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GAPPING EFFECTS DURING CYCLIC LATERAL LOADING OF PILES IN CLAY

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ABSTRACT

The results of an investigations of the effect of gapping, that is the formation of an opening between the pile shaft and the surrounding soil, on the cyclic lateral stiffness of piles embedded in clay are presented. A method for analysing the pile response under cyclic lateral loading has been developed which is based on the subgrade reaction model with Winkler springs on both sides of the pile. The soil-pile interaction stiffness is represented with a nonlinear soil model which, for monotonic loading, requires two parameters: the initial soil stiffness, and the ultimate lateral soil resistance. A third parameter is needed for the analysis of gapping: the force in the soil springs prior to any lateral loading. Gapping leads to a reduction in the lateral stiffness of the pile. The paper discusses the simple numerical model that was used to monitor gap formation and presents results giving the development of pile head displacement and rotation, maximum bending moment, and the depth of gap with the number of uniform load cycles.

KEYWORDS

Pile lateral stiffness, cyclic loading, clay, gapping, Winkler spring model, nonlinear p-y relation.

INTRODUCTION

When a pile embedded in a cohesive soil is subject to cyclic lateral loading it is often observed that a gap is formed at the ground line between the pile shaft and the surrounding soil. Examples of this are given in Fig. 1 which shows the gapping observed after the 1989 Loma Prieta earthquake at the foundations of a railway bridge over a modest stream near Watsonville in California. Figure 1a is for a pier, about 2 m in diameter under the middle of the bridge, whilst Fig. 1b shows the gapping adjacent to some timber piles supporting the approaches to the bridge. As the gap is reasonably wide at the ground surface it would be of interest to have information about the depth to which the gap extends, the effect of the gap on the lateral stiffness of the pile, as well as the influence of gapping on the maximum moment in the pile shaft. The purpose of this paper is to present the results of some simple numerical modelling of the gapping process and give an assessment of the significance of the phenomenon.

The numerical calculations were done by modifying a Winkler spring finite element program that had been developed for calculating the non-gapping response of piles to lateral loading.

Fig. 1 Gapping adjacent to bridge piles near Watsonville after the Loma Prieta earthquake. *Left* a large diameter pier near the middle of the bridge; *right* smaller diameter timber piles in the approach span.

NON GAPPING SOIL-PILE MODEL

The original program, developed by Carter (1984), models the nonlinear stiffness and local failure of the soil adjacent to the pile shaft. The pile loads are applied at ground level as a combination of horizontal force and moment. The program also has the ability to analyse the pile and soil responses under a set of constraints on pile displacement, both rotation and deflection, at any node along the pile shaft. This facility is useful for the fixed-head and socketed pile cases.

The stiffness of the soil surrounding the pile is represented by a series of nonlinear springs attached to the pile shaft. The form of the nonlinear spring stiffness relation incorporated into the finite element programme is hyperbolic. Two parameters, the ultimate lateral pressure and the initial small strain stiffness, define the pressure deflection curve (p-y) for the springs representing a particular soil. These are illustrated in Fig. 2; further details are given by Carter (1984), Ling (1988), and Pender (1993).

The generally satisfactory nature of the predictions obtained with Carter's programme has been verified by analysing the data available for published prototype scale lateral loading tests. This information is discussed in summary form by Pender (1993) and given in more detail by Carter (1985) and Ling (1988).

The modulus of subgrade reaction for clay soils is obtained by first estimating the Young's modulus of the soil for initial loading. Based on the conclusions of the analysis of the prototype tests Ling (1988) found the following relations for the soil Young's modulus: $300s_u$ for $s_u = 0 - 40$ kPa, $600s_u$ for $40 < s_u \leq 200$ kPa, and: $1200s_u$ for $s_u > 200$ kPa.

