



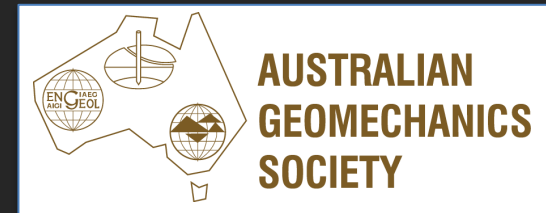
CONTINUOUS FLIGHT AUGER PILES (CFA)

Design, Construction & Verification

Presentation to the Australian Geomechanics Society, Victoria

8 September 2021

Dr Ben Collingwood



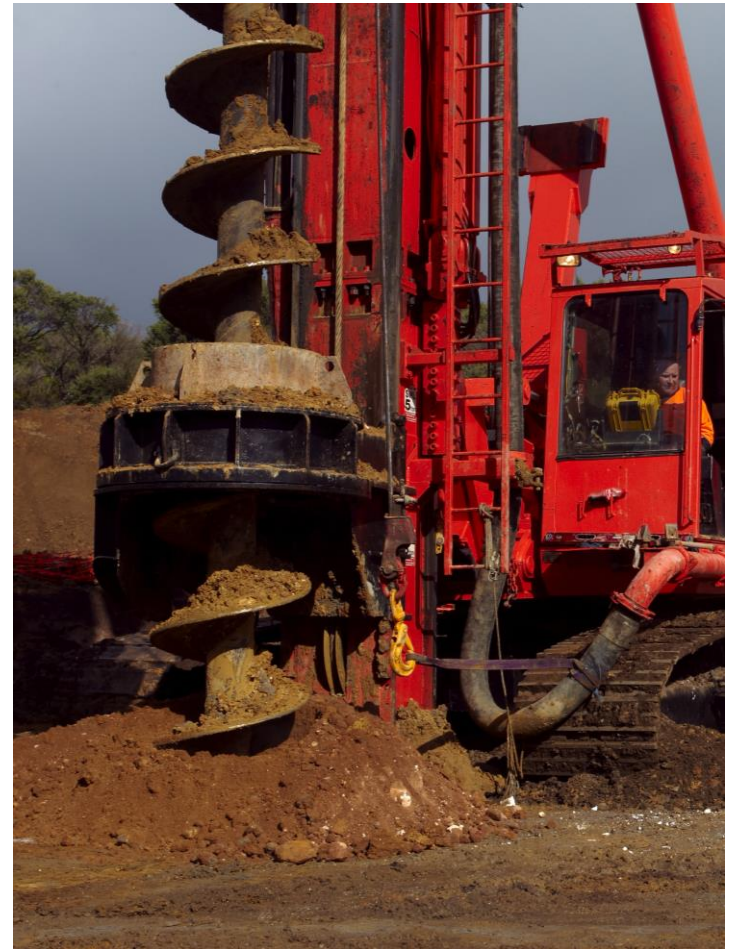
▶ Presentation Outline

Overview of CFA Piling and Current Practice for Geotechnical Practitioners

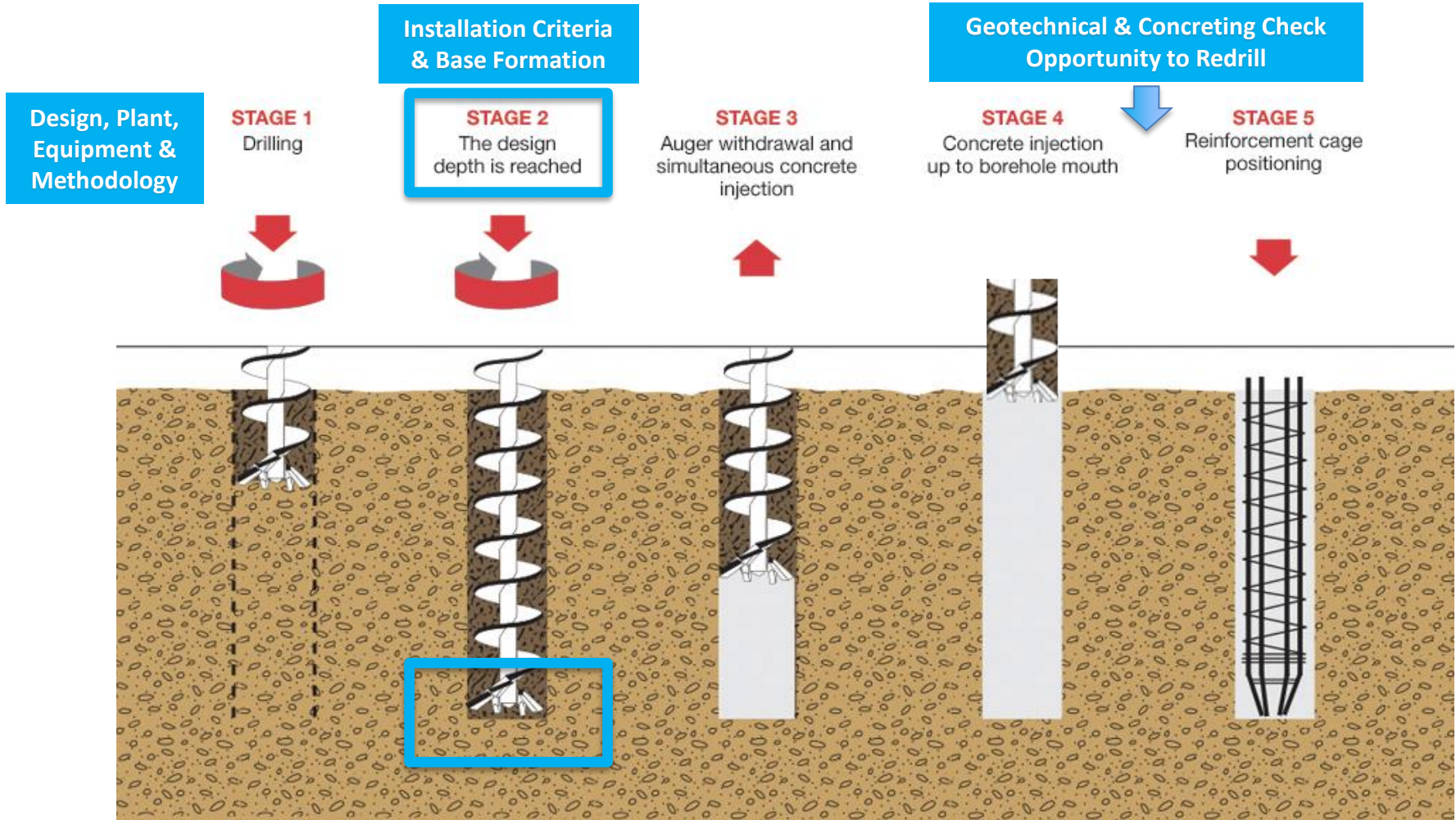
- Basics of construction methodology
- Advantages/Limitations
- Building vs Infrastructure:
 - Commercial and practical considerations
 - Some observations of current practice
- Codes and guidance
- Some key issues to understand

Case Study

- First Transport SA major project on CFA piles
Urban Superway Project, Adelaide
 - Overview & background
 - Design, construction and verification



Continuous Flight Auger (CFA) Piles



► Advantages of CFA Piles

- Relatively fast and cost effective to install (particularly in urban areas where concrete supply is good).
- High geotechnical capacities can be achieved by founding piles in rock.
- Full computer instrumentation (when properly used, calibrated and working) provides a relatively high degree of QC.
- Can be installed through collapsible soils (soil on the auger prevents collapse as long as penetration rate is appropriate).
- Can achieve good end bearing in sands below the water table.



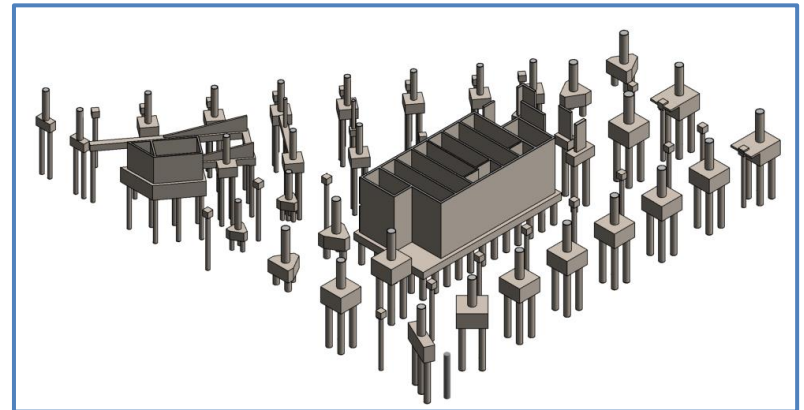
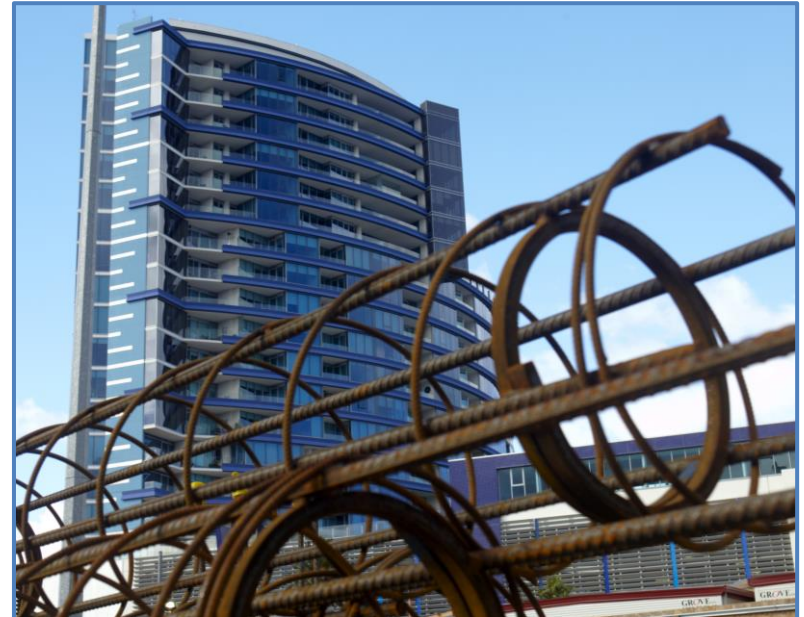
▶ Limitations of CFA Piles

- Heavily reliant on concrete quality (cage installation) and service (productivity).
- Performance influenced by “installation effects” (operator competence, company construction procedures and rig capability).
- This risk can be mitigated with computer instrumentation and PDA testing.
- Cages practically limited to ~ 20m length (with experienced contractor and good concrete). Deeper than this is possible, but increasingly risky. Central bars can be installed over full length.
- Piles limited to <1200mm diameter.
- Generate spoil which must be disposed of.
- Assessment of untested pile capacity requires interpretation.



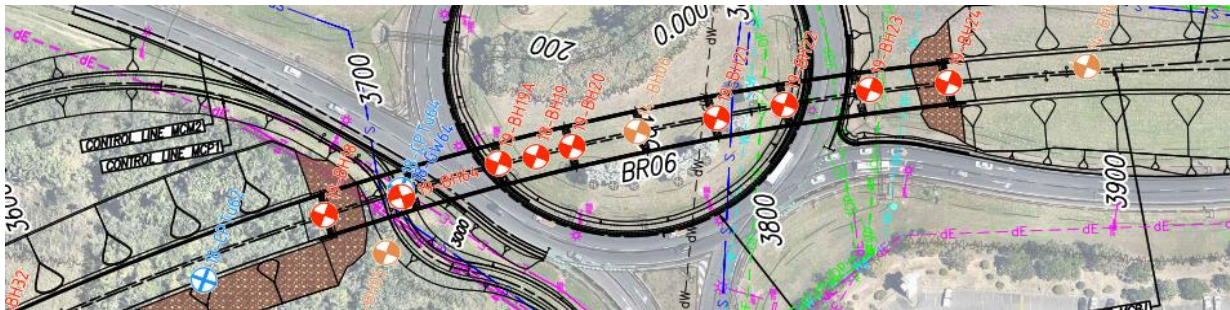
▶ Building Foundation Projects

- CFA piles in building:
 - First used in Australia in 1970s but reliability was an issue in early decades
 - Developed heavily in past 20 years as plant capacity and concrete technology improved
 - Cost effective for foundations and retention in the right ground conditions
- Large concentrated loads - axial usually governs
- Geotechnical investigation requirements not as rigid – scope and quality is quite variable
- Foundation works are always critical path
- Builders rely on specialist piling contractors to design and construct a suitable foundation solution
- Foundation systems are often contractor driven alternative designs
- Current industry practice evolved largely in building. [AS2159-2009](#) is governing code.



