Key parameters in pseudo-static analysis of piles in liquefying sand

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ABSTRACT

Soil-pile interaction in liquefying soils is very complex and involves rapid changes in soil characteristics and loads on piles. Thus, when analyzing the behaviour of piles with a simplified pseudo-static approach, the key issue is how to determine appropriate values for the parameters of the model while considering the inherent uncertainties associated with liquefaction. This paper identifies key parameters in the pseudo-static analysis of piles in liquefying soils and provides guidance for their determination based on observations from case histories and full-size tests.

1 INTRODUCTION

There are several methods available for analysis of piles in liquefying soils including sophisticated finite element analysis based on the effective stress principle and simplified methods using the pseudo-static approach. Irrespective of the adopted analytical method, however, the analysis of piles in liquefying soils is burdened by unknowns and uncertainties associated with liquefaction and lateral spreading in particular. For example, it is very difficult to estimate the strength and stiffness of liquefied soils or predict the magnitude and spatial distribution of lateral spreading displacements. One of the key aspects of the simplified analysis is therefore to properly address these uncertainties through parametric studies using a relatively simple model with conventional engineering parameters. This paper examines the use of the pseudo-static analysis of piles in liquefying soils and identifies key parameters influencing the pile response.

2 CYCLIC LIQUEFACTION AND LATERAL SPREADING

When analyzing the behaviour of piles in liquefied soils, it is useful to distinguish between two different phases in the soil-pile interaction: a cyclic phase in the course of the intense ground shaking and consequent development of liquefaction, and a lateral spreading phase following the liquefaction. During the cyclic phase, the piles are subjected to cyclic horizontal loads due to ground movement (kinematic loads) and inertial loads from the superstructure, as illustrated schematically in Figure 1a. The combination of these oscillatory kinematic and inertial loads determines the critical load for the integrity of the pile during the shaking. Lateral spreading, on the

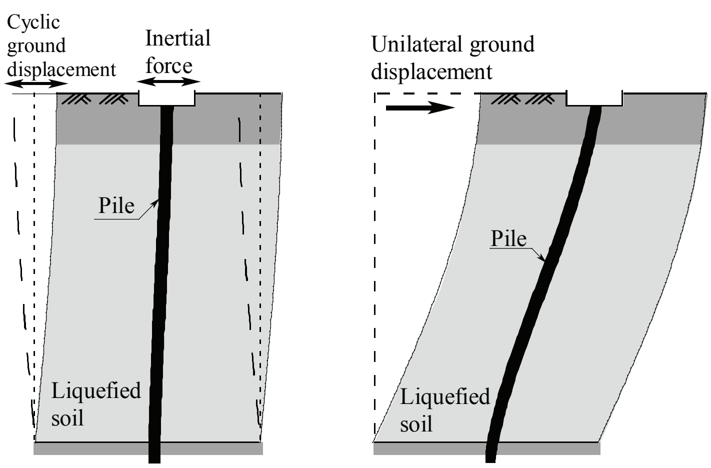

Figure 1. Cyclic phase and lateral spreading phase

other hand, is primarily a post-liquefaction phenomenon that is characterized by very large unilateral ground displacements and relatively small inertial effects (Figure 1b). Thus, both liquefaction characteristics and lateral loads on piles are quite different between the cyclic phase and the subsequent lateral spreading phase, and therefore, these two phases should be considered separately in the simplified pseudo-static analysis of piles.

3 PSEUDO-STATIC APPROACH FOR SIMPLIFIED ANALYSIS

The most frequently encountered soil profile for piles in liquefied deposits consists of three distinct layers, as illustrated in Figure 2 where the liquefied layer is sandwiched between a non-liquefied crust layer at the ground surface and non-liquefied base layer. Liquefaction during strong ground shaking results in almost a complete loss of strength and stiffness of the liquefied soil, and consequent large lateral ground displacements. Particularly large and damaging for piles are post-liquefaction displacements due to lateral spreading of the ground. During spreading, the non-liquefied surface layer is carried along with the underlying spreading soil, and when driven against embedded piles, the crust layer is envisioned to exert large lateral loads on the piles. Thus, the excessive lateral movement of the liquefied soil, lateral loads from the surface layer and significant stiffness reduction in the liquefied layer, are key features that need to be considered when evaluating the pile response to lateral spreading.

