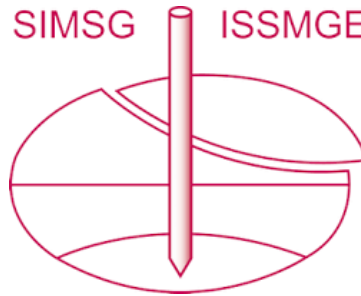


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Advanced laboratory characterization of a fine marine sand from Dunkirk, France

Caractérisation laboratoire avancée d'un sable marin fin de Dunkerque, France

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ABSTRACT: Dense fine marine sand is encountered at the Dunkirk ZIP Les Huttes test site located in northern France that has been employed extensively for research into pile behaviour. Laboratory testing of the sand is required to fully characterise site conditions and determine parameter inputs for analysing the field pile experiments. This paper summarises some of the comprehensive laboratory testing programmes undertaken to investigate the sand's mechanical behaviour, including stress-strain relationships, stiffness and strength anisotropy, cyclic behaviour, and interface shear properties. The paper first reviews the site's geotechnical conditions and their potential variations over time. The stringent laboratory requirements that are necessary for the accurate measurement of shear stiffness, strength, and creep strains are then discussed, before presenting illustrative results regarding the sand's small strain stiffness and time-dependent behaviour. The importance of reproducing site conditions and stress states are also addressed in relation to integrating the laboratory research with field observations and analyses of both recent and historical piling experiments at the Dunkirk test site.

RÉSUMÉ : Dense fine sable marin est rencontré sur le site de test de Dunkirk ZIP Les Huttes situé dans le nord de la France qui a été largement utilisé pour la recherche sur le comportement de pieux battus. Des essais en laboratoire du sable sont exigés pour bien caractériser les conditions du site et déterminer les entrées de paramètres pour les analyses des expériences de pieux sur site. Cet article résume certains des tests de laboratoire complets entrepris pour étudier le comportement mécanique du sable, y compris les relations contrainte-déformation, la rigidité et l'anisotropie de résistance, le comportement cyclique et les propriétés de cisaillement d'interface. Le document passe d'abord en revue les conditions géotechniques du site et ses variations potentielles au fil du temps. Les rigoureuses conditions de laboratoire requis qui sont nécessaires pour la mesure précise de la rigidité et du fluage sont ensuite discutées, avant de présenter des résultats illustratifs concernant la rigidité de la petite déformation du sable et le comportement dépendante du temps. L'importance de reproduire les conditions du site et les états de stress est également abordée dans le cadre de l'intégration de la recherche en laboratoire avec des observations sur le site et des analyses des expériences de pieux récentes et historiques sur le test site.

KEYWORDS: driven piles; sand; laboratory element tests; stress-strain behaviour; time-dependence; pile installation

1 INTRODUCTION

Extensive research has been conducted at a site near Dunkirk, Northern France to advance the understanding and prediction of driven pile behaviour in sands subject to axial and lateral loading under both static and cyclic conditions. The programmes include the CLAROMP pile driving project (Brucy *et al.*, 1991), an Imperial College project (Chow, 1997), the GOPAL jet grouting project (Parker, 2000), a Health and Safety Executive/Imperial College project (Jardine *et al.*, 2006, Jardine & Standing, 2012), the nearby SOLCYP cyclic loading study (Puech *et al.*, 2012), the PISA lateral loading project (Byrne *et al.*, 2015, Zdravković *et al.*, 2015), and a current Grenoble-Tech/IC micro-pile testing programme.

The Dunkirk site has been characterised in several stages for the above research projects. Rotary borehole sampling down to 26.4 m conducted under the CLAROMP project showed a hydraulic fill sand layer to 3 m and a thick Flandrian marine sand deposit that extends to 30 m. The hydraulic fill, which was placed between 1972 and 1975, was allowed to drain without artificial compaction or surcharging, while the Flandrian sand layer is separated at some depths by organic layers. Chow (1997) presented the typical site profile and CPT trace, as shown in Figure 1.

More recent site investigations at a nearby location revealed variations from the conditions established 20 years ago. Piezocone soundings undertaken in the PISA test area indicated a generally lower water table than previously reported in the CLAROMP and GOPAL tests and a trend for both higher CPT q_c cone resistances and greater shear velocities in both the hydraulic fill and the upper 5m of Flandrian sand (Zdravković *et al.*, 2015). The PISA test area also manifested less distinct (or absent) organic layers. Figure 2 compares the maximum shear

stiffness G_{vh} profiles from in-situ seismic CPT (SCPT), highlighting the higher recent values. Laboratory Bender element tests and resonant column tests that aimed to match the stress state and relative density profile estimated in the 1990s, showed G_{vh} values that matched the earlier SCPT measurements (Jardine, 2013), but fall below the recent G_{vh} profiles. The higher stiffness seen in recent SCPT tests may reflect spatial variations, the effects of long-term natural drainage, sand ageing with time, or a combination of factors.