► Infrastructure Foundation Projects

- Variety of loading conditions:
 - Axial load often more moderate (compared to buildings)
 - Lateral loading can govern pile sizes
- Geotechnical investigation requirements more prescriptive
- Many stakeholders – represented by Designers, PE, IR. **Design and approval processes involve multiple parties and are much more involved**
- Specialist piling contractors are often consulted, but do not control the foundation solution (exception can be temp. works)
- **AS5100.3-2017, AS2159-2009 and Authority Specifications are applicable**



Typical Allocation of Responsibility

Activity	Building Projects	Infrastructure Projects
Design	Piling Contractor	Consultant
Construction	Piling Contractor	Piling Contractor
Construction Monitoring & Verification Processes	Piling Contractor	Multiple Parties
Verification (Sign-off)	Piling Contractor	Consultant (Designer), PE, IR

Contractor plant, capability, experience and execution is critical.

Requires understanding and alignment for good outcomes

Mixture of designer, specialist geotech, piling contractor, main contractor, client rep.

Concerns & discrepancies hard to resolve if preceding stages are not well executed



Building Projects

Observations of Current Practice

Design

- Key element of industry competition
- Often quite aggressive

Construction

- Expanding group of market participants
- Plant, equipment and capability varies significantly across piling contractors
- Level of engineering supervision also varies

Verification

- Pile testing (load & integrity)
 - rate and quality of execution not always consistent with design and construction challenges
- Attention to validating installation and design varies



Important for clients to carefully consider project requirements in selecting contractor



Infrastructure Projects

Observations of Current Practice

Design

- Approaches vary, but less aggressive
- Alignment with reviewers sometimes a challenge
- Trial piles sometimes incorporated

Construction

- Access and program are key factors
- More likely to be construct only
- Engineering supervision varies

Verification

- Number and distribution of test piles often minimized due to access, cost and program
- Geotechnical inspections – inconsistent approach across projects
- Often a lack of clarity around processes and responsibilities



Need for more practitioner guidance and understanding of key issues

▶ Codes & Guidance

AS2159-2009 – Piling Design and Installation

- Flexible design and verification approach
- Minimum requirements for construction & record keeping
- Pile testing (load & integrity) must align with design assumptions
- Tested piles must be properly representative

How practical & useful
to Industry Participants?

Do they produce positive
project outcomes?

AS5100-2017

- Defers to AS2159-2009

RMS NSW (Specification B63)

- Prescriptive on ground profiles that are suitable for CFA piles – to avoid ‘flighting’, not allowed in:
 - cohesive soil formations inter-bedded with granular layers;
 - hard layers overlain by soft layers.
- Requirements for additional geotechnical investigation – 4m to furthest pile
- During augering and concreting of the first pile of each pile group a Geotechnical Engineer must be in attendance. Further inspections in complex ground.
- Multi-pass base formation approach – raise and redrill 500mm

Codes & Guidance

How practical & useful to Industry Participants?
Do they produce positive project outcomes?

Vicroads Section 607

- Variation of the CFA pile founding level shall be subject to proof-engineering
- The Contractor shall produce a field log of the materials encountered over the full depth of the excavation. The materials retrieved at 1 metre depth intervals during the course of the drilling shall be recorded and inspected by the Contractor's geotechnical consultant
- If it is necessary to increase the depth of the pile to achieve the required pile capacity, the Contractor shall:
 - obtain confirmation from the Contractor's geotechnical consultant of the required increase in depth of the pile;
 - provide a full account of the need for the increase to the Superintendent for review.
- Where piles are founded on rock, they shall extend the specified minimum distance into rock of the type and quality shown on the drawings.
- Dynamic load testing of 1 pile per group

Limited clear, consistent and practical guidance
available to practitioners in these codes and standards!
Leads to lots of departure requests!!



Department of Infrastructure and Transport, SA Standard Specification

- Developed a Standard Specification for CFA Piling in 2019 based on other national standards and local experience following a number of large-scale CFA projects in SA (including Case Study Project)

Specification ST-PI-C3 Continuous Flight Auger (CFA) Piles



Document Information

K Net Number:	13523415
Document Version:	2
Document Date:	19/09/2019

- Based on a genuine understanding of what is important to achieving good outcomes
- Incorporates local experience and ground conditions
- Addresses geotechnical inspection and testing requirements

Authority specification which serves the industry best (in my view)

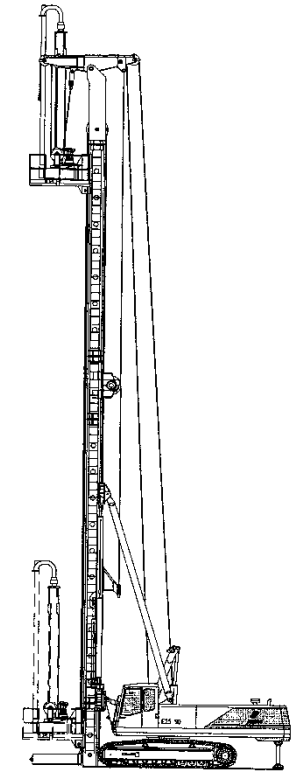
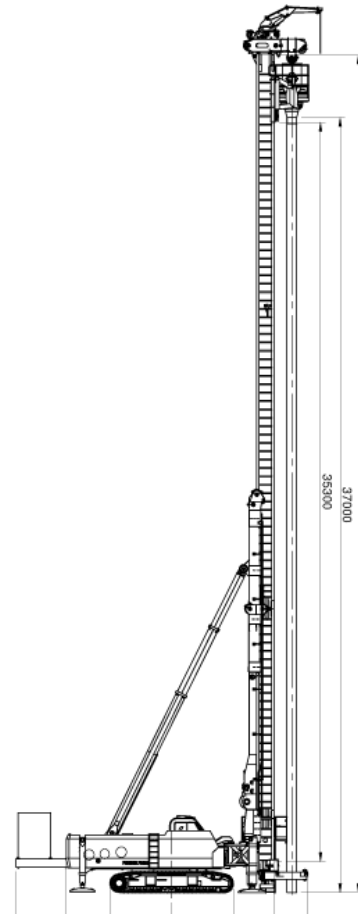
► Some Key Issues

- Drilling equipment and methodology
- Drilling termination criteria
- Base formation
- Geotechnical inspections
- Testing considerations



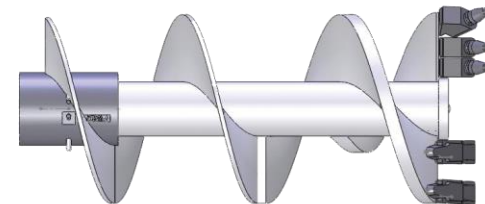
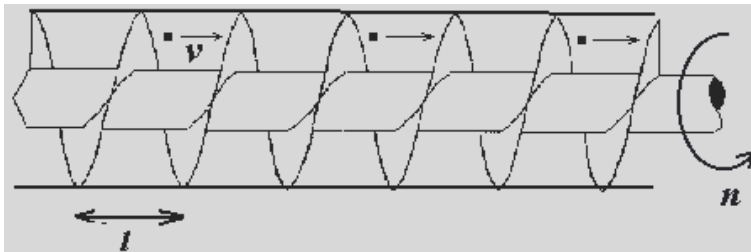
▶ Drilling Equipment & Methodology

- Sufficient rotary torque and crowd is necessary to mitigate installation effects.
- Preferred minimum torque is ~ 20tm.
- Industry leading equipment is ~47tm and ~40m long mast.
- Rigs with long masts are generally preferable.
- Auger extensions are required for very deep CFA piles (up to 54m piles have been constructed in Australia).

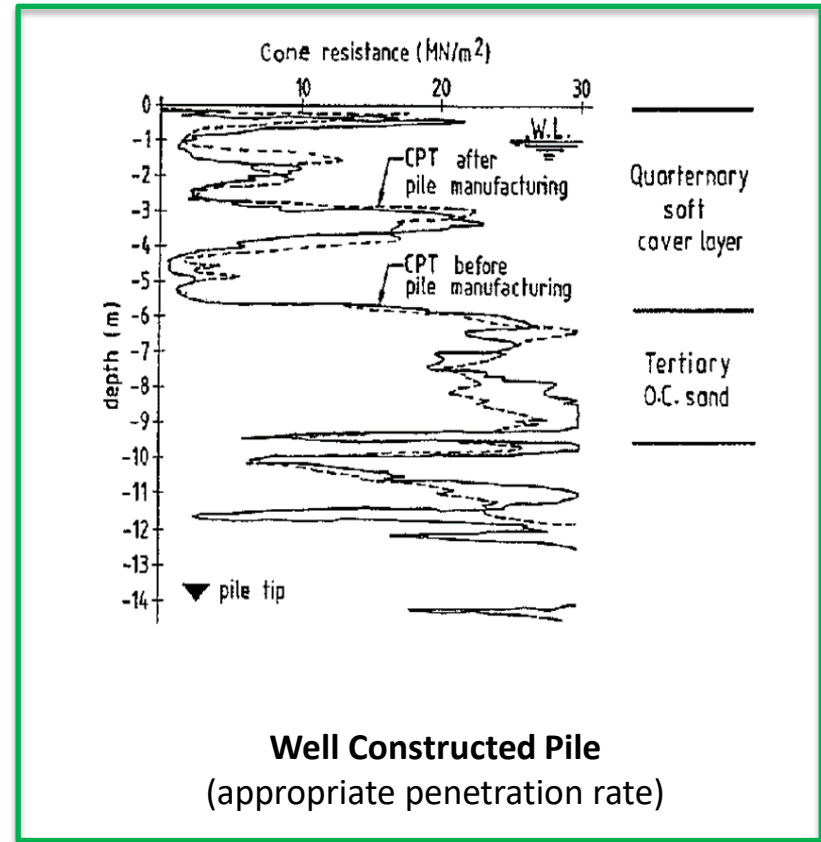
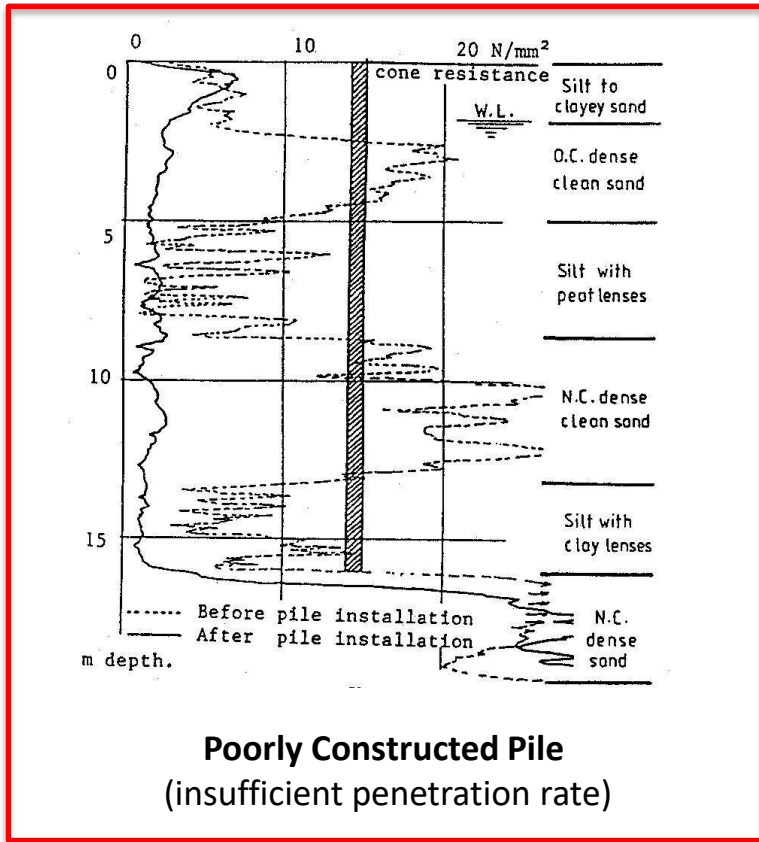


▶ Drilling Equipment & Methodology

- CFA augers are soil conveyors (Archimedes Screws).
- Theoretically, the volume of soil excavated should equal the volume of the auger introduced.
- Experience tells us that generally a penetration rate in the order of 50% of pitch results in minimal disturbance.
- **Slow penetration rates can cause ‘flighting’ in sands.**
- Slower penetration rates are acceptable in clays & rocks as these materials do not “flight”.
- The most obvious sign of significant flighting is surface coning.



