A competition to assess the reliability of pile prediction methods

Un concours pour établir la fiabilité des méthodes d'estimation de la capacité des pieux

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ABSTRACT: An international and open competition was organized by the Authors to test the ability of experienced practising engineers to predict the behaviour of plain driven and jet grout enhanced piles under static and cyclic loading. The paper first reviews the background, including prior assessments of design reliability, geotechnical conditions at the dense sand test site, the piles' construction, and testing the methods adopted. The organization of the competition is then described before considering the ranges of predictions offered in comparison with the field measurements made. General conclusions are drawn from these observations.

RÉSUMÉ: Un concours international a été organisé par les Auteurs afin de tester la capacité d'ingénieurs praticiens reconnus à prédire le comportement de pieux foncés simples et renforcés par jet grouting, sous chargement statique et cyclique. Cet article en présente tout d'abord le contexte, notamment les estimations antérieures de la fiabilité du processus de conception, les conditions géotechniques du site d'essai en sable dense, la construction des pieux, et l'évaluation des méthodes adoptées. L'organisation du concours est ensuite décrite et les gammes de prédictions offertes sont comparées aux mesures effectuées sur site. Des conclusions générales sont enfin tirées de ces observations.

1. BACKGROUND

1.1 *The competition*

The predictions competition described in this paper ran as part of *Geotechnics in the New Millennium*, a symposium that was held in September 1999 to both celebrate 50 years of Soil Mechanics at Imperial College, and debate the future of geotechnical research. The contest was intended to (i) assess how well geotechnical practitioners could predict pile behaviour, exposing the real levels of uncertainty in pile design; (ii) draw attention to some surprising research results and finally (iii) convince practitioners of the need to develop and adopt improved design procedures.

Entrants were asked to predict the outcome of field tests run by Imperial College at the Dunkirk experimental site in the course of the GOPAL collaborative project (involving Bachy Soletanche, Imperial College and D'Appolonia) and a subsidiary cyclic loading study funded by the UK Health and Safety Executive (HSE). The competition was publicised internationally and entries were invited by post, fax, e-mail or the internet. A special website was set up by Dr Andrew Bond of Geocentrix, while Mr Fin Jardine of CIRIA, the UK Construction Industry Research Information Association ran the competition confidentially, and independently from Imperial College.

1.2 *The reliability of pile design procedures*

One of the principal purposes of the competition was to draw attention to the poor reliability of popular methods of pile design. Briaud and Tucker (1988) carried out a broadly based assessment, plotting probability distributions generated from a substantial load test data base. Figure 1 shows their results for axial capacity, Q. Ideal methods would offer very strong correlations between $Q_{calculated}$ and $Q_{measured}$, leading to Gaussian distributions for Q_c/Q_m that centred around 1.00, with narrow data spreads to either side. However, none of the methods considered gave such results; most showed severe skews and wide scatter bands.

While load tests can help to mitigate designers' uncertainties, tests may not always be feasible or cost-effective. For example, it is rarely possible to test the large steel tubular driven piles that are often used in offshore applications. The American Petroleum Institute (API) RP2A 20th edition (1993) recommendations are generally considered as best practice benchmarks for such cases, and are used widely with confidence. However, Jardine and Chow (1996) and others show that even these procedures are not particularly reliable. Considering piles driven in sand, Jardine and Chow (1996) found Coefficients of Variation (COV defined as the standard deviation, s, divided by the mean μ) of 0.65 (shaft) and 0.79 (base). These COV values are uncomfortably large when compared with the relatively low recommended safety margins (1.5 to 2.0).

Even greater uncertainty exists concerning the load-deflection characteristics, especially when considering lateral forces, turning moments and repeated load cycles. Jardine and Potts (1988, 1992) used comparisons with full scale field monitoring data to show that conventional (T-Z, P-Y and elastic group interaction) procedures led to errors of around 300% for two cases involving groups tubular piles driven at North Sea sites.

