Joint research into the behaviour of driven piles

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Abstract. Large driven piles are used widely in both onshore and offshore construction. Predicting their limiting capacities and load-displacement behaviour under a range of static and cyclic, axial, lateral and moment loading conditions is critical to many engineering applications. This paper reviews relevant recent joint research by groups at Imperial College London (ICL) and Zhejiang University China (ZJU). Two tracks of enquiry are outlined: (i) assembling and analysing a major and open database of high quality load tests conducted on industrial scale piles at well characterised sites; and (ii) modelling the effective stress regime developed around piles driven in sands. Both avenues of research are vital to enabling scientifically well-founded and yet industrially credible improvements to practical pile design methods. The scope of future joint research is also outlined.

Keywords: Driven piles, Sands, Database, Stress regime, Joint research.

1 Introduction

Large driven piles provide support worldwide for large bridges, harbour works and also the thousands of offshore structures that have been installed to produce oil, gas and renewable energy supplies. Designers need to ensure that their foundation piles can be driven successfully and are able to sustain the static and cyclic loads imposed safely, especially in severe marine environments. A need to reduce infrastructure costs, especially in offshore energy projects where oil prices and renewable power tariffs have reduced dramatically, has led to equal attention being given to ensuring economy in design. Up to 30% of the capital costs of offshore wind energy are associated with wind-turbine foundations. Geotechnical engineering advances have contributed to the increasing competitiveness of this important renewable energy resource.

Jardine [1] summarised findings from several recent and current research projects involving the Imperial College Geotechnics group that have contributed to advancing the design of large driven piles. These included the PISA Joint Industry study for monopiles under lateral and moment loading in sands and clays [2], work with international colleagues on a range of experimental, theoretical and database projects and large scale investigations of pile behaviour under axial loading in chalk [3-5]. The latter have involved the first large-scale offshore field tests of which we are aware where autonomous underwater pile tests have been conducted on the seabed. The systems shown in Figure 1 were deployed in 40m of water to test 1.37m outside diameter piles driven in a succession of glacial till over low-to-medium density chalk at three locations in the Wikinger windfarm, sited in the German sector of the Baltic Sea. Other case histories that demonstrate the industrial impact of the research include those given by [6-9].

We concentrate in this paper on two strands of research that has been undertaken jointly by Imperial College London (ICL) and Zhejiang University (ZJU) with support from a Newton Advanced Fellowship awarded from the UK's Royal Society and supported by matching funding from Natural Science Foundation of China.

2 Joint ZJU-ICL studies into the reliability of axial capacity predictions

The joint driven pile research involves first a macro-level approach that recognises the lack of international agreement on which design methods offer the most reliable predictions for axial capacity – the factor that dominates the design of multi-legged jacket structures. Here the ZJU-ICL team concentrated first on collating new databases of pile load tests, ensuring the quality of the tests and associated site investigations and adding value to the tests by conducting new experiments and analyses. Growing from earlier work summarised by [10-11], new tests have been added while the application of stricter quality criteria have eliminated other. Table 1 summarises the 117 tests assembled for piles driven in sands that were reduced into a consistent database format and made publicly accessible by [12-13].

The extended sand database provided the key resources that enabled the assessment of 6 different axial capacity design methods, which is summarised in Table 2. As may be seen, the physically based ICP-05 [11] and UWA-05 [17] 'CPT' methods led to the best reliability statistics when expressed as mean values and Coefficients of Variation (CoV) for the ratios of calculated Q_c and measured Q_m axial capacities. The Q_c/Q_m statistics found from the 80 'age filtered' tests in the ZJU-ICL database are summarised in Table 2. The individual Q_c/Q_m ratio results varied by up to ±0.1 when all 117 tests were included; this order of sensitivity to the specific dataset is typical of surveys involving around 100 piles; the statistics become far more sensitive to individual cases with smaller populations. Table 2 indicates slightly more favourable outcomes for the API [14] Main Text method than earlier studies. The Yang et al [13] analysis also highlighted the significantly poorer statistical outcomes when the "offshore variants" of the ICP-05 and UWA-05 approaches were considered. While the latter approaches are preferred in the API [14] Commentary sections, it is better to retain the full ICP-05 procedure for use in practical design.

