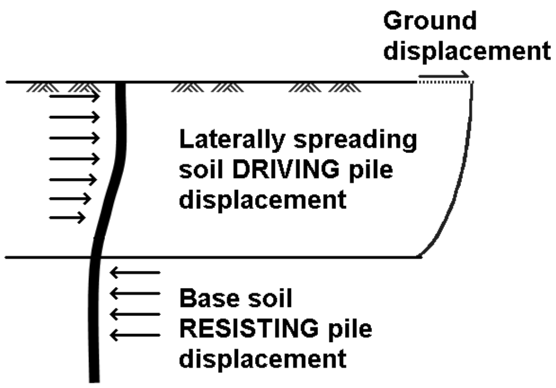

Figure 1. Illustration of the soil layers driving and resisting pile displacement in lateral spreads

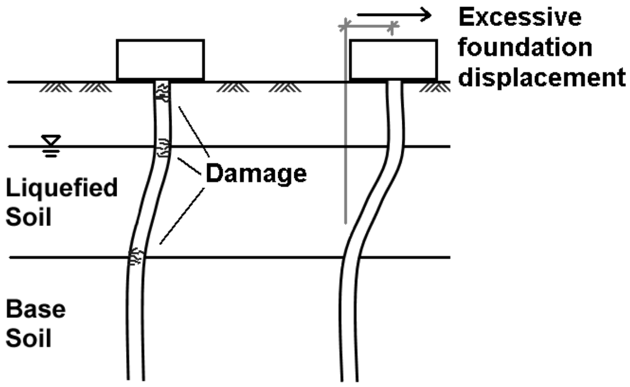

Figure 2. The two most common modes of 'failure' of piles in laterally spreading soils: pile damage and excessive foundation displacement

2 PERFORMANCE OF PILES IN LATERALLY SPREADING SOILS

During the initial strong shaking phase of an earthquake, a pile foundation is subjected to inertial loads due to the motion of the superstructure, and pressures due to the cyclic displacement of the surrounding soil. As liquefaction develops the strength and stiffness of the soil are degraded, and after the strong ground motion has ceased, it can take some time for the liquefied soil to regain strength. It is during this time that large lateral spreading displacements may occur. This displacing soil can apply very large kinematic pressures to the piles. Figure 1 illustrates the different soil layers driving and resisting pile displacement as lateral spreading occurs.

In order to fully appreciate the significance of parametric uncertainties in the assessment of pile performance, it is important to understand the characteristics of lateral spreading loads and the nature of the pile response. Case studies of past lateral spreading events (e.g. Abdoun & Dobry 2002; Finn & Fujita 2002) reveal that the extent to which piles follow or resist the displacement of the soil varies. As noted by Cubrinovski et al. (2006b), this response depends on the lateral stiffness of the piles and the magnitude of the pressure from the displacing soil. Another common observation from case histories is the concentration of pile damage (cracking, yielding, and even complete rupture of the pile) at the connection to the pile cap and the upper and lower boundaries of the liquefied soil, where there is a sudden change in soil properties (Tokimatsu & Asaka 1998; Cubrinovski et al. 2006a).

To achieve acceptable performance, not only must damage of the foundation itself be avoided, but the safety and serviceability of the structure, which are likely to be influenced by foundation displacements, must be ensured. These two failure/deformation modes are illustrated in Figure 2.

3 SIMPLIFIED ANALYSIS METHODS

There is no universally accepted method for the simplified design and analysis of piles in laterally spreading soils, although many have been developed (e.g. Cubrinovski & Ishihara 2004). In force-based or 'seismic coefficient' methods, a pseudo-static load representing the pressure from the spreading soil is estimated and applied to the pile directly. However, the soil pressure that is actually mobilised depends on the relative displacement of the soil and the pile, and hence depends on the pile response. Force-based methods typically do not take account of this, resulting in incompatible soil pressures and displacements. They are thus unable to reliably capture the mechanism of soil-pile interaction.

In contrast, displacement-based methods typically model the soil-pile system as a series of springs and beam elements, to which pseudo-static soil displacements (in this case representing the lateral spreading of the soil) can be applied via movement of the soil springs, as illustrated in Figure 3. As the forces developed in the soil springs are compatible with the displacement of the pile, displacement-based methods are better able to capture the pile response and the mechanism of soil-pile interaction, and are thus superior to force-based methods both in practice, and for the purpose of uncertainty analysis.