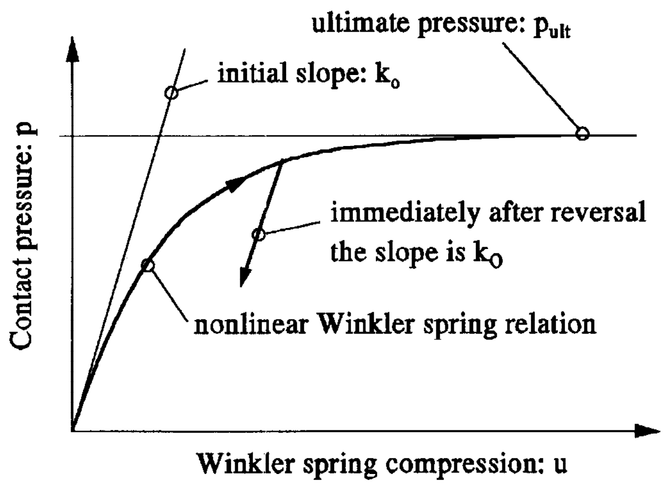

Fig. 2 Nonlinear soil-pile p-y relationship.

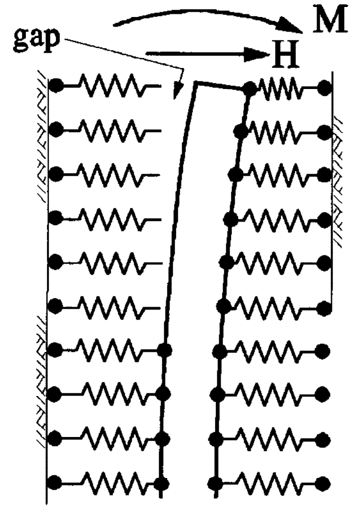

Fig. 3 Winkler spring modelling of gap formation.

Once the soil Young's modulus is available the Vesic (1961) equation is used to calculate the initial modulus of subgrade reaction (k_o). This equation was originally intended to give the subgrade modulus for beams resting on the ground surface. As a pile has soil on both sides the usual approach is to double the value of k_o obtained from the Vesic equation to arrive at the value appropriate for a laterally loaded pile.

The ultimate pressure for any point in a clay soil is also a function of the undrained shear strength s_u: $p_{ult} = C(z)\ s_u$. The ultimate pressure coefficient, C(z), is a function of depth. Carter achieved good matching of published data with the following distribution of values: at the ground surface C(z) is taken as 5, at a depth of 5 pile diameters it has a value of 12 with a linear distribution between this depth and the ground surface, and at depths greater than 5 diameters it is constant at 12.

CYCLIC LOADING

The work reported in this paper is based on an extension of Carter's program to accommodate cyclic lateral loading of piles in cohesive soils with the formation of gaps. However, it is essentially still a static analysis as no inertia forces are involved in the calculations, also it is assumed that no degradation of the soil stiffness occurs during the limited number of cycles expected during a typical earthquake.

The gapping is modelled by having springs on the both sides of the pile shaft and monitoring the force in each spring. Prior to the lateral loading, each spring has an initial force to represent the fact that the installation of the pile will generate horizontal stresses at the soil - pile interface. For all the calculations reported herein the initial lateral pressure at a given depth is equal to the vertical pressure. For each pile load increment the calculated forces in the springs on the "rear" side of the pile are reduced and those on the "front" are increased. When the force in a spring on the "rear" side reaches zero that spring is detached from the pile shaft and undergoes no further displacement, this is illustrated in Fig. 3. As the load increases the gap gets deeper. For the springs on the "front" side of the pile the ultimate pressure (p_{ult}) is compressive. For the unloading direction the nonlinear aspect of the p-y curve is calculated on the assumption of the existence of an ultimate tensile pressure having the same magnitude as that in compression. In reality this will never be reached as the program will detach the spring first. The finite element calculations are done in an incremental manner with the loading being applied in a series of small steps. At each step the current tangent spring stiffness is evaluated using the hyperbolic p-y relationship shown in Fig. 2.

It is assumed that there is no adhesion between the cohesive soil and the pile shaft. As there is no surcharge at the ground surface there is no initial pressure in the springs at the surface; hence gapping starts to occur at the surface as soon as the lateral load is applied.