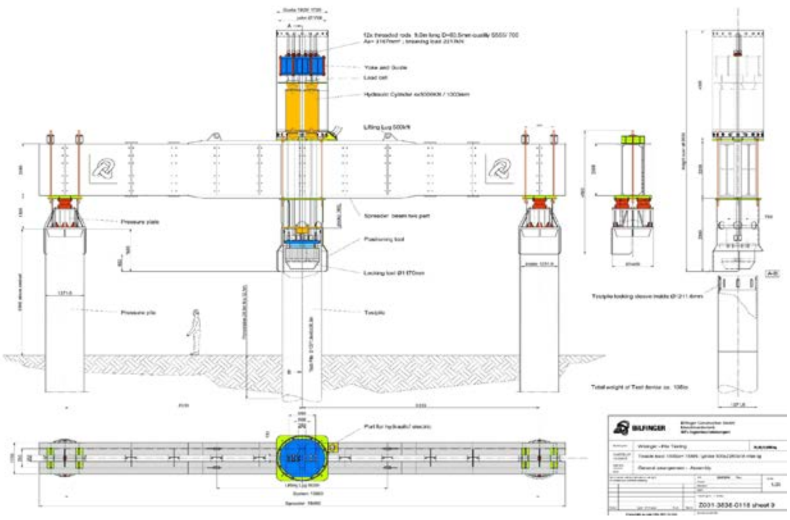


Fig. 1. Load test arrangements employed by Bilfinger for Wikinger project, German Baltic Sea, after Barbosa et al [3]).

A parallel Joint Industry study led by NGI led to broadly compatible conclusions regarding the Q_c/Q_m ratios applying to piles driven in sand, as summarised by [2]. The ZJU-ICL joint database study is now turning to consider the behaviour of piles driven in clay.

The NGI led Joint Industry database project identified significant shortfalls in the best current international datasets (see Lehane et al [2]) and the ongoing ZJU-ICL study is now seeking to identify both new tests and conduct additional laboratory and field investigations to add value to existing case histories for which vital information is currently unavailable. Approaches have been made to colleagues internationally, including the ISSMGE's TC 212. The Authors would be grateful to any delegates who may have suitable test and SI data that they can contribute to the construction of an authoritative, reliable and accessible international database.

The novel features of the successful 'CPT' sand methods listed in Table 2 originated in the use of highly instrumented displacement piles to investigate the key factors that governed shaft and base failure in sands, with a focus on the local shear and radial stress distributions developed on the pile shafts during installation, equalisation and load testing to failure. Establishing reliable experimental observations of the stress regimes developed around displacement piles and understanding how these may change is vital to making any further improvements and to considering key features of field behaviour that remain poorly understood, including the marked effects of pile ageing on shaft capacity [19-20] and the impact of cyclic loading [21].

These questions are being investigated in the second main strand of collaborative work, which focuses on the detailed processes and mechanics of the soil responses, which include consideration down to the micro-level of how individual soil grains behave around the shafts of driven piles.

Table 1. Main features of ZJU-ICL database for piles driven in sand; after Yang et al [13]

	All entries			Filtered entries with age= 10-100 days		
	Closed	Open	All	Closed	Open	All
Number of piles	62	55	117	48	32	80
Steel	25	48	73	18	26	44
Concrete	37	7	44	30	6	36
Tension tests	10	31	41	8	16	24
Compression tests	52	24	76	40	16	56
Average length L (m)	17.6	25.2	21.2	18.9	26.0	21.8
Range of lengths L (m)	6.2-45	5.3-79.1	5.3-79.1	6.2-45	5.3-79.1	5.3-79.1
Average of diameter D (m)	0.413	0.645	0.522	0.422	0.667	0.520
Range of diameter D (m)	0.2-0.7	0.324-2.0	0.2-2.0	0.2-0.7	0.324-2.0	0.2-2.0
Average of density D_r (%)	54	60	57	54	61	57
Range of D_r (%)	28-89	30-88	28-89	31-89	30-87	30-89
Average test time after installation	35	80	61	43	28	35