Based on the characteristics and kinematic mechanism as described above, a three-layer soil model was adopted for a simplified pseudo-static analysis of piles in a previous study (Cubrinovski and Ishihara, 2004). As indicated in Figure 3, in this model the pile is represented by a continuous beam while the interaction between the liquefied soil and the pile (p-δ relationship) is specified by an equivalent linear spring ($\beta_2 k_2$). Here, k_2 is the subgrade reaction coefficient while β_2 is a scaling factor representing the degradation of stiffness due to liquefaction. In the analysis, cyclic or spreading ground movement is represented by a horizontal free-field displacement of the liquefied soil while effects of the surface layer are modelled by an earth pressure and lateral force at the pile head. Note that the lateral force at the pile head may also include inertial loads from the superstructure. Needless to say, one may use an FEM beam-spring model instead of the above closed-form solution and conduct even more rigorous analysis, because it will permit consideration of multiple load-deformation relationships along the pile length. In principle, however, the following discussion applies to the pseudo-static analysis of piles, in general.

Input parameters of the computational model and adopted load-deformation relationships for the soil and the pile are shown in Figure 3. Three bilinear p-δ relationships are adopted for the respective soil layers while tri-linear moment-curvature relationship (M-ϕ) is used for the pile. The

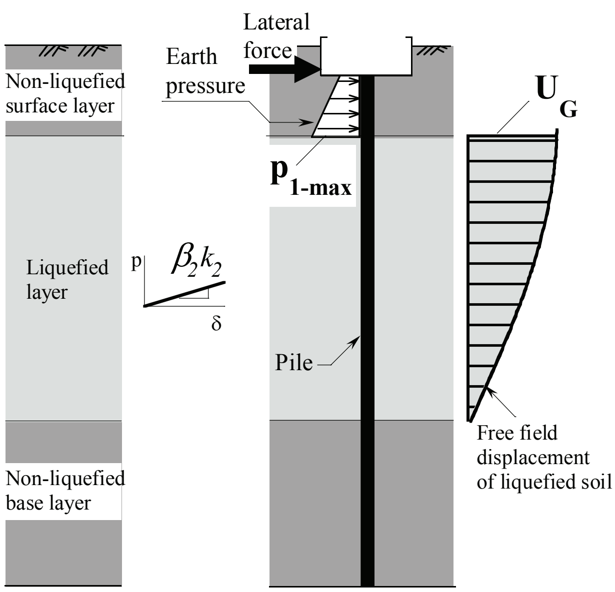

Figure 2. Simplified mechanism of lateral spreading

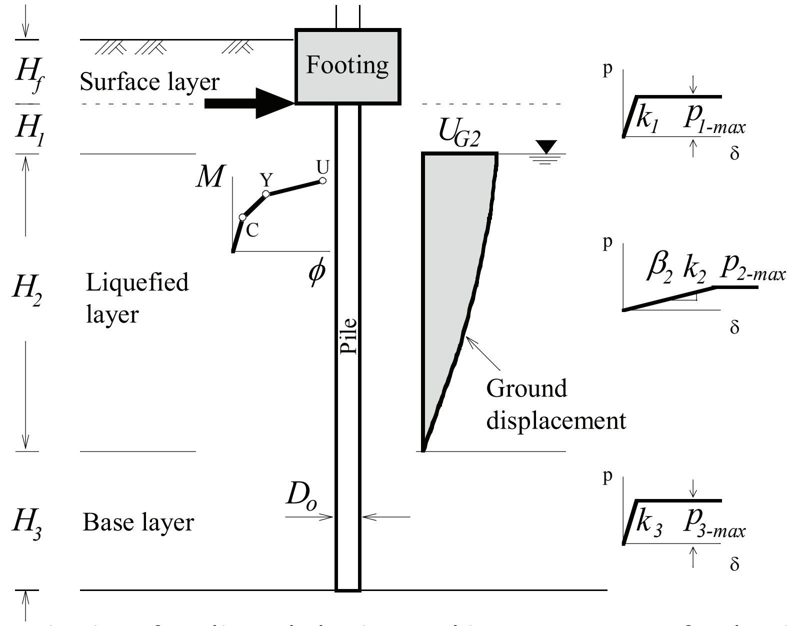

Figure 3. Characterization of nonlinear behaviour and input parameters for the simplified analysis