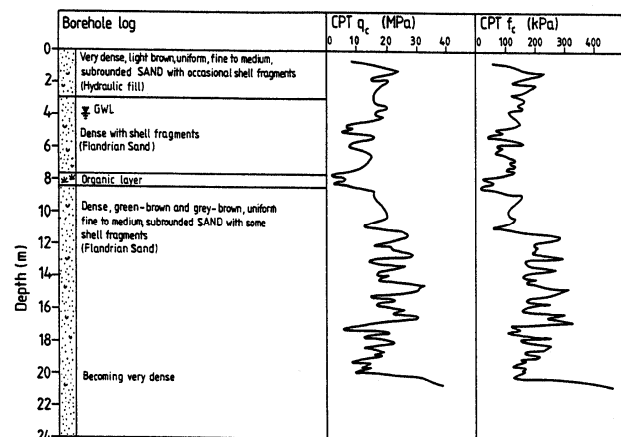


Figure 1. Dunkirk: typical profile for CLAROMP/Imperial College test site (Chow, 1997, Jardine *et al.*, 2006)

Extensive laboratory research has been carried out at Imperial College to investigate the Dunkirk sand's stress-strain relationships, anisotropy, time dependency behaviour (creep and ageing), grain-crushing, interface shearing, and cyclic loading responses (Kuwano, 1999, Jardine, 2013, Aghakouchak,

2015). In particular, the studies show that the sand's stiffness parameters are markedly anisotropic and pressure dependent. The laboratory research is integrated with the field experiments and numerical simulations, providing both fundamental understanding of the sand and key data to aid the modelling of pile behaviour and so refine pile design methods.

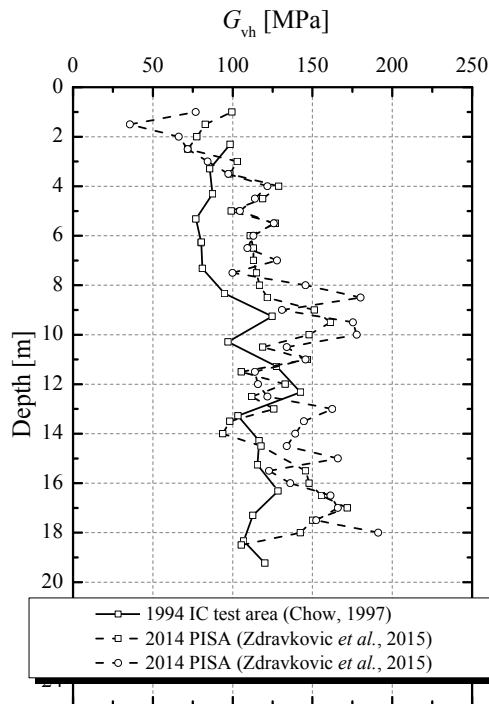


Figure 2. Dunkirk: shear stiffness G_{vh} determined from in-situ seismic CPT measurements

This paper summaries features from recent advanced laboratory testing programmes on Dunkirk sand. The principal focus is on stress-strain and time-dependent behaviour, including cyclic loading. The importance of addressing pile installation process and reproducing pile stress conditions and stress history in laboratory element testing are also discussed.

2 TESTING MATERIAL AND KEY APPARATUSES

The Dunkirk sand mainly composites silica quartz, with sub-rounded to rounded grain shapes. Mineralogy analysis reported by Chow (1997) noted an average composition of 84% SiO_2 quartz, 8% Feldspar and 8% Calcium carbonate shell fragments, while multiple tests for the CLAROM project also indicated an average of 11.5% CaCO_3 shell fragments. Microscope analyses on the sand samples indicated angular and flat shell fragmentation shapes, which explain the material's greater compressibility and crushability in comparison with pure silica sands, such as the Fontainebleau NE34 sand (Aghakouchak, 2015). The recent research has focused on mixed batches of Dunkirk sand prepared from near surface samples. The basic physical properties of the sands are summarised in Table 1.

The equipment employed in the recent research includes fully instrumented automated hydraulic stress path triaxial apparatus, hollow cylinder apparatus (HCA), Bishop ring-shear apparatus, and micro-structural analysis. Detailed descriptions of these apparatuses and their capabilities were given by Kuwano (1999) and Aghakouchak (2015). Continuous improvements and enhancements have been made in the local strain measurements, non-destructive dynamic testing, temperature stability, and testing control and logging capabilities. A recent example is the novel local radial strain measuring technique reported by Ackerley *et al.* (2016).