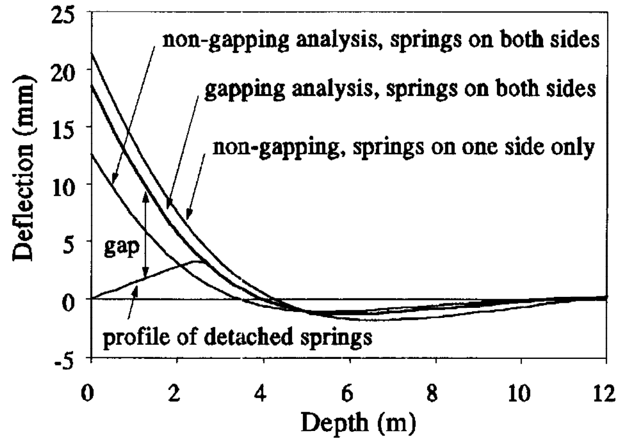

Fig. 4 Comparison of gapping and non-gapping analyses with linear soil behaviour.

When the cyclic loading reverses direction, the pile shaft approaches the previously unloaded springs. When it comes into contact with a detached spring it is re-engaged and again contributes to the stiffness of the system. On the other hand some of the previously loaded springs will disengage.

Two types of nonlinearity occur in this analysis. The first is due to the soil nonlinearity that follows from Carter's nonlinear p-y curve, the other is due to the gapping phenomenon which involves a change in the stiffness of the system because the springs are detached and re-attached to the pile shaft.

One paper that reports a similar analysis to that discussed herein is by Swane and Poulos (1984). They considered one-way cyclic loading of a laterally loaded steel tube pile embedded in clay. The p-y model they used for the soil springs was elastic-perfectly-plastic rather than the hyperbolic model used for the calculations reported herein.

As Swane and Poulos were considering foundations for offshore structures the number of load cycles was large and consequently some degradation of the soil modulus is to be expected. The Swane and Poulos example problem was used as a means of comparison. The output of the modified Carter program was found to produce displacements up to twice those reported by Swane and Poulos. This is thought to be a consequence of the nonlinear p-y curve used herein which would be expected to produce larger displacements than the elastic-perfectly-plastic model used by Swane and Poulos.