Installation Effects - Drilling



(Van Weele, 1988)

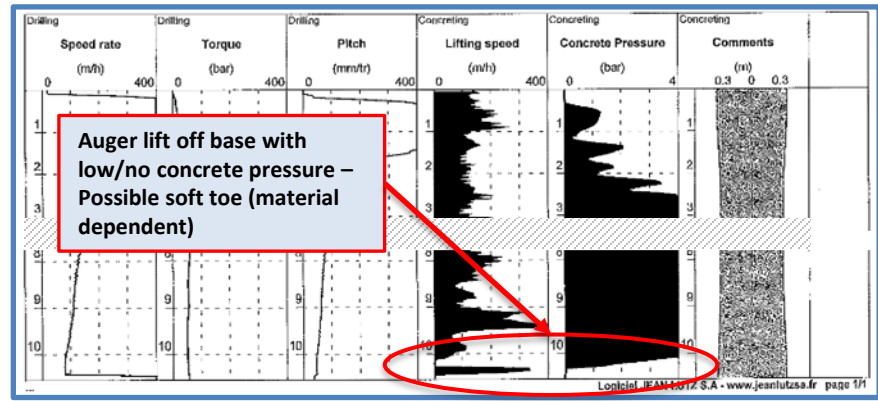
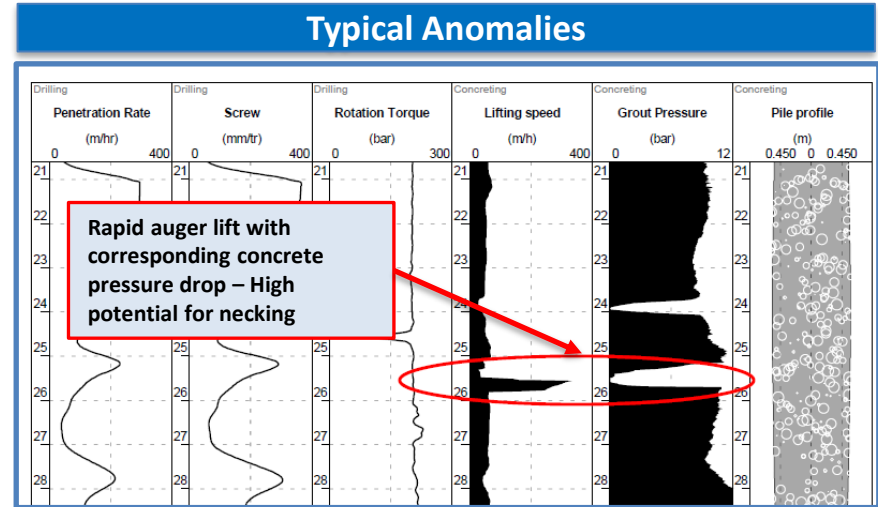
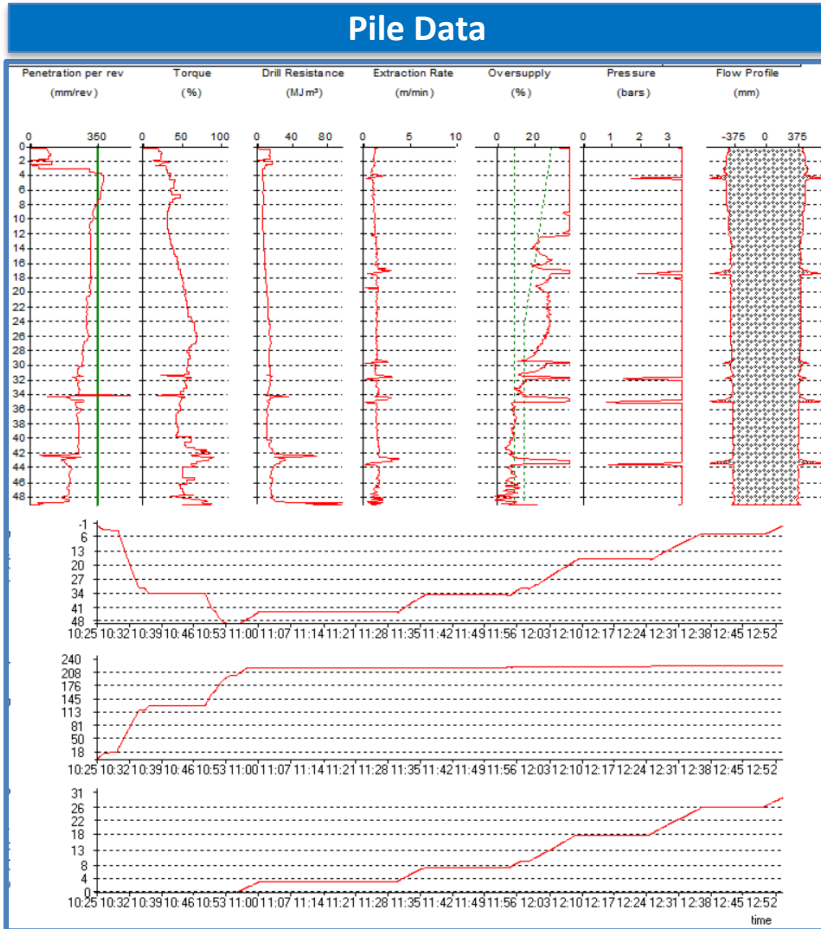
Ultimate geotechnical strength and serviceability performance in sands is influenced by installation effects

Installation Monitoring

- There are a variety of proprietary systems available.
- A range of installation, extraction and concreting parameters are recorded.
- Instrumentation can be used to identify distinct bands only. The use of torque to estimate pile capacity is not technically robust.
- Concrete volume is inferred rather than measured (via pump strokes and pump efficiency).
 - Concrete volume is a critical aspect of QC.
 - In order for it to be reliable, pump efficiency must be monitored by comparing delivered and injected volumes.



Installation Monitoring



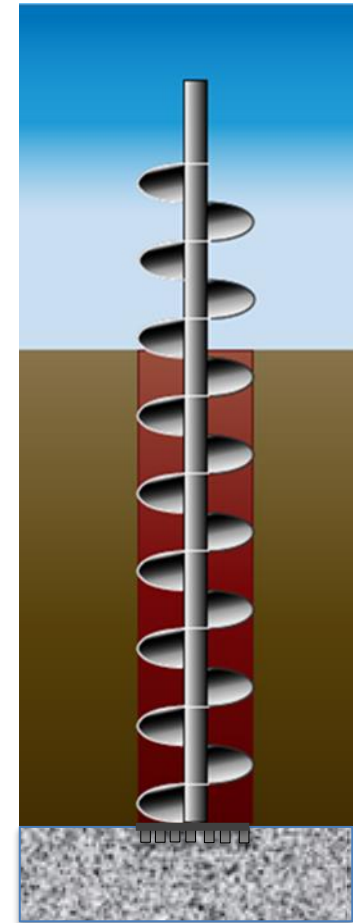
▶ Drilling Termination Criteria

Every pile should have a termination criteria, some or all of:

- Design toe RL
- Critical founding material
- Drilling refusal criteria
- Installation parameters

What is 'Drilling Refusal' & what does it mean?

- Drilling refusal is the depth at which the auger can no longer penetrate effectively
 - Criteria should be defined, e.g. penetration rate/crowd
- Material reached varies with plant/tools
- Where critical, end bearing resistance that can be assumed needs to be demonstrated/calibrated with load testing results
- Consistency is required across all piles for reliable outcomes



► Base Formation

Base formation technique

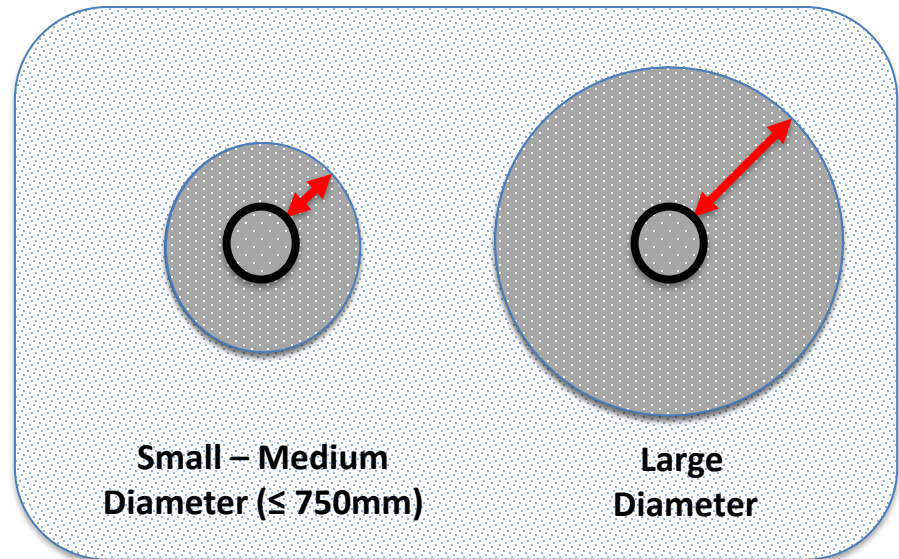
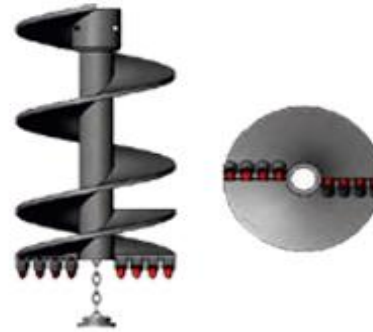
- Timing of concrete flow and commencing auger lifting is critical
- Equipment plays a role – e.g. outlet location
- Different techniques & preferences
- Must be compatible with equipment

