



Gapping effects on the lateral stiffness of piles in cohesive soil

Satyawan Pranjoto

Engineering Geology, Auckland, New Zealand.

M. J. Pender

Department of Civil and Environmental Engineering, University of Auckland, New Zealand.

ABSTRACT: This paper summaries research on the effect of gap formation adjacent to single piles embedded in cohesive soil when subject to cyclic lateral loading. Pile-soil interaction and gap formation are modelled using detachable Winkler springs at the front and rear of the pile shaft. Linear soil behaviour demonstrates that gap formation produces non-linear pile head stiffness that rapidly approaches half of the stiffness when the springs on both sides of the pile shaft are active. Non-linear soil behaviour shows a gradual approach to a steady state situation with increasing number of cycles. The steady state gap width at the ground surface widens and the gap depth increases as the magnitude of loading and number of cycles increase. Factors investigated in the parametric study are number of load cycles, level of load, load eccentricity, pile size, pile-soil stiffness ratio, and the undrained shear strength of the soil in which the pile is embedded. As a rule of thumb gapping reduces the lateral stiffness of the pile head to about half that when no gap is present.

1 INTRODUCTION

Gapping occurs at the rear of laterally loaded pile shafts in cohesive soil. In pseudo-random back-and-forth cyclic loading, such as occurs in an earthquake, gapping will occur near the ground surface on both sides of the pile shaft. In the 1989 Loma Prieta earthquake gapping was observed at ground level adjacent to railway bridge foundations near Watsonville, California (Pender and Pranjoto 1996). Gapping has also been suggested as the primary cause of cyclic degradation in the stiffness of a submerged pile embedded in a stiff clay.

To model the effect of gap formation on pile behaviour under cyclic loading, the authors developed a pile-soil interaction model using Winkler springs on both the front and rear faces of the pile shaft. The model was encoded into a finite element program which was used to evaluate pile response under slow cyclic loading for which inertial effects are negligible.

Back analysis of several published full scale and laboratory pile test data sets have been used to validate the model and to calibrate the modified Vesic equation used to specify the Winkler spring stiffness. Parametric studies were undertaken to gain insight into the effect of gapping under both monotonic and cyclic loading. The former is part of the calibration process for the modified Vesic equation, and the latter to gain insight into gapping effects on cyclic pile behaviour.

Not presented herein, because of space restrictions, is a set of equations for predicting pile responses under two-way cyclic loading. These were obtained as a result of a parametric study carried out for a wide range of cyclic lateral loading magnitude and eccentricity, pile diameter, pile-soil stiffness ratio and undrained shear strength. Predictive equations were developed from regression analyses of the output obtained from a parametric study using the finite element programme. These give pile head displacement and rotation as well as the maximum pile shaft moment.

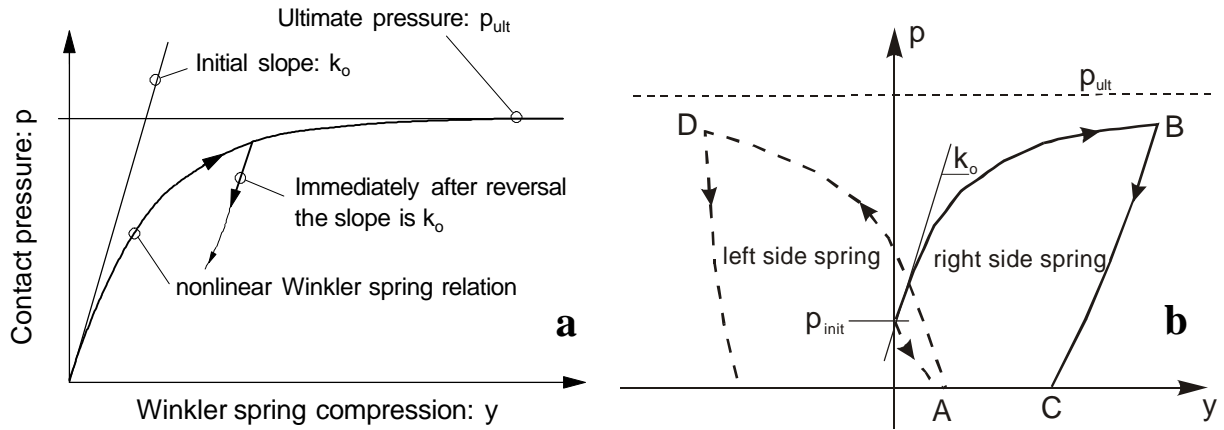


Figure 1 (a) Nonlinear Winkler spring p-y relationship. (b) Detaching and reattachment of springs on the front and rear of the pile shaft.