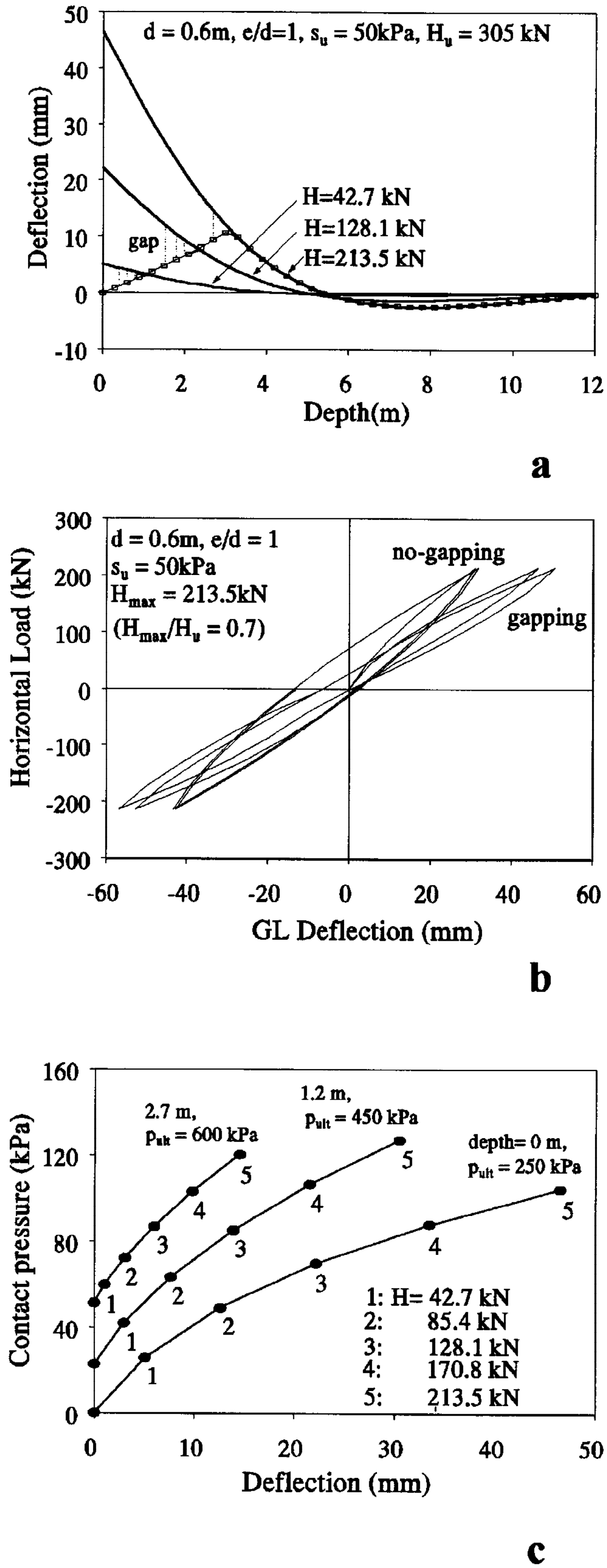

Fig. 5 Results of gapping analyses including nonlinear soil behaviour. (a) Pile deflected shape and gap extent for three loads, (b) hysteresis loops for gapping and non-gapping cases, (c) distribution of pile shaft pressure at three depths for five loads.

RESULTS

Soil and pile properties used for all the calculations

All the calculations were done for a 600 mm diameter reinforced concrete pile 12 m long. The yield moment of the pile section was 636 kNm. The soil in which the pile is embedded has an undrained shear strength of 50 kPa and a unit weight of 19 kN/m^3. The horizontal stress the soil exerts against the pile shaft prior to the application of lateral load is assumed to be equal to the vertical stress at that depth.

Calculations were done for 25 cycles of two-way lateral loading which is thought to cover the likely number of cycles of interest for aseismic pile foundation design.

The lateral loads were applied as various fractions of the ultimate lateral load of the pile. This ultimate lateral load (H_u), which is a function of the ratio (e/d) (e is the equivalent height above the ground surface of the point of application of the horizontal load and d is pile diameter), was estimated from the equations given by Pender (1993), it is comparable to the value given by the well known Broms (1964) method for long piles in clay. With e/d = 1 cyclic loads of amplitude H were applied such that H/H_u = 0.1, 0.2, 0.3, 0.5 and 0.7. The effect of moment to shear ratio was investigated by a cyclic horizontal load having an amplitude of 0.2H_u applied at the following values of e/d: 0, 1, 2, 4, and 8.

In addition some calculations were done for fixed head piles.

Linear soil springs with and without gapping

Since, as explained above, there are two elements of nonlinearity in most of the calculations it is of interest to first of all investigate the effect of the gapping only and keep the soil spring behaviour linear. In Fig. 4 the results of these calculations are presented. There are three separate results given in the plot; firstly the calculations without gapping are done for two values of the modulus of subgrade reaction, one half of the other. This gives bounds on the response for the case with gapping as is apparent from the third curve in the diagram which was calculated using the gapping programme. The lateral load amplitude was 0.7 H_u and the e/d ratio was 1. From these results it is apparent that gapping has the effect of reducing the lateral stiffness of the pile to about the same as that for a pile with spring support along one side only. This suggests that the usual assumption of the pile interacting with the soil on both sides of the pile is not realistic for loads of the level used in the calculations. This observation is based on the results of calculations for one value of the ratio of horizontal to vertical stress in the soil adjacent to the pile shaft. The details of the gap profile will change for other values but the final conclusion is unlikely to be altered.

Nonlinear soil springs with gapping

In this section some of the calculated results are used to illustrate how the gap develops, the pressure distribution against the pile shaft changes with load level, and how the hysteresis loops are affected by the gapping.

Figure 5a shows the pile deflected profile for three load levels, H/H_u = 0.14, 0.42 and 0.70 with e/d = 1, and also indicates the length of the pile shaft that is subject to gapping. The plot gives the deflected shape of the pile shaft and near the ground surface where the gap occurs the shape of the unloaded springs is used to denote the extent of the gap, as expected this increases with increasing pile head load.