1.2 *Research programme*

Imperial College, London, has undertaken a long-term research programme to improve the reliability of driven pile design. A decade of research has led to practical procedures that can predict the behaviour of driven piles with greatly improved accuracy. The experiments, theory and validation procedures are described in the references listed at the end of the paper.

The competition was based on field research carried out at Dunkirk, in 1998 and 1999 under two programme headings. The first was the GOPAL project, a collaborative study coordinated funded by the CEC and managed by Mr Eric Parker of D'Appolonia, which investigated the use of jet grout to enhance the base capacity of driven piles (Parker et al 1999) and ageing processes. The UK Health and Safety Executive (HSE) funded the second study into the cyclic behaviour of driven piles in sand (see Jardine 2000). The two strands were closely co-ordinated, making use of the same test location, equipment and personnel.

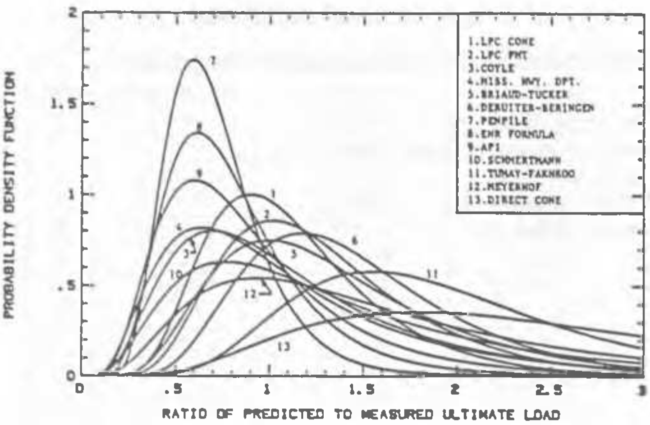

Figure 1. Reliability of popular methods for predicting pile axial capacity, after Briaud and Tucker (1988).

2. THE DUNKIRK SITE AND THE PILE TESTING

2.1 *General ground conditions*

The pile tests were performed at Zip des Huttes, west of Dunkirk, NW France. The ground conditions are summarized by the typical borehole log and CPT profile given in Figure 2. Multiple CPT soundings were performed to account for the lateral variability of the marine sands. The water table was found at around 4m depth at all locations and, although the CPT traces varied significantly, the same general pattern was invariably repeated of hydraulic fill (dredged Flandrain sand) down to around 3m, overlying the undisturbed Flandrian marine sand down to 30m. The sand sequence is often broken by organic layers that had accumulated during transgressions. The sands were in a generally dense to medium dense state, with looser conditions being interpreted in organic layers.

Detailed investigations had been made at the site by the French CLAROM group, Imperial College, the UK Building Research Establishment (BRE) and the GOPAL project partners. A 45 page long information pack that synthesized this data was made available to all competitors, either through the dedicated website, or by post from CIRIA. Details were given of the geotechnical conditions and soil properties, including stress-path test data, geophysical and CPT soundings, sand-steel and grout-steel interface shear studies, and comprehensive information on the jet grout properties. A local CPT sounding was given for each test pile, along with details of the piles' construction and the pile load testing methods.

2.2 *Earlier research at Dunkirk*

The tests described in this paper followed from a 1994 study by Imperial College that involved both tests with highly instrumented model piles and re-tests performed on piles that had been driven in 1988 by the French CLAROM group (Chow 1997). The re-tests on full-scale, open-ended piles driven into the dense Dunkirk marine sands revealed an astonishing 85% gain in shaft capacity after five years; Chow et al (1997). The 1994 tests have considerable implications for practice, and it was concluded that: (i) gradual creep in the circumferential stresses developed around the pile shaft allowed radial effective stresses to build up and increase capacity and (ii) greater dilation effects could be caused by sand ageing and in-situ chemical processes. These factors, which had a considerable bearing on the 1998/1999 tests, were brought to the attention of the competitors.