This paper focuses in particular on a simplified, displacement-based method developed by Cubrinovski and others (Cubrinovski & Ishihara 2004; Cubrinovski et al. 2006a). The method is straightforward to use, requiring conventional engineering parameters as input, but is flexible in terms of the soil-pile systems that can be modelled, making it suitable for use in practice. Through the use of tri-linear beam elements to model the pile, the method is able to accurately predict both the pattern of damage to the pile and the maximum bending moment. Figure 4 shows the tri-linear moment-curvature relationship for a typical 1200 mm diameter reinforced concrete pile, indicating the threshold curvatures for cracking, yielding, and ultimate failure of the pile. Furthermore, this analysis method can accommodate non-linear soil behaviour through the use of bi-linear soil springs, allowing the stresses mobilised in the soil to be reasonably predicted.

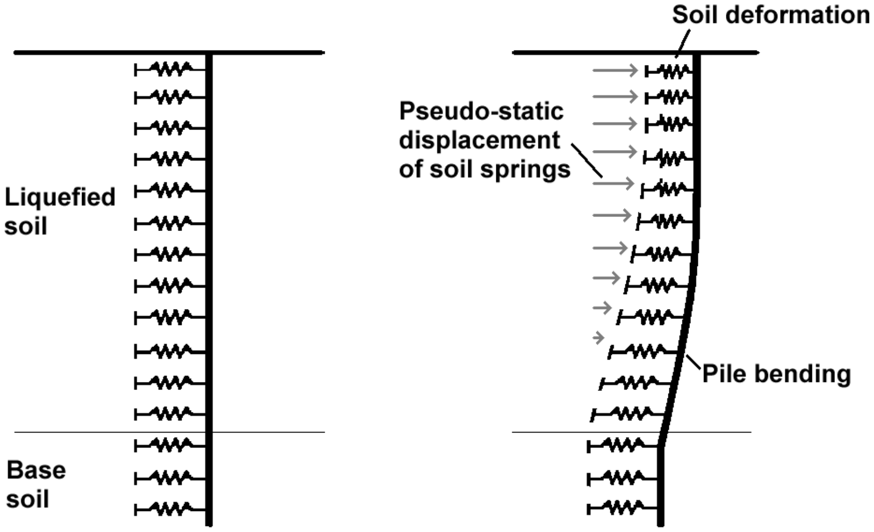

Figure 3. Beam-spring finite element model representing the soil-pile system showing the application of lateral spreading demands via the movement of the soil springs

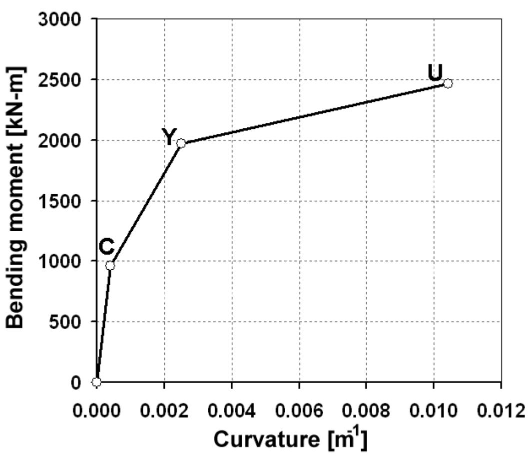

Figure 4. Tri-linear moment-curvature relationship for a typical 1200 mm diameter reinforced concrete pile

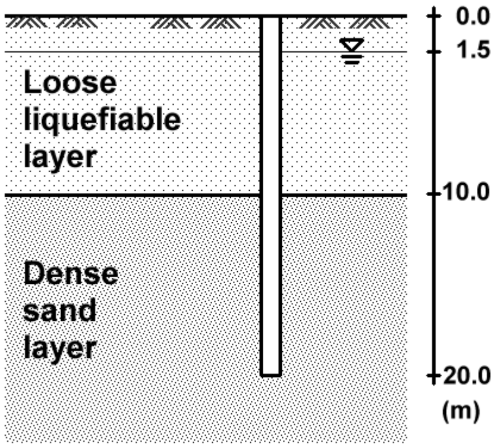

Figure 5. Example soil-pile system for the illustration of lateral spreading demands on piles

