Observing friction fatigue on a jacked pile

D. J. White & M.D. Bolton
Cambridge University Engineering Department

ABSTRACT: Calibration chamber testing combined with a new technique of displacement measurement using image analysis has allowed the penetration mechanism of a jacked pile to be quantified. Observation of soil adjacent to an advancing pile revealed movement towards the shaft. This movement is linked to 'friction fatigue'. The mechanism of this process is observed to be volume reduction in the boundary layer at the pile-soil interface combined with horizontal unloading in the far field. The possibility of replicating this behaviour in a constitutive or centrifuge model is discussed.

1 INTRODUCTION

1.1 Jacked piles

The axial capacity of displacement piles in sand is arguably the subject of greatest uncertainty in geotechnical engineering (Randolph et al. 1994). There is no accepted consensus of the mechanism by which a pile penetrates soil. As a consequence, the most widely used design methods (eg. API 1993, Fleming et al. 1992, Eslami & Fellenius 1997) remain highly empirical, and must be accompanied by large safety factors.

Most design methods have evolved from experience of dynamically installed piles. Since pile hammers and vibrators are rarely permitted in urban areas, displacement piles are increasingly being installed by jacking. Press-in pile drivers can install pre-formed piles up to a maximum jacking force of 400 tonnes (4 MN) without exceeding urban noise and vibration limits (White et al. 2002). For this installation method to be safely utilized in axially loaded applications, the differences in behaviour of jacked and driven piles must be established.

1.2 'Friction fatigue'

Recent field and laboratory testing (notably Lehane 1992, Chow 1997, De Nicola 1996, Bruno 1999) has revealed some aspects of pile behaviour which are not captured in conventional design methods. One key observation is the 'friction fatigue' or 'h/R' effect, where h/R represents the vertical distance above the pile tip normalised by pile radius. This is the phenomenon by which the horizontal effective stress, σ'_h (and hence local shaft friction, τ_s) acting on the pile shaft at a given soil horizon decreases as the pile tip penetrates deeper (Fig. 1).

The design framework described by Randolph et al. (1994) captures the 'h/R' effect by predicting the horizontal earth pressure coefficient (K) to decay exponentially with distance from the pile tip (Equation 1). The variables in this formulation are the maximum and minimum values (K_{max}, K_{min}) and the decay rate (μ). Design values for μ have been deduced from four different sources (Table 1). Figure 2a shows normalized curves of local shaft friction for each decay rate shown in Table 1, assuming $K_{min} = 0.2$, $K_{max} = 1$ and L/D = 20. These curves predict significantly different profiles of local shaft friction. This raises the question; why does each dataset reported in Table 1 display a different decay rate?

$$K(h) = K_{min} + (K_{max} - K_{min})\, e^{-(\mu h/D)} \qquad (1)$$

Table 1: Friction fatigue parameters deduced from field and laboratory testing

Author	Description	Pile size	Decay rate, μ	Distance from pile tip to $\tau_s = \tau_{max}/2$ ($h_{50\%}$): Actual $h_{50\%}$	Prototype $h_{50\%}$	$h_{50\%}/D$	$h_{50\%}/D_{50}$
Randolph *et al* (1994)	Best fit to database of field tests.	Database of various. L/D=15–60	0.05	20 m*	20 m*	13*	≈200000* (Silty sand $D_{50} \approx 0.1$mm)
De Nicola (1996)	Best fit to database of centrifuge tests.	L= 150 mm D= 16 mm	0.25–0.35	66 mm	6.6 m	3.7	1300 (D_{50} = 45 µm)
Bruno (1999)	Best fit to database of centrifuge tests.	L= 200 mm D=11.5 mm	0.65	24 mm	2.4 m	2.1	500 (D_{50} = 45 µm)
Bruno (1999)	Best fit to field test.	L= 45 m D= 0.76 m	0.2	4 m	4 m	5.2	≈40000 (Fine sand & silt $D_{50} \approx 0.1$ mm)

* Data from worked example in original reference for L= 50m, D= 1.5m.

