Nonlinear behaviour of laterally loaded free-head pile groups

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ABSTRACT

To estimate response of pile groups under lateral loading, a widely accepted approach is to use the curve of soil resistance, *p* versus local pile deflection, *y (p-y curve)*. As the response is dominated by the limiting force per unit length p_u, various expressions have been developed for evaluating p_u. Given a generic p_u profile, response of a laterally loaded pile or group can be readily predicted using a spreadsheet program called GASLGROUP, which in turn is based on closed-form solutions for a single pile (Both the solutions and program were developed by the author). In light of 70 field tests on single piles and 30 tests on pile groups, an extensive back-estimation carried out recently indicates that only three parameters along with *p*-multipliers are sufficient to accurately predict the response of laterally loaded single piles and pile groups.

In this paper, p_u profiles are deduced against measured response of a single pile and two typical pile groups under static and cyclic loading. The shadowing effect (p-multipliers), and the effect of the p_u profile, and loading properties (static or cyclic) on piles in groups are examined. Typical calculations are presented in figures and tables.

1 INTRODUCTION

Pile groups are often subjected to lateral load exerted by soil, wave, wind and/or traffic forces etc (Poulos and Davis, 1980). To estimate the group response under lateral loading, a widely accepted approach is to use the curve of soil resistance, *p* versus local pile deflection, *y (p-y curve)*. The p attains a limiting force per unit length p_u within a depth normally taken as 8*d* (*d* = diameter of a pile), and the response of laterally loaded piles is generally controlled by the mobilized p_u. Thus, determination of this p_u is critical to a satisfactory prediction of the pile response. Using a generic profile of limiting force per unit length (LFP), elastic-plastic solutions have been developed for response of a laterally loaded, free-head (Guo 2006) or fixed-head pile by the author (Guo 2007). These solutions allow response of single piles to be readily predicted using a spreadsheet program operating in EXCEL™ called GASLFP. They, in conjunction with p-multipliers, allow response of a laterally loaded pile group to be predicted via an updated spreadsheet of GASLFP called GASLGROUP (Guo 2007). These solutions compare well with finite element analysis (FEA) and measured data (e.g. McVay et al. 1998; Rollins et al. 2006a,b). The solutions allow the p_u to be estimated. Various expressions have been developed previously for the p_u, the values of the p-multipliers are also deduced (Brown, et al. 1988). Recently, based on 70 field tests on single piles and 30 tests on pile groups (Guo 2006), an extensive back-estimation carried out by the author and his team indicates that only three parameters (A_L, α_0, n in Eq. (1)) are required to produce a sufficiently accurate limiting force profile (LFP). It was conducted for single piles tested in clay, sand and calcareous sand, and model pile groups tested in sand. It shows that the existing methods are probably unnecessarily complicated, in terms of many input parameters.

In this paper, using GASLGROUP, the effect of group interaction, pile stiffness, and loading properties (cyclic/static) on response of free-head pile groups was examined, against typical in-situ tests in clay.

2 GASLGROUP

2.1 Theoretical background

The solutions for infinitely long, free-head, and fixed-head piles (Guo 2006, 2007) are based on an identical coupled model schematically illustrated in Figure 1a. Free-head means that no constraints are imposed on piles but soil resistance, while fixed-head requires that the pile-head is restrained from rotating but free to move laterally. Irrespective of the head constraints, the pile-soil interaction at each point is depicted by an elastic-perfectly plastic spring, with the p-y curve shown in Figure 1c. Within elastic state, each spring has a subgrade modulus, *k*, which is the slope of the p-y curve. The springs are linked together by a fictitious membrane with a tension, N_p to cater for the coupled effect. Constant with depth, the *k* and N_p are functions of modified Bessel functions of a non-dimensional factor (Guo and Lee 2001) that is dependent on pile slenderness ratio (length, *L* over diameter, d), pile-soil relative stiffness, E_p/G_s (E_p = Young's modulus of an equivalent solid pile; G_s = Shear modulus of soil), and pile-head conditions. Where the soil resistance reaches the limiting force, relative slip takes place along the pile-soil interface. The slip extends to a depth called slip depth, x_p. Within the x_p, interactions among the springs may be ignored by utilizing N_p = 0. A generalized form of LFP may be given by (Guo 2001, 2006)

