Earthquake Geotechnical Engineering Satellite Conference
XVIIth International Conference on Soil Mechanics & Geotechnical Engineering
2-3. 10. 2009, Alexandria, Egypt

THE EFFECT OF SHEAR STRENGTH NORMALISATION ON THE RESPONSE OF PILES IN LATERALLY SPREADING SOILS

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ABSTRACT

In the simplified pseudo-static analysis of piles, the ultimate lateral pressure from the liquefied soil is commonly approximated based on the residual strength of liquefied soils. This strength does not have sound theoretical basis, but rather is estimated from one of several empirical relationships between the residual strength and penetration resistance. The two empirical relationships adopted in this study, even though originating from the same database, result in substantially different strength profiles (ultimate lateral pressures on the pile) throughout the depth of the liquefied layer. Series of analyses were conducted to investigate the effects of strength normalisation on the pile response predicted by the pseudo-static analysis. It was found that effects of strength normalisation can be quite significant and that they depend on the relative stiffness of the pile and thickness of a non-liquefiable crust at the ground surface.
Keywords: Liquefaction, lateral spreading, pile, pseudo-static analysis

INTRODUCTION

The response of piles in liquefying deposits during earthquakes is very complex involving rapidly varying dynamic loads and significant reduction in soil stiffness and strength caused by liquefaction. During lateral spreading of liquefied soils, the piles are subjected to large kinematic loads due to lateral movement of the spreading soil and comparatively smaller inertial loads from the diminishing vibration of the superstructure. As illustrated schematically in Figure 1, the liquefied soil and an overlying crust at the ground surface provide driving forces for the pile displacement in the direction of spreading, while the base soil resists the pile movement. In the pseudo-static method of analysis, a relatively simple soil-pile model based on this mechanism is used to estimate the maximum deformation of the pile and its consequent damage due to spreading.

The simplified pseudo-static analysis is burdened by significant uncertainties regarding the characterization of lateral loads on the pile and properties of the adopted soil-pile model. The uncertainties and difficulties in the modelling are particularly pronounced for the parameters of the liquefied soil, such as stiffness, strength and displacement of the liquefied soil. This paper focuses on one particular aspect in the modelling of the lateral pressure from the liquefied soil and its effects on the pile response. Namely, the approximation of the ultimate pressure from the liquefied layer on the pile based on the residual strength of liquefied soils. A couple of well-known empirical relationships are available for estimating the residual strength of liquefied soils, one using non-normalised residual strength (S_r) and the other using normalised residual strength (S_r/σ'_{vo}). The key difference in the context of pile analysis is that these two relationships suggest very different distributions of strength (ultimate lateral pressure from the soil on the pile) throughout the depth of the liquefied layer. In this study, series of pseudo-static analyses were conducted to examine and quantify the effects of stress normalisation on the pile response predicted by the pseudo-static analysis. Models with different crust thickness and piles of different stiffness were considered in the analyses.

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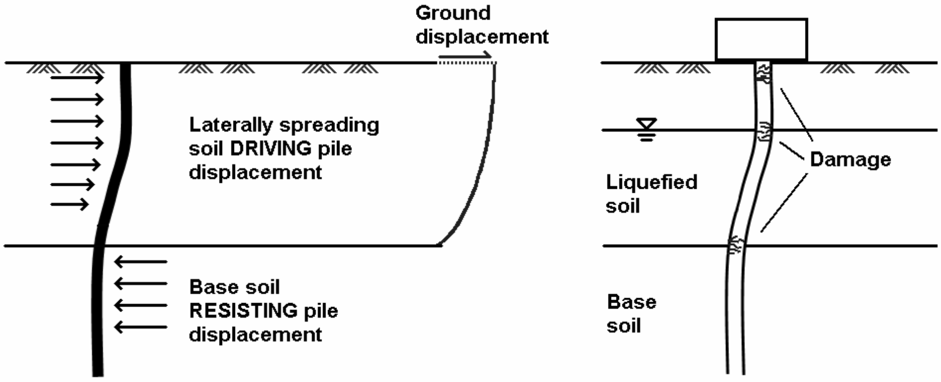

Figure 1. Schematic illustration of lateral loads on piles due to spreading of liquefied soils and consequent damage

PSEUDO-STATIC ANALYSIS OF PILES

The pseudo-static method of analysis provides a practical engineering approach for seismic assessment of piles based on routine computations and use of relatively simple models. It aims at estimating the peak response of the pile (maximum strains or curvature of the pile) due to earthquake shaking or lateral spreading under the assumption that complex dynamic loads can be idealized as static actions. Generally, two approaches are used for pseudo-static analysis of piles subjected to lateral spreading: force-based methods and displacement-based methods. These two approaches differ in the way in which the lateral load on pile due to ground movement (kinematic load) is considered.