Ground Conditions

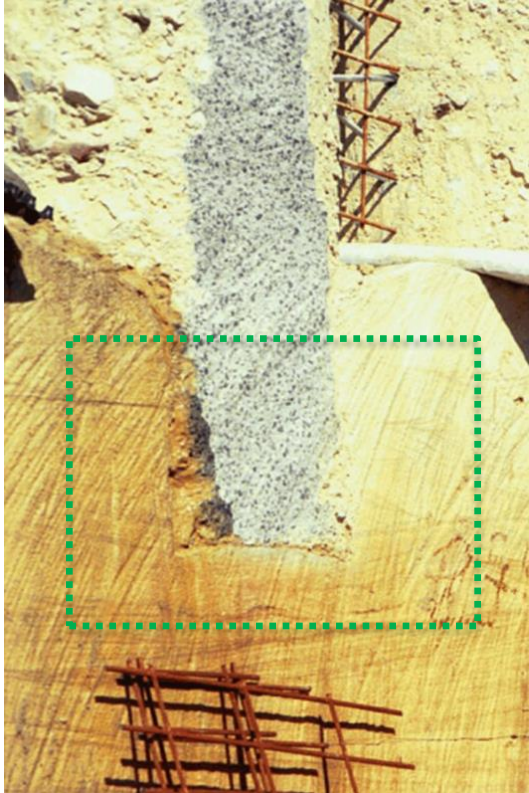
- Some conditions more sensitive than others, e.g. sand vs rock
- Achieving any particular end bearing should not be assumed without attention to base formation and appropriate verification

Pile Diameter

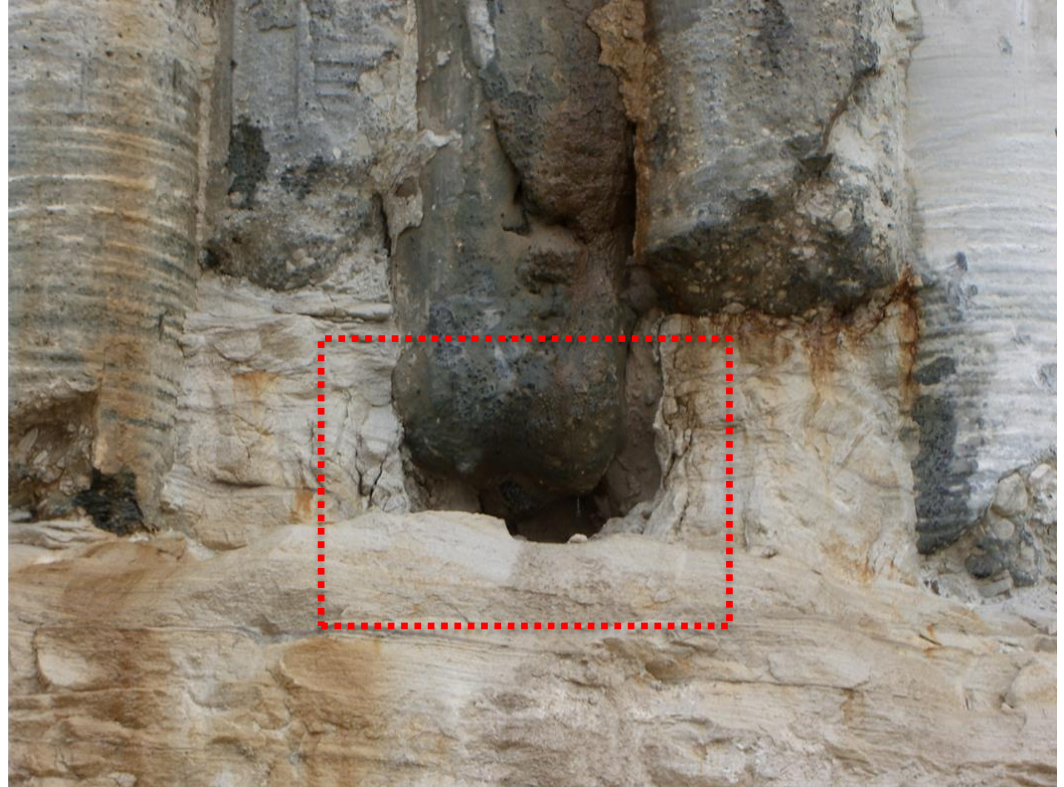
- Concrete flow can be limiting
- Easier to maintain integrity/quality of base in small diameter piles
- More difficult to achieve high end bearing in large diameter in some conditions



▶ Base Formation



High Quality Toe



Soft Toe



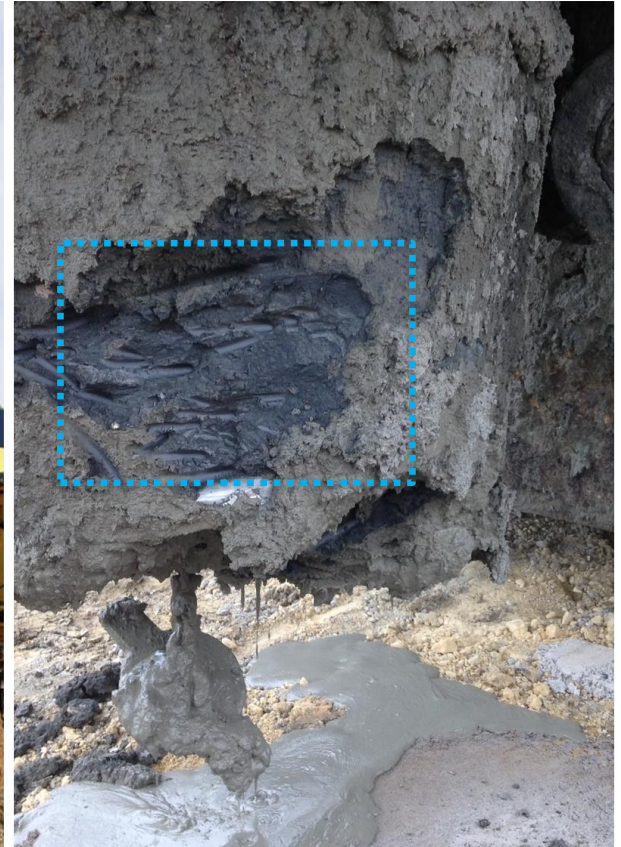
Geotechnical Inspections - What you can see



Spoil on Auger
(Heavily transported)



Lower Flights
(Somewhat Transported)



Material at Toe
(Disturbed but readily Identifiable)

Geotechnical Observations

Upper soil layers:

- Generally limited impact on design

Middle soil layers:

- Heavily transported
- Only broad interpretation of material types is possible
- Look only for major differences in expected conditions

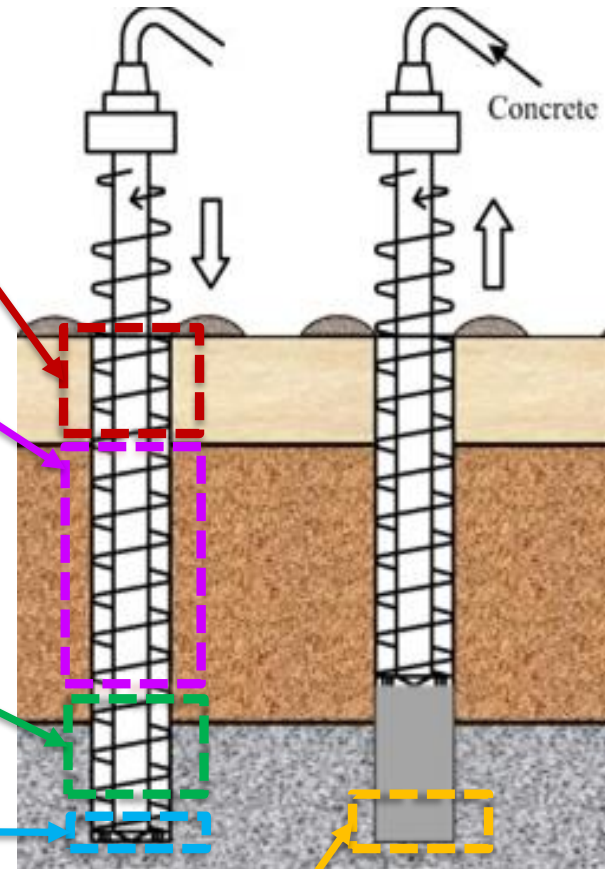
Lower flights:

- Heavily transported but often more critical to design
- Confirm founding material near toe

Tip of Auger:

- Check material at base

Commencement of Concreting: Consistent across all piles



Inspections & Verification

Plant and Equipment

- Consistent with approved methodology?
- Augers, joints and concrete outlet
- Concrete pump calibration

Drilling Termination Criteria

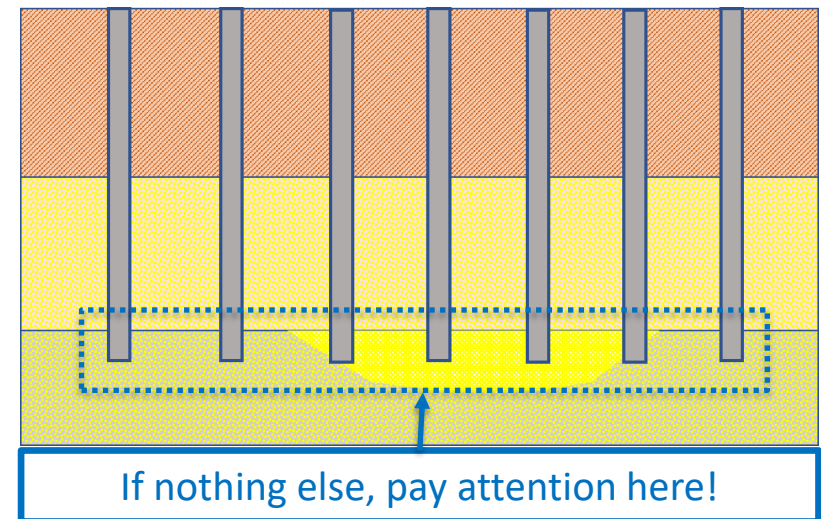
- Design toe level or refusal?
- Is criteria consistently met?

Base formation technique

- Consistent base formation approach and concreting commencement process

Verification approach

- Founding conditions achieved?
- All piles installed consistent with tested piles?
- Monitoring working consistently and effectively?



▶ Testing Considerations

Minimum requirements

- Must comply with AS2159-2009 (regardless of other applicable standards)
- Must be consistent with design assumptions
- Test Piles must be suitably representative of piles they represent
- Untested piles must be correlated to Test Piles by some method. Should consider:
 - Installation parameters/refusal criteria
 - Toe levels
 - Geotech observations
 - Boreholes/CPTs

Other considerations

- Testing requirements should always be tailored to project requirements
- Test piles are to demonstrate methodology as well as performance



Urban Superway Project, Adelaide



Design and Construction of Piled Foundations for 2.8 km Elevated Roadway

- First Transport SA (DTEI) Major Project on CFA Piles
- Very high level of client engagement and involvement in development and execution
- Rigorous review and assessment of design, construction methodology, execution and verification

Presentation to Australian Geomechanics Society – SA

Design and Constructability Considerations

- Lateral and rotational response of pile groups is critical aspect of design, so changes to pile layouts would be problematic
- Extensive design review and approval process
- Maximum drilled depth of around 30m due to rig limitations
- Capacities must be able to be verified by dynamic testing of working piles
- Smooth piling progress required for effective site and traffic management:
 - Returning to piling sites for remediation not practical or desirable
 - Stakeholder considerations
- Tight program meant that good piling production was paramount
- Productivity was a significant driver to piling cost