4 PARAMETRIC UNCERTAINTIES

The principal requirement of the users of simplified pile analysis methods is the ‘translation’ of the complex soil-pile system that exists in reality into an equivalent model that exhibits the same fundamental behaviour. Aside from the properties of the pile, which are the choice of the engineer, the model parameters (essentially the force-displacement (P-δ) curves for the soil springs, and the lateral spreading demand) must be determined indirectly as functions of various soil properties and the input ground motion (earthquake demand). The soil properties would typically be estimated from site investigation data via established empirical relationships. Such relationships are inexact and thus introduce uncertainties to the model. These introduced uncertainties are in addition to the inherent uncertainties associated with soil liquefaction and lateral spreading, in particular: the degradation of the soil stiffness due to liquefaction, the ultimate pressure from the liquefied soil, and the magnitude of the lateral spreading displacement.

Taking the soil profile shown in Figure 5 as an example (in which a 10 m thick layer of loose, liquefiable soil overlies a dense, non-liquefiable sand), the shaded envelope of Figure 6 illustrates the range of P-δ curves that might reasonably be expected to represent the liquefied soil. Specifically, the degraded stiffness liquefied soil can be anything from 0.1 to 1% of the initial soil stiffness, k_i, and its ultimate strength, P_{max}, might vary by a factor of 6. In addition, there is significant uncertainty in the magnitude of the lateral spreading displacement. For example, using Youd et al.’s empirical (case history-based) lateral spreading equations (Bartlett & Youd 1995; Youd et al. 2002) to estimate a surface ground displacement of 0.5 m, an envelope of expected displacement ranging from 0.25-1.0 m should be considered (Fig. 7), simply reflecting the scatter of the empirical correlation.

5 SENSITIVITY OF THE PILE RESPONSE

Having considered the typical scale of variation of the model parameters due to uncertainties in their definition, we now focus on how these variations affect the prediction of pile response, in particular:

- The sensitivity of the pile response (pile head displacement and peak pile curvature) to variations of the model parameters, and thus whether a range of values for each parameter need to be considered.
- Which of the uncertain parameters have the greatest influence on the pile response, and thus require the greatest investment of time and resources when specifying the simplified model, and which have a negligible effect on pile response and can justifiably be ignored.
- How the parametric sensitivities relate to the mechanism of soil-pile interaction.

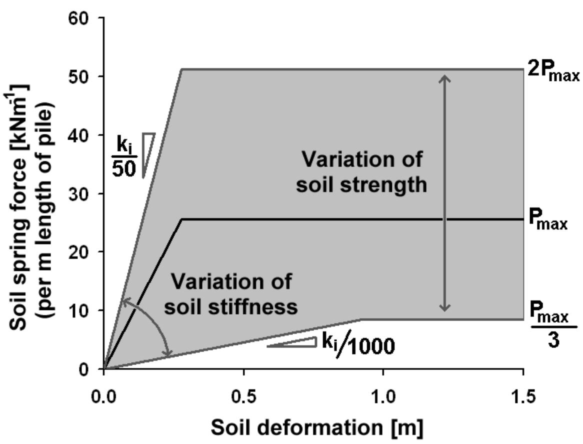

Figure 6. Expected variation of the bi-linear P-δ curve representing the liquefied, laterally spreading soil

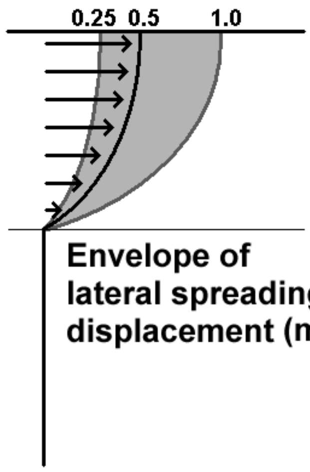

Figure 7. Expected variation of the lateral spreading soil displacement

Parametric analyses designed to isolate each of the sources of uncertainty affecting the soil spring properties have been conducted for a wide range of soil-pile systems and lateral spreading demands (summarised in Fig. 8). The details and full results from these analyses are presented by Haskell (2008).