In force-based methods, an equivalent static load representing the pressure from the laterally spreading soil is applied to the pile. For a typical three-layer configuration with a liquefied layer sandwiched between a non-liquefied surface layer (crust) and a non-liquefied base layer, the lateral earth pressures from the crust and liquefied layer are estimated and applied as driving loads (pushing the pile in the direction of spreading), as shown in Figure 2a. One serious deficiency of this approach is that it ignores the dependence of the magnitude of the mobilized lateral soil pressure on the pile response (or relative displacement between the soil and the pile). In this context, the displacement-based methods offer more rigorous modelling that is compatible with the mechanism of soil-pile interaction. In this approach lateral ground displacements (representing free field ground movement) are applied at the free end of soil springs attached to the pile, as illustrated in Figure 2b. In this case, the forces that develop in the soil springs are compatible with the relative

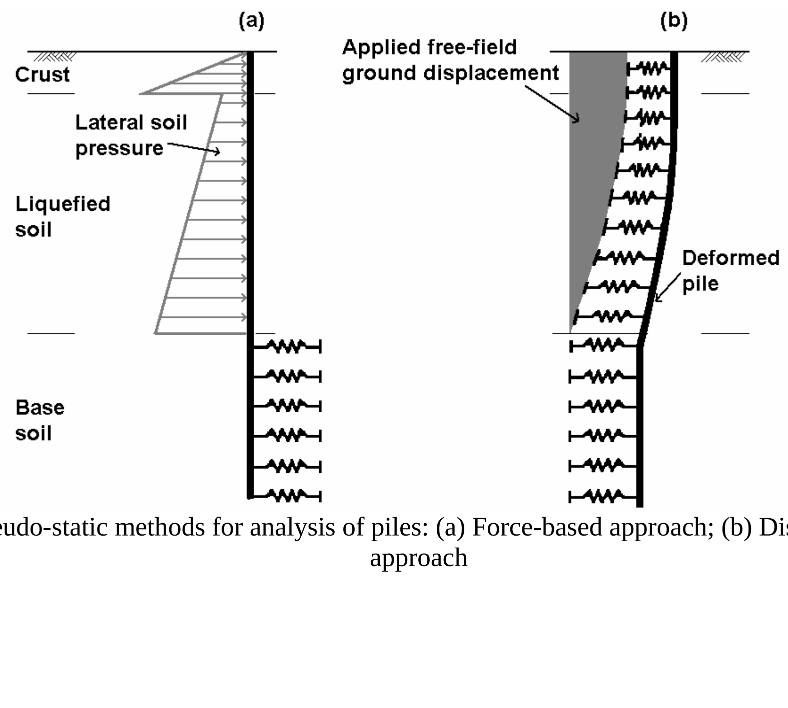

Figure 2. Pseudo-static methods for analysis of piles: (a) Force-based approach; (b) Displacement-based approach

displacement between the soil and the pile, and hence, the mobilized lateral soil pressure is compatible with the induced pile response. The displacement-based approach allows scrutiny of the behaviour of piles over the entire range of deformation, from elastic (small lateral loads) to failure (large lateral loads), and therefore was adopted in this study. Note however that, in principle, the conclusions with regard to the effects of shear strength normalisation on the pile response (the subject of this study) are applicable to both displacement-based and force-based methods.

A typical beam-spring model representing the soil-pile system in the simplified pseudo-static analysis is shown in Figure 3. Since a key requirement of the analysis is to estimate the inelastic deformation and damage to the pile, simple but non-linear load-deformation relationships are used for the soil-pile model. The pile is modelled using a series of beam elements with a trilinear moment-curvature relationship, while the soil is represented by bilinear springs in which degraded stiffness and strength of the soil are employed to account for effects of nonlinear behaviour and liquefaction. Since the behaviour of piles in liquefying soils is extremely complex, involving very large and rapid changes in soil stiffness, strength and lateral loads on the pile, one of the key questions in the implementation of the pseudo-static analysis is how to select appropriate values for these parameters in the equivalent static analysis. In other words, what are the appropriate values for β, $p_{L\text{-}max}$, U_G and F in the model shown in Figure 3? While discussion on their determination, uncertainties in these parameters and the sensitivity of the pile response to their variation can be found in Cubrinovski et al. (2009), Cubrinovski and Bradley (2008) and Haskell et al. (2009) respectively, the attention focus here is one particular aspect in the modelling of the lateral pressure from the liquefied soil on the pile.

LATERAL PRESSURE FROM LIQUEFIED SOILS

The significant uncertainties associated with the stiffness and strength of liquefied soils result in a large anticipated variation of the bilinear p-δ relationship for the liquefied soil, as illustrated in Figure 4. The ultimate lateral pressure from the liquefied soil ($p_{L\text{-}max}$) is often approximated based on the residual (shear) strength of liquefied soils (S_r) as

$$p_{L-\max} = \alpha_L S_r \tag{1}$$

where α_L is a factor that accounts for the volume of soil contributing to the generation of soil pressure on the pile (equivalent to the wedge-mechanism concept).