2 PILE-SOIL INTERACTION MODEL

2.1 Nonlinear Winkler spring p-y curve

The pile-soil interaction model uses detachable Winkler springs at the front and rear of the pile shaft. The pressure-deflection, i.e. p-y curve, relationship for a spring is defined by three parameters: the ultimate lateral pressure, the initial small displacement stiffness, and an index which controls curvature of the pressure-deflection curve. The basic form of the p-y curve, shown in Figure 1a, is specified by:

$$y = \frac{p}{k_o} \frac{p_{ult}^n}{(p_{ult}^n - p^n)} \quad (1)$$

where: y = lateral displacement, p = contact pressure, k_o = initial (small displacement) coefficient of subgrade reaction, p_{ult} = the ultimate contact pressure, n = the curvature parameter that controls the spring non-linearity (1.0 for sand; 0.2 - 0.3 for clay).

Lateral stresses in the ground greater than zero, the usual case, are modelled by setting the initial contact pressure, p_{init} in Figure 1b, between the soil and the pile shaft to a positive value.

2.2 Gapping Mechanism

For cyclic loading the rules that govern the cyclic p-y curve are illustrated in Figure 1b. When there is a reversal in the displacement direction the spring stiffness is reset to the initial value, k_o , and the sign of the ultimate pressure is reversed, being positive when the spring is being compressed and negative for extension. If the contact pressure in a spring at the rear of the pile is reduced to zero, the spring is detached as adhesion between the adjacent soil and the pile shaft is assumed to be negligible. The spring will then remain detached until the respective shaft node re-approaches following a reversal in the loading direction of the pile. The spring is then re-engaged and a new nonlinear spring relationship is established with an initial stiffness k_o . Under repeated cyclic loading, springs will be repeatedly detached and reattached, but the position of disengagement of the spring will move further away from the initial position of the shaft as the number of cycles increases, in other words, gap grows wider at the ground surface and becomes deeper during cycling.

The sequence of detachment and reattachment is illustrated in Figure 1b. At a particular level the initial state, i.e. at zero lateral displacement, has the springs at the front and rear of the pile shaft each with a pressure p_{init} . For movement of the pile to the right there is an increase in the spring pressure for the right hand spring accompanied by a decrease for the left hand spring until it detaches at the point

marked A. At some lateral load there is a reversal and the right hand spring starts to unload, point B, and it becomes detached at point C. When the lateral position of the left hand side of the pile shaft again reaches A the spring reattaches and follows a nonlinear p-y curve up to the next reversal in direction, point D.

2.3 Initial Soil Stiffness and Ultimate Pressure

The modulus of subgrade reaction for clay soils is obtained by first estimating the Young's modulus of the soil for initial loading which is based on the undrained shear strength of the soil, s_u . The relationship used is: $E_s = \alpha s_u$, where α is 600 for s_u between 50 and 100 kPa, these values being based on the conclusions of Ling (1986).

The initial modulus of subgrade reaction (k_o) is then obtained using a modification to the relationship proposed by Vesic (1961) between the modulus of subgrade reaction and the Young's modulus of the surrounding soil:

$$k = \frac{1.3 E_s}{(1 - \nu_s)} \sqrt[12]{\frac{E_s d^4}{E_p I_p}} \frac{d}{d_{ref}} \quad (2)$$

where: E_s is the soil Young's modulus, E_p is the Young's modulus for the pile material, ν_s is the Poisson's ratio for the soil, d is the diameter of the pile shaft, and d_{ref} is the reference diameter, taken as 1.0 m. The Vesic equation was originally proposed for beams resting on the ground surface having soil resistance from one side only. In equation (2) it is modified to include the pile diameter effect, d/d_{ref} , (Carter, 1984), and the Vesic coefficient (0.65) is doubled when soil is on both sides of the pile.