Table 1 Physical properties of Dunkirk sand

G_s	$e_{\max}$	$e_{\min}$	d_{90} [μm]	d_{50} [μm]
2.65	0.91	0.57	423.9	268.8
d_{10} [μm]	C_u	Sphericity	Elongation	
185.9	1.56	0.89	0.51	

3 RESEARCH PROGRAMMES AND RESULTS

3.1 Stress-strain behaviour: small strain to large strains

High resolution amplified LVDT instruments (Cuccovillo & Coop, 1997) allow axial strains to be resolved to 0.00005%, so enabling the vertical stiffness to be measured over the quasi-elastic range in triaxial tests that also investigated yielding and failure behaviour at large strains. Results are illustrated from two series of drained static triaxial tests on (i) isotropically and (ii) anisotropically (K_0) consolidated water pluviated Dunkirk sand samples, in which the initial relative density and effective stress level were varied systematically. Figure 3 presents illustrative trends for how the vertical tangent effective Young's modulus $E'_{v,\tan}$ degraded as a function of axial strain (when normalised by the void ratio function $f(e)$ proposed by Hardin & Richart (1963)). Figure 4 shows how the normalised vertical quasi-elastic maximum stiffness varied as functions of vertical effective stress σ'_v , following trends that can be represented by power law equations. Experiments conducted from a range of initial conditions confirmed Kuwano & Jardine (2002a)'s conclusion that the vertical quasi-elastic effective Young's modulus depends principally on the vertical effective stress, although other factors such as initial fabric and stress history may also play significant roles.

Figure 3 highlights the significant influence of effective stress history (OCR) on the larger strain non-linear tangent stiffness variations. Comparison between the normally consolidated sample ($OCR = 1$) and those over-consolidated ($OCRs = 4, 12$) shows that imposing preloading prior to shearing raised the normalised initial quasi-elastic and the non-stiffness characteristics. However, the highest OCR sample ($OCR = 12$) had lower normalised stiffness than at $OCR = 4$.

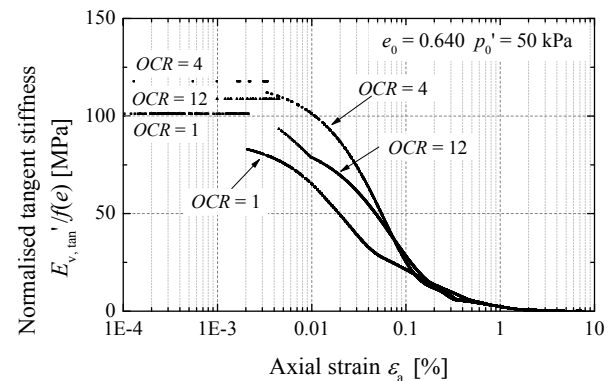


Figure 3. Degradation of the normalised vertical tangent effective Young's moduli against strains from triaxial compression tests on samples with different over-consolidated ratios

The stress-strain and volumetric behaviour of sands at large shearing strains depends on both stress level and void ratio and is best interpreted using a critical state framework, such as the state parameter approach (Jefferies & Bean, 2006, Taborda, 2011). The critical state line of Dunkirk sand determined from drained triaxial tests by Aghakouchak (2015) is presented in Figure 5, where ϕ_{cs}' was found equal to 32.1° . In the current testing, the potential effects on critical state behaviour of sample size, end roughness, membrane penetration and constraint, and particle crushing are being systematically examined in order to characterise the large strain behaviour and confirm the critical state trends. Large-displacement interface

shear tests on Dunkirk sand against steel 'pile' surfaces showed an ultimate interface friction angle $\delta = 26^\circ$. The interpretation provided key inputs into a critical state bounding surface constitutive model for use in advanced Finite Element analyses of the PISA test piles' behaviour under lateral and moment loading (Zdravković *et al.*, 2015).