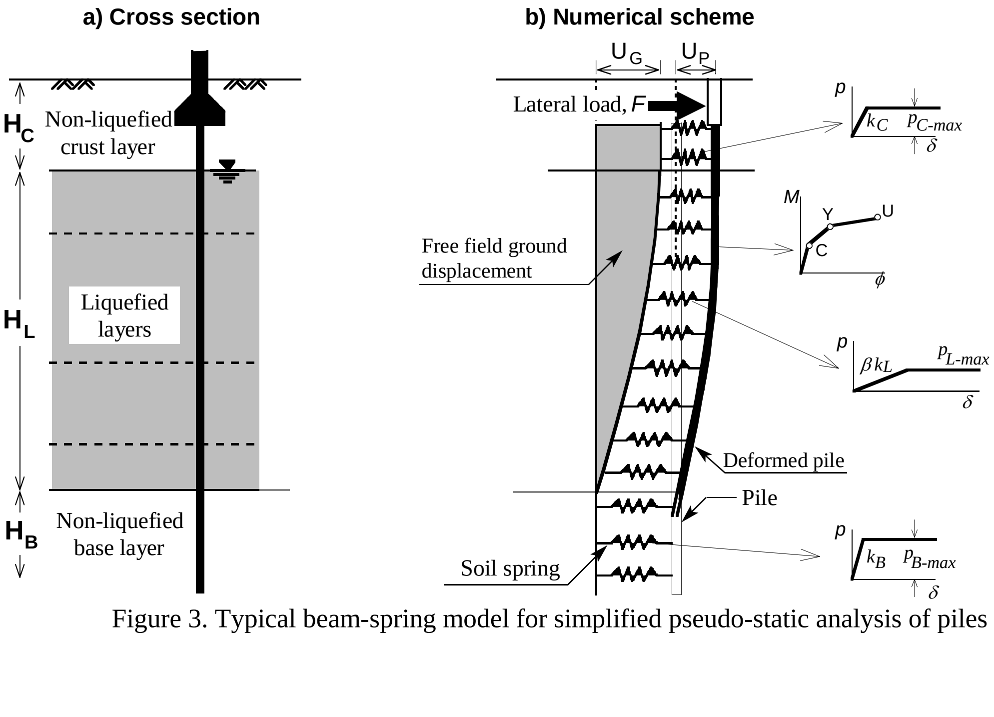

Figure 3. Typical beam-spring model for simplified pseudo-static analysis of piles

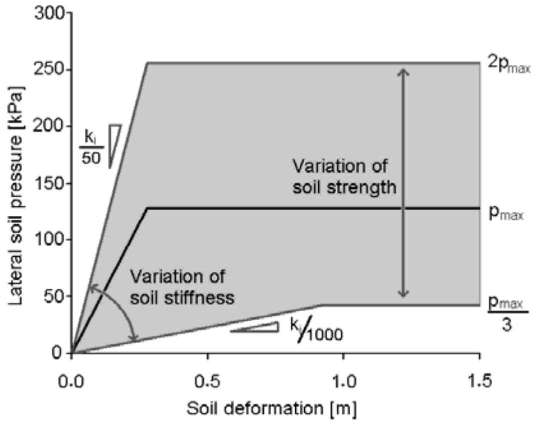

Figure 4. Schematic illustration of variation in the *p*-δ relationship for the liquefied soil

There are several empirical relationships between the residual strength of liquefied soils and penetration resistance established using back-calculations from liquefaction case histories. Based on an earlier work by Seed (1987), Seed and Harder (1990) proposed an empirical relationship between S_r and SPT blow count $(N_1)_{60cs}$, shown in Figure 5a. The relationship encompasses data of roughly 20 case histories and is characterized by considerable scatter. For example, for a normalised equivalent-sand blow count of $(N_1)_{60cs}$ = 10, the residual strength takes values between 5 kPa and 25 kPa. Using the same case history data, Olson and Stark (2002) proposed an alternative relationship between the residual strength and SPT resistance in which a normalised residual strength (S_r/σ'_{vo}) is correlated with $(N_1)_{60}$, as shown in Figure 5b. Here, the shear strength of the liquefied soil at depth *z* is normalised by the respective effective overburden stress, $\sigma'_{vo}(z)$. Recently, Idriss and Boulanger (2008) reinterpreted the same data set and proposed a pair of empirical relationships, discriminating between cases in which voids ratio redistribution (loosening of the soil during the liquefaction process) occurs or not. Again, they presented their relationships in two forms, non-normalised S_r-$(N_1)_{60}$, and normalised (S_r/σ'_{vo})-$(N_1)_{60}$.

The normalisation (or not) of shear strength of liquefied soils is an unresolved issue and recommendation of one method in preference to the other is beyond the scope of this paper. Rather, this study investigates the effect of this normalisation on the response of piles predicted using the simplified pseudo-static analysis.

