NONLINEAR ANALYSIS OF TORSIONALLY LOADED PILE GROUPS[i]

Discussion by FRANCESCO BASILE[ii]

The authors describe an empirical approach to analyse the torsional behaviour of pile groups in which single-pile response is modelled by means of load-transfer curves, including an empirical factor (β) to model the interaction between lateral and torsional response, while group effects are treated using the elastic solutions of Mindlin (1936) and Randolph (1981). The comparison with centrifuge model tests performed by the same authors shows that the proposed approach is capable of simulating the non-linear behaviour of individual piles and capturing the main effects of interaction between piles in the group.

When applied to routine pile design, the approach, however, suffers from some limitations, mainly associated with the selection of the key parameter required by load-transfer methods, i.e., the modulus of subgrade reaction. Indeed, this is not an intrinsic soil property but an empirical parameter also depends on the dimensions of the pile. Consequently, no soil test can be conducted to derive the modulus of subgrade reaction, and its value can only be determined with sufficient confidence by back-figuring from the results of a field test on an instrumented pile. Another limitation of load-transfer approaches is related to the disregarding of continuity through the soil which makes it impossible to find a reliable way to quantify the interaction effects between piles in a group. The load-transfer approach may therefore be regarded as a link between the interpretation of full-scale pile tests and the design of similar single piles rather than as a general tool for pile group design.

The above limitations may be removed by means of soil continuum based solutions, generally adopting finite element, finite difference or boundary element formulations. These solutions provide an efficient means of retaining the essential aspects of pile interaction through the soil continuum and hence a more realistic representation of the problem. While finite element and finite difference methods are not considered practical for routine design (owing to their complexity and high computational costs), computer programs based on the boundary element method provide a more convenient solution to the pile group problem. Among these, the program PGROUPN (Basile, 2003) performs a complete non-linear analysis of the soil continuum while retaining a computationally efficient code, and has recently been extended to torsional loading (Basile, 2010).

Figures 1–6 show a comparison between PGROUPN, the authors' method and centrifuge model tests on torsionally loaded single piles and pile groups reported by the same authors. A summary of the main input

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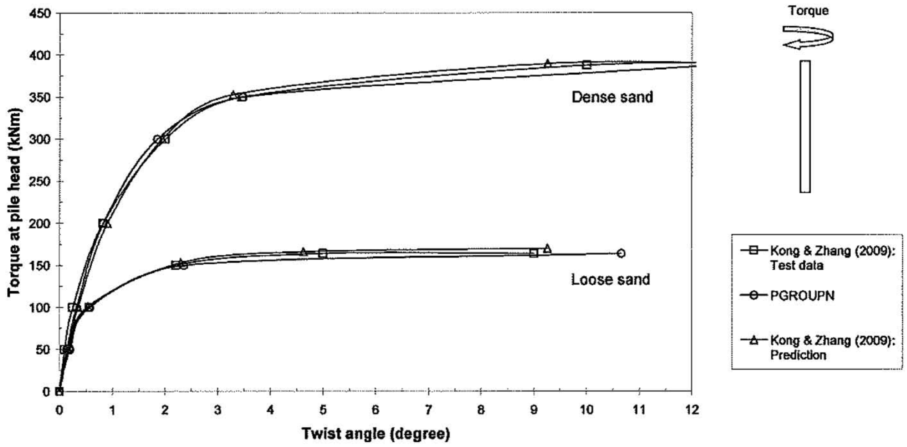