Equation (2) was implemented as a one-sided no-gap Winkler spring model (1s no-gap model) for monotonic loading (Carter 1984, and Ling 1986). That implementation was extended further, Pranjoto (2000), to account for gapping incorporating detachable springs on both sides of the pile shaft (2s-gap model).

The available ultimate lateral pressure is a function of the undrained shear strength of the clay and the depth beneath the ground surface:

$$P_{ult} = C(z) s_u \quad (3)$$

Carter (1984) achieved good matching of published data on prototype scale lateral load tests with the following values for $C(z)$: 5 at ground surface, increasing linearly with depth up to 12 at depth of 3.5 pile diameters, and constant at 12 beneath this depth.

3 GAPPING EFFECTS ON THE PILE-SOIL STIFFNESS

3.1 Initial calculations

A series of calculations was done to demonstrate the effect of gapping on the pile-head stiffness. The pile analysed was 600mm in diameter and 12 m long. The embedding soil had a uniform undrained shear strength of 50 kPa and a unit weight of 19 kN/m³. The ratio of initial horizontal to vertical stress in the soil adjacent to the pile shaft prior to the application of lateral load was varied over the range: 0, 0.5, 1.0, 1.5 and 2.0. Both linear and non-linear soil models were used.

3.2 Nonlinear pile head lateral stiffness

There are two aspects to nonlinear pile head stiffness. One, due to changes in the structural model because of detaching springs and gap formation, occurs even when all the springs are linear elastic. The other is a consequence of the nonlinear spring behaviour described by equation (1). Figure 2 shows the ground-line deflection versus lateral load using linear springs and various values of the ratio of the lateral to vertical stress in the ground (denoted herein by K_o). The modified Vesic equation (equation 2)

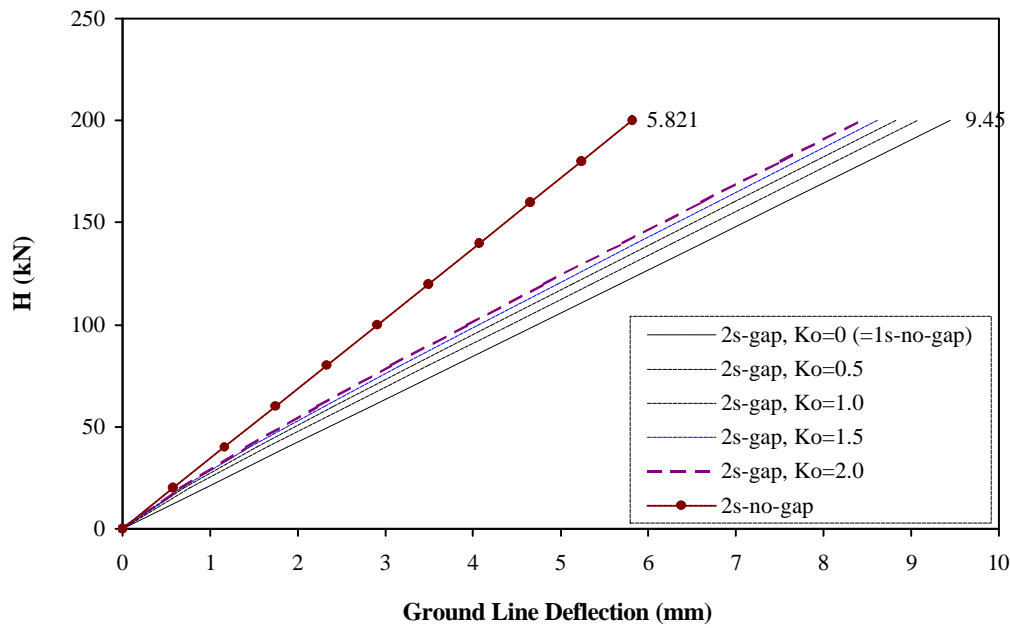


Figure 2 Ground-line deflection versus lateral load (H) for 2s-gap model with varying K_o values and 2s-no gap model, $e/d = 1$ (linear spring model)