$$p_u = A_L(\alpha_0 + x)^n \tag{1}$$

where p_u = limiting force per unit length [FL^{-1}]; A_L = gradient of the LFP [FL^{-1-n}]; α_0 = a constant to include the resistance at ground surface [L]; x = depth below ground surface [L]; n = power to the sum of α_0 and x. For piles in sand, it follows: $A_L = N_g\gamma_s' d^{2-n}$, in which γ_s' = effective unit weight of the sand; N_g = a limiting force factor, $N_g = (0.4\text{~}2.5)K_p^2$; with $K_p = \tan^2(45 + \phi'/2)$, ϕ' = effective friction angle of the sand. For piles in clay, $A_L = N_g C_u d^{1-n}$ in which C_u = undrained shear strength, and N_g = 0.4~4.79. $\alpha_0 \approx 0$ for piles in sand (except for driven piles), whereas $\alpha_0 \approx$ 0.05~0.2m in clay. A reduced N_g should be used for cyclic loading. Real values of n, α_0, and N_g may be back-figured through matching predicted with measured overall responses of displacement, w_g, maximum bending moment M_{max}, and depth of the M_{max}, x_{max} under various pile-head loads, P (Guo 2006).

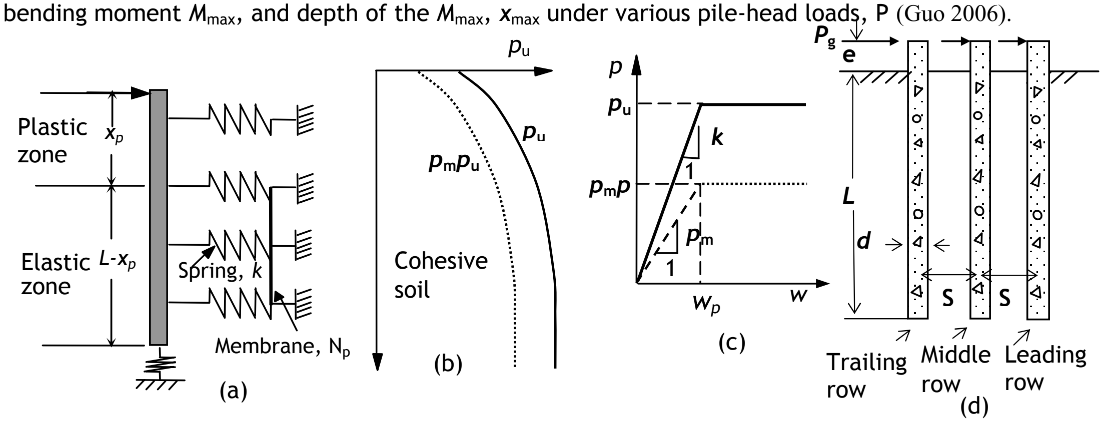

Figure 1: Modeling of free-head piles and pile groups (Guo 2006, 2007)

2.2 Prediction of response of pile groups

Lateral response of a pile group may be estimated using the aforementioned closed-form solutions for a single pile, with the shadowing effect on each row of piles being catered for by using the *p*-multipliers concept suggested by Brown et al (1988). The latter is achieved via the following treatment: For any displacement, the *k* and *p* determined from a p-y curve for a pile in isolated form is reduced by multiplying the *p-multipliers* to gain those for a pile in a group (Fig. 1(c)). Using the closed-form solutions, a slip depth can be obtained for a desired pile-head displacement, which in turn allows a pile-head load for each pile in a row to be estimated. Multiplying the load by number of piles in the row gives the total load on the row. This calculation is repeated for each row in a group (keeping in mind that each row generally uses a different *p-multiplier*), thus the total load on the group is calculated. Given a series of displacements, a number of the total loads are calculated accordingly, thus a load-displacement curve is obtained. This procedure has been implemented into the program GASLGROUP (Guo 2007).