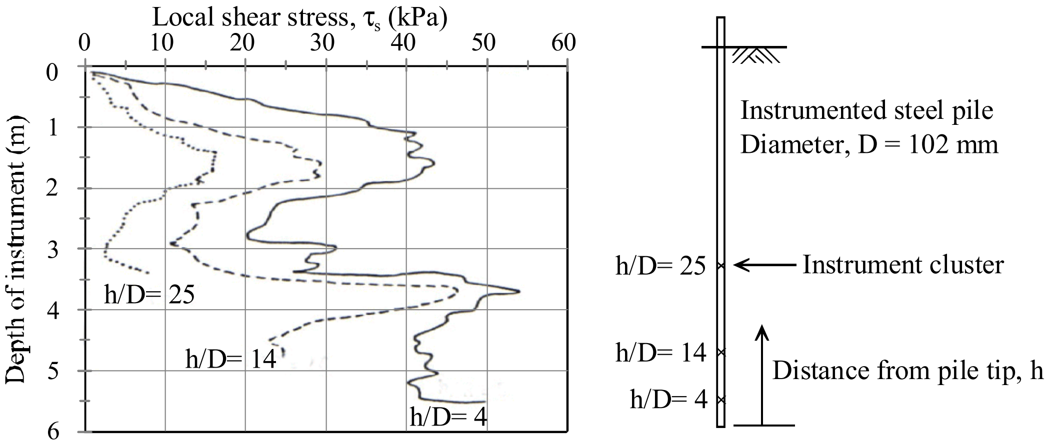

Figure 1. Local shear stresses during installation of an instrumented pile (after Lehane 1992)