subgrade reaction coefficients in the bilinear p-δ relationships can be evaluated using empirical correlations based on the elastic property or SPT blow count of the soil, as described in Cubrinovski and Ishihara (2004). In the analysis of a given pile, it is envisioned that β_2 will serve as a parameter that will be varied over a relevant range of values, thus permitting evaluation of the pile response by assuming different stiffness characteristics of the liquefied soil. p_{max} defines the ultimate lateral pressure that can be applied by the soil to the pile in the course of cyclic liquefaction and lateral spreading. In the following section, key parameters in the adopted model are identified and selection of their most appropriate values is discussed based on results from large-scale experiments and back-calculations from case histories.

4 KEY PARAMETERS IN THE PSEUDO-STATIC ANALYSIS

4.1 Lateral ground displacement

In both cases of cyclic displacements and spreading displacements, the lateral ground displacement that is used as an input in the simplified analysis is a free field ground displacement which is unaffected by the pile foundation.

Cyclic ground displacements can be estimated relatively accurately by means of an effective stress analysis, but the use of an advanced analysis for defining the input in a simplified analysis is not practical. Hence, it seems more appropriate for the pseudo-static analysis to estimate the peak cyclic displacements by using simplified charts correlating the maximum cyclic shear strain that will develop in the liquefied layer with the cyclic stress ratio and SPT blow count, as suggested by Tokimatsu and Asaka (1998), for example. The horizontal cyclic displacement profile can be then easily obtained by integrating the shear strains throughout the depth of the liquefied layer.

The lateral displacement of the spreading soil can be evaluated using empirical correlations for ground displacements of lateral spreads (Ishihara et al., 1997; Tokimatsu and Asaka, 1998; Youd et al., 2002). It is important to recognize, however, that in most cases it would be very difficult to make a reliable prediction for spreading displacements, and therefore it would be necessary to vary the magnitude of the spreading displacement within the estimated range of values.

4.2 Lateral pressure from the crust layer

The lateral load from the unliquefied crust layer may often be the critical load for the integrity of the pile because of its large magnitude and unfavourable position as a “top-heavy” load acting above

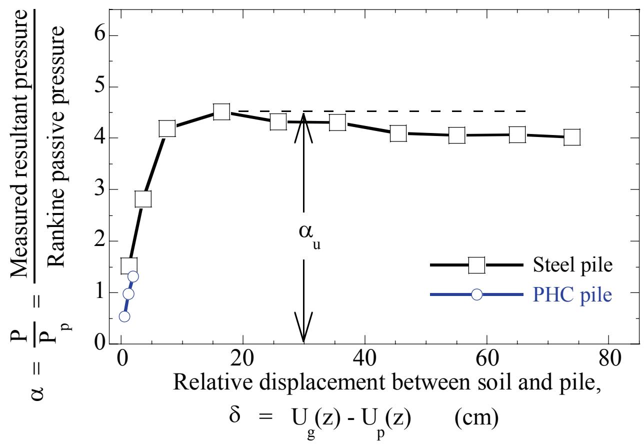

Figure 4. Lateral pressure from the crust layer on a single pile (full-size test on piles)

above a laterally unsupported portion of the pile in the liquefied soil. For the adopted bilinear p-δ relationship for the crust layer, the key input parameter is the ultimate lateral pressure, $p_{1\text{-}max}$.

The ultimate soil pressure from the surface layer per unit width of the pile can be estimated using a simplified expression such as, $p_{1\text{-}max} = \alpha_u\, p_p$, where $p_p(z_1)$ is the Rankine passive pressure while α_u is a scaling factor to account for the difference in the lateral pressure between a single pile and an equivalent wall. Figure 4 shows the variation of α_u with the relative displacement observed in a lateral spreading experiment on full-size piles (Cubrinovski et al., 2006) with the maximum lateral pressure on the single pile being about 4.5 times the Rankine passive pressure. Note that α_u can be also used for considering a possible reduction in the mobilized pressure from the crust layer due to sand-boils, fissuring of the ground or impediment of ground deformation by adjacent foundations.