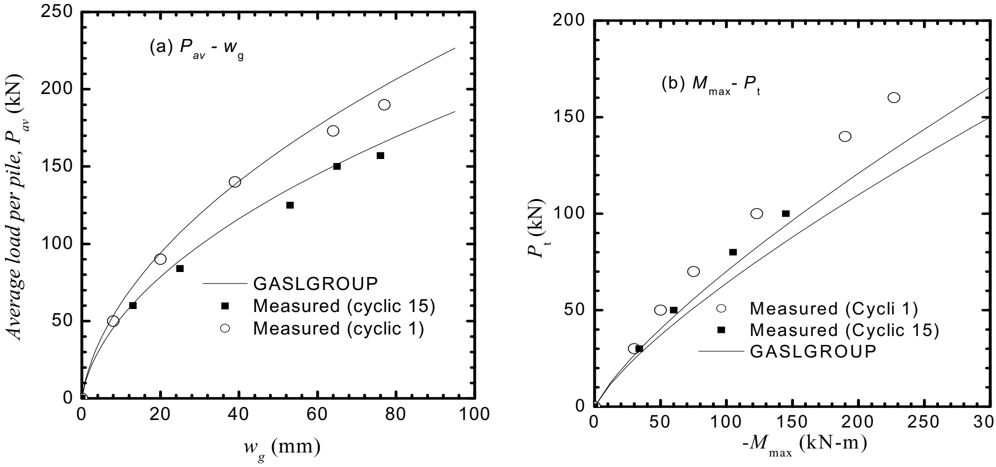

Figure 2: Predicted vs. measured (Rollins et al. 2006a) response (single pile)

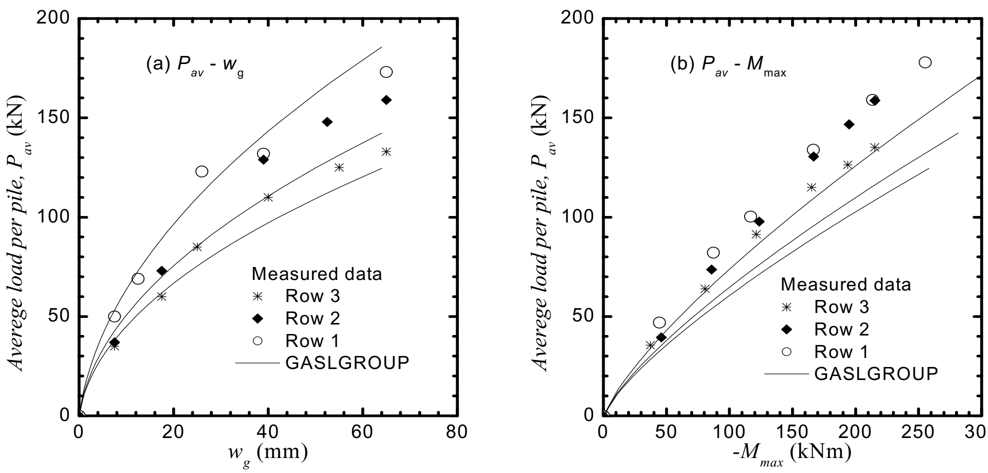

Figure 3: Predicted vs. measured (Rollins et al. 2006b) response (3x3 group, static, 5.65d)