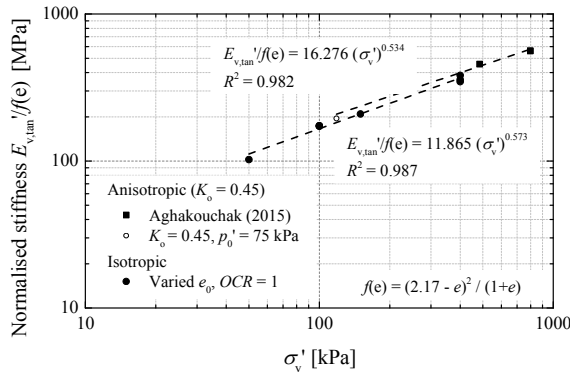


Figure 4. Normalised quasi-elastic vertical tangent effective Young's moduli against vertical effective stresses from triaxial compression tests

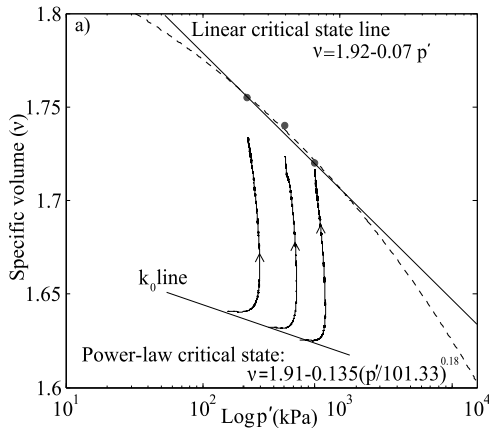


Figure 5 Critical state line of Dunkirk sand (Aghakouchak, 2015)

3.2 Time-dependent behaviour

The field research at Dunkirk identified time-dependent (creep, ageing, and cyclic) behaviour in the piles driven in sands. Chow (1997) and Jardine *et al.* (2006) noted marked increase in ultimate shaft capacity with age, while Jardine & Standing (2012) showed that the piles could lose shaft capacity under unstable cyclic loading conditions.

As documented by Kuwano & Jardine (2002b) and Jardine (2013), stringent testing requirements are required when investigating the sands' creep response in the laboratory, including very stable and high-resolution local strain sensors and high quality pressure and temperature control systems. Similar conclusions flow from the Authors' recent experiments. Figure 6 compares Dunkirk sand creep data recorded by identical axial strain and temperature sensors in two laboratories that employed different environmental temperature control systems. The creep strain accumulation trend can be discerned clearly under more stable (mostly $\pm 0.2^\circ\text{C}$) temperature control in Lab 1, while $\pm 0.75^\circ\text{C}$ temperature fluctuation that developed with roughly 2 hour cycles in Lab 2 led to larger apparent strain variations.

The effects of ageing and creep deformation were carefully examined in the current triaxial testing programme. The samples were allowed to age prior to shearing until the axial strain rate reduced down to 0.002%/day. Examples of the evolution of specific volume against mean effective stress under continuous isotropic compression and 48 hour creep is

illustrated in Figure 7, indicating marked creep strains in all samples. Further experiments employing non-destructive stiffness techniques are also being carried out to examine the evolution of stiffness during the creep period (ageing effects).

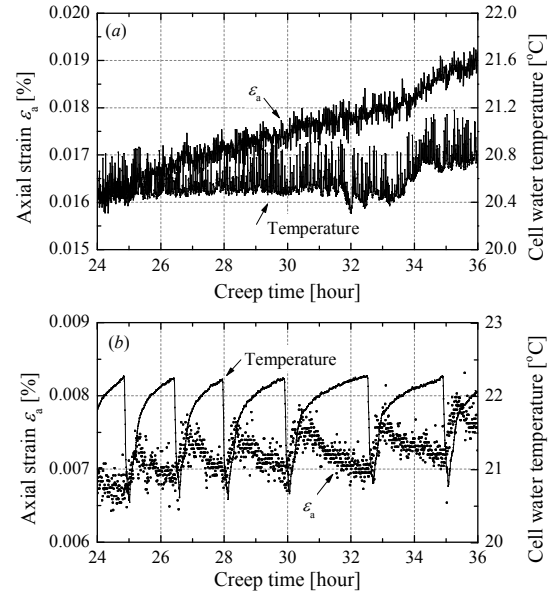


Figure 6. Effects of temperature fluctuation on creep strain measurements: (a) Lab 1, (b) Lab 2

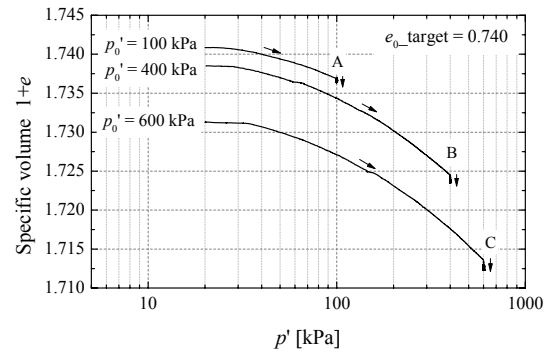


Figure 7. Evolution of specific volume of the samples under isotropic compression and 48 hour creep