Figure 5b gives hysteresis loops for the first few cycles of loading for the gapping and non-gapping cases. This shows how gapping reduces the lateral stiffness of the pile for these few cycles by a factor of about 2.

Finally Fig. 5c shows how the soil reaction develops against the pile shaft at three depths for five levels of lateral loading. Although the nonlinear effects on the pressure distribution are apparent the pressures are considerably less than the ultimate value of 5s_u at the ground surface and 12s_u at depths greater than 5 pile

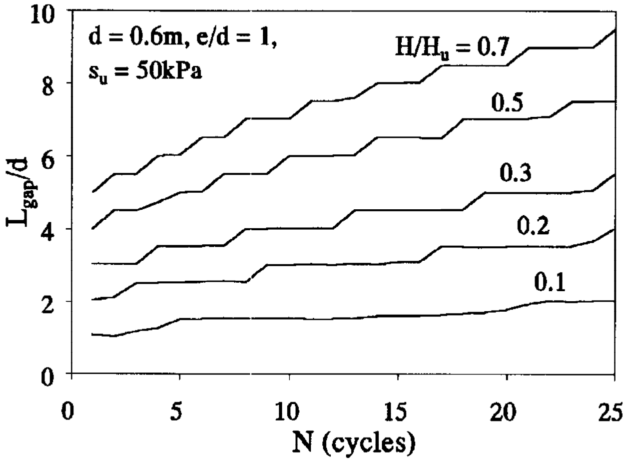

Fig. 6 Development of gap depth with number of load cycles for e/d = 1.

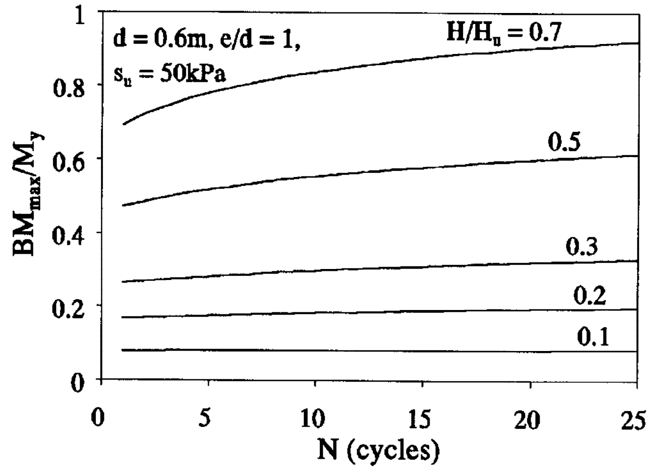

Fig. 7 Effect of cyclic loading on the maximum pile shaft moment at maximum load.

diameters. As the maximum load is 70% of H_u, the capacity of the system for this case is controlled by the yielding of the pile section rather than the strength of the soil.

Figure 6 shows the development of the gap depth at the maximum load in each cycle for various load levels for $e/d = 1.0$. The step-like nature of the plot reflects the length of the elements in the finite element mesh. Figure 7 shows how the maximum pile shaft moment at maximum load develops as the number of cycles increases for $e/d = 1$. Figure 8 gives the pile head displacement at maximum load and Fig. 9 the pile head rotation (in milli-radians: mrad) at maximum load as a function of cycle number for $e/d = 1$.

Figure 10 shows how the depth of gap at maximum load develops for various values of e/d and for the fixed head case with $H/H_u = 0.2$. Figure 11 gives the maximum moment for various values of e/d with H/H_u of 0.2. Also included is the magnitude of the maximum moment for the fixed head case.

Figure 12 gives the maximum groundline displacement and Fig. 13 the maximum groundline rotation for various values of e/d with H/H_u of 0.2 and also for the fixed head case.

DISCUSSION

Figures 6 and 10 show that the maximum depth of the gap in each cycle can be quite large for loads which are well within the capacity of the pile. This, in conjunction with Fig. 4, suggests that the manner in which the modulus of subgrade reaction is estimated for laterally loaded piles in clay needs to be reconsidered. The formation of gaps to significant depths means that the pile in effect has support on only one side over most of the active length of the pile shaft (cf Pender (1993).