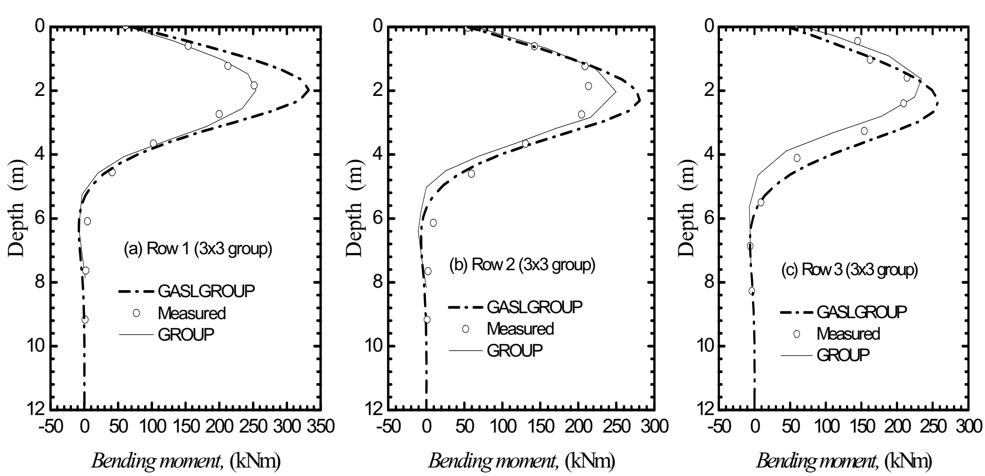

Figure 4: Predicted vs. measured (Rollins, et al. 2006b) bending moment profiles (3x3, w_g = 64 mm)

3 TYPICAL EXAMPES

Rollins et al (2006a) performed lateral loading tests on two isolated single piles, and three (3×3, 3×4, and 3×5) groups under free–head condition (via a special loading apparatus). The test site to a depth of 5 m consists of overconsolidated stiff clays and a sand interlayer. The subsoil profile was simplified (Rollins et al, 2006b) as follows: The clay has a C_u of 70 kPa above the sand interlayer, and 105 kPa below the layer until a depth of 3.02 m. The sand interlayer is 0.31m thick located between a depth of 1.34m and 1.65m. It has a relative density D_r of 60%, and an angle of friction of 36°. Groundwater located at a depth 1.07 m. The steel pipe piles were driven closed-ended to a depth of 11.9 m, with 324 mm o.d., 9 mm wall thickness. The moment of inertia was 1.43×10^8 mm^4 owing to irons attached for protecting strain gauges. This gives a flexural stiffness E_pI_p of 28.6 MN-m^2. The center-to-center spacings in longitudinal (loading) direction were 5.65 pile diameters for the 3×3 group, and 4.4 pile diameters for the 3×4 group. The transverse spacing was 3.3 pile diameters in both cases.

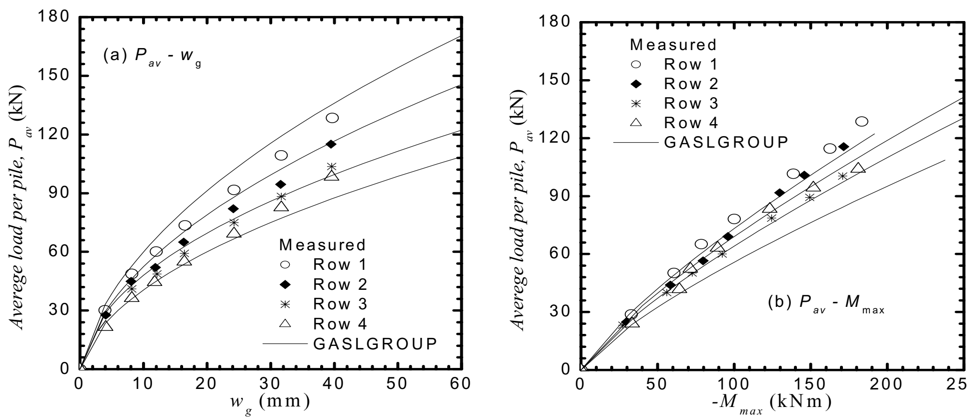

Figure 5: Predicted vs. measured (Rollins, et al. 2006b) response (3x4 group, static at 4.4d)