Table 2. Joint ZJU-ICL database test assessment of approaches for axial capacity prediction in sands; means and coefficients of variation (CoV) for Qc/Qm ratios; summarised from Yang et al [13]

Method	Mean	CoV
API [14], Main Text	0.88	0.55
Fugro-05 [15]	1.20	0.47
ICP-05 (full) [11]	0.94	0.30
NGI-05 [16]	1.23	0.48
UWA-05 (full) [17]	1.05	0.35
LCPC-82 [18]	1.25	0.40

3 Characterising the effective stress regime around piles driven in sands

In addition to the practical macro-level studies outlined above, the joint ZJU-ICL research into driven pile behaviour has tackled the fundamental mechanics of pile driving, ageing in-situ and loading under both static and cyclic conditions. The research started with Yang's work with Imperial College and the late Professor Pierre Foray's group at the Université Grenoble Alpes' 3S-R laboratory. Their large calibration chamber was modified considerably to allow long-term, highly instrumented, model pile experiments to be conducted under closely controlled pressurized conditions. Jardine et al [22], Zhu et al [23], Yang et al [24], Tsuha et al [25], Jardine et al [26-27], and Rimoy et al [20] describe multiple static and cyclic experiments with a stainless steel cyclically jacked mini-ICP pile (with 36mm diameter, 1m length) that could monitor shaft shear and normal stresses at three levels. As indicated in Figure 2, dozens of soil stress sensors were also deployed within the masses of Fontainebleau sand (of both NE34 and GA39 grades) that were air-pluviated into a medium dense (75% relative density) state before being pre-loaded and aged under 150 kPa vertical stress to match the average sand state (void ratio and pressure) applying to the field and calibration chamber tests. The NE34 silica sand has both a similar grading and comparable grain shapes to the sands found at the Dunkirk site in Northern France where large scale field tests were conducted earlier, as described by Jardine et al [19]. Parallel laboratory testing was conducted at Imperial College that employed high pressure triaxial cells to study NE34 sand's behaviour under the extreme stress conditions imposed by pile installation; [28-30].

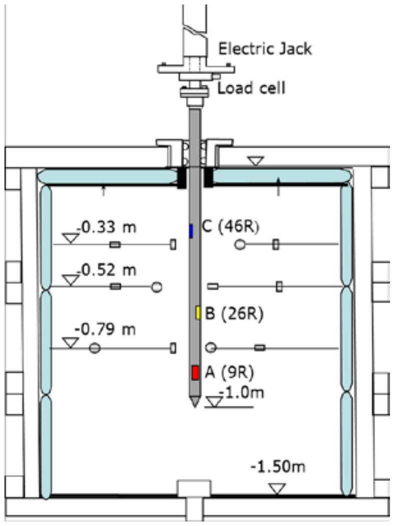


Fig. 2. Calibration chamber test arrangements at Grenoble 3S-R laboratory for mini-ICP pile experiments in NE-34 Fontainebleau sand mass equipped with multiple soil stress sensors and subjected to 150 kPa vertical stresses; after Jardine et al [22].

Among the many findings from the research were the micro-level observations presented by Yang et al [24] of the particle crushing that takes place beneath the pile tip and leads to a ‘crust’ of crushed and densified material adhering to the pile shaft, which has also been found in field tests at Dunkirk and elsewhere. This observation, along with the observations made of the soil stress system during installation that are illustrated in Figure 3 and the pile tip loads provide benchmarks against which new theoretical predictions may be tested and, hopefully, refined.

Professor Einav’s group at Sydney was the first to attempt simulations of the Calibration Chamber pile experiments. They employed a crushable soil grain model that had been calibrated to the soil element testing conducted at Imperial College and applying an Arbitrary Lagrangian Eulerian (ALE) FE technique were able to capture some key aspects of the experiments, as outlined by [31-32]. Their simulations for the soil stress regime gave encouraging results and also indicated scope for further improvement. Particle by particle (Discrete Element Method) simulations were undertaken by [33-34] at Imperial College in which half a million (over-sized) crushable grains were employed along with a reduced size soil volume. These analyses provided similarly good simulations of the experimentally observed pile tip resistances and grain crushing zones and gave predictions for the stress regime developed by pile installation.