INVESTIGATED SOIL-PILE MODELS

Comprehensive series of parametric analyses were conducted for different soil profiles and piles encompassing a wide range of soil properties (very loose to medium dense liquefied soil; very soft

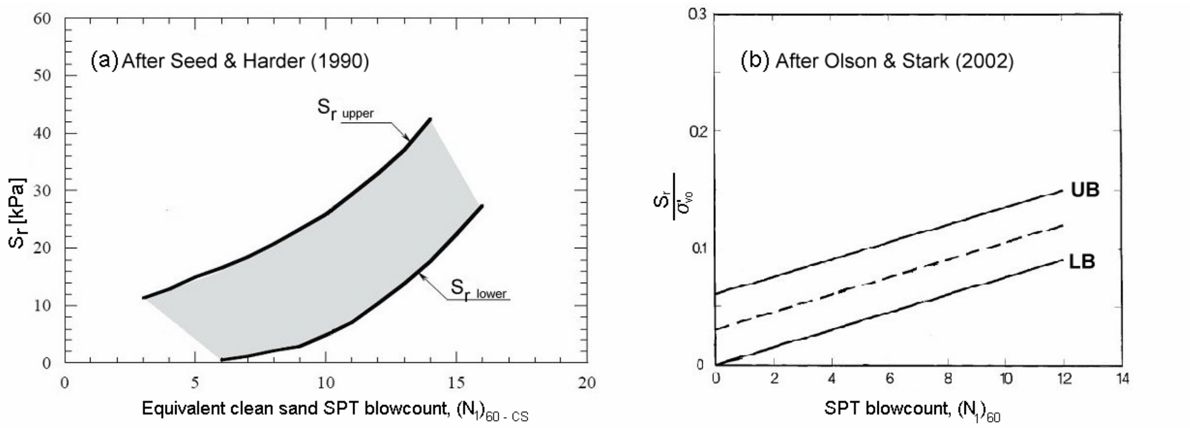

Figure 5. Empirical relationships between residual strength of liquefied soil and penetration resistance:
(a) Non-normalised, Seed and Harder (1990); (b) Normalised, Olson and Stark (2002)

to very dense base layer) and pile characteristics (flexible to stiff piles). Here, analyses and results for one of these soil profiles are presented in order to illustrate the effects of strength normalisation on the pile response. As shown in Figure 6, a 20 metre-long pile is embedded in a deposit consisting of two layers, a loose sand layer (N =5) overlying a non-liquefiable base layer of stiff gravel. Both layers have a thickness of 10 m. Assuming that the soil above the water table acts as a crust of non-liquefiable surface soil, five different scenarios were adopted for the location of the water table between z = 0 and 2 m depth, defining a crust of thickness of H_C = 0, 0.5, 1, 1.5 and 2 m respectively. The remaining part of the loose sand layer below the water table defined the thickness of the liquefiable layer, $H_L = 10 - H_C$ = 10, 9.5, 9, 8.5 and 8 m respectively. To account for the effects of relative pile stiffness on the response, three different piles with diameters of 400, 800 and 1200 mm were considered as representatives of a relatively flexible (*F-Pile*), intermediate *(M-Pile*) and relatively stiff pile *(S-Pile*) respectively. Trilinear moment-curvature relationships of actual reinforced concrete piles were adopted for the piles. In total 15 computational models were considered, with five different thicknesses of the crust and three different piles.

Details about determination of model parameters including range of realistic values, best-estimates or reference values, and effects of uncertainties on the pile response are given in Haskell et al. (2009). In the analyses of the strength normalisation effects presented herein, models with reference values of the parameters were used. For example, for the parameter α_L a reference value of α_L = 3 was adopted from a range of expected realistic values from 1 to 6. For each of the 15 computational models introduced above, lateral spreading displacements (U_G) ranging from 0.1 to 2.0 m were applied as input in the pseudo-static analysis. For each case considered, two analyses were performed, one using non-normalised strength for the liquefied soil (as proposed by Seed and Harder, 1990) and the other using normalised strength for the liquefied soil (as proposed by Olson and Stark, 2002). The resulting difference in the shear strength profiles (and respective distribution of ultimate pressure on the pile) for the two methods is schematically illustrated in Figure 7.

