Working with Pierre Foray to understand the behaviour of piles driven in sand

Pierre Foray Homage

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Background

Topic central for current large, multi €bn offshore wind-energy and hydrocarbon projects

Difficult, considered fully resistant to ‘theoretical refinement’ by Terzaghi & Peck

Conventional API & other approaches have poor reliability

Advances made in 25 years of Anglo-French research, last decade working with Pierre Foray and Grenoble 3S-R Lab

Continuing collaboration with France: SOLCYP, TC-209, Grenoble 3S-R and current PISA tests

Programme started in 1990 with Labenne field experiments with Prof Roger Frank’s LCPC team
IC instrumented piles

102mm diameter; up to 20m long

SSTs measure local $\sigma_r$ and $\tau$ on shaft

Intensive testing in sand at Labenne and Dunkerque 1990-95

...and 4 UK clay sites 1985-96

The 4 + 2 Anglo-French team at Labenne, SW France, 1990
See Lehane, Jardine, Bond & Frank (1993), ASCE
Interrogating nature...

Do conventional theories work? Constant K earth pressures and $N_q$ models? Or direct in-situ test methods?

If not, what really controls failure shaft shear $\tau$ and normal $\sigma'_rf$ stresses & end-bearing $q_b$?

What are the missing key variables?

Are there really upper limits to $\tau$ and $q_b$?

Compression versus tension loading?
Multiple tests:
Loose dune sand: Labenne
Dense marine sand: Dunkerque

Continuous profiles of shaft radial and shear stresses, axial loads and tip resistance

Installation, equalisation and loading to failure

Tip pressures controlled by local $q_c$; shaft stresses also vary with pile tip position $h$

Shaft stresses vary strongly during loading
Labenne: end bearing
Pile end resistance $q_b$ mirrors CPT $q_c$
Local shaft radial effective stresses

Shaft $\sigma'_r$ during penetration at Labenne

Mirror $q_c$ profile & vary with pile tip depth $h$

No constant $K$, but

$\sigma'_r = f (q_c, \sigma'_{vo}, h/R)$

Confirmed in dense Dunkerque sand

Effect of $h/R$
Loading response & effective stress paths, similar at Dunkerque and Labenne

$\sigma'_r$ varies under load

Tension $\neq$ compression

Simple interface law

$\Delta \sigma'_{rd} = 2G \frac{\delta r}{R}$

$D_r$ influence is through $G$

$\delta_{cv}$ not affected by $D_r$

Tests on CLAROM piles explore open-end effects
Basis for new ICP design rules used for oil, gas & wind energy

Piled tripods for Borkum West II
German N. Sea Merritt et al 2012

Overy 2007
Practical impact: one large UK jacket based windfarm

Critical economies in onshore and offshore projects

But surprising ageing results from large scale Dunkerque tests:


1998-9 tests on fresh GOPAL piles

And cyclic tests on GOPAL Piles
Dunkerque tests in dense marine sands: 1988-2015

CLAROM, ICP, GOPAL, SOLCYP and current PISA tests

Variable $q_c$ profile, up to 30 MPa

GOPAL: 8 steel pipe piles 457mm OD, 19m

Static & cyclic loading

Pile ages: 9 days to 1 year after driving

Ageing, creep & non-linear axial shaft stiffness,

Creep important at $Q > 1\text{MN}$

1st tension tests varying with age
Impact of axial cyclic loading

Load controlled
T = 60s

One-Way: tension
Two-Way: tension & compression

Plus: tension tests to failure

Failure depends on $N$, $Q_{cyclic}$, $Q_{mean}$ & static tension capacity $Q_T$

Loads normalised $Q_{cyclic}/Q_T$ & $Q_{mean}/Q_T$ to allow for age & pre-testing
Impact of axial cyclic loading: can halve capacity

Jardine and Standing (2012)

Failure $N_f < 100$

$100 < N_f < 1000$

Stable to $N > 1000$

Shaft capacity grows

Cycling adds to ageing

Degradation much worse with bored piles: SOLCYP, Puech et al 2013
Need for scientific exploration of these ‘new’ phenomena