Pile Design had to be robust, verifiable and conducive to production

Overview of Foundation System

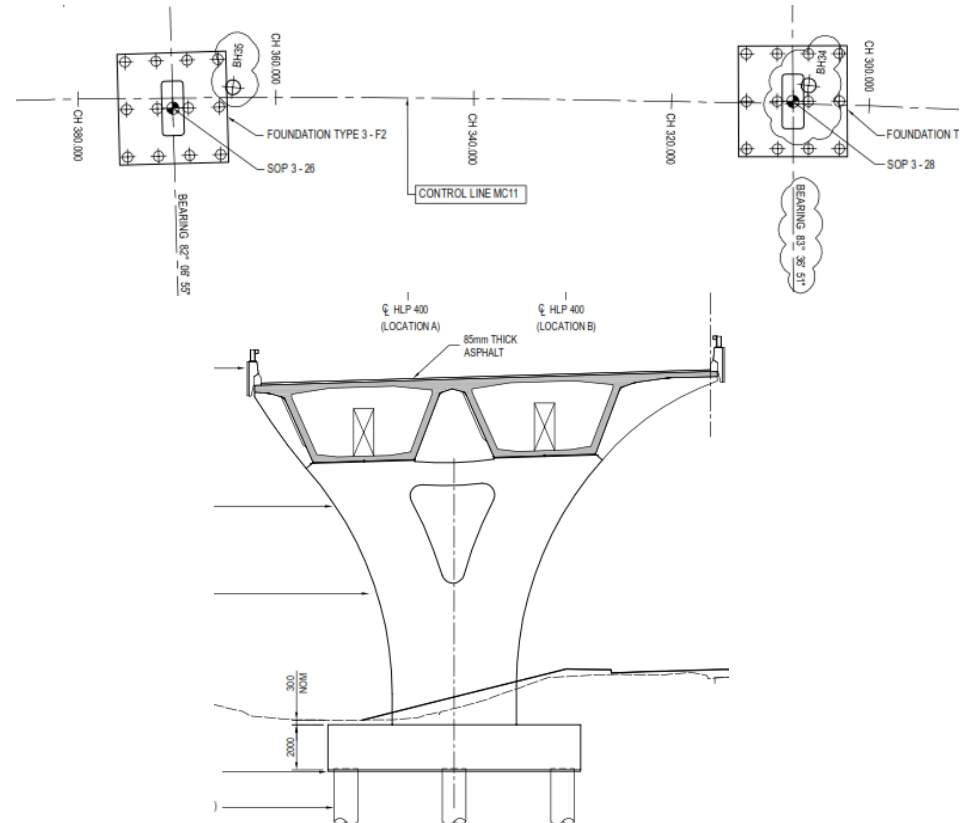
Main Piers and Abutments:

- 1050mm diameter CFA piles
- Installation depths typically 27m to 30m
- Groups of up to 16 piles

Northern Abutment Area:

- 900mm diameter CFA piles
- Installation depths 24m to 30m

Full length reinforcing cages up to around 30m depth

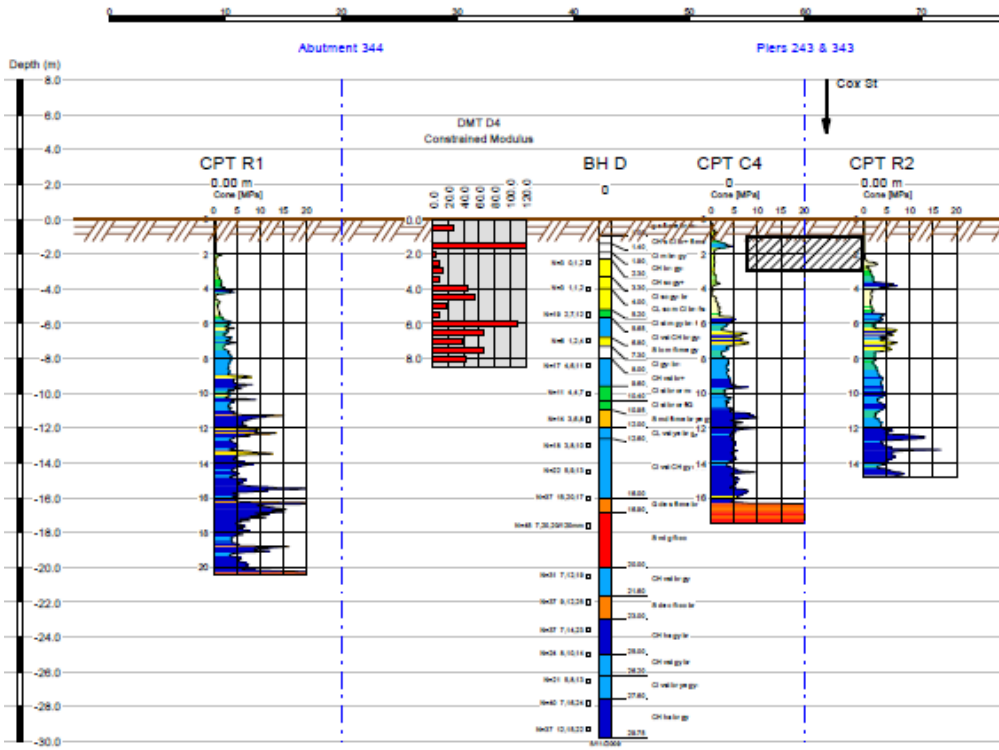




Geotechnical Conditions

Site Investigation Data

- 26 boreholes (BH)
- 77 Cone Penetration test (CPT)
- 19 Dilatometer tests (DMT)
- Static and dynamic testing of steel, bored and CFA piles.
- Various laboratory tests





Geotechnical Interpretation

General Approach

- Borehole logs and in-situ and laboratory testing, including (DMT testing data) used to identify the types of materials present and characterize the mechanical properties
- Load testing results were used to assess the expected performance of piles, based on the ground conditions present at each test site.
- CPT data was used to characterize trends within the soil profile along the project alignment and relate soil properties measured at specific borehole and CPT locations to other areas of the site via appropriate correlations (site specific)

Table L1.2. Summary of Regional Geology.

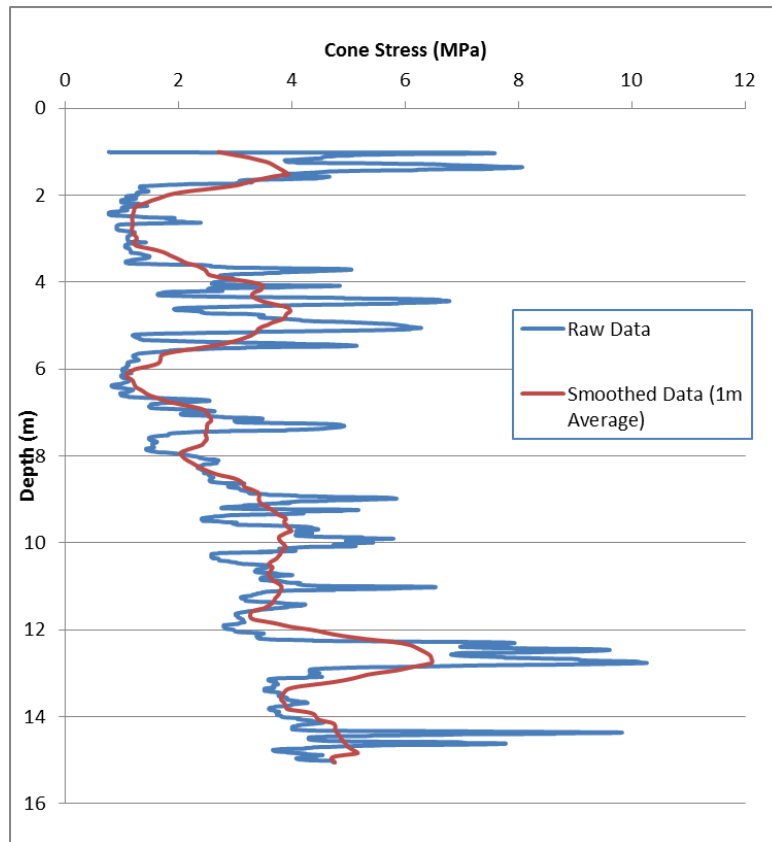
Group	General Location	Unit	Age
Cainozoic	North of Grand Junction Road	St Kilda Formation	Quaternary (Holocene)
		Glanville Formation	Quaternary (Pleistocene)
	South of Grand Junction Road	Pooraka Formation	Quaternary (Pleistocene)
	Whole alignment	Hindmarsh Clay	Quaternary (Pleistocene)

Vst – H Clay found around 10 -15m Depth
Primary founding material



Geotechnical Interpretation

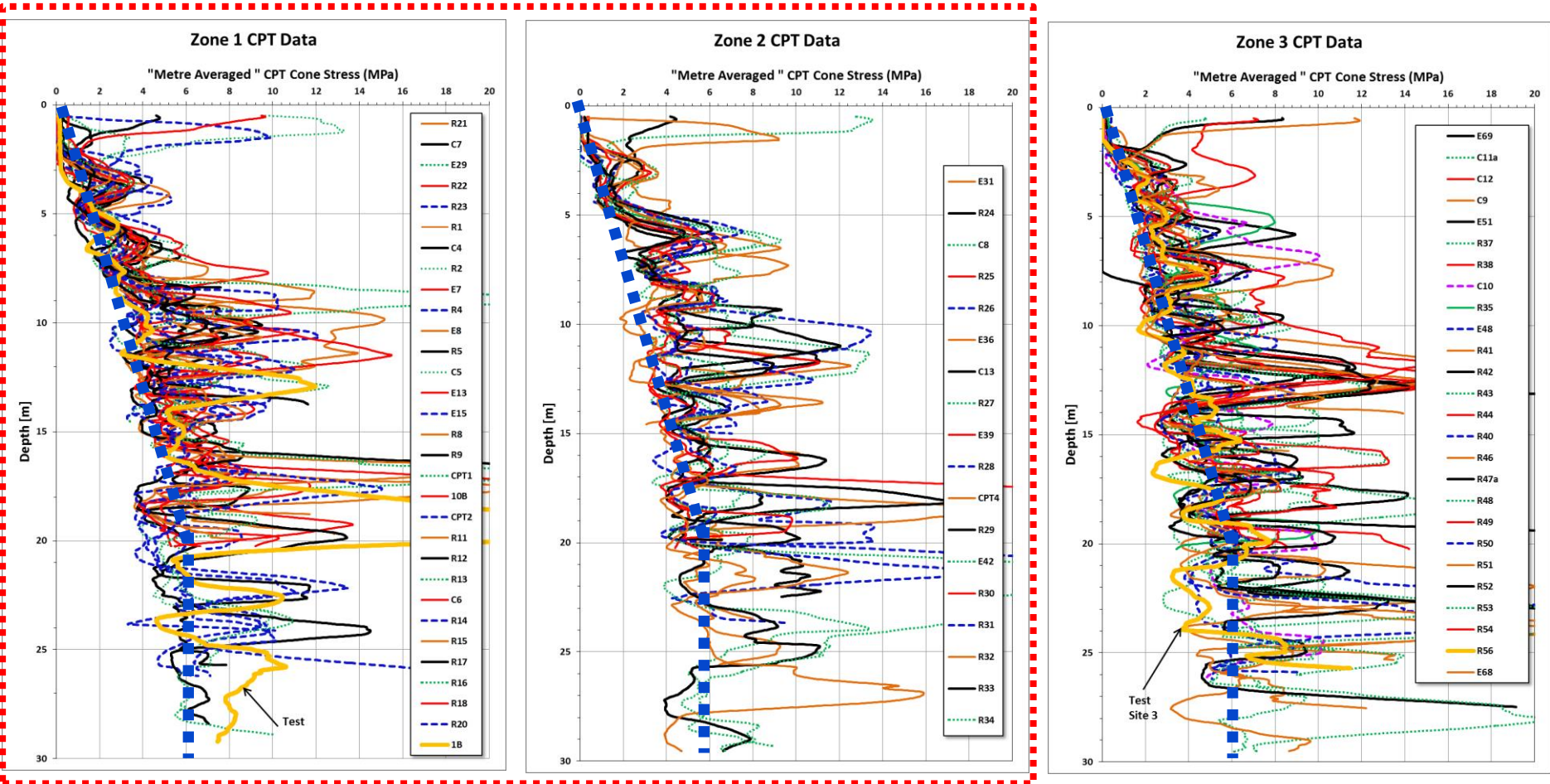
CPT Data (Smoothed)



- Raw CPT data difficult to compare due to multiple sharp peaks
- CPT Data averaged over 1m depth interval to enable easier comparison of different plots and subsequent interpretation
- Allows harder layers to be incorporated in assessments without dominating the profiles



Geotechnical Interpretation: Strength Profiles – CPT Data (Smoothed)





Geotechnical Interpretation:

Outcomes

- **Representative soil models for North and South Zones.**
- **Axial pile design model based on range of soil profiles across site.**
- **Upper and Lower Bound lateral stiffness models:**
 - Site specific Correlation between DMT modulus and CPT data to enable estimation of lateral soil stiffness at any CPT location
- **Used to develop a generalised design approach which allows for project wide soil variability**

Adequacy of Site Investigation

- **AS5100.3, Section 1.6.2:**
 - Unless otherwise specified by the relevant authority, the minimum number of boreholes shall be as follows:
 - (a) *For bridge foundations* - Minimum of one per abutment or pier for bridges with bridge width less than 10 m
- **AS5100.3 Commentary:**
 - It should be noted ... that the word borehole should be taken to include any site investigation method chosen for the particular project.
- Given that CPT tests provide the primary source of site data on this project, this requirement is considered to be satisfied (refer also next slide)

Adequacy of Site Investigation

- **Other Relevant Factors:**
 - Intermittent dense layers are not relied upon in the design. Macro - ground conditions in the founding zone are broadly similar across the site and transition slowly and predictably.
 - Pile design is a “generalised” design which considers the range of expected conditions: not pier-specific, but general and statistical.
 - Pier-specific information is therefore not imperative, and it is not necessary to have geotechnical information at the exact location of each pier.
 - Hindmarsh Clay known to extend to significant depth in the area of the site. No evidence or expectation of compressible materials at depth in this geological unit.