4.3 Stiffness and strength of the liquefied layer

The factor β_2, which specifies the reduction of stiffness due to liquefaction ($\beta_2 k_2$) is affected by a number of factors including the density of sand, excess pore pressures, magnitude and rate of ground displacements, and drainage conditions. Typically, β_2 takes values in the range between 1/50 and 1/10 for cyclic liquefaction and between 1/1000 and 1/50 in the case of lateral spreading. Because of this large variation in β_2, it is recommended to examine the effects of stiffness reduction on the pile response through parametric studies, by varying β_2 in the relevant range of values.

The ultimate soil pressure in the bilinear $p\text{-}\delta$ relationship for the liquefied layer can be approximated with the undrained residual strength of the soil. The empirical correlation between the undrained strength and SPT blow count proposed by Seed and Harder (1991) can be used for this purpose (Figure 5). Since the scatter of the data is quite large and hence the value of S_u may vary significantly for a given SPT blow count, the two bounding values for the residual strength might be used, i.e. the upper bound value $S_{u\text{-}ub}$ and the lower bound value $S_{u\text{-}lb}$ respectively, as indicated in Figure 5. Whereas a relatively wide range of values has to be considered for the parameters introduced above, it is important to adopt a consistent approach in the selection of the values where, for example, a relatively small ground displacement will be associated with higher stiffness (β_2 value) and higher ultimate pressure (S_u value) for the liquefied soil. Application of the method to a case study and effects of the selected of S_u on the pile response are discussed in the companion paper Bowen et al. (2007).

4.4 Pile group effects

Piles in a group are almost invariably rigidly connected at the pile head, and therefore, when subjected to lateral loads, all piles will share nearly identical horizontal displacements at the pile head. During lateral spreading of liquefied soils in a waterfront area, each of the piles will be subjected to a different lateral load from the surrounding soils, depending upon its particular location within the group and the spatial distribution of the spreading displacements. Consequently, both the interaction force at the pile head and the lateral soil pressure along the length of the pile

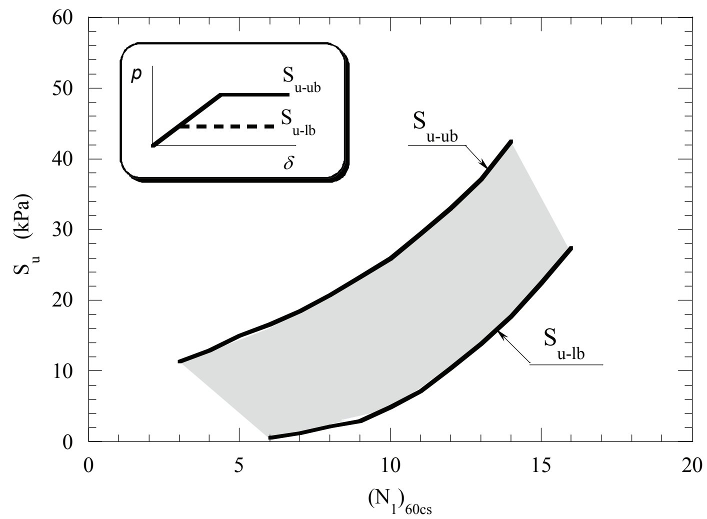

Figure 5. Undrained residual strength (S_u) from case histories (after Seed and Harder, 1990)

will be different for each pile, thus leading to a development of distinct patterns of deformation and stresses along the length of individual piles in the group.

In addition to the cross-interaction effects discussed above, piles in a group may affect the value of key parameters such as the magnitude and distribution of ground displacements, stiffness characteristics of spreading soils and ultimate soil pressure. Figure 6, for example, shows pile-group effects on the ultimate lateral pressure from the crust layer where decrease in p_{max} is seen with increasing number of piles with spacing of 2.5 to 3 diameters. Experimental data on pile groups in liquefiable soils is scarce and not conclusive, and therefore further evidence for the pile-group effects on key parameters such as U_{G2}, β_2, p_{1-max} and p_{2-max} is urgently needed.