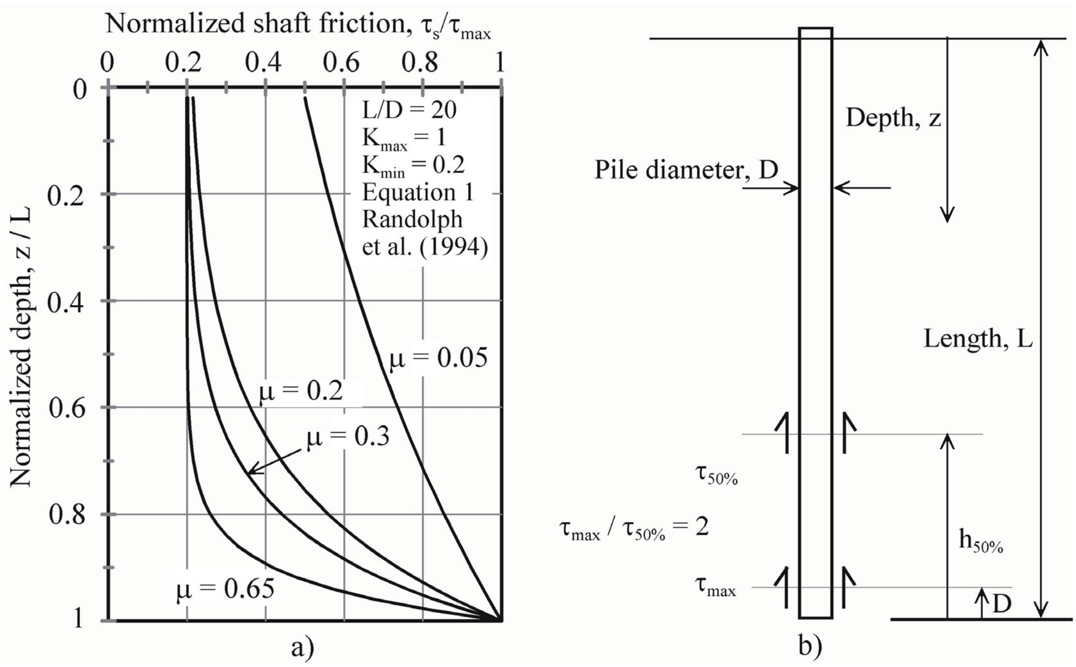

Figure 2. The decay of local shaft friction

It might be expected that the different scales and embedment ratios of the pile tests shown in Table 1 would offer some insight into the origin of μ. If the initial ('unfatigued') local shaft friction is defined as the shear stress acting one diameter behind the pile tip, a reference distance over which the shearing process reduces local shaft friction by a factor of 2 can be defined as $h_{50\%}$ (Fig. 2b). This definition neglects any change in τ_{max} over the short distance $h_{50\%}$. This reference distance has been extracted from the original data reported in Table 1, and has been non-dimensionalized by normalizing with two local length scales; pile diameter and original D_{50} grain size. No clear trend is evident. The decay in normal effective stress is not a direct function of absolute distance sheared (prototype or centrifuge scale) or distance sheared normalized by pile diameter or original D_{50} grain size.

The pile tests listed in Table 1 all involved dynamic installation. Would a different rate of decay have been observed if the piles were installed by jacking? De Nicola & Randolph (1997) examined the distribution of horizontal earth pressure coefficient within a tubular model pile. It was found that the internal shaft friction in a driven (hammered) pile was best predicted by assuming a degradation of K typically from $K_{max} = 1$ to $K_{min} = 0.4$ along the internal soil column. In contrast, for a jacked model pile, a best match was achieved if K was assumed to remain constant at K_{max} along the internal soil column. This suggests that friction fatigue predictions obtained from dynamically installed piles may under-predict the capacity of jacked piles.

2 EXPERIMENTAL METHODOLOGY

2.1 Calibration chamber

Calibration chambers are widely used to study penetration resistance (eg. Houlsby & Hitchman 1988, Salgado et al. 1997, Yasufuku & Hyde 1995). The stresses and deformations around the tip of an advancing CPT or pile can be correctly replicated by applying a surcharge pressure. In order to observe the deformation around an advancing pile, a plane strain chamber with observation windows has been constructed (Fig. 3). Sheets of glass are placed on the inner faces of the box to reduce side friction. A surcharge pressure is applied through a rubber bag. The model pile is jacked into the chamber at a rate of 1 mm/minute. Digital cameras are used to record images of the soil and pile at regular intervals. In this paper, some results from a test on dry medium dense (relative density 44%, voids ratio 1.48) Dog's Bay carbonate sand are presented. The mechanical behaviour of this soil is described by Coop (1990).

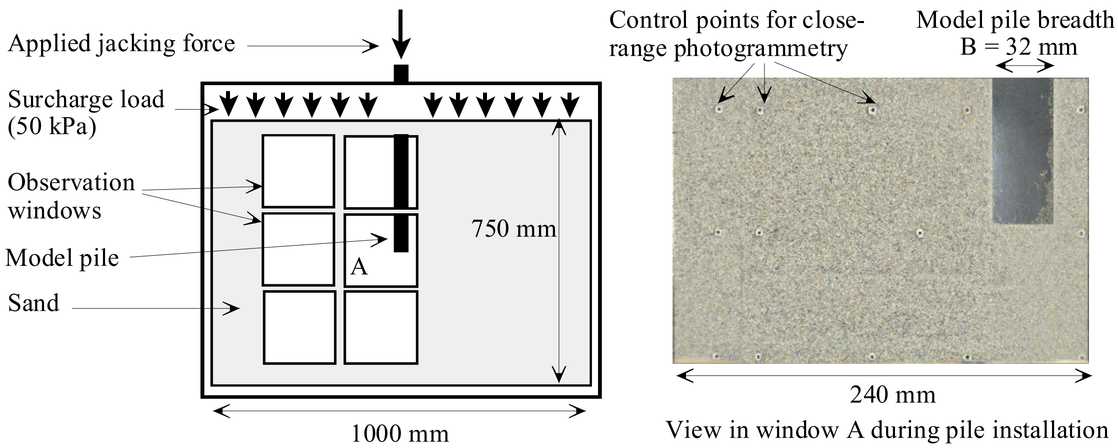

Figure 3. Plane strain calibration chamber

2.2 Displacement measurement using PIV image analysis and close-range photogrammetry

A novel technique for non-contact measurement of soil deformation in physical models has been developed. This system combines digital photography, close-range photogrammetry and image analysis using Particle Image Velocimetry (PIV). Soil displacements are measured to a high precision without requiring intrusive target markers to be installed in the soil.