Existing Site Investigation was Broadly Adequate for Pile Design Purposes although BH/CPT Not at Every Pier



Design Pile Design

Design Resistances versus Test Piles

DTEI 600mm Diameter x 27m CFA Test Piles:

Pile No.	Test Site	Pile Type	Shaft Resistance	End Bearing	Total	Equivalent for 1050mm Diameter CFA
			[kN]	[kN]	[kN]	
1	1	CFA	6913	2573 (9091 kPa)	9485	19.9 MN
6	3	CFA	6750	1455 (5141 kPa)	8205	16.2 MN

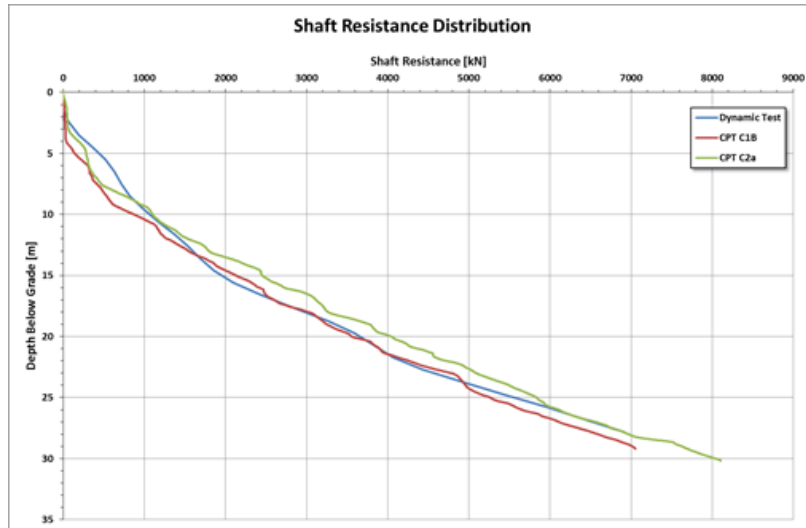
Adopted Design Ultimate Pile Resistances for 1050 Dia x 27m:

- Lower Bound = 12 MN
- Upper Bound = 15-19 MN

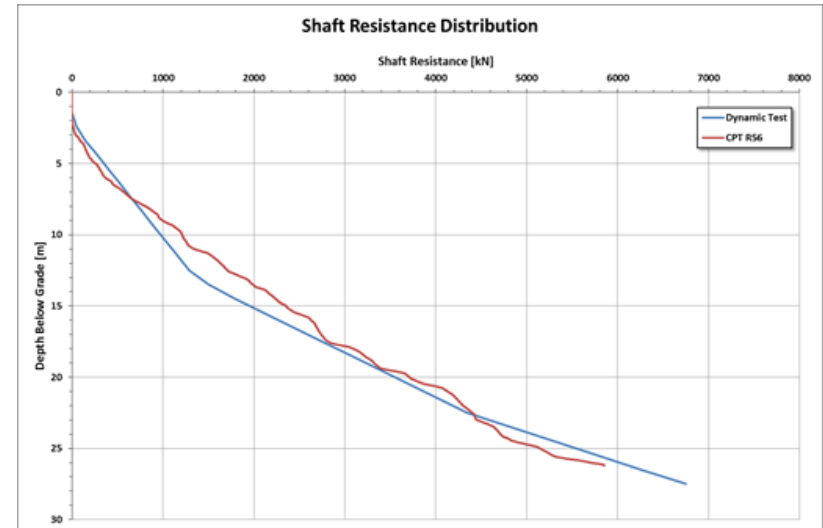


Axial Pile Design

Shaft Resistance Correlations



TEST SITE 1: 600 CFA Test Pile

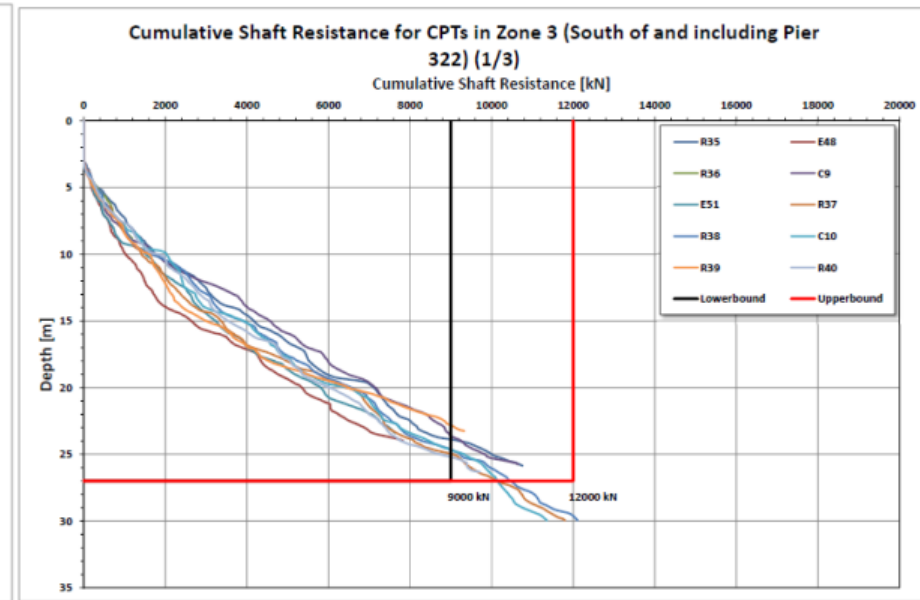
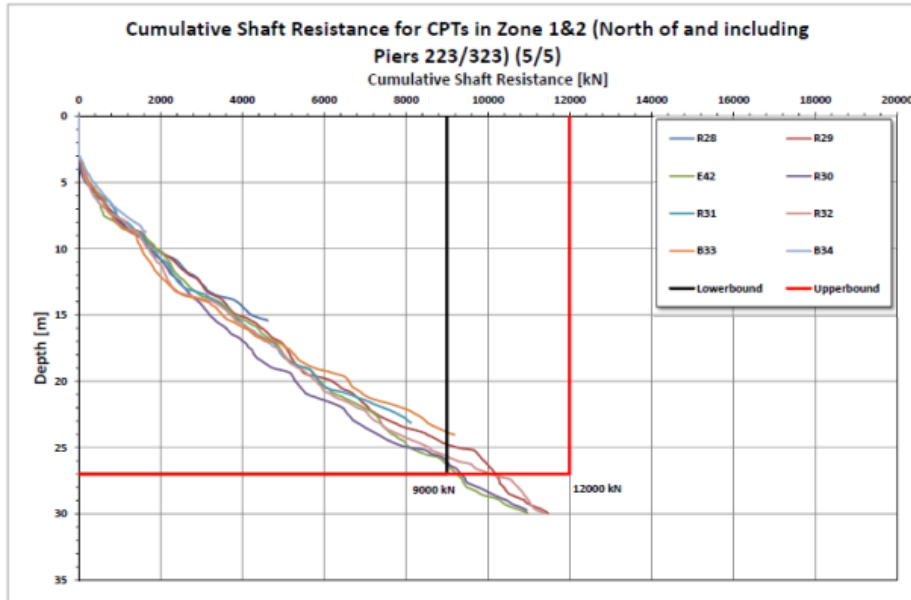


TEST SITE 3: 600 CFA Test Pile

Shaft Resistance Correlations with CPT data determined from Load Tests (Reduction Factor Applied to Sleeve Friction)



Axial Pile Capacity: *Shaft Resistance Estimates from CPTs*



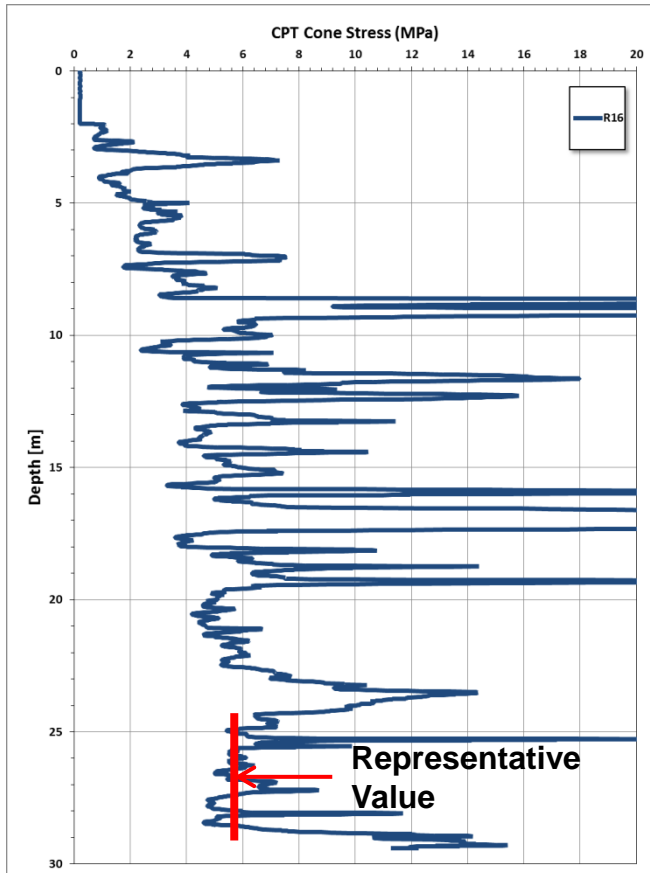
Shaft Resistance for 1050mm Diameter CFA Piles Estimated from CPT data for Each Test Location

Upper Bound Design Shaft Resistance = 12,000 kN
Lower Bound Design Shaft Resistance = 9,000 kN



Axial Pile Design

Base Resistance



- Lower Bound Base Resistance needs to be evaluated assuming clay at base as sand layers cannot be relied upon
- Most variability in pile load capacity likely to come from end bearing component
- Typically 2 MN (2300 kPa) or less required from Base Resistance
- 3MN (3600 kPa) Base Resistance Required for worst case (conservative) Shaft Resistance