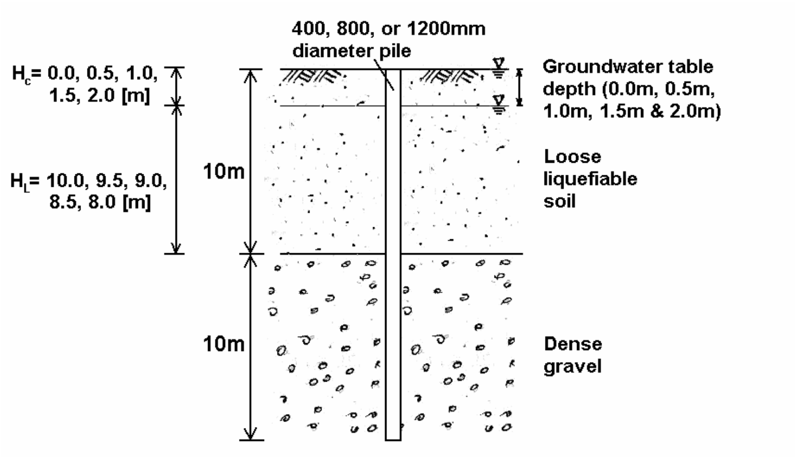

Figure 6. Soil profiles and piles adopted in the analyses

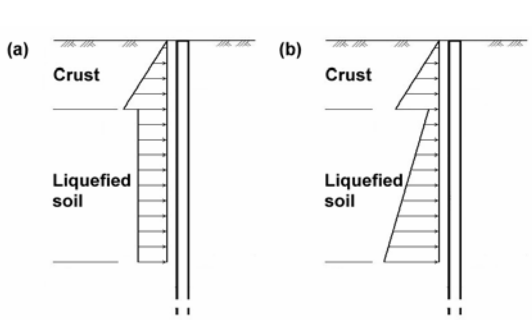

Figure 7. Distribution of residual soil strength (ultimate lateral pressure from the liquefied soil) for the methods based on: (a) Non-normalised strength, S_r; (b) Normalised strength, (S_r/σ'_{vo})

ANALYSIS RESULTS

Results of the analyses are presented in terms of the computed peak pile curvature along the length of the pile, because this curvature indicates both the size of the pile response and the level of damage to the pile. Figure 8 comparatively shows the peak pile curvatures computed in the analyses using normalised residual strength (S_r/σ'_{vo}) and non-normalised strength (S_r) for the liquefied soil. There are three phases in the relationship shown in this idealised plot that are directly related to the load-deformation mechanism of the pile. Before initiation of soil yielding (from the origin to point *A*), both analysis methods produce identical results, because in this phase the pile response is not affected by $p_{L\text{-}max}$ (strength S_r). However, once soil yielding is initiated (point *A* in Figure *8*) the response deviates from the 1:1 relationship. In the second phase (from point *A* to point *B*), the rate of increase of curvature with applied ground displacement reduces in the analysis using normalised residual strength as compared to the analysis using non-normalised residual strength. In other words, for a given ground displacement, a smaller curvature is computed in the analysis using normalised residual strength in the calculation of $p_{L\text{-}max}$. To clarify this response we need to compare the process of soil yielding for the two methods. In the analysis with normalised residual strength, soil yielding first occurs at the top of the liquefied layer as this is the location where the yield stress in the liquefied soil is the lowest, as apparent in Figure 7. The soil yielding effectively limits the lateral load from the soil on the pile, resulting in a smaller pile displacement (U_P) and consequently, larger relative displacement between the soil and the pile, $\delta = U_G - U_P$. This in turn causes propagation of the soil yielding front from the top of the liquefied layer towards the base of this layer. Eventually, the relationship levels off at point *B*, once soil yielding has been triggered throughout the entire depth of the liquefied layer and the maximum lateral load from the liquefied soil has been mobilized. The same process applies to the analysis with non-normalised strength, except that it starts and ends at larger ground displacements and pile curvatures.

Comparative plots of computed peak pile curvatures are shown in Figures 9a, 9b and 9c for piles with diameters of 400, 800 and 1200 mm respectively. For each case, results for five different thicknesses of the crust (H_C = 0, 0.5, 1, 1.5 and 2 m) are presented. For the flexible pile (*F-Pile*), very large effects of normalisation are seen for the case without crust. For this case, the ultimate pile curvature (ϕ_U) was exceeded in the analysis using non-normalised strength, whereas in the corresponding analysis using normalised strength, the computed curvature was below the cracking level. In other words, the normalisation changed the pile performance from ‘failure’ to ‘no damage’. Much smaller effects of normalisation are seen for a deposit with a 0.5 m thick crust, while no effects are seen for crusts with thicknesses of 1, 1.5 and 2 m. Effects of normalisation in reducing the peak pile curvature are also evident for the *M-Pile* and *S-Pile* for all cases with a crust thickness below 2 m.