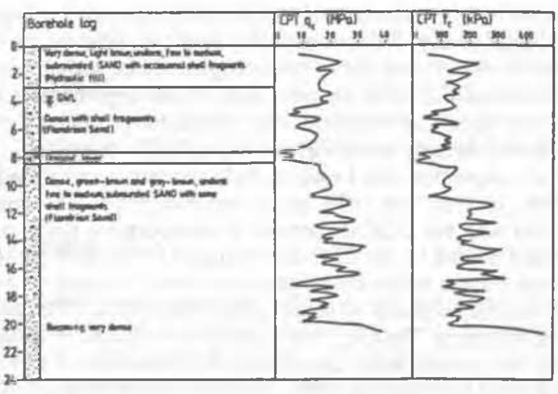

Figure 2. Typical geotechnical profile for Dunkirk test site, after Chow et al (1997)

2.3 *1998 to 1999 research programme*

The research programme from which the competition was developed involved experiments on eight 456mm diameter open ended driven steel pipe piles. The GOPAL research centred on two 10m long test piles: C1 and JP1. JP1 was enhanced by base jet grouting, as described by Parker et al (1999) and illustrated in Figure 3. The GOPAL test piles, along with six reaction piles, were driven by conventional drop hammering in late August 1998. The jet grouting, which was carried out three days after driving, involved drilling centrally through a partial sand plug to a depth 5m below the pile tip and then performing high pressure jet grouting as the drill and monitor were slowly revolved and withdrawn.

CPT testing established that the cylindrical jet grout bulb extended out to a diameter of around 2.8m, while coring performed after the end of the tests confirmed that good quality grout was present down to 5m below the base of the steel shaft.

The six 20m long reaction piles were not taken near failure in the GOPAL experiments, so they were available to study the influence of time on tension capacity, and the effects of cyclic loading. Jardine and Standing (2000)a, b and Jardine (2000) report the results of the ageing and load cycling studies. Their main conclusions were: (i) the shaft capacity of undisturbed piles increases even more rapidly than was anticipated from the 1994 re-test experiments, and (ii) that high level cycling can

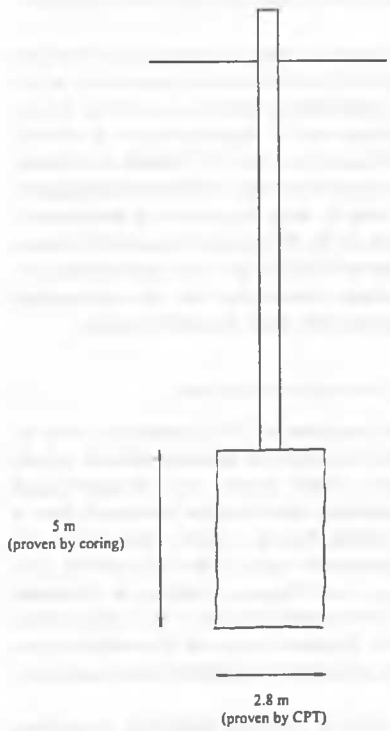

Figure 3. Geometry of jet grouted pile JP1 formed at Dunkirk

lead to a losses in capacity which can be severe under two-way loading patterns.

2.4 *The competition pile load tests*

The competition was organized to avoid any risk of professional embarrassment. Competitors could enter under an anonymous team name and only the three closest predictors were asked to identify themselves through codewords. The independent judges only became aware of the winning teams' identities only after the decisions had been made. Thirty six groups from around the world registered for the competition, and sixteen serious entries were received. The adjudication process involved eight hours of close debate by four experts (Dr Andrew Bond, Mr Fin Jardine, Dr George Milligan and Mr Duncan Nicholson), during which a comprehensive marking scheme was developed and applied. The competitors were asked to predict three main events:

1. The compression capacity and static load-displacement behaviour of the plain driven pile, C1
2. The compression capacity and static load-displacement behaviour of the jet grouted pile, JP1
3. The response of pile C1 to two-way cyclic loading following its initial compression test to failure.