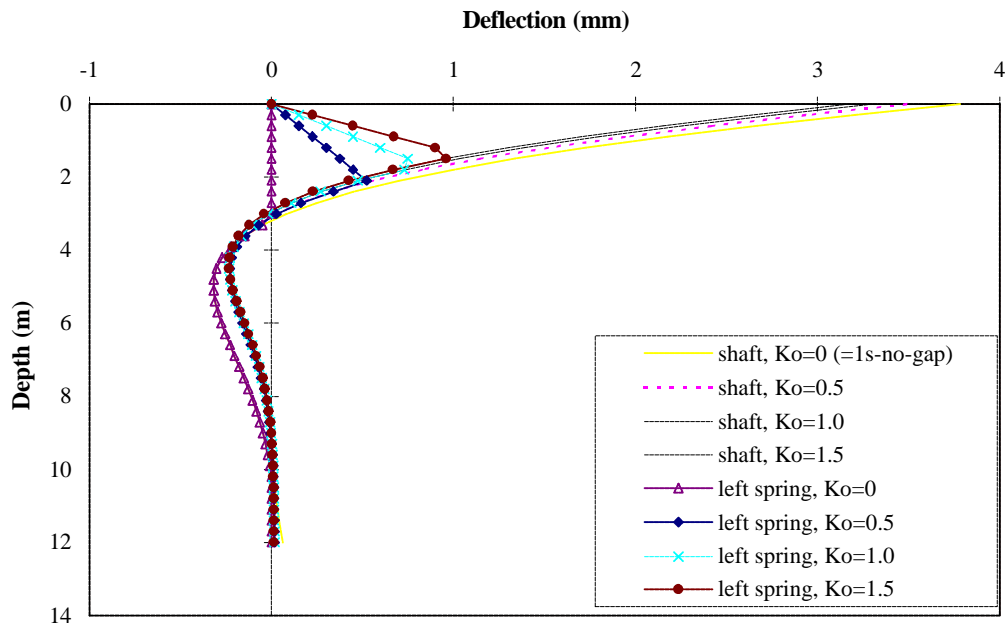


Figure 3 Pile shaft and Winkler spring deflections with depth for the 2s-gap model with varying K_o values when $H=80$ kN (linear spring model).

was used in setting the initial spring stiffnesses. When $K_o = 0$ the 2s-gap model has zero initial contact pressures in the springs and gapping occurs immediately the load is applied; therefore the deflection curve is linear and identical to that of 1s-no-gap model. In the 2s-no-gap mode the springs can sustain tensile contact pressures, as gap formation is prevented, so the deflection curve is also linear with about half the deflection of 2s-gap model with $K_o=0$. Lying between these two extremes are the deflection curves from the 2s-gap analyses with non-zero K_o values. For K_o as high as 2.0 the effect of gap formation is significant even at low values of H , so the load deflection curves in Figure 2 are positioned nearer the 2s-gap $K_o = 0$ curve than the 2s-no-gap curve.