Fig. 13. Torque-twist angle curves for single pile

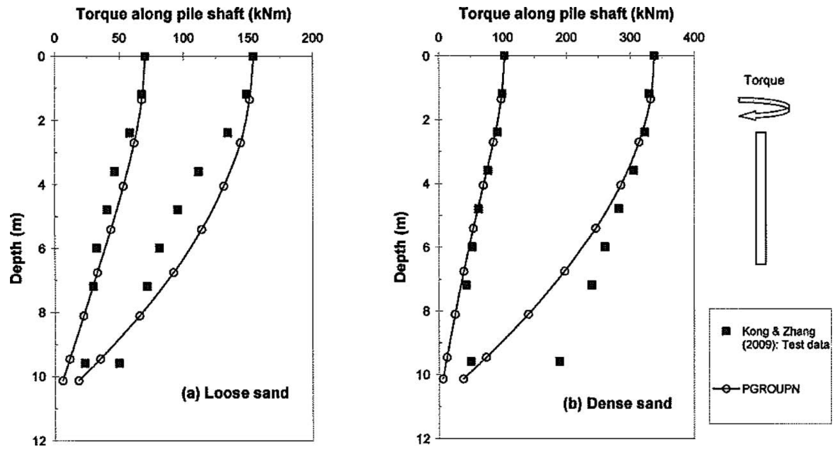

Fig. 14. Torque distribution along depth for single pile

Table 2. Input parameters for comparisons of Figs. 1–6

	Pile embedded length, m	Pile free-standing length, m	Pile diameter, m		Pile torsional rigidity, MNm^2		Pile flexural stiffness, MNm^2	Pile Poisson's ratio	Soil Poisson's ratio	Soil friction angle, degrees	Soil buoyant unit weight, kN/m^3
			single pile	pile groups	single pile	pile groups					
Loose sand	10.8	1.2	0.664	0.760	162.0	169.9	220.5	0.25	0.2	33	13.7
Dense sand									0.3	39	14.7

parameters is reported in Table 1. In addition, PGROUPN adopts an uniform soil modulus (E_s) of 7 MPa and a coefficient of horizontal soil stress (K_s) of 0.6 for the loose sand, while the corresponding values for the dense sand are $E_s = 11$ MPa and $K_s = 1.1$ (Note: K_s is required by PGROUPN in order to calculate the limiting torsional stress equal to $K_s \sigma'_v \tan \delta$, where σ'_v is the effective vertical stress and δ is the angle of friction between pile and soil, taken as 0.8ϕ).

It may be observed that the above values of soil modulus are relatively low when compared to the values normally used in the analysis and design of full-scale piles in sand. However, as reported by the authors, pile jacking in centrifuge tests has significant effects on the soil adjacent to the pile and therefore the value of soil modulus can be significantly different from the value before pile jacking. In addition, scale effects remain an important issue in centrifuge modelling and a higher influence of pile-soil interface properties in a model than in a prototype can be expected. Thus, in the PGROUPN analyses for single pile, the above values of E_s and K_s were selected in order to fit the initial portion and the failure load of the torque-twist angle curves obtained from the centrifuge tests. Then, in the subsequent pile group analyses, the same values of E_s and K_s used for the single-pile analyses have been kept (i.e., without any curve fitting with the