5 STIFF VERSUS FLEXIBLE PILE BEHAVIOUR

When piles are subjected to large lateral ground displacements, they generally behave either as flexible or stiff piles. Flexible piles follow the ground movement, and hence the relative displacement between the pile and the soil is small, as shown in Figure 7. Consequently, the ultimate lateral pressures from the crust layer and liquefied layer may never be mobilized. The magnitude of the ground displacement is the key parameter controlling the response of flexible piles since it practically defines the maximum deflection of the pile.

Stiff piles show strong lateral resistance and do not follow the ground movement. Consequently, the relative displacement between the pile and spreading soil is very large, with the ultimate lateral

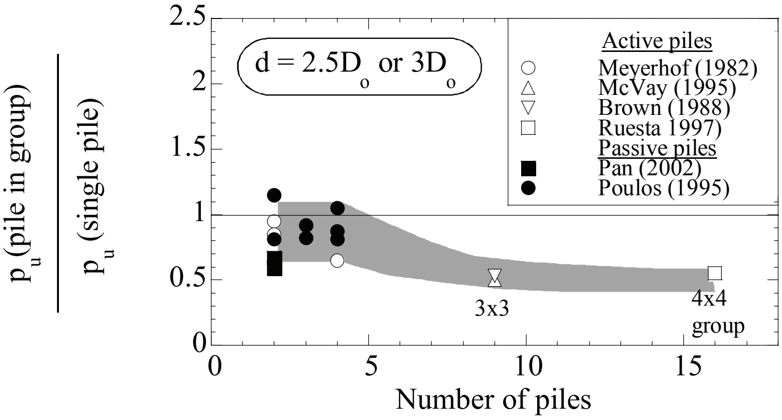

Figure 6. Pile group effects on the ultimate soil pressure

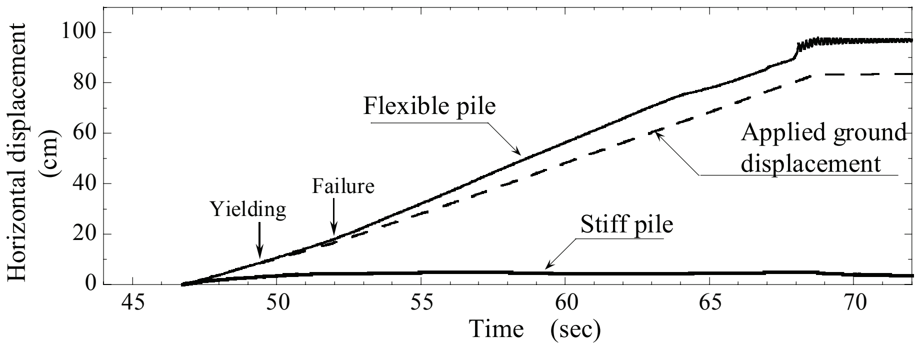

Figure 7. Measured lateral displacements of stiff and flexible piles during spreading

soil pressure being applied by the crust layer and liquefied layer to the pile. Hence, for stiff piles, the ultimate soil pressure is the key parameter in the analysis while the magnitude of ground displacement is not critically important. Note that the stiffness degradation parameter β_2 affects the relative stiffness of the pile, and that the pile response is most sensitive to β_2 when the change in the value of β_2 changes the behaviour from flexible to stiff pile behaviour and vice versa.

6 CONCLUSIONS

A simplified method for analysis of piles in liquefying soils based on the pseudo-static approach has been presented. The method uses a relatively simple model with a set of conventional engineering parameters for simulating the soil-pile interaction in liquefying soils. Because of the gross simplification of the problem and significant uncertainties associated with liquefaction and lateral spreading, the key parameters in the analysis are not uniquely defined, but rather they may vary over a wide range of values. Methods for determination of the parameters and range of relevant values for the stiffness degradation β_2 and ultimate soil pressures from the crust layer and liquefied layer, $p_{1\text{-}max}$ and $p_{2\text{-}max}$ respectively, have been presented. The relative significance of the parameters depends on the pile behaviour and is quite different for flexible piles and stiff piles. Pile groups effects on key parameters need to be accounted for especially because these effects are significant and the pseudo-static analysis is commonly performed using a single-pile model.

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