Working with Professor Pierre Foray
2005-2014
Model experiments with Prof. Pierre Foray

3S-R chamber, temperature & pressure control
Dense NE34 sand; CPT: $20 < q_c < 25$ MPa
Tests over months under 150 kPa
Up to 36 stress sensors

Instrumented Mini-ICP

Mini-ICP model pile

Stainless steel: 36mm OD

Cyclic jacking installation

Local measurements at three h/R levels of:
- Axial load
- Surface $\tau_{rz}$ & $\sigma_r$
- Plus tip loads etc

“Hands-on” with Pierre Foray in the 3S-R laboratory
“Heads-down” – problem solving...

Working even with a geo-endoscope
Many successful tests over 2007-2013 main programme
International team:
Academics, Post-Doc, PhD, MSc & technicians

Members from:
- Brazil
- Chile
- China
- France
- Italy
- Tanzania
- United Kingdom
What did we find?

Distributions of $\sigma'_r$, $\sigma'_z$ & $\sigma_\theta$ around piles

Key to modelling ageing, cyclic response, group effects..

Supported by IC-Grenoble laboratory element & particle scale studies
Installation $\sigma'_r$ trends in sand mass:

1000s data contoured

$\sigma_r/q_c = f(h/R, r/R, \sigma_{zo})$

Intense tip concentration
Unloading above tip

Sharp changes over each jacking cycle

Corresponding $\sigma_z$ & $\sigma_\theta$ trends

Jardine, Zhu, Foray & Yang 2013
Geotechnique
Radial profiles of $\sigma'_r/q_c$ and $\sigma'_\theta/q_c$ shortly after installation

$\sigma_r$ and $\sigma_\theta$ profiles interlinked, peaks in at $2 < r/R < 4$

Critical to shaft capacity ageing theories

Compared later to advanced analysis
Local stress paths at Leading pile instrument
One cycle towards end of installation

![Graph showing stress paths with labels for peak load, unloading, start of push, and end point.](c)
Interface shear zone; Yang, Jardine, Zhu, Foray & Tsuha 2010; Geotechnique

Grey dense fractured shear zone ‘crust’ 0.5-1.5mm thick, growing with h. Not present if $q_c < 6$ MPa.
Breakage Zones 1, 2 & 3

Breakage starts under tip $\sigma'_{v} > 20$ MPa

Fractured sand displaced & spread over shaft: Zone 1

Further abrasion on shaft

Partial fracturing in outer Zones 2 & 3
Micro analysis of progressive grain crushing

(a) Fresh
(b) Zone 1
(c) Zone 2
(d) Zone 3
Qic-Pic laser analyses of small samples: Progression from fresh sand to Zone 1 ‘crust’

Breakage most severe in Zone 1, less in Zones 2 & 3
Related laboratory tests at Imperial College

Matching pile conditions in lab tests

Oedometer, interface ring-shear, high-to-low pressure stress path & cyclic experiments
High pressure oedometer compared to Zone 1
Void ratios, limits & sand states

Fresh NE34
$e = 0.63$

Average Zone 1
$e = 0.36$

Yang et al. (2010)
Replicating shear zones: ‘Bishop’ ring-shear interface tests

Coarse example of sands sheared against steel for metres $\sigma'_n$ up to 800 kPa; Ho et al 2011

Wide range of sands: different trends to direct shear interface tests
High-to-Low Pressure Triaxial tests

High-to-Low pressures, without dismantling & changing soil fabric

Matching model pile installation stress paths

Altuhafi & Jardine 2011
High-to-Low pressure stress-path tests

- **K₀ compression**: tip advancing from above
- **Active shearing**: tip arrival with \( \sigma'_v > 20\text{MPa} \)
- **Unloading**: tip advancing to greater depth
- **Re-shearing**: in compression or extension at high ‘OCR’
Effects on angle of shearing resistance?