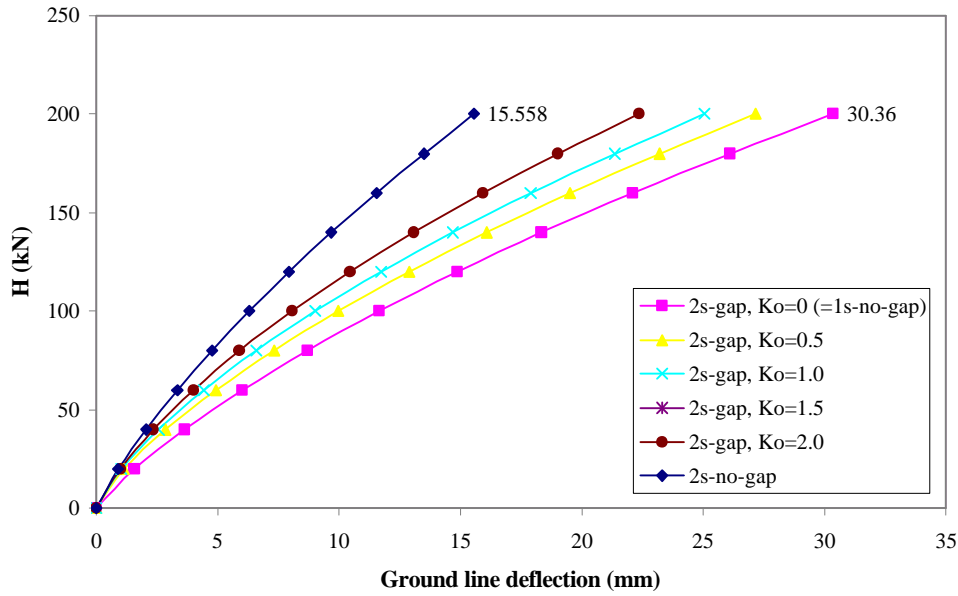


Figure 4 Ground-line deflection vs. lateral load for the 2s-gap model with varying K_o values and 2s-no gap model, $e/d=1$ (non-linear soil model)

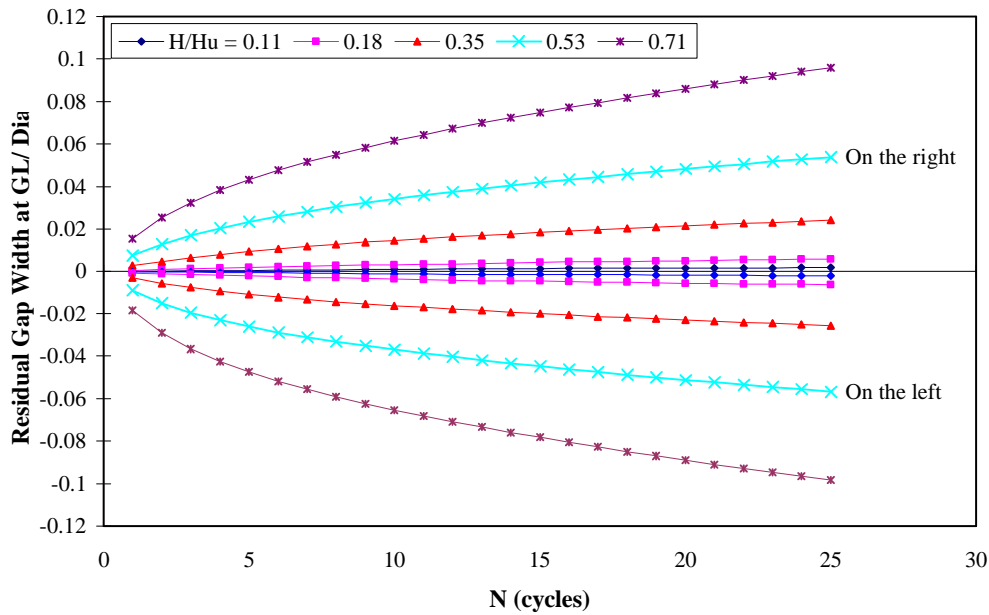


Figure 5 Residual gap width at the ground surface normalised with respect to pile diameter for $e/d=1$.

Figure 3 gives the deflected shape of the pile shaft and spring displacements when a pile head lateral load of 80 kN acts to the right. This shows that the gap depth is about 5 pile diameters when $K_o = 0.0$ and about 3 pile diameters when $K_o = 1.5$.

The ground-line deflection curves obtained with non-linear soil springs and gap formation are shown in Figure 4. Comparison of Figures 2 and 4 shows that with nonlinear springs the curves with different K_o values are more uniformly spread between the 2s gap $K_o = 0$ and 2s no-gap curves. Figure 5 shows how the width of the residual gap at the ground surface increases with load level and numbers of cycles. At the higher load levels the gap width has not stabilised within 25 cycles, thus steady state conditions are not likely to be reached during a design level earthquake.