The maximum pile head displacement and rotation information, Figs. 8, 9, 12 and 13, show that these are sensitive to the level of loading and that for the larger load levels there is a steady increase in displacement and rotation with increasing numbers of cycles. Thus the most conspicuous effect of gapping for free head piles is the decrease in the operational lateral stiffness.

The maximum pile shaft moments, Figs. 7 and 11, are not particularly sensitive to gapping. This is as would be expected because it is well known that for the Winkler model the moment is much less sensitive to changes in soil stiffness than the displacements.

Figure 10 shows that fixed head piles are less susceptible to gapping than free head piles.

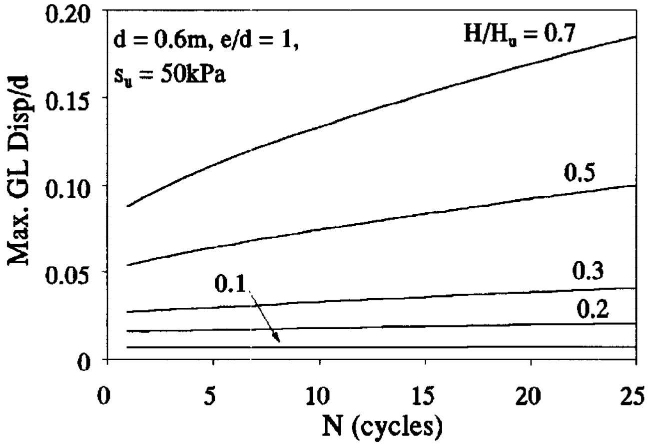

Fig. 8 Maximum groundline displacement at maximum load in each cycle for e/d = 1.

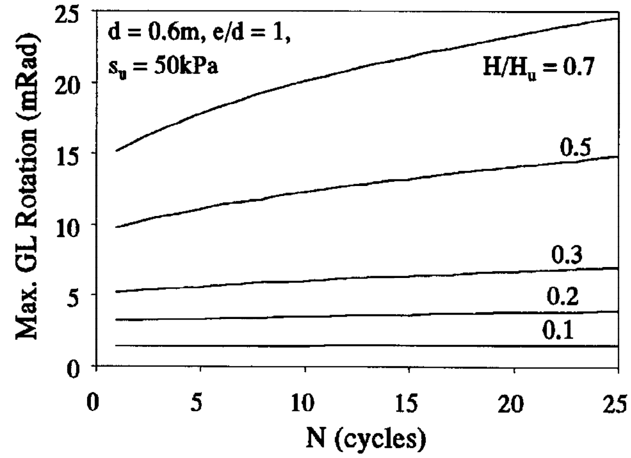

Fig. 9 Groundline rotation at maximum load in each cycle for e/d = 1.

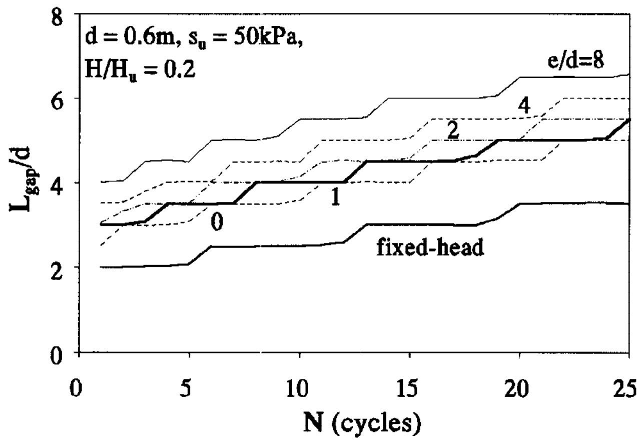

Fig. 10 Development of gap length for various values of e/d.