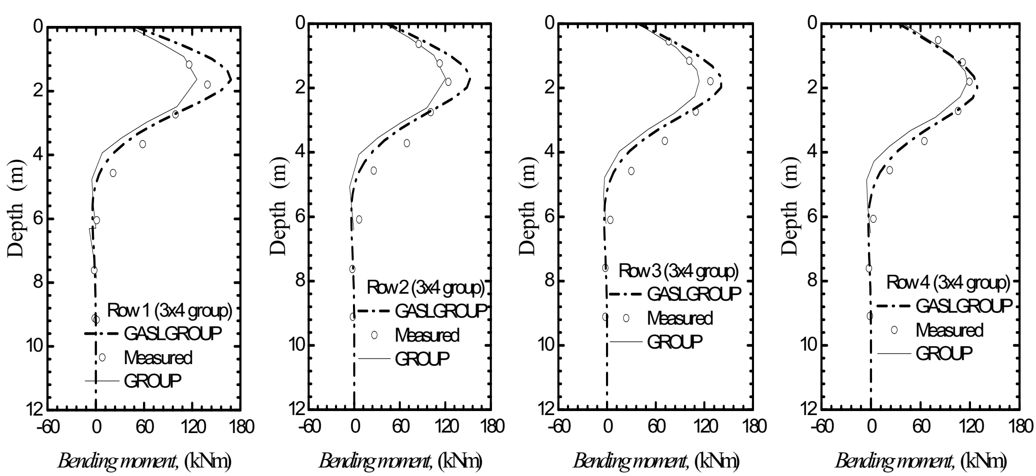

Figure 6: Predicted vs. measured (Rollins, et al. 2006b) bending moment (3x4, w_g = 25 mm)

Load was applied at (e =) 0.38 m above ground line for the virgin (single) pile test, and at e = 0.49 m for the 15 cyclic loading. The responses of the single piles were measured and are presented in Figure 2. Lateral (static) load test on the 3×3 group was conducted at e = 0.38 m. The measured results are shown in Figure 3, with bending moment distribution along each pile in the 3 different rows being depicted in Figure 4 (at a displacement w_g of 64mm). Lateral load test on the 3×4 group was undertaken under e = 0.48 m. The measured responses are shown in Figure 5, with bending moment distribution along each pile being presented in Figure 6. Cyclic tests were also conducted, with the response of the 3×4 group being plotted in Figure 7. The program GROUP (Reese, et al. 1996) was used to predict the response of the pile groups using back-figured p-multipliers (Rollins et al. 2006b). These have been plotted in Figures 4 and 6.

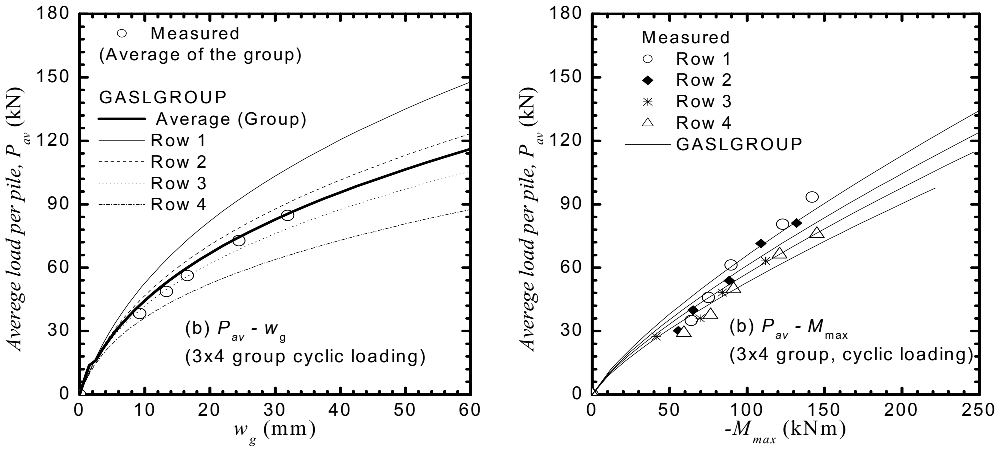

Figure 7: Predicted vs. measured (Rollins, et al. 2006a) response (3x4 group, Cyclic, 5.65d)