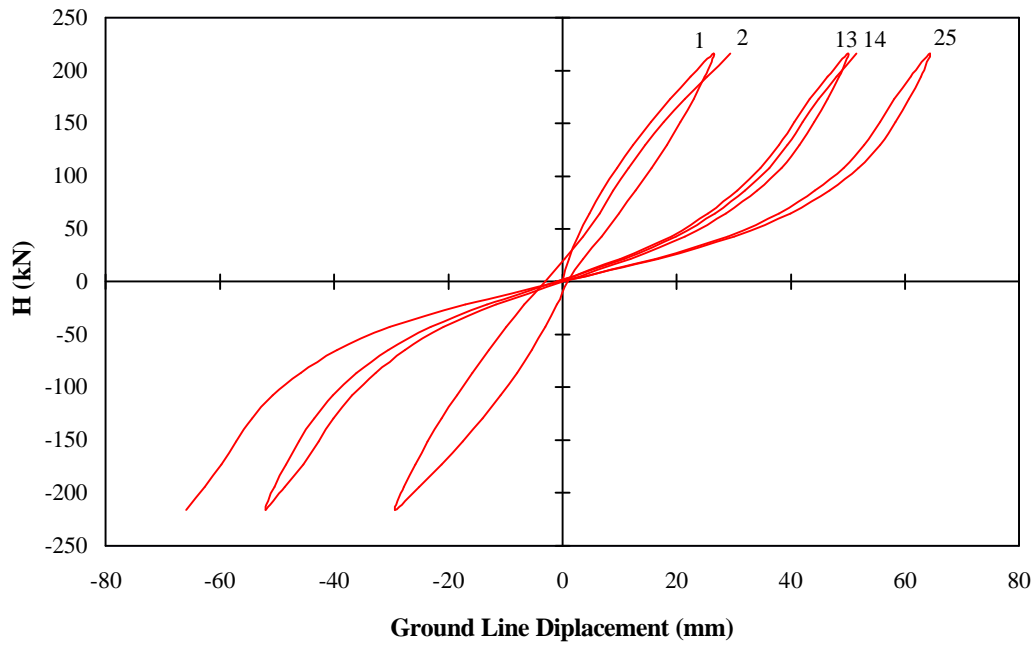


Figure 6 Hysteretic ground-line displacement vs. lateral load for cycles no. 1, 13, 25 at $e/d = 1$ for 2s-gap model.

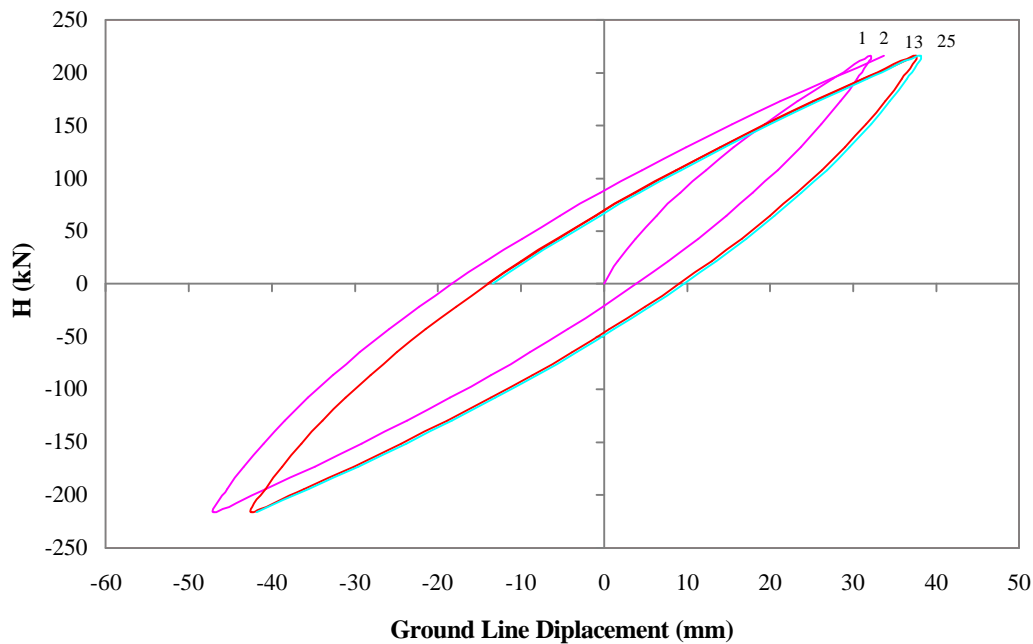


Figure 7 Hysteretic ground-line displacement vs. lateral load for cycles no. 1, 13, 25 at $e/d = 1$ for 1s-nogap model.