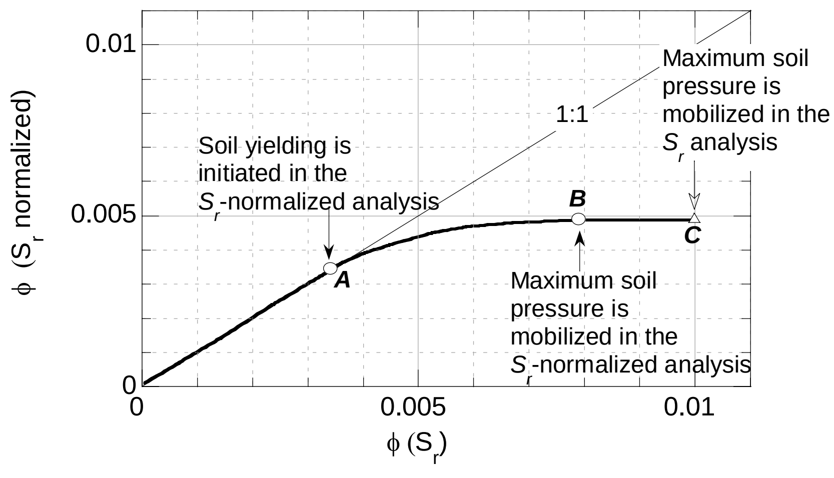

Figure 8. Typical relationship between peak pile curvatures computed in the analyses with non-normalised (S_r) and normalised strength (S_r/σ'_{vo})

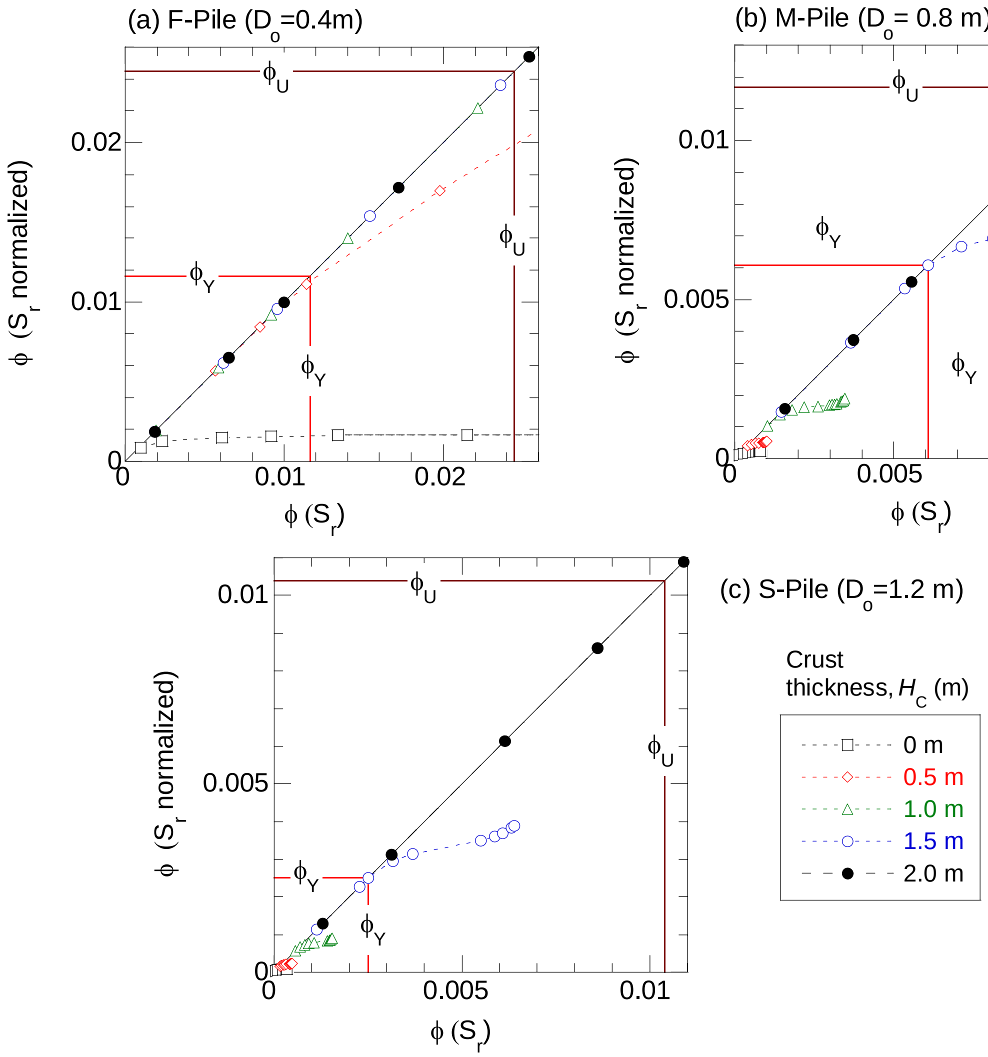

Figure 9. Comparison of peak pile curvatures computed in the analyses with non-normalised (S_r) and normalised strength (S_r/σ'_{vo}): (a) *F-Pile*; (b) *M-Pile*; (c) *S-Pile*

Clearly, the effects of normalisation on the pile response predicted by the pseudo-static analysis could be significant, and they depend both on the properties of the pile and thickness of the crust layer. To summarize these effects, the ratio of curvatures ϕ_A/ϕ_U is plotted against the thickness of the crust (H_C) in Figure 10. Here, ϕ_A and ϕ_U denote the peak pile curvature at which effects of normalisation start to influence the pile response (corresponding to point *A* in Figure 8) and the ultimate curvature of the pile respectively. The plot basically indicates whether or not the normalisation will affect the pre-failure response of the pile, as a function of pile stiffness and crust thickness. For example, for relatively flexible piles (*F-Pile*), the strength normalisation would affect the response of the pile only if the crust thickness is less than 0.9 m. On the other hand, for relatively stiff piles (*S-Pile*), the normalisation will affect the pre-failure response of the pile when the thickness of the crust is less than 1.75 m. In other words, the load from the crust would practically govern the pile response and obscure the effects of strength normalisation for the liquefied soil when H_C > 1.75m. Hence for these cases, the normalisation of the strength of the liquefied soil is not an issue.