3.3 Reproducing stress condition and state in soil elements adjacent to driven piles

Careful local stress measurements made in large laboratory calibration chambers of the conditions developed around model displacement driven piles revealed a process of very considerable stress build-up in elements near the pile axis as the tip approaches from above, a maximum stress developing as the tip passes, followed by stress reversal and substantial relaxation and creep straining over time (Yang *et al.*, 2010, Jardine *et al.*, 2013a, Jardine *et al.*, 2013b). These observations led to a new testing stress path protocol being adopted for a cyclic element testing programme that aimed to match the pre-conditioning process imposed by pile installation, and so model the near shaft sand response to axial cyclic loading (Aghakouchak, 2015, Aghakouchak *et al.*, 2015). The protocol included: 1) an initial stress build-up (under K_o condition) followed by partial unloading; 2) 30 pre-cycles imposed with a Cyclic Stress Ratio ($\text{CSR} = \Delta q/p_o' = 0.5$) that matched that experienced during pile driving; 3) extended creep and ageing pauses. A series of constant volume cyclic triaxial tests and parallel hollow cylinder (HCA) tests were carried out by Aghakouchak (2015) adopting the protocol, and the effects of several factors, including initial density, effective stress history, creep and

ageing, pre-cycling, and cyclic stress ratio were examined. The effects of the pre-cycles on the subsequent response to constant volume axial cycling are demonstrated in Figure 8, concentrating on the effects of pre-cycling on the relative mean effective stress drift $\Delta p'/p_0'$ that developed as a function of the number of cycles N . It is clear that pre-cycling engendered a more positive response to subsequent cycling. The experiments proved that pre-loading had a major influence on cyclic response. They also identified the important effects of the creep duration imposed prior to cycling on the subsequent cyclic response shown in Figure 9. It is clear that the longer the sand was allowed to creep, the greater the undrained cyclic resistance. Correlation by Aghakouchak (2015) between cyclic laboratory test outcome and field tests at Dunkirk confirms that it is possible for laboratory element tests to provide accurate site-specific cyclic predictions for driven piles, provided that the stress level, history and states (relative density) presented at the pile shafts are matched in a representative manner.

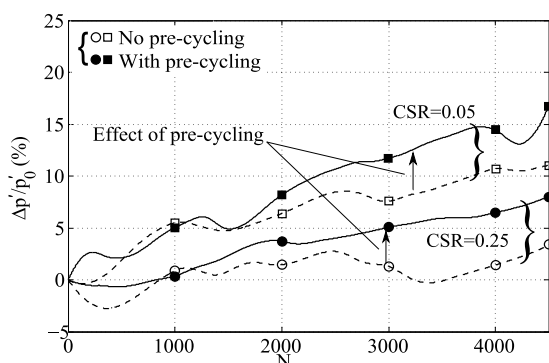


Figure 8. Effect of pre-cycling on the undrained cyclic response of sands (Aghakouchak, 2015, Aghakouchak *et al.*, 2015)

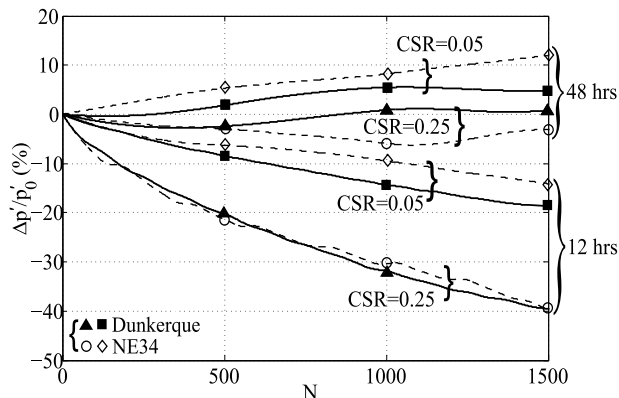


Figure 9. Effect of creep time on p' drift in undrained cyclic tests (Aghakouchak, 2015, Aghakouchak *et al.*, 2015)

4. CONCLUSIONS

Several laboratory testing programmes have been undertaken at Imperial College on a fine marine sand from Dunkirk that focus on features of behaviour that affect the interpretation and analysis of driven pile experiments conducted over decades at this test site. To obtain representative stress-strain behaviour from very small to large strains and investigate time-dependent behaviour calls for stringent laboratory requirements, particularly high-resolution local strain sensors, high quality temperature control systems, and testing protocols that include specimen conditioning stages designed to match pile installation effects. Outputs from the ongoing laboratory programmes are being integrated with the interpretation of the field observations and advanced numerical modelling.

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