3.3 Effect of gapping under two-way cyclic loading

With nonlinear springs a residual gap remains at the ground surface after cyclic loading. This leaves the upper part of pile shaft unsupported at zero and small lateral loads. Figure 6 illustrates how this produces a “pinched” load-displacement loop for the pile head. In Figure 7 the hysteresis loops for the no-gap model are plotted. Comparison of Figures 6 and 7 shows that gapping greatly reduces the energy dissipation in cyclic loading. Furthermore it is apparent that gapping reduces the secant value of the lateral stiffness to about 60% of the no-gap value. These two comments indicate the importance of the soil layers near the ground surface in determining the lateral stiffness and energy dissipation for cyclic lateral loading of piles and conversely the degrading effect of gapping.

4 CASE STUDY

The pile-soil stiffness and gapping mechanism was applied to full-scale pile test data reported by Reese and Welch (1975). The pile was embedded in an overconsolidated clay. The concrete pile was 760 mm diameter, 13 m long, with EI ranging from 766 MNm² to 418 MNm² along the section. Concrete cracking occurs at a bending moment of 188 kNm, I of cracked section is 0.38 of that for the full section. The undrained shear strength, s_u , for the analysis is taken as 150 kPa at the ground surface, increasing linearly to 350 kPa at 1 m depth, then decreasing linearly to 150 kPa at 3m, and staying about constant for the deeper layers.

For depths down to 6.1 m (8 pile diameters), the limit to which gapping was calculated with the finite element programme, cyclic degradation was applied to the soil properties. A simple approach in the analysis was adopted by reducing the initial soil stiffness value to 20 % of its original after the spring reaches 0.1 of the ultimate pressure. This simplifies the p-y curve proposed by Reese et al (1975).

The loading was applied in 5 stages, each having 20 cycles: 0 - 95, 95 – 187.5, 187.5 – 280, 280 – 365, 365 – 445 kN. The shear load was applied at ground-line level with no moment.

The results are shown in Figures 5a, 5b and 5c. Figure 5a gives the ground-line deflection, Figure 5b ground-line rotation, and Figure 5c the maximum bending moment. The markers in the figures indicate the data resulted in the testing at the maximum load in each stage for cycles: 1, 2, 5, 10, 15, 20. The dotted lines connect all the 1st cycle data and the 20th cycle data.

The analysis results match the test data well. To enable the finite element results to follow the trend of the test data, it was found to be essential to use the cracked section properties for a pile shaft segment that has reached the cracking bending moment, and to use a reduced soil stiffness for a spring once its pressure reaches the stress threshold for cyclic degradation.

5 CONCLUSIONS

A pile-soil interaction model with detachable Winkler springs on the front and rear faces of a pile shaft was used to model the gapping induced during cyclic lateral loading of piles embedded in clay soils. This model was calibrated against case history data derived from cyclic lateral loading of a prototype scale pile embedded in overconsolidated clay. It was then used to investigate the significance of gapping on pile head stiffness. The results indicate, as a rule of thumb, that after a number of cycles the pile head stiffness is reduced to approximately half the stiffness during the first loading cycle.

The main consequences of gapping are increases in the lateral displacement of the pile head, pile head rotation, and the maximum pile shaft moment. Nonlinear soil behaviour leads to a gradual increase in the depth of the gap. The rate of change in gap length and pile head displacement decreases with increasing numbers of cycles, eventually a steady state is reached. At lateral loads, which mobilise a significant fraction of the ultimate lateral capacity of the pile shaft, the steady state was not reached within 25 cycles. Consequently during a design earthquake steady state conditions are unlikely to be reached.

A further consequence of gapping in clay soils is the formation of a residual gap, so that, for small lateral loads, a section of the pile shaft near the ground surface is unsupported. This leads to lateral load-deformation loops that are “pinched” and which consequently provide relatively little hysteretic energy dissipation. This is in contrast to the “fat” hysteresis loops derived with the no-gap model.

Equations to predict the amplification in pile responses during two-way cyclic loading have been developed (but are not presented herein). These were derived from the results of a parametric study using a purpose written finite element programme. By implementing these equations in a spreadsheet or similar software, information can be obtained which is useful and practical for the preliminary design of long piles subject to two-way cyclic loading.