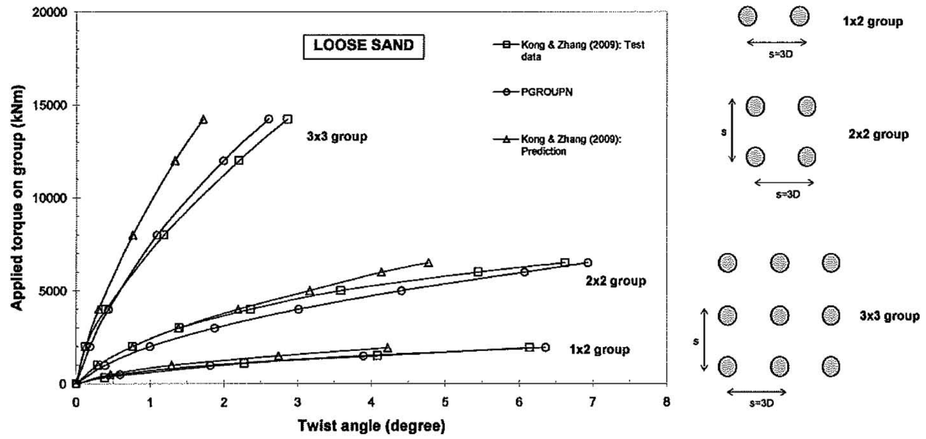

Fig. 15. Torque-twist angle curves for pile groups in loose sand

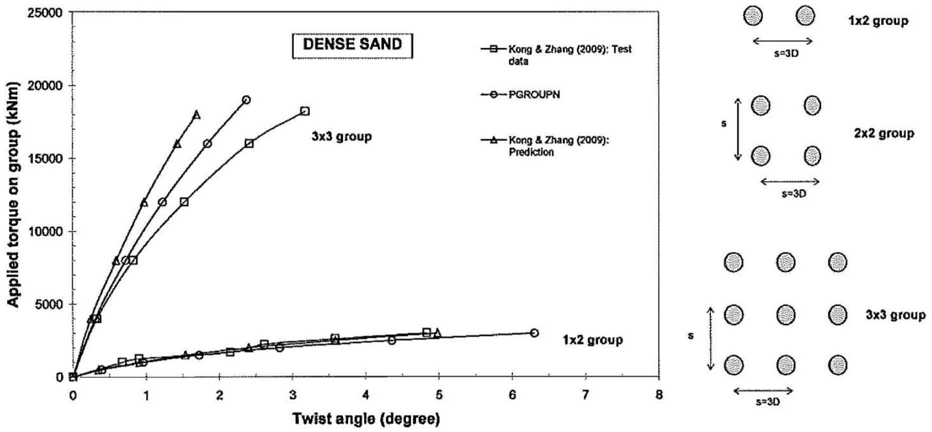

Fig. 16. Torque-twist angle curves for pile groups in dense sand

test data) in order to simulate the application of PGROUPN in normal design (when only single-pile test data, if any, is available).

Turning to pile-group behaviour, the centrifuge tests were carried out on piles arranged in 1×2, 2×2, and 3×3 configurations, with a centre-to-centre spacing of three pile diameters and connected by a rigid cap (1.2 m thick) with a clearance of 1.2 m from the groundline in the prototype. Figures 3 and 4 compare the experimental torque-twist angle curves with the corresponding numerical predictions from Kong and Zhang (2009) and from PGROUPN. A good agreement between test data and numerical predictions is observed for the 1×2 and 2×2 groups, while the numerical analyses (particularly that from Kong and Zhang) tend to overpredict the pile resistance at high load levels for the 3×3 groups. As discussed by Kong (2006), soil densification during pile installation may be a possible reason for this discrepancy; namely, pile jacking densifies the soil inside and near the pile groups in loose sand but loosens the soil inside and near the pile groups in dense sand. This effect becomes more pronounced as the number of piles in the group increases. A plausible reason for the larger discrepancy between the numerical prediction by Kong and Zhang and the test data may be related to the assumption of linear elastic soil adopted in the simulation of pile-soil-pile interaction effects. However, that is far from realistic for real soil whose behaviour is highly non-linear, even at low load levels.

It is important to observe that, for both single piles and pile groups, the numerical predictions of Kong and Zhang are based on a back-analysis of the data from the centrifuge tests, including the use of a back-calculated parameter (i.e., the coupling coefficient, β) in order to reproduce the experimental curves for the pile groups. By contrast, the PGROUPN analyses for the pile groups were carried out using the same soil parameters adopted for the single-pile analyses, without using any additional curve-fitting parameter to improve the agreement with the centrifuge test data. It is noted, however, that the PGROUPN results are of comparable accuracy to those obtained from the numerical predictions of Kong and Zhang, thereby confirming the validity of PGROUPN as a practical tool for pile group design.