In this paper, predictions were made using the program GASLGROUP. The shear modulus G_s was taken as $190s_u$ (s_u=75 kPa) and N_g taken as 0.55 for single pile under static loading. As ground heaving of 75 ~ 100 mm within pile group during driving was observed, an increase value of N_g = 0.6 was adopted for pile groups. Parameters n and α_o are assumed unchanged for all cases. Values of p-multipliers are calculated using Guo (2007)'s suggestion, which is in turn deduced from test results of 27 capped pile groups. Thus the values of p_m are smaller than those adopted by Rollins, et al. (2006b). These parameters are provided in Table 1. They allow predictions of the group to be made using GASLGROUP (assuming free-head condition) for all the single piles and group piles under static or cyclic loading. In particular, the calculated parameters for elastic static response of the single piles are provided in Table 2. As shown in all the preceding figures, the current predictions compare well with the measured load-displacement curves. The maximum bending moment was overestimated at large load levels against measured data. Parametric analysis (not shown herein) shows that the moment can be well predicted by reducing the pile stiffness (and increase in value of N_g). Thus the overestimation may be attributed to the stiffness or the use of equivalent stiffness E_p (= $E_pI_p/(\pi d^4/64)$) based on enlarged cross-section. The latter use has not been justified before.

Table 1: Input parameters (static loading)

References	G_s [a] (MPa)	Group [b]	N_g [c]	s/d [d]	p_m by row				n & α_o
					1st	2nd	3rd	4th	
In situ tests (Rollins et al. 2006b) in clay. s_u = 75 kPa, γ_s = 15.3kN/m^3	14.25	1×1	0.55						For all cases: n =1.6 α_o= 0.05
		3×3	0.60	5.65	$\frac{0.87}{0.95^e}$	$\frac{0.49}{0.88}$	$\frac{0.37}{0.77}$		
		3×4	0.60	4.4	$\frac{0.85}{0.90}$	$\frac{0.6}{0.80}$	$\frac{0.45}{0.69}$	$\frac{0.32}{0.73}$	

[a] Shear modulus G_s (= $190s_u$) was multiplied by p_m to gain that for a pile in a group. [b] Normalised center to center spacing in loading direction, but s = 3.3d within any a row. [c] Under cyclic loading, the N_g was multiplied by a ratio of 0.65 to obtain that for single pile and by 0.8 for group piles. [e] P_m in denominator was adopted by Rollins, et al. (2006b).

Table 2: Parameters for *elastic response* of single piles in clay

Items	γ	*k* (MPa)	$N_p/(2E_pI_p)$	α_N	β_N	λ (1/m)	Note
	0.136798	48.818	0.211828	0.8713	0.7398	0.8082	G_s = 14.25 MPa

Note: Expressions for determining the parameters can be found in Reference by Guo (2006)

3.1 Comments on current approach

The current calculation was based on E_p determined for an equivalent solid circular pile, using the enlarged stiffness. It should be stressed that without this conversion of E_p, a good solution would also be gained. However, the parameters deduced then would not be the true values. The example presented herein was for free-head piles in clay. In comparison with the previous calculations for fixed-head (capped) piles in clay and sand, alterations of p-multipliers were noted. However, the prediction seems to be affected more by E_p than values of p-multipliers. The values of n = 1.6 and N_g = 0.55 ~ 0.6 are quite consistent with previous conclusions.

4 CONCLUSIONS

In this paper, responses of laterally loaded pile groups were investigated using the spreadsheet program GASLGROUP based on elastic-plastic closed-form solutions. The study was focused on free-head piles. It is concluded that: (1) 3 parameters A_L, α_0, n are sufficient for an accurate prediction of single pile response. (2) Under cyclic loading, N_g reduces to 65 % that used for static loading for simulating a single isolated pile, and to 80% for simulating piles in groups, respectively. (3) An accurate determination of p-multipliers is not critical but the equivalent pile stiffness for an enlarged cross-section is. And (4) *p*-multipliers concept generally works well.

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