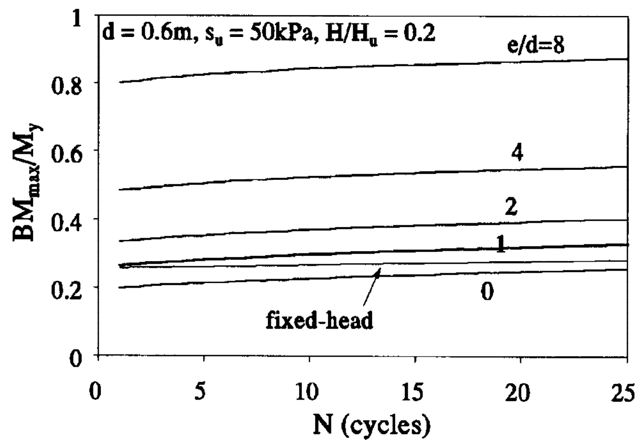

Fig. 11 Maximum pile shaft bending moment for various values of e/d.

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The residual displacements and gap lengths were calculated but have not been plotted. The gap when the pile is unloaded is smaller than the maximum value but is still significant. This suggests that once a gap has formed the lateral stiffness of the pile will be permanently affected.

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Another way of evaluating the effect of gapping is to consider how it might affect the natural period of a mass supported on a pile. Figures 8, 9, 12 and 13 can be used to estimate that a period lengthening as great as 50% or more could be expected as a result of gapping.

The results show that for the number of cycles expected in an earthquake "shakedown", that is the achievement of a state in which the displacements cycle between constant values, will not occur for all but the lowest load levels.

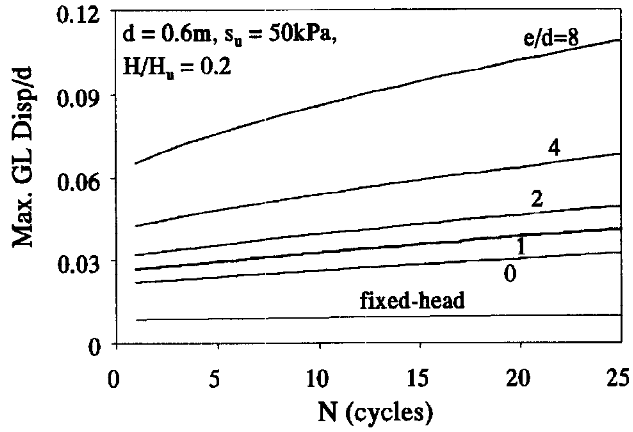

Fig. 12 Maximum groundline displacement for various values of e/d.

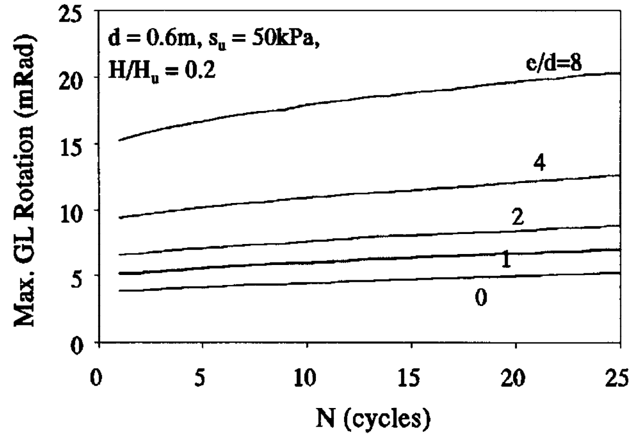

Fig. 13 Maximum groundline rotation for various values of e/d with H/H_u = 0.2.

The calculations reported did not allow for any degradation of the soil stiffness with numbers of cycles. This is probably not significant for stiff clays over earthquake numbers of cycles. On the other hand for soft clays or saturated sands this effect might be significant and thus needs to be modelled.

CONCLUSIONS

The results of the above analyses show that gapping has a significant effect on the stiffness of free head piles, particularly at loads which are a significant fraction of the ultimate lateral capacity of the pile. Gapping was seen to have only a small effect on the maximum pile shaft moment.

For the fixed head case the reduction in lateral stiffness with increasing numbers of cycles is much less significant than for the free head case.

The programme needs to be extended to cover dynamic effects. A parametric study is underway to cover variations in pile diameter, the values of s_u, and the lateral stress that the soil exerted on the pile shaft prior to lateral loading.

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