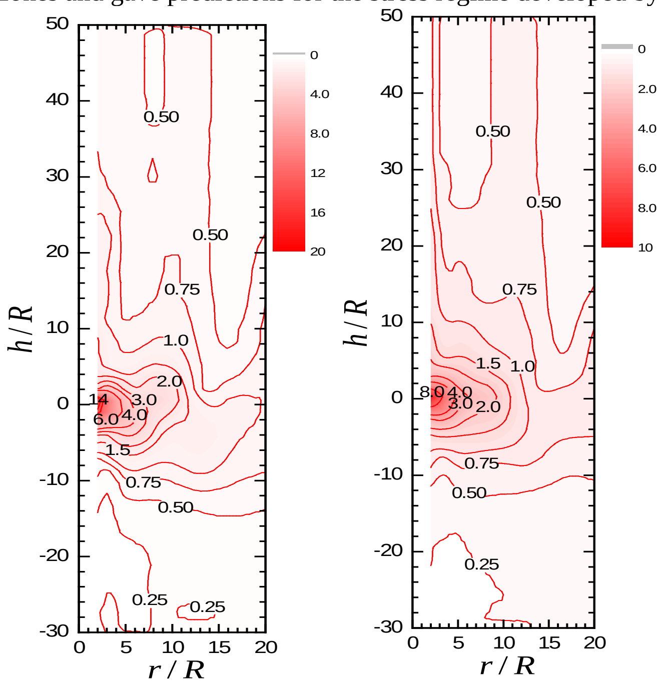


Fig. 3. Experimental observations of normalised radial effective stress regime, σ'_r/q_c developed in sand mass around the mini-ICP during (left) penetration stages and (right) paused between strokes of cyclic jacking installation process in pressurised NE34 sand; after Jardine et al [27]. Note q_c is local CPT tip resistance.

However, scope exists for further improvements in the numerical analysis of displacement pile installation. In addition to seeking still better matches for the Calibration Chamber tests, major developments are required to allow analyses to be undertaken of the stress regime developed around the open-ended tubular piles employed in most large scale offshore, harbour and bridge driven pile projects.

A team led by Yang has been advancing such studies at ZJU as part of the joint work with Imperial College. The ALE technique within ABAQUS has been applied first to simulate the calibration chamber experiments described above. The ALE option is efficient as it can adopt a 2D axisymmetric mesh and employ relatively low numbers of finite elements; see Figure 4. In the simulation, the pile is considered as a rigid Lagrangian body with a standard cone tip (D=2R= 36 mm), a total length of 1.5 m and a 1m final embedment (L), giving (L/R$\approx$ 56). The sand mass was regarded as deformable material subject to ALE adaptive mesh control. The same mesh dimensions as the calibration chamber were adopted to match any boundary effects, with width w = 0.6 m, height H = 1.5 m, w/R = 33.3. The default ALE control parameters were adopted in all the simulations attempted. The contact between the pile and soil adopted ABAQUS' built-in surface-to-surface contact laws, based on a master-slave-principle, in which the pile is treated as master surface and sand as the slave. The penalty friction formulation was adopted with a friction coefficient of 0.46, taken from the interface friction angle measurements of 25^{o}-27^{o} found in interface ring shear tests by Yang et al [24].

A simple Mohr-Coulomb elastic-plastic soil model was adopted for the sand with the material parameters being calibrated to generate equivalent q_c profiles with experiments. Based on the experimental results, the sand mass can be partitioned into different zones with the distinct mean normal stress and the plastic shear strain in each zone, as illustrated in Figure 5. The varying dilatancy angle ψ and friction angle φ can be assigned in each zone to accommodate the state and strain-level dependency of the sand's behaviour. Figure 6 presents the stress distributions obtained from numerical simulations. Figure 6(a) presents the normalized radial stresses measured at radial distances r/R=2 at three levels in sand mass, z/R=10.6, 30.6 and 46.1, the same as those measurements made in Jardine et al [27]. Figure 6(b) presents the normalised radial stress contour maps. These results match well with the experimental data reported by [27]. The deformation fields developed during the pile penetration were also captured by the numerical simulations, as illustrated in Figure 7. Figure 7(a) presents the radial displacement contours, while Figure 7(b) gives the radial strain contours. The numerical simulations appear to show encouraging agreement with experimental results obtained by Arshad [35] in another calibration chamber that offered scope for Digital Image Correlation analysis of the sand movements that employed a 'half-cylindrical' arrangement that differed from the Grenoble chamber and employed a different test sand.