Continuing the earlier example (the 1200 mm diameter reinforced concrete pile embedded in loose, liquefiable soil and dense, non-liquefiable base layer of sand, as shown in Fig. 5), Figure 9 shows the predicted pile displacement and bending moment distribution when the 'reference' or 'best guess' values are used for all model parameters. The pile head displacement, approximately 0.12 m, is much less than the 0.5 m lateral spreading displacement (as depicted in Fig. 9a), meaning the pile is largely resisting the soil movement. The peak moment demand, approximately 2160 kN-m, exceeds the yield capacity of the pile, 1970 kN-m, indicating significant pile damage is likely to occur.

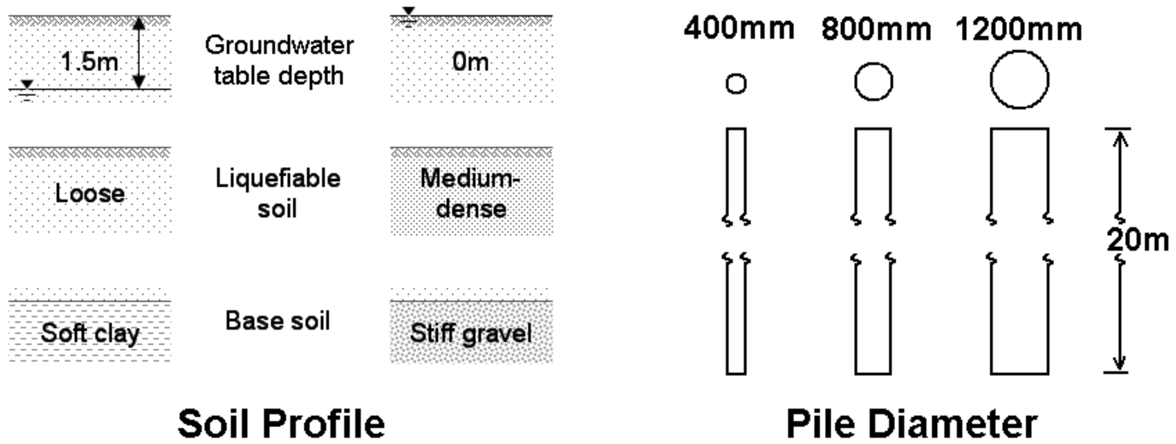

Figure 8. Range of soil and pile properties considered by Haskell (2008) in the full suite of analyses

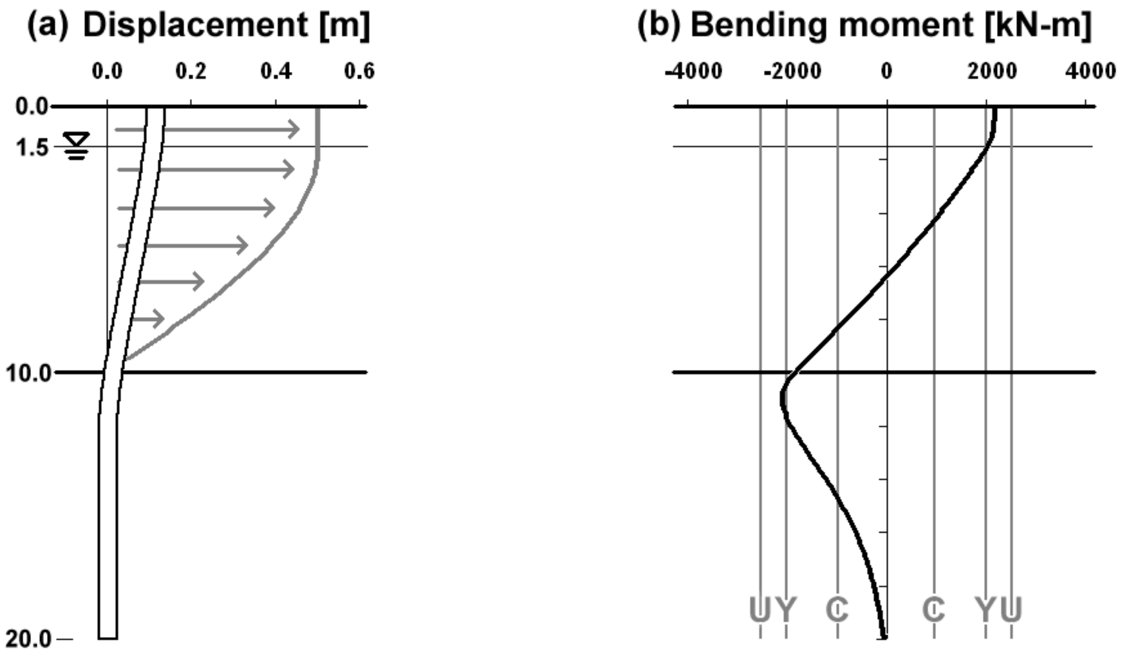

Figure 9. Reference pile (a) displacement and (b) bending moment distribution for a ground surface displacement of 0.5 m