The static tests were performed under load control. Pause periods of at least 30 minutes were imposed between load steps during which the creep behaviour was observed. The load steps became progressively smaller and the pause periods longer once significant creep had been detected. Tests C1 and JP1 involved 16 to 20 load increments each and the tests took 18 and 10 hours (respectively) to reach their peak capacities. The procedures followed allowed peak capacities to be defined clearly.

The load cycling imposed on pile C1 (and that in later studies on the reaction piles) was also applied through a load-controlled rig. The competitors were asked to predict how many cycles would be required to cause failure as the loads varied between 640 kN compression and 561 kN tension at a rate of around 50 cycles per hour.

Naturally, all organizations connected with the research were excluded from the competition. However, the Imperial College group did send pile capacity predictions to Mr Eric Parker in Genoa before the tests took place. Numerical methods were also applied after the fieldwork to make hind-casts for the piles' load-displacement behaviour and cyclic response (Jardine and Standing 2000a, Jardine and Kovacevic 2000).

2.5 *Results*

The static tests on piles C1 and JP1 gave the capacities summarized below in Table 1, and the load-displacement characteristics plotted in Figure 4.

Neither JP1 or C1 developed a clear peak in capacity and the values quoted in Table 1 were defined as the head loads required to cause settlements equal to 10% of the steel piles' diameter. A slight extrapolation had to be made for the test on C1, because of difficulties experienced with the loading frame. Rod extensometers were mounted on the steel piles to help estimate the distribution of axial load between base and shaft, and competitors were asked to estimate this split, along with the piles' overall capacities and load-displacement behaviours.

Rotary cores taken through the axis of JP1 showed that the

Table 1. Test results and predictions made for axial capacities of piles C1 and JP1

Capacities, MN	Pile C1, plain driven	Pile JP1, jet grouted
Measured in tests	2.86	5.25
Imperial College predictions	2.59	4.89
Mean of competitors predictions	2.27	13.00
COV of competitors predictions*	0.53	1.30

*Note COV is non-dimensional (standard deviation/mean)

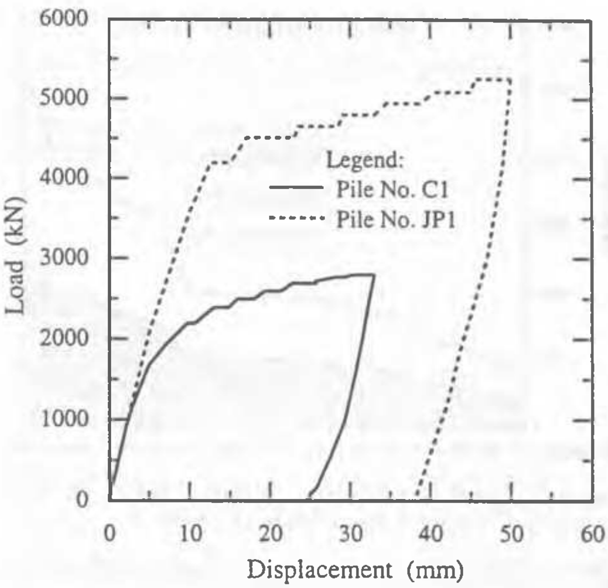

Figure 4. Load-displacement behaviour of jet grouted pile JP1 and plain driven pile C1 in first compression tests to failure.

failure involved the grout column cracking above and below the tip of the steel pile, with the cracking penetrating around 3m into the jet grout bulb.

The subsequent cyclic test on pile C1 reached failure in 41 cycles. However, as none of the competing teams made a serious attempt to analyse the cyclic experiment comparable statistics cannot be given in Table 1.

The competitors applied a wide range of theories and approaches in their submissions. None of the teams predicted all aspects of the tests accurately and the judges' prolonged discussions led to the first prize being awarded to Mr Tim Chapman and Ms Isobel Coman from Arup Geotechnics (UK), with the second and third prizes going to Dr Serge Borel of LCPC (France) and Dr Julio Moya Barrios of Colombia respectively.

3 RANGE OF PREDICTIONS MADE

3.1 *Axial capacity*

Table 1 summarises the predictions made. The first Author's 'Class A' estimate are given along with the mean and COV of the competition entries, while Figures 5 and 6 illustrate the wide ranges of predictions made for overall axial capacity.