Numerical simulations of full scale tubular piles pose more changeling tasks. Multiple elements are required across the width of the annular pile tip and these lead to very large overall elements numbers being required for precise FE analysis and render the problem beyond the capacity of conventional computation. A multiscale approach appears to be a more attractive solution, where material close to the inner and outer pile shaft could be modelled by a Discrete Element Method (DEM) approach and the far field be treated by FE. In this way, the contact between the pile surface and the sand grains, and the large deformations taking place at the soil-pile interface, can be handled more conveniently. Soil plugging phenomena can also be explored in more detail and its effect on the capacity of open-ended piles can be considered. Such work is in progress and will be reported in the near future.

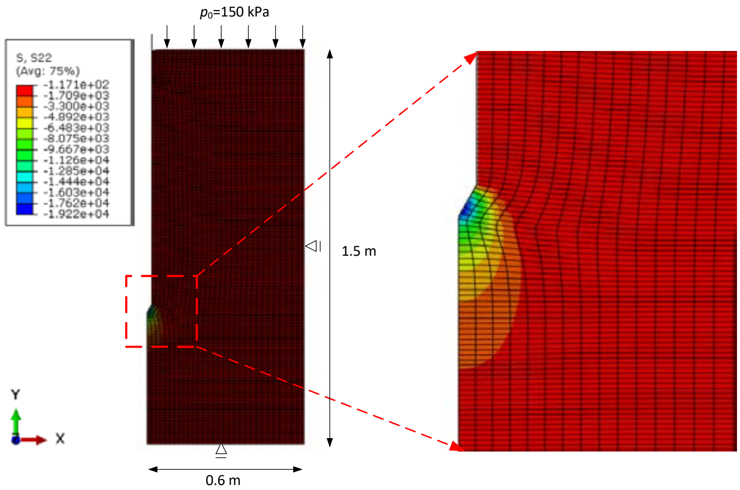


Fig. 4. Detained information of the 2D ALE model for calibration chamber experiments