If a purely deterministic procedure is being followed, involving only a single analysis of the pile response using ‘best guess’ values for the model parameters, the engineer must now decide whether or not this level of performance (i.e. 0.12 m displacement and yielding of the pile) is acceptable, and then proceed to either complete the design or select another pile. Regardless of their decision, they proceed without any knowledge of the consequences of their modelling choices. Furthermore, the complexity of the interaction between piles and laterally spreading soils means it is not obvious whether erring towards higher or lower values for certain model parameters results in a greater demand on the pile. For example, the more dense the liquefiable soil, the greater its resistance to liquefaction and lateral spreading and thus the smaller the lateral spreading displacement is likely to be. However, denser liquefiable soil is also likely to have a greater stiffness and ultimate strength, meaning it can apply a greater load on the pile. It is thus not possible to adopt an overly conservative stance in lieu of a proper understanding of the soil and pile response.

Figure 10 shows the influence of the lateral spreading displacement on the predicted pile response. For this relatively stiff pile, the variation of soil displacement does not greatly affect the pile head displacement or the peak bending moment/peak pile curvature. Furthermore, the pile response becomes less sensitive to the magnitude of the lateral spreading displacement as the applied displacement is increased, suggesting that the soil springs have yielded and that greater-than-expected soil movements will not alter the mechanism of soil-pile interaction.

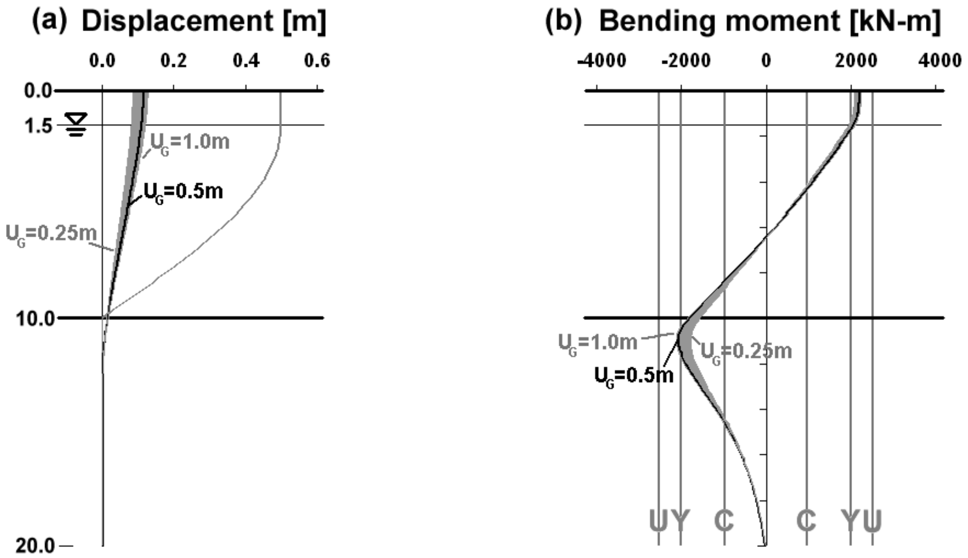

Figure 10.Variation of (a) the pile displacement and (b) the bending moment distribution when the ground displacement is varied from 0.25-1.0 m