When a pile group is subjected to torsion, the sustained torque by each pile in the group is shared by the pile torsional component plus the lateral contribution from the pile shear force. Figure 5 shows the decomposition of the

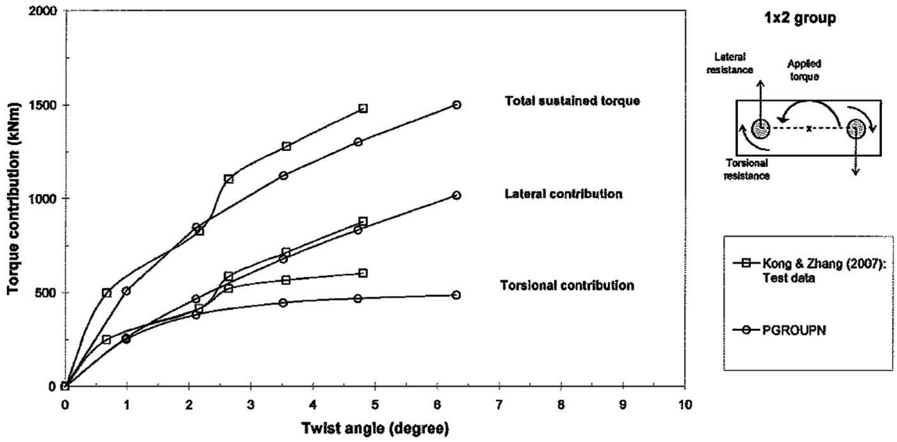

Fig. 17. Components of sustained torque in 1×2 pile group in dense sand

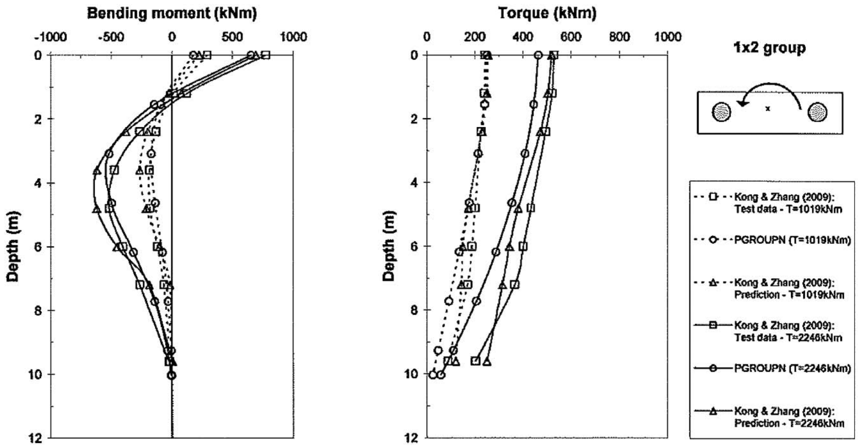

Fig. 18. Distribution of bending moment and torque along depth in 1×2 pile group in dense sand

torsional resistance components for a pile in the 1×2 group in dense sand, as an example. It is worth noting that the torsional contribution is largely mobilised at a twist angle of about 2.5 degrees, while the lateral contribution continues to increase with the twist angle. This feature of behaviour (also found by Kong and Zhang in the other pile group tests) implies that, at small twist angles, the torsional resistances take larger proportions of the sustained torques and that the proportions decrease at large twist angles. Although some discrepancies (up to about 20%) between the PGROUPN predictions and the test data are observed, it is worth noting that PGROUPN is capable of capturing the above behavioural feature. For the same 1×2 pile group in dense sand, Fig. 6 shows the bending moment and torque profiles for two values of the total applied torque ($T=1019$ kNm and $T=2246$ kNm). A reasonable agreement between numerical predictions and test data is observed.

Overall it may be concluded that both numerical approaches show the importance of having a satisfactory non-linear solution as compared to the previous generation of linear elastic models. However, from a practical point of view, the discusser believes there are many advantages in using a method which deals with pile behaviour on a more fundamental basis.

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