Considering the conventional driven pile C1 first, we see that the competitors were, on average, conservative by around 20%, perhaps because of the sand's relative density, and the failure of most entrants to consider the full effects of the pile's age (80 days compared to the more typical 10 days used in most tests). However, the range of predictions was very wide, leading to a COV of 0.53 between predictions and measurements in this one, well-characterised site. This may be compared with the COV (0.65) assessed by Jardine and Chow (1996) for the API RP2A method as applied generally to piles driven in sand.

Familiarity with the site and knowledge of the piles' ageing characteristics allowed the Imperial College group to predict capacity more accurately. However, an error of 10% was still made, despite these advantages.

Cyclic hindcast calculations were run by Mr Mark Manzocchi of WS-Atkins using a simple numerical model described by Jardine and Standing (2000)a. Initial estimates of the relevant soil parameters (made from experience, in the absence of site specific laboratory tests) led to failure being delayed beyond the measured 41 cycles. Tuning the input parameters allowed a

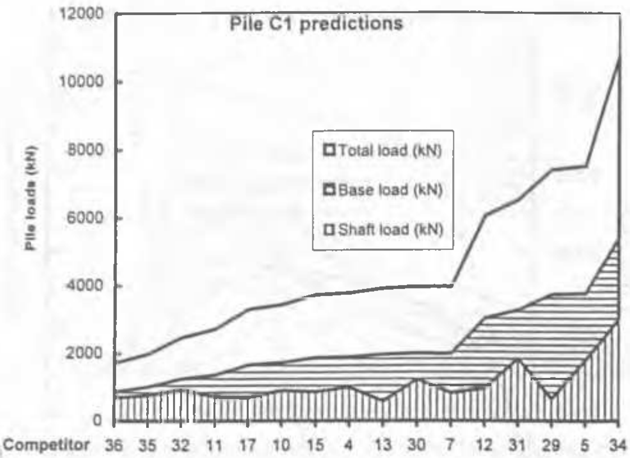

Figure 5. Spread of predictions for axial capacity of plain driven pile C1 in first compression test to failure

closer fit (Jardine and Standing 2000a, b). Precise prediction of cyclic events clearly remains very difficult.

The scatter between predictions made for the jet grouted pile was still greater. As summarised in Table 1 and in Figure 6, the entrants were, on average, un-conservative by a considerable margin (150% error), with a large COV of 1.30. The Author's Class A prediction was fortuitously close (within 7%). A crucial factor was recognising that the failure mode involved crushing and cracking of the brittle grout under load.

3.2 *Load-displacement behaviour*

The competition judges took into account the accuracy of the settlements predicted at working loads. Considering the means and COVs of the ratio between predicted and measured settlement defined at a Factor of Safety = 2.5, the competitors were generally conservative, overestimating settlements by around 100% in both cases. The wide scatter led to settlement COV's of 0.7 and 1.3 respectively for piles C1 and JP1 respectively.

The Imperial College group did not make any Class A load-displacement predictions. Hindcasts following the non-linear procedure outlined by Jardine and Potts (1988, 1992) employing data from locally instrumented stress path tests run by Kuwano (1999) led to reasonable matches with the field curves.