Axial Pile Design

Base Resistance

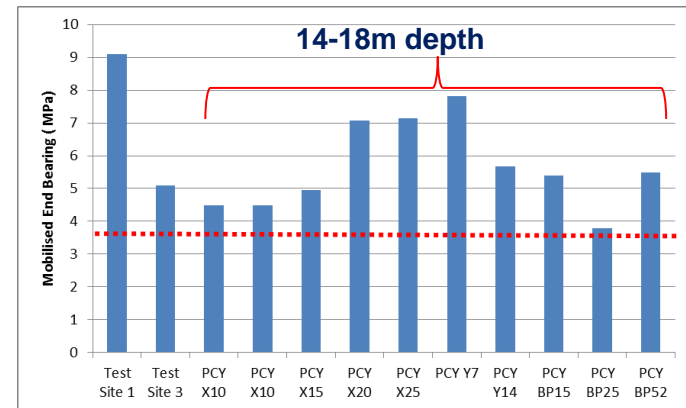
Conventional Design Approach:

Parameter	Expected Range
Representative Undrained Shear Strength of Clay (c_u) at 27m Depth	300 kPa to 350 kPa
Base Resistance Capacity Factor, N_c	9 to 15
Adopted Design Ultimate Base Resistance = 3600 kPa, or 3117 kN for a 1050mm diameter pile	

CPT Based Design Approach (Ramsey):

- End Bearing = $0.7 \times Q_c$, where Q_c is averaged for 1.5 D above and below base of pile
- Minimum Q_c to achieve 3.6 MPa would be approximately 5 MPa average

Superway Precast Yard Load Test Results:



Soil Model Summary

- **Soil model zones:**
 - North of Chainage 4200m
 - South of Chainage 4200m
- **Axial pile response (27m x 1050mm diameter pile):**
 - Lower Bound - 12,000 MN capacity
(Governs group geotechnical capacity and group settlement checks)
 - Upper Bound – 15,000 MN capacity
(Run to assess mobilized compression load for structural check, and rotational stiffness)
- **Lateral pile group response:**
 - Lower bound – governs maximum bending moments vs depth profile
 - Upper bound – governs pile cap restraint in superstructure modeling

▶ ULS Design Axial Resistance

Geotechnical Reduction Factor = 0.72 (AS2159-2009)

- Average Risk Rating = 2.14 (Low)
- Rate of Dynamic testing assumed to be 6% (1 in 16 or more)

Conditions	Design Geotechnical Strength, $\phi_g \times R_{d,ug}$
Lower Bound	0.72 x 12 MN = 8.6 MN
Upper Bound	0.72 x 15 MN = 10.8 MN

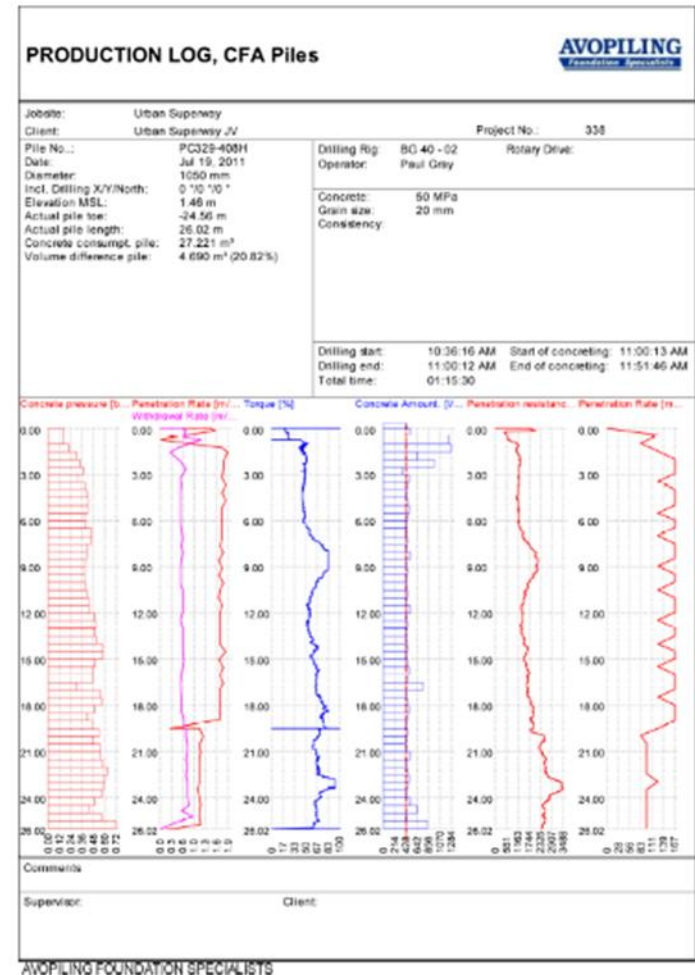
► Pile Installation (Main Alignment Piles)

- BG40 drill rig with CFA set-up
- Drilled in single pass up to up to 30m
- Compressed air used to assist penetration
- Cage installed to full depth
- Super-flowable concrete mix



► Pile Testing and Verification

- Trial piling program prior to commencement of production piles, including dynamic testing:
 - Verification of installation methodology (drill, concrete, cage)
- High Strain Dynamic Testing of around 6% of production piles, typically 1 pile per cap, with CAPWAP analysis
- Low Strain Integrity Testing of all piles (100%)
- Review of installation data to relate untested piles to tested piles





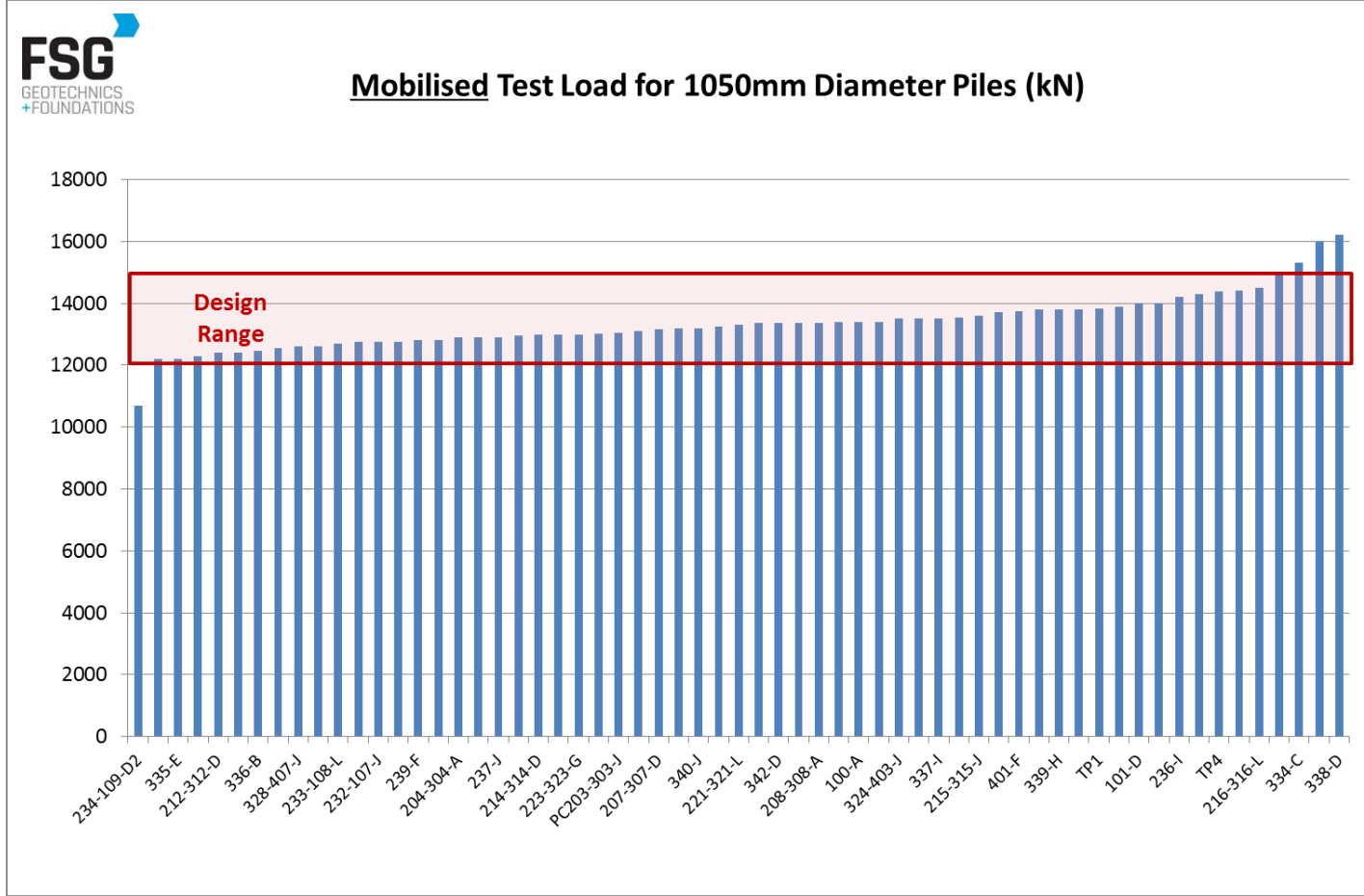
Installation – Initial Benchmarking

USJV Benchmarking Review																	
From Rig Instrumentation																	
Date installed	Pile Reference	pile length	time to drill	Time to drill pile	time to drill 15m to founding level	Time to Drill 15m to founding level	total number of rotations	No of Rotations per lin m	Concrete Oversupply	Maximu m Torque (%)	pda test mobilised load	Pda test result- Shaft Friction	Pda test result- Base Capacity	Pda Test assessment of overbreak	PIT Test Result	Overall Concrete Wastage for the Day	Comments /Further Anlysis
		m	mins	Lin m/hr	mins	lin m/hr	no.	Rot/ lin m	%	%	Kn	Kn	Kn	%		%	
				A		B		C									
16/04/2011	TP6	18	30	36	0	0	248	0.1	11	45							
16/04/2011	TP5	18	36	30	0	0	268	0.1	10	45							31
16/04/2011	TP1	27	34	48	15	48	325	0.1	10	55	13829	11280	2549				31
18/04/2011	TP2	27	34	48	20	36	344	0.1	20.5	67	12833	11350	1483				32
18/04/2011	TP3	27	37	44	16	45	347	0.1	6	67	13022	9656	3366				32
19/04/2011	TP4	30	40	45	17	53	394	0.1	14	67	14385	12806	1579				27
3/05/2011	202/302-C	27	43	38	23	31	401	0.1	18	100							23
3/05/2011	202/302-B	27	50	32	23	31	487	0.1	19	100							23
4/05/2011	202/302-K	27.6	21	79	6	126	129	0.2	12	50							48
4/05/2010	202/302-L	27	39	42	16	45	342	0.1	20	67							48
5/05/2011	202/302-A	27	39	42	21	34	386	0.1	19	67							26
6/05/2011	202/302-J	27	32	51	16	45	316	0.1	16.5	88							20
6/05/2011	202/302-I	27	33	49	15	48	339	0.1	14	75							20
6/05/2011	202/302-D	27	33	49	16	45	308	0.1	14	75							20
6/05/2011	202/302-H	27	29	56	14	51	239	0.1	16.5	62							20
9/05/2011	202/302-E	27	27	60	12	60	243	0.1	12	83							24
9/05/2011	202/302-G	27	30	54	11	65	248	0.1	18	83							24
9/05/2011	202/302-F	27	44	37	11	65	225	0.1	12	83							REDRILL DUE TO BLOCKAGE -