Image processing algorithms based on PIV have been written to track the movement of small patches of soil (typically 2 - 4 mm in size) through a series of digital images to a precision of 1/15th of a pixel (White et al. 2001a). The images presented in this paper were captured using a Kodak DC280 digital camera, with a pixel resolution of 1760 x 1168. Having measured the image-space coordinates of the deforming soil by PIV, these must be converted into model-space coordinates. This process is known as camera calibration. The calibration routine developed in this research has 18 parameters to describe the model-space to image-space transformation and has a measured precision of 1/18500 of the field of view (White et al. 2001b).

3 RESULTS

The phenomenon of friction fatigue has been examined by measuring the movement of a horizon of soil adjacent to the pile shaft as the pile penetrates beyond this horizon. Image 1 (Fig. 4a) shows the tip of the pile entering the field of view, with a mesh of PIV patches established adjacent to the pile shaft (Fig. 4c). Comparison with a subsequent image (Figs. 4b, 4d) taken after 80mm (2.5 pile widths) of further penetration allows the intervening soil movement to be measured. The PIV analysis reveals that the soil is moving towards the pile shaft (Fig. 4e), with the greatest vector (250 µm, 1.9 pixels) being measured in the patch closest to the pile shaft. Similar vectors were obtained from analysis of the opposite face of the pile.

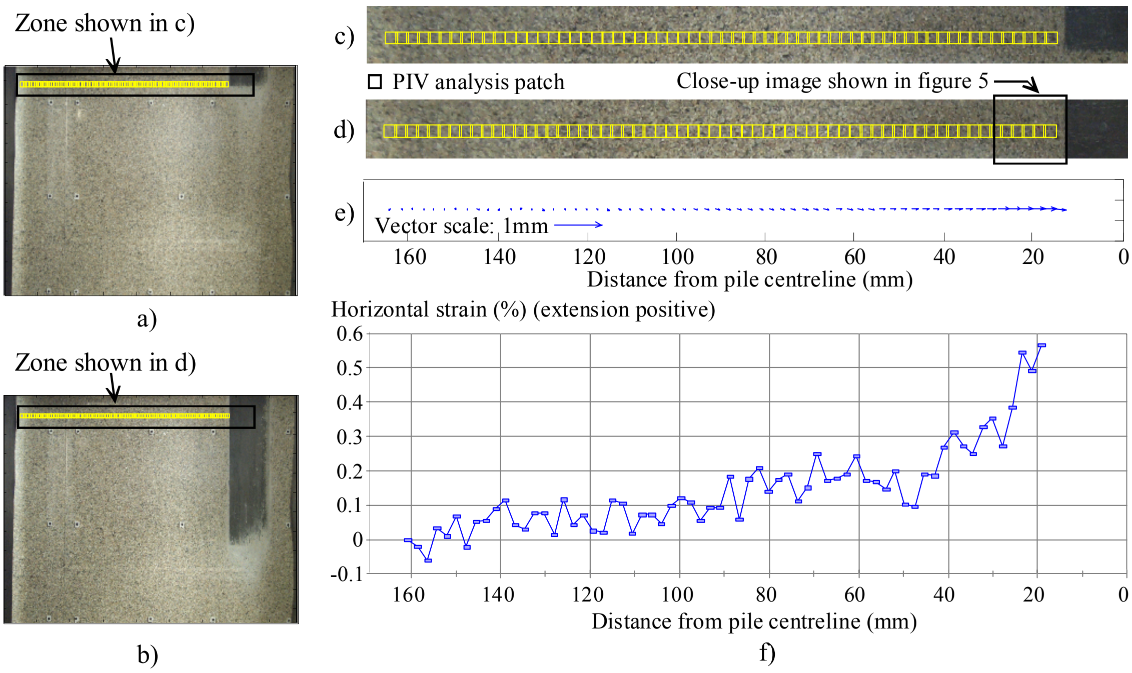

Figure 4. PIV analysis of sand adjacent to pile shaft

Differentiation of the horizontal component of displacement with respect to the gauge length between adjacent PIV patches allows horizontal strain to be plotted (Fig. 4f). This reveals that the soil is unloading in horizontal extension, with the greatest strain (0.6%) occurring close to the pile shaft. After completion of the test, the chamber was disassembled, and the sand adjacent to the shaft was photographed (Fig. 5a). The measured displacements are superimposed on this image.