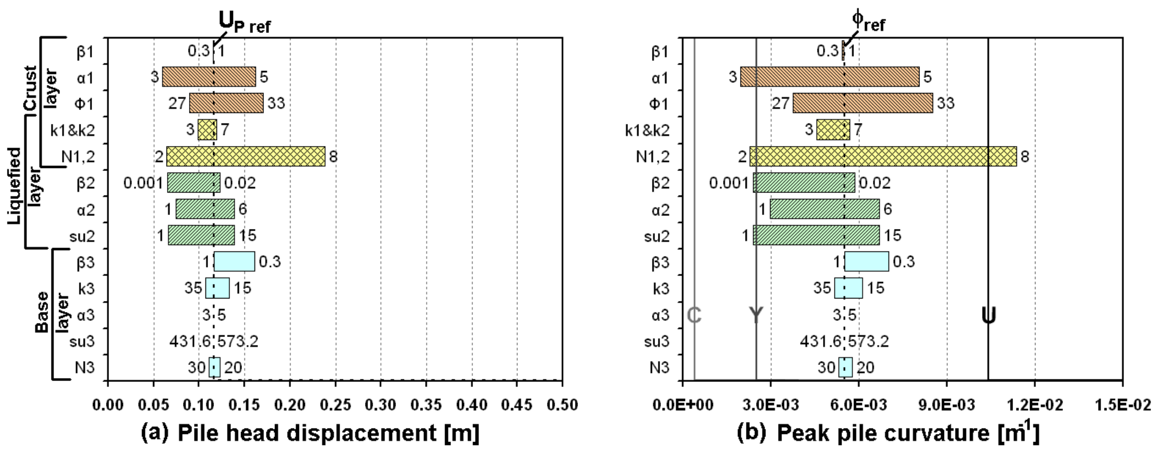

Figure 11. Effect of variation of the soil properties on (a) the predicted pile head displacement and (b) the peak pile curvature for a ground displacement of 0.5 m

The potential variation of pile head displacement and peak pile curvature due to variation of the soil spring properties is illustrated in Figure 11. Each bar of these 'tornado charts' corresponds to a specific source of uncertainty (Haskell 2008). The dashed lines represent the reference response, obtained using the reference values for all the model parameters and an applied ground displacement of 0.5 m. The cracking, yielding, and ultimate curvatures of the pile are indicated in Figure 11b, allowing the damage to the pile to be readily assessed. The numbers at the ends of the bars show the range of variation of each input parameter and, while not a feature of this discussion, have been provided as they clearly indicate the scale of the uncertainties being considered. As mentioned earlier, these ranges of variation, while intended to represent the uncertainty in the values of the model parameters, do not have a statistical probabilistic significance. They are based on the observations and analyses from lateral spreading case histories and physical models tests, and the empirical relationships used to calculate the values of the model parameters.

The selection of certain parameter values can roughly double (or halve) the predicted pile response and, in this case, will determine whether or not the ultimate curvature capacity of the pile is exceeded. In contrast, the pile response is relatively insensitive to the properties of the base layer, and any variation of these properties results in a change in the 'fixity' of the pile, with softening of the base soil resulting in greater compliance, rather than a fundamental change in the mechanism of soil-pile interaction. Ultimately 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 to an increase (or decrease) of the relative stiffness of the pile and the soil.

Clearly some parameters (specifically the strength and stiffness of the liquefied soil and the load from any overlying layer of non-liquefied soil) are more critical than others, essentially controlling the magnitude of the pile response. The results from the full suite of parametric analyses suggest that the relative importance of these critical parameters depends on the nature of the pile response and the mechanism of soil-pile interaction.

For the critical parameters, the relationship between the sensitivity of the pile response to parametric variations and the mechanism of interaction between the soil and pile is summarised in Figure 12, which covers the full range of soil-pile systems outlined earlier (i.e. 400, 800, and 1200 mm diameter piles, loose to medium-dense liquefiable soil, soft clay and dense sand base layers, and lateral spreading displacements ranging from 0.1 to 2.0 m). On the x-axis is the 'yield ratio' of the liquefied soil, the ratio of the relative soil-pile displacement and the yield displacement of the soil springs at the ground surface. It is analogous to 'ductility' (as defined in structural mechanics), and indicates both the extent of yielding of the liquefied soil and the mechanism of soil-pile interaction. For example, small yield ratios (less than 1) indicate that the soil has not yielded and the pile is essentially following the displacement of the laterally spreading soil, while larger yield ratios mean the pile is resisting the soil displacement and the ultimate soil pressures have been mobilised (i.e. the bi-linear soil springs have yielded). The y-axis shows the sensitivity of the predicted peak pile curvature to the variation of a particular parameter (for example the stiffness degradation of the liquefied soil). The sensitivity is defined as the change in the predicted peak pile curvature (i.e. the length of the bar of the curvature tornado chart corresponding to the parameter) relative to the reference peak pile curvature.