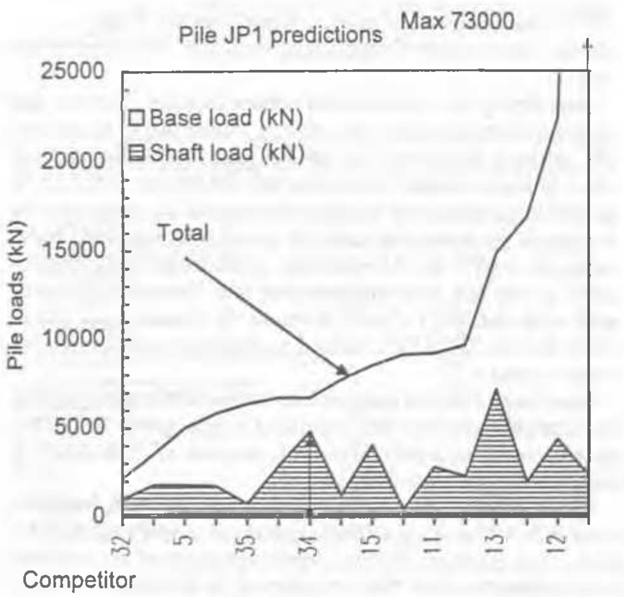

Figure 6. Spread of predictions for axial capacity of jet grouted driven pile JP1 in first compression test to failure

The first trial numerical analyses under-estimated working load settlement by around 25%, but it was difficult to match the final stages of the test accurately because the time dependent (creep) settlements became the dominant source of incremental movement; see Jardine and Standing (2000)a,b.

4. CONCLUSIONS

1. The error margins associated with predicting pile behaviour are surprisingly broad.
2. The blind trial described showed that predictions made by even experienced engineers for piles driven in sand cannot be expected to be accurate to within ±50%.
3. The reliability with which predictions can be made for novel pile types, such as the jet grouted pile JP1, and for load displacement behaviour is even lower. None of the competitors were able to offer convincing predictions for the cyclic load test.
4. Research has identified many of the phenomena that lead to poor predictions being made. Applying recently acquired knowledge concerning the effective stress conditions set up by pile installation and loading, ageing processes, small strain behaviour, the properties of jet grouts, progressive failure and cyclic loading allowed the Imperial College group to predict the field tests far more closely than was possible by conventional means.
5. The competition demonstrates the need for, and value of, research into pile behaviour. It also indicates the scope for design to be improved by adopting more modern tools.

ACKNOWLEDGEMENTS

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REFERENCES

Briaud J.L. and Tucker, L.M. 1988. Measured and Predicted Axial Response of 98 Piles. *ASCE JG.E.* Vol 114, No. 9, pp 984-1001.

Chow, F.C. 1997. Investigations into displacement pile behaviour for offshore foundations. *Ph.D Thesis, Imp. College, Univ. London.*

Chow, F.C., Jardine, R.J., Nauroy, J.F. and Brucy, F. 1997. Time-related increases in the shaft capacities of driven piles in sand, *Géotechnique*, 47, No. 2, pp 353-361.

Jardine, R. J. and Potts, D. M. 1988. Hutton Tension Leg Platform Foundations: an approach to the prediction of pile behaviour. *Geotechnique*, Vol.38, No.2, pp 231-252.

Jardine R.J and Potts D.M. 1992. Magnus foundations: soil properties and predictions of field behaviour. *Large scale pile tests in clay.* Thomas Telford, London, pp 69-83.

Jardine, R.J. and Chow, F.C. 1996. New design methods for offshore piles. *MTD Publication 96/103*, MTD, London.

Jardine, R.J. and Standing, R.J. 2000. Pile load testing performed for HSE cyclic loading study at Dunkirk, France. Volume 1. *Report OTO 2000 007; Health and Safety Executive*, London. 60.p.

Jardine, R.J. and Standing, R.J. 2000. Pile load testing performed for HSE cyclic loading study at Dunkirk, France. Volume 2. *Report OTO 2000 007; Health and Safety Executive*, London. 200.p.

Jardine, R.J. and Kovacevic, N. (2000) Finite Element Analysis of GOPAL jet grouted pile loading test. *Report to CEC*, 46p.

Jardine, R.J.. 2000. Some surprising results from research into the behaviour of piles driven in sand. *Revista Italiana Geotecnica.* 34, 8, pp 5-16.

Kuwano, R. 1999. The stiffness and yielding anisotropy of sand. *PhD Thesis, Imp College*, University of London.

Parker, E. J., Jardine, R.J., Standing, J.R. and Xavier, J. 1999. Jet grouting to improve offshore pile capacity. *Offshore Technology Conference, Houston*, OTC 10828.