Particle size analysis of sand taken from zone B (within 3 mm of the pile shaft) was carried out using a single particle optical sensing method (AccuSizer 780/DPS, http://www.christison.com). This device measures the mean diameter of individual particles flowing past a laserdiode sensor. A significant shift in the grading curve is evident, with the d_{10} size being reduced from 330 µm to 150 µm (Fig. 5b).

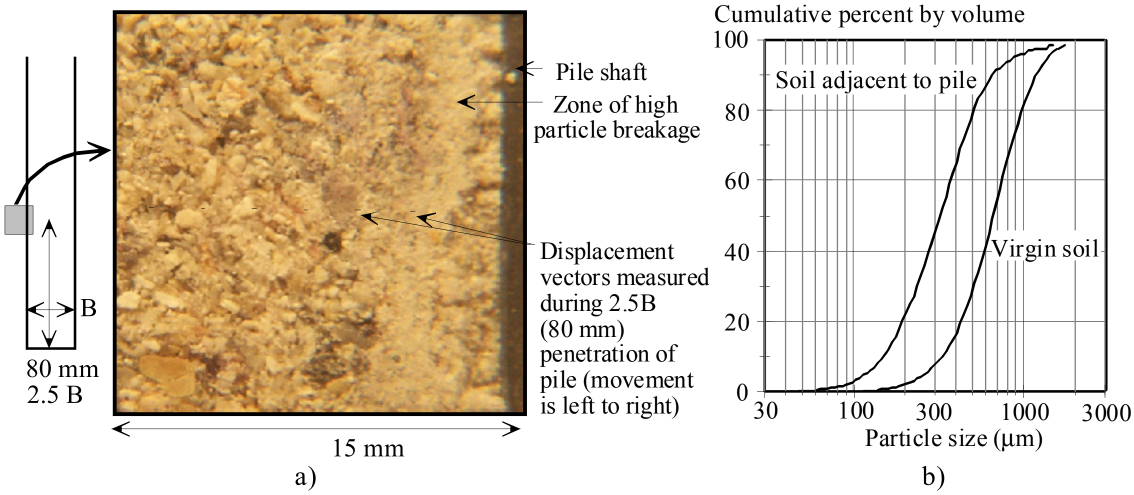

Figure 5. Post-mortem analysis of sand adjacent to pile shaft

4 DISCUSSION

The measured displacements and strains, combined with the insight offered by the close-up photography, allow the kinematics of friction fatigue to be deduced (Fig. 6a). The 3 mm thick zone of sand closer to the pile than the closest PIV patch undergoes volume reduction, due to continued shearing at the pile-soil interface. This volume reduction permits the soil further from the shaft to relax inwards.