Figure 12 shows that, at low yield ratios the stiffness of the liquefied soil is the most critical, and can cause the peak pile curvature to vary by more than a factor of 2 when the groundwater table is at the ground surface. In contrast, the soil strength governs the pile response at higher yield ratios, when there is significant yielding of the liquefied soil. Varying the strength of the liquefied soil in the simplified model (within the range of values that it might reasonably be expected to take) can cause a fourfold variation of the peak pile curvature. For all yield ratios, the sensitivity of the response to both the stiffness and the strength of the liquefied soil reduces as the thickness of the non-liquefied crust is increased (i.e. the groundwater table is lowered below the ground surface), implying that the load from the crust is beginning to dominate the pile response. Regardless of the properties of the pile and the various soil layers, the yield ratio provides a robust index of the mechanism of soil-pile interaction and the relative importance and potential influence of values adopted for the critical parameters affecting the predicted pile response. Variations of different model parameters that have the same effect on the yield ratio can, in many ways, be regarded as equivalent.

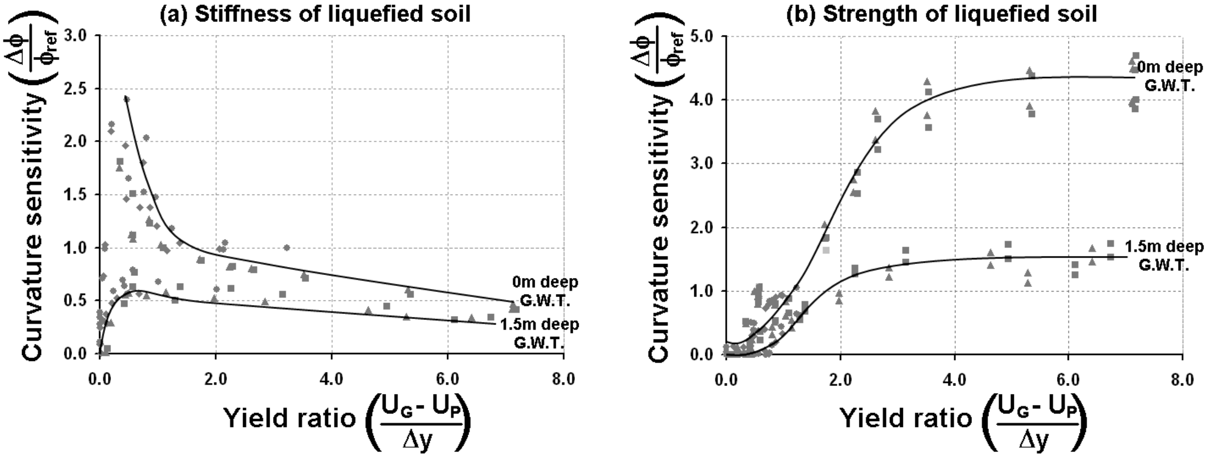

Figure 12. Sensitivity of the predicted peak pile curvature to variation of (a) the stiffness and (b) the strength of the liquefied, laterally spreading soil, showing the change in their relative importance a yielding of the liquefied soil occurs

6 CONCLUSIONS

The ultimate goal in the simplified analysis of piles in laterally spreading soils is to capture the essential features of the pile and soil behaviour. The considerable uncertainties affecting the response of piles mean that 'unique' or 'exact' values for the various parameters in a model cannot be reliably defined, and the precise response of the pile cannot be 'predicted'.

By considering the likely variation of those parameters that critically affect the pile response (namely the stiffness and strength of the liquefied soil, and the load from any overlying crust of non-liquefied soil), the full variation of pile performance for a given soil-pile system and lateral spreading demand can be estimated. By way of the yield ratio, the sensitivity of the response to these critical parameters also provides an insight into the likely mechanism of soil-pile interaction.

The analysis of pile response using simplified deterministic methods is straightforward, but unreliable, unless due consideration is given to the sensitivity of the predicted response to the variation of critical model parameters. By taking an additional step and exploring the effect of parametric variations on the predicted response, a much more robust assessment of the likely pile performance can be made, resulting in more consistent use of simplified methods for the preliminary design of piles. In this way simplified methods provide the engineer with a tool to enhance, but not replace their engineering judgement.

ACKNOWLEDGEMENT

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