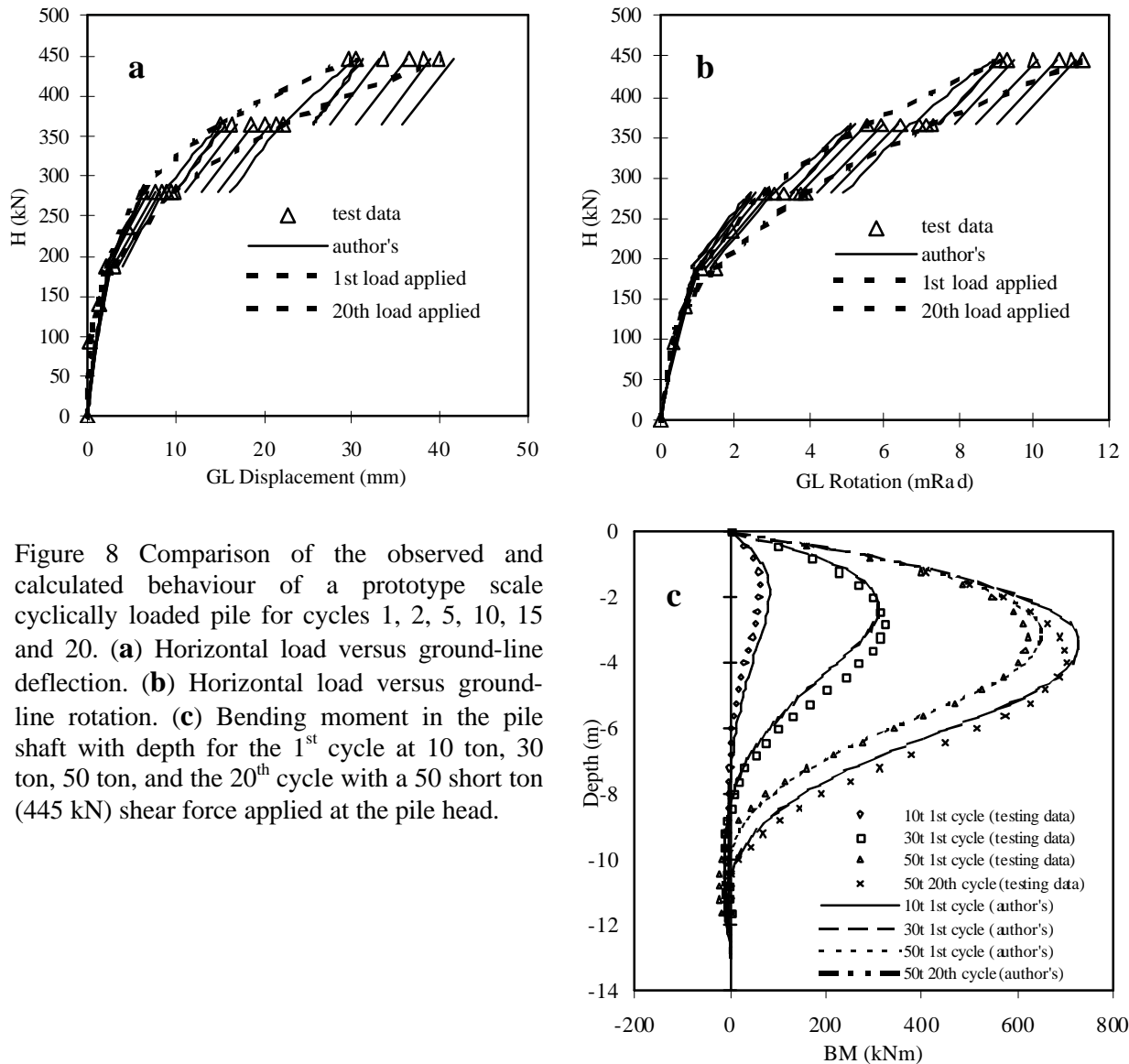


Figure 8 Comparison of the observed and calculated behaviour of a prototype scale cyclically loaded pile for cycles 1, 2, 5, 10, 15 and 20. (a) Horizontal load versus ground-line deflection. (b) Horizontal load versus ground-line rotation. (c) Bending moment in the pile shaft with depth for the 1st cycle at 10 ton, 30 ton, 50 ton, and the 20th cycle with a 50 short ton (445 kN) shear force applied at the pile head.

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