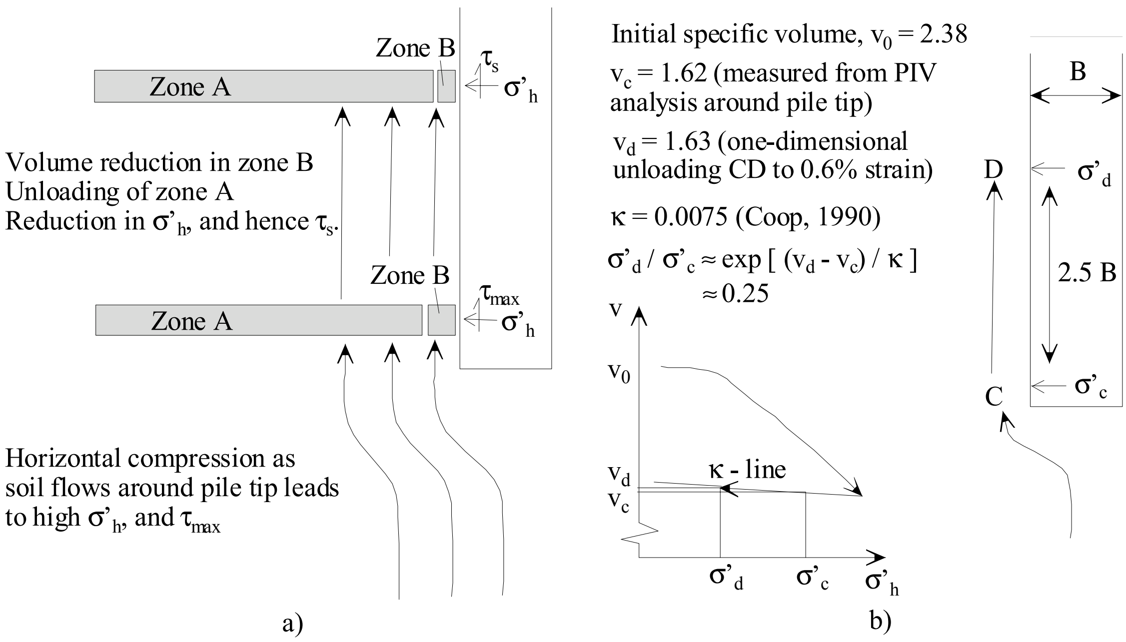

Figure 6. Friction fatigue mechanism

Figure 6b shows a simple calculation in which the measured volume changes are used to predict the change in horizontal stress adjacent to the pile shaft, with the unloading stiffness in ln σ'_h – v space being approximated as κ. This framework predicts a four-fold decay in horizontal stress after 80 mm of shearing, which is comparable to the decay rates presented in Table 1 for reduced-scale modelling (Bruno 1999, De Nicola 1996).

The friction fatigue mechanism hypothesized in figure 6 suggests that the reduction of horizontal effective stress acting on the pile shaft is governed by two processes:

Process 1: Volume reduction in zone B due to continued shearing at the pile-soil interface.

It is hypothesized that this process is associated with two mechanisms of volume reduction. Firstly, rearrangement and repacking of the sand grains is caused by the agitative action of the rough pile surface. Secondly, further repacking in the boundary layer is permitted by diffusion of the fine broken particles away from the pile-soil interface into the more open matrix of uncrushed soil in the far field. The one-way shearing created by jacking is likely to create less rearrangement than two-way cycling during dynamic pile installation.

Process 2: Horizontal unloading in zone A.

This is a continuum unloading process. The governing stiffness will depend not only on the *in situ* soil properties, but also on the installation-induced stress level at that soil horizon (which will have occurred as the pile tip passed) and also the installation-induced strain level (high in the near field, low in the far field).

Since the focus of this workshop is the contrast between centrifuge and constitutive modelling, a key question is whether this mechanism of friction fatigue can be correctly replicated using either of these modelling techniques.

Process 1 is not continuum behaviour and hence is not captured by conventional constitutive models. This process *will* occur in centrifuge models, but may not scale correctly. Conventional centrifuge laws of scaling particle size and surface roughness are unlikely to create self-similar diffusion of fine particles. Also, attempts to model shaft friction by maintaining the ratio of pile roughness to particle size fail when breakage occurs since particle strength (and hence change in grading curve for a given stress history) is a function of particle size (McDowell & Bolton 1998).

Process 2 will occur in a centrifuge model, and the stress and strain-histories will be correctly replicated. However, if process 2 is to be correctly modelled in a numerical simulation using a conventional constitutive model, the entire installation process must be simulated to capture the stress- and strain-histories of the soil around the pile.

The difference in particle size between the virgin soil and the soil around the pile shaft (Fig. 6b) has an influence not just on friction fatigue and the horizontal stress on the pile shaft, but also affects the coefficient of pile-soil friction. Correlations between mean particle size and coefficient of friction derived from interface shear box testing (eg. Jardine et al 1993, Kishida & Uesugi 1987) do not acknowledge that the soil adjacent to the pile shaft has a significantly different grading curve.