High pressure 1\textsuperscript{st} shearing:
- Ductile response low peak $\phi'$

Low pressure re-shear:
- Brittle and much higher peak $\phi'$
- Critical to pile test interpretation

Graph shows the relationship between external strain and angle of shearing resistance. The graph includes data points for different pressures (P-T1, P-T2, P-T3) and external strain percentages.
Ongoing research

Ageing studies in lab and field
Rimoy, Silva, Jardine, Foray, Yang, Zhu & Tsuha (2015)
Under Review, Geotechnique

Simulating crushing and pile installation stresses
‘ALE’ Finite Element method with breakage mechanics:
Zhang, Yang, Nguyen, Jardine & Einav (2014)
Geotechnique Letters
End bearing and breakage: Zhang et al’s predictions

Predicted and measured pile tip stresses $q_c$

Contours of breakage parameter $B$:
- Fresh sand $B = 0$
- Fully fractured $B = 1$

Graph showing $q_c$ (MPa) vs. penetration (mm) with curves for 50mm ID top membrane and numerical simulation.
σ'_r/q_c and σ'_θ/q_c profiles predicted during installation

Maxima within 30% of measurements

Encouraging agreement with cyclic penetration model pile tests

But predictions steady at h/R > 10, while shaft σ_r/q_c measurements keep falling with h/R

Improve by modelling shaft abrasion & cyclic penetration?
Second main theme in 3S-R experiments

Cyclic axial loading

Model pile lab tests: similar overall trends to Dunkerque field experiments, new insights

Parallel cyclic lab element testing

Integration into practical design
Stable Mini-ICP cycling: interface stress paths
Load-controlled to N > 1000
Stresses remain within $Y_2$ shaft capacity rises

Unstable stress paths
Mini ICP tests failing with $N < 100$

Displacement-controlled
Two-Way tests engage $Y_3$ and $Y_4$
Phase transformation at interface

Load-controlled
One-Way tests engage $Y_2$
Drift towards interface failure

Shaft capacity falls markedly
Matching cyclic conditions in lab element tests

Interface $\frac{\delta \sigma'}{\delta r} = 2G/R$
Constant Normal Stiffness? $G \neq$ constant, $R =$ variable

Apply undrained CNS = $\infty$ in Cyclic Triaxial CTX

Or Simple Shear CSS tests
Best performed in HCA

Pre-cycling stress path?
Undrained cyclic element tests: NE34 & Dunkerque sands

Yielding patterns and $p'$ drift rates depend on:
- $CSR = q_{cyclic}/p'$ and $N$
- Shearing mode (TXL or HCA-SS)
- OCR & pre-cycling; creep & ageing periods

Pile stress paths, OCR = 4
Aghacouchak, Sim & Jardine 2015
SOLCYP and applications

SOLCYP: Puech et al 2013

AXIAL

LOADS (ULS)

Idealized cyclic loads
Rainflow

N=100

CYCLIC STABILITY DIAGRAM

Soil Data

Pile characteristics

CYCLIC DESIGN

Static design

DEGRADATION LAWS

Lab Testing:
- Soils: TXc/CSS
- Interfaces: CNS

Experimental data
- Model tests
- Field tests

in-situ testing:
- PMTc
- CPTc

Local Soil-Pile Analyses

Cyclic T-Z curves

Envelope t-z

SCARP

RATZ/PAXcy

Soil and Interface Behavioural Laws

Global Pile Analyses

Degraded capacity
Accumulated pile-head displacements

FEM Analyses

Jardine, Puech & Anderson 2012
Anderson, Puech & Jardine 2013

SUT 2012, Paris 2013 workshop

ICP static and cyclic methods for Borkum West II; Merritt et al 2012

Image from www.heavyliftspecialist.com
Summary

• Challenges posed by field behaviour. New scientific insights needed into ageing & cyclic response

• Critical investigations with Pierre Foray into pile installation stresses, grain-crushing, interface-shear & cyclic behaviour

• Intensively instrumented laboratory model experiments integrated with field, soil element & analytical research

• Results applied in major projects

• Still problems to solve:
  • Effect of scale on driven pile ageing?
  • More field tests needed: at Dunkerque, Larvik or Blessington?
  • Lateral/moment loading – new PISA programme underway: monopiles, tripods, jackets etc
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