To illustrate the magnitude of the normalisation effects on the pile response, Figure 11 shows the ratio of the peak pile curvatures computed by the two analysis methods as a function of the applied ground displacement. The figure depicts the amount of reduction in the pile response due to strength normalisation for different pile stiffness and thicknesses of the crust. The reduction is very pronounced (70-90%) for deposits without crust, and is still significant (30-40%) for medium-stiff to stiff piles with crusts of up to 1.5 m thick.

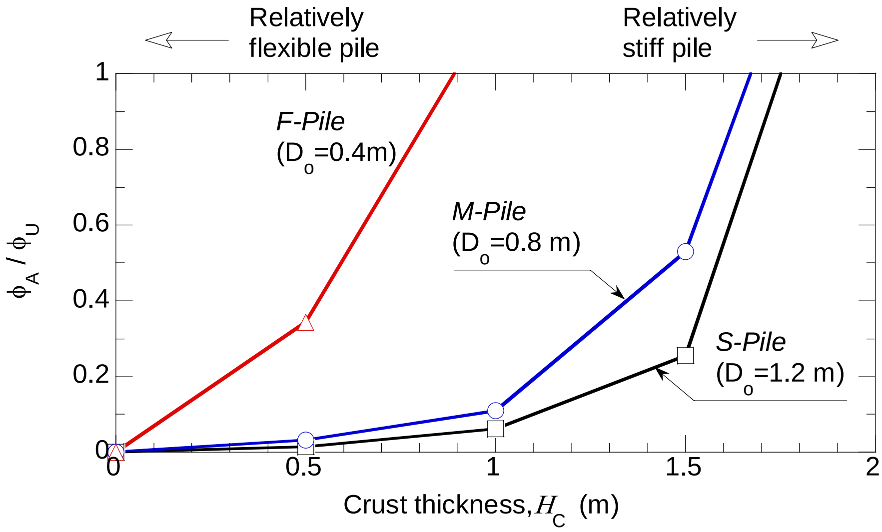

Figure 10. Illustration of curvature levels (ϕ_A/ϕ_U) at which strength normalisation starts to influence the pile response, as a function of pile stiffness and crust thickness