5 CONCLUSIONS

Calibration chamber testing combined with a new technique of displacement measurement using image analysis has allowed the penetration mechanism of a jacked pile to be quantified. Observation of soil adjacent to an advancing pile revealed movement towards the shaft. This movement is linked to the decrease in horizontal stress acting on the pile shaft; a process known as ‘friction fatigue’.

A mechanism for this process consists of i) volume reduction in the boundary layer at the pile-soil interface combined with ii) horizontal unloading in the far field. This process involves physical behaviour that cannot be captured by a continuum constitutive model nor replicated at small scale using conventional scaling laws.

6 REFERENCES

American Petroleum Institute (API) 1993. RP2A: Recommended practice of planning, designing and constructing fixed offshore platforms- Working stress design, 20th edition. Washington 59-61.

Bruno, D. 1999. Dynamic and static load testing of driven piles in sand. PhD thesis, University of Western Australia.

Chow, F.C. 1997. Investigations into the behaviour of displacement piles for offshore foundations. PhD thesis, University of London (Imperial College).

Coop, M.R. 1990. The mechanics of uncemented carbonate sands. *Géotechnique* 40(4): 607-626.

De Nicola, A. 1996. The performance of pipe piles in sand. PhD thesis, University of Western Australia.

De Nicola, A. & Randolph, M.F. 1997. The plugging behaviour of driven and jacked piles in sand. *Géotechnique* 47(4): 841-856.

Eslami, A. & Fellenius, B.H. 1997. Pile capacity by direct CPT and CPTu methods applied to 102 case histories. *Canadian Geotechnical Journal* 34(6): 886-904.

Fleming, W.G.K., Weltman, A.J., Randolph, M.F. & Elson, W.K. 1992. Piling Engineering. *Blackie (Halsted Press), Glasgow*.

Houlsby, G.T. & Hitchman, R. 1988. Calibration chamber tests of a cone penetrometer in sand. *Géotechnique* 38(1): 39-44.

Jardine, R.J., Lehane, B.M. & Everton, S.J. 1993. Friction coefficients for piles in sands and silts. *Vol. 28: Offshore Site Investigation and Foundation Behaviour, Soc. for Underwater Technology* pp 661-677.

Kishida, H. & Uesugi, M. 1987. Tests of the interface between sand and steel in the simple shear apparatus. *Géotechnique* 37(1): 45-52.

Lehane, B.M. 1992. Experimental investigations of pile behaviour using instrumented field piles. PhD thesis, University of London (Imperial College).

McDowell, G.R. & Bolton, M.D. 1998. On the micromechanics of crushable aggregates. *Géotechnique* 48 (5): 667-679.

Randolph, M.F., Dolwin, J. & Beck, R. 1994. Design of driven piles in sand. *Géotechnique* 44(3): 427-448.

Salgado, R., Mitchell, J.K. & Jamiolkowski, M. 1997. Cavity expansion and penetration resistance in sand. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 123(4): 344-354.

White, D.J., Take, W.A, Bolton, M.D. 2001a. Measuring soil deformation in geotechnical models using digital images and PIV analysis. *Proc. 10th Int. Conf. on Computer Methods and Advances in Geomechanics. Tucson, Arizona.* 997-1002 Rotterdam: Balkema.

White, D.J., Take, W.A, Bolton, M.D. & Munachen, S.E. 2001b. A deformation measuring system for geotechnical testing based on digital imaging, close-range photogrammetry, and PIV image analysis. *Proc. 15th Int. Conf. on Soil Mechanics and Geotechnical Engineering. Istanbul, Turkey*. Rotterdam: Balkema.

White, D.J., Finlay T.C.R., Bolton, M.D. & Bearss, G. 2002. Press-in piling: Ground vibration and noise during pile installation. *Proc. International Deep Foundations Congress. Orlando, USA. ASCE Special Publication 116 pp363-371.*

Yasufuku, N. & Hyde, A.F.L. 1995. Pile end-bearing capacity in crushable sands. *Géotechnique* 45(4): 663-676.