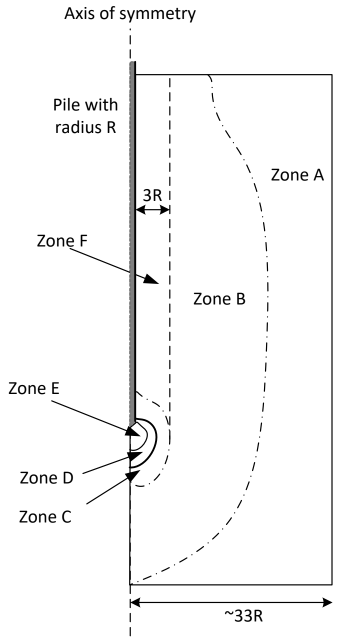


Fig. 5. Schematic diagram of zones with different dilatancy and friction angles

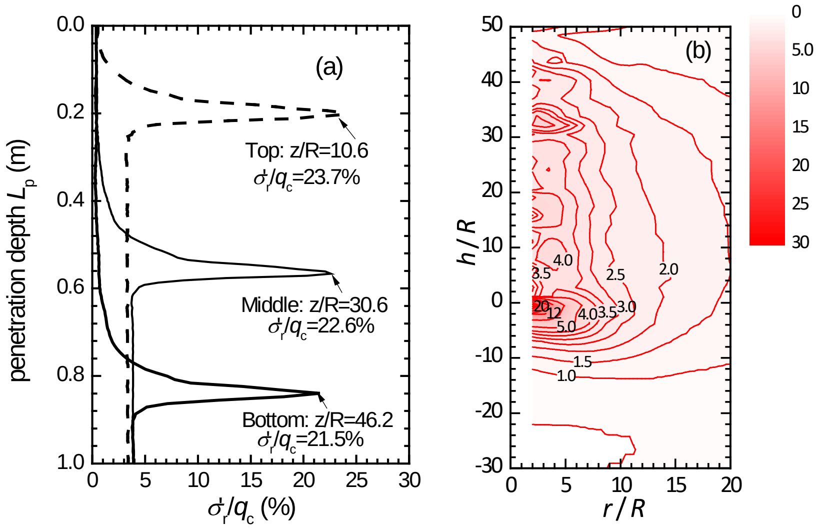
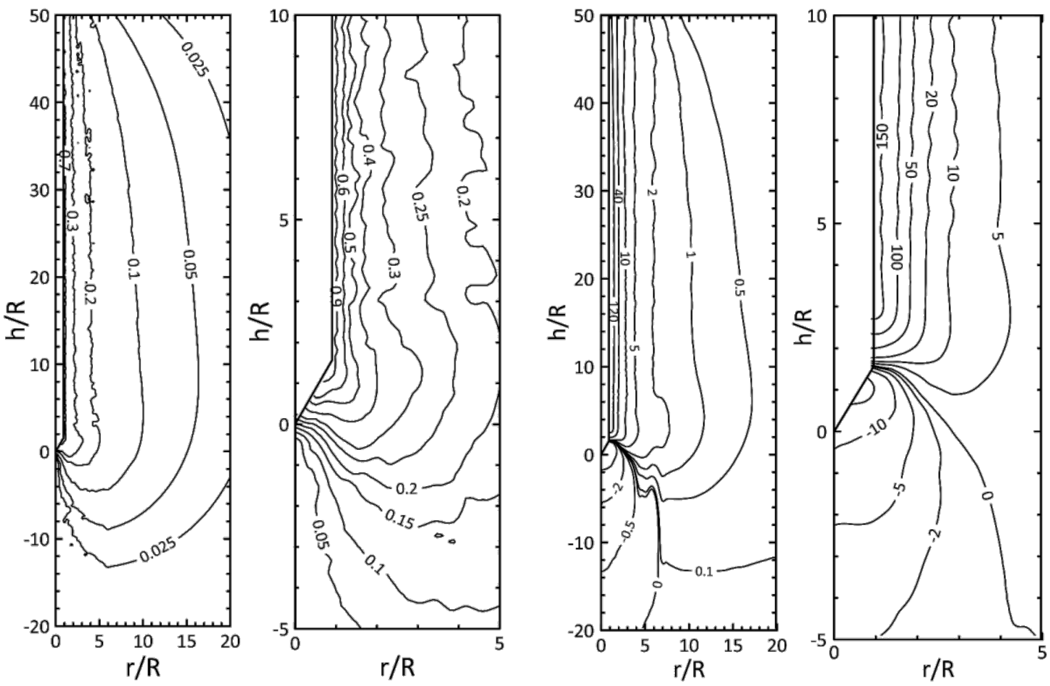


Fig. 6. ALE simulations of normalized radial stresses during penetration (a) measured at r/R=2; (b) contours



(a) radial displacement (b) radial strain

Fig. 7. ALE simulations of radial displacement/strain during penetration (a) displacement (b) strain

4 Summary and conclusions

A considerable demand exists, particularly from the offshore engineering sector, for improvements in the design tools available for large driven piles. Joint work between Imperial College London and Zhejiang University China is contributing to meeting this demand. Our joint paper has outlined two tracks of research that tackle the problem from (i) the macro-level, by assembling and adding value to industrial scale pile tests in a major database study and (ii) from a fundamental level that works from the grain scale upwards and includes new simulations of the detailed stress field developed around driven piles. Both avenues of research are vital to enabling scientifically well-founded and yet industrially credible improvements to practical pile design methods.

Although not described in this paper, the joint ZJU-ICL team is also conducting parallel research into other societally important geotechnical topics, which include the analysis of how the cyclic loading imposed by moving vehicles impacts on the settlements of the ground beneath road and railway pavements.

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