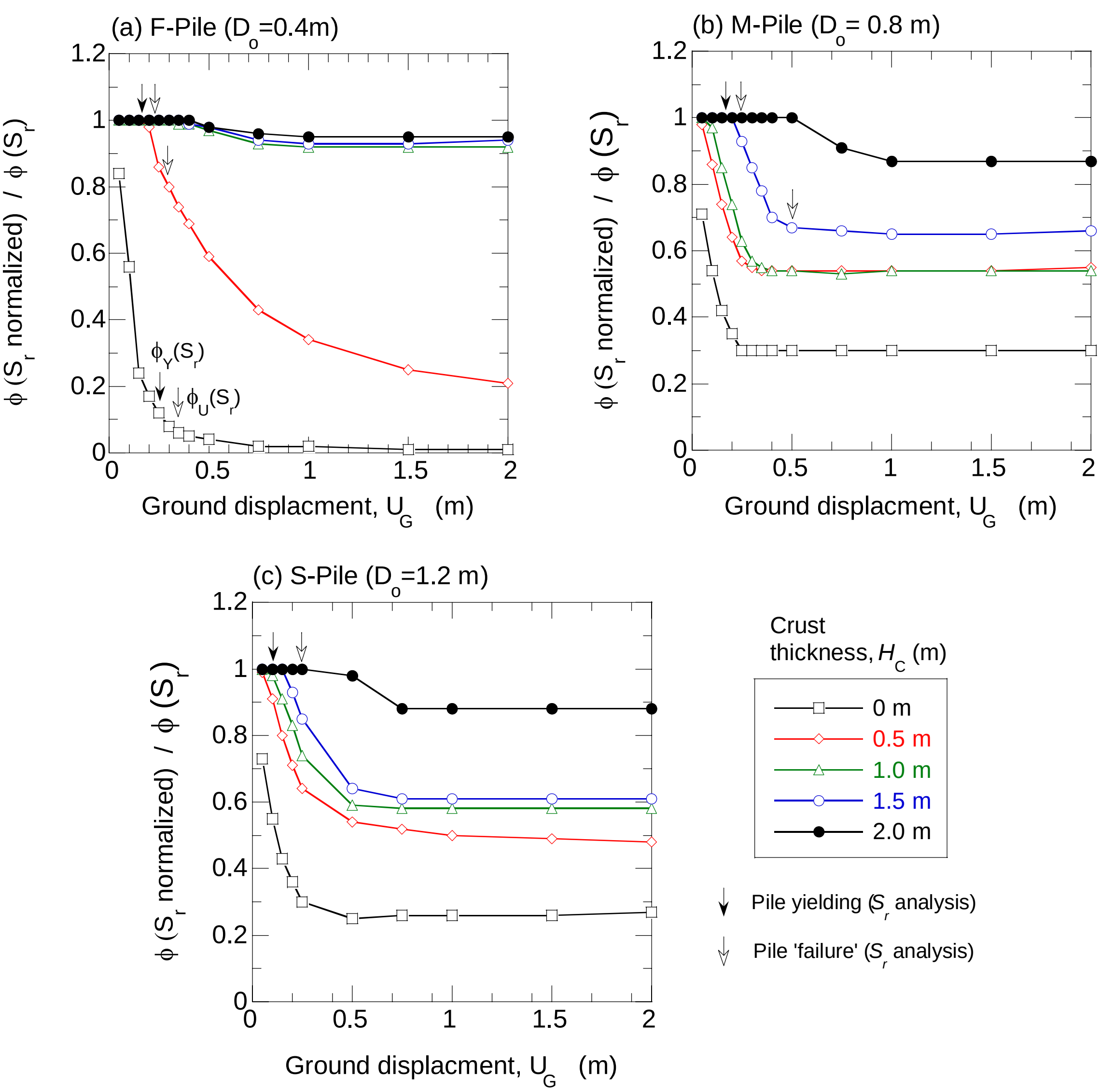

Figure 11. Reduction in pile response due to strength normalisation, for different pile stiffness and thicknesses of the crust: (a) *F-Pile*; (b) *M-Pile*; (c) *S-Pile*

CONCLUSIONS

Effects of soil strength normalisation on the pile response predicted by a simple pseudo-static analysis have been investigated in this paper. Two well-known empirical relationships for residual strength of liquefied soils, one non-normalised (Seed and Harder, 1990) and the other normalised (Olson and Stark, 2002) were adopted for modelling the ultimate lateral pressure from the liquefied soil on the pile, $p_{L\text{-}max}$. Key findings from a series of parametric analyses can be summarized as follows:

- Effects of shear strength normalisation of the liquefied soil could be significant for the pile response predicted by pseudo-static analysis. In the extreme case, the normalisation reduces the pile response from the ultimate level (failure) to the pre-cracking level (no damage).
- The magnitude of normalisation effects depends on the relative stiffness of the pile and the thickness of the non-liquefied crust at the ground surface.
- Effects of strength normalisation are largest in the absence of a crust, and decrease with the thickness of the crust. For the 10 m thick loose sand layer considered, the effects of soil strength normalisation were eliminated once the thickness of the crust exceeded 1.75 m.

It is important to recognize that the normalisation effects depend on the modelling of the ultimate load from the crust, which in this study was adopted to be 4.5 times the Rankine passive pressure. For other methods specifying smaller load from the crust, the effects of normalisation are expected to be greater than those presented herein. Similarly, one should note that the normalisation effects and derived threshold values for the thickness of the crust should be considered in the context of the adopted 10 m deposit of loose liquefiable soil.

Acknowledgement

The authors would like to acknowledge the financial support provided by the Earthquake Commission (EQC), New Zealand.

REFERENCES

Cubrinovski, M. and Bradley B.A. (2008) "Assessment of seismic performance of soil-structure systems," *Invited Lecture*, 18th *NZGS 2008 Symposium, Auckland,* 111-127.

Cubrinovski, M., Ishihara, K., Poulos, H. (2009) "Pseudo-static analysis of piles subjected to lateral spreading. *Special Issue, Bulletin of NZ Society for Earthquake Engineering,* 42(1): 28-38.

Haskell, J.J.M., Cubrinovski, M., Bradley B.A. (2009) "Critical uncertainties in the analysis of piles in liquefying soils" *Proc. 17th ICSMGE, Alexandria,* (in print).

Idriss, I.M. and Boulanger, R.W. (2008) "Soil liquefaction during earthquakes," *Earthquake Engineering Research Institute, MNO-12.*

Olson S.M. and Stark T.D. (2002) "Liquefied strength ratio from liquefaction flow case histories," *Canadian Geotechnical J.* 39: 629-647.

Seed H.B. (1987) "Design problems in soil liquefaction," *J. Geotechnical Eng. ASCE* 113(8), 827-845.

Seed, R.B. & Harder, L.F. (1991) "SPT-based analysis of cyclic pore pressure generation and undrained residual strength", *Proc. H. Bolton Seed Memorial Symposium*, 2: 351-376.