Pile Performance

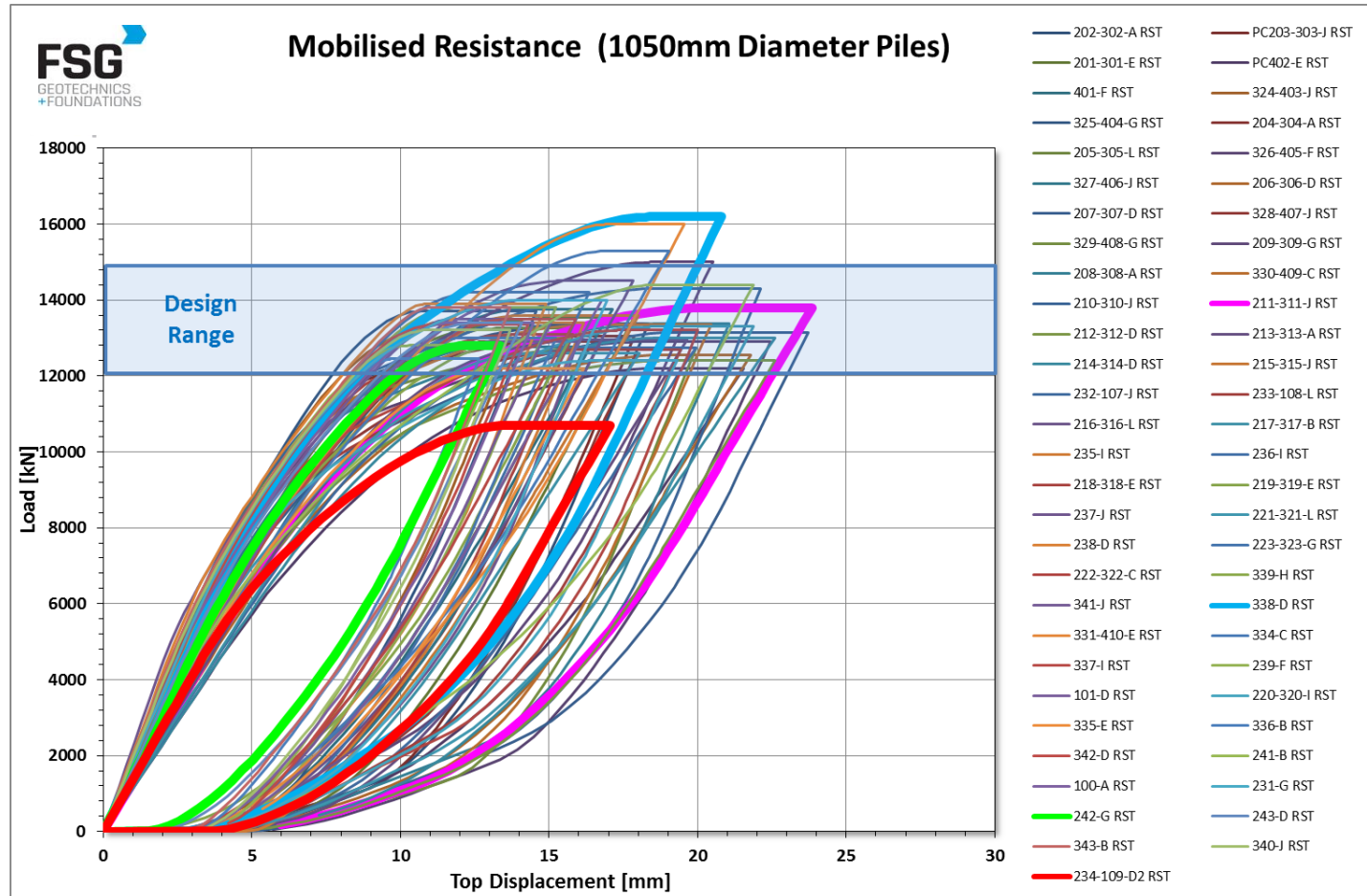
Dynamic Load Test Results





Pile Performance

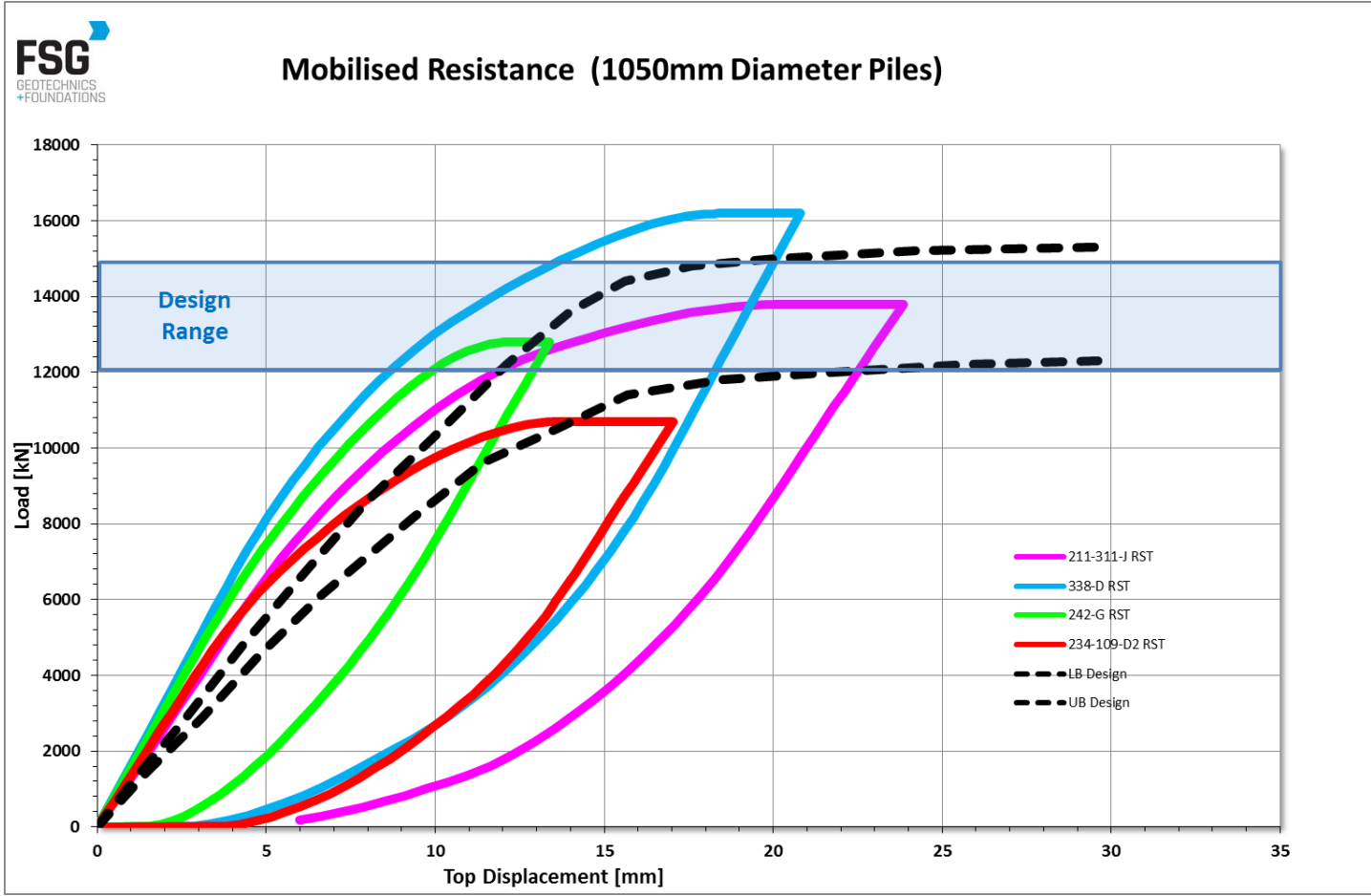
Dynamic Test Results





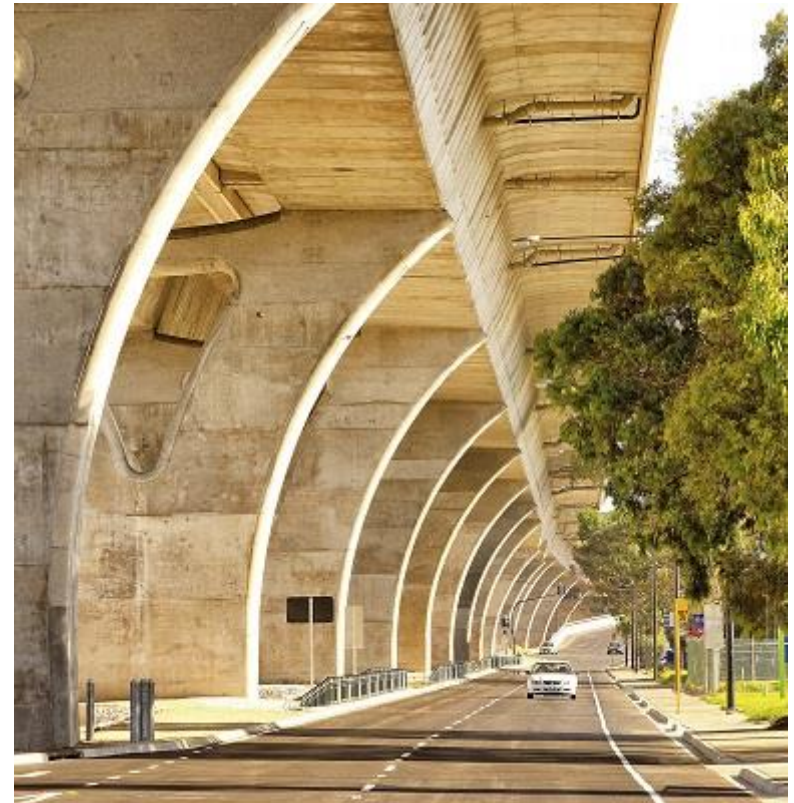
Pile Performance

Dynamic Test Results



▶ Superway Summary

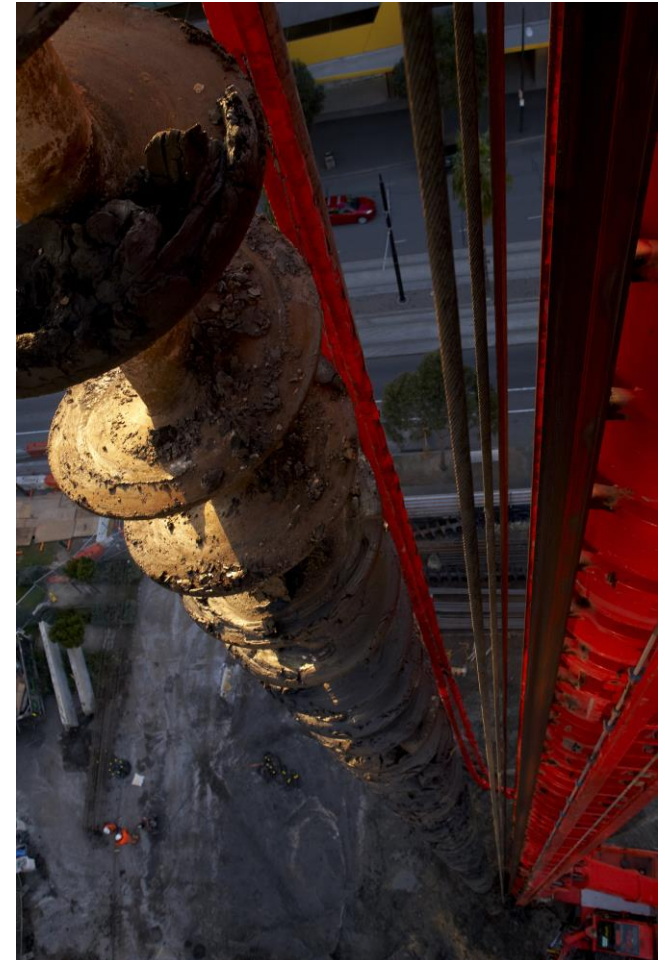
- CFA methodology offered cost savings and environmental benefits, but design, construction and verification processes needed to address project specific requirements
- Complex and rigorous pile design process governed by pile group response and particularly lateral pile group response
- Robust generalized design methodology adopted based on thorough site investigation and interpretation
- Performance generally consistent with design
- Remains a good example of planning, design, installation and verification best practice for CFA piling, although each project should be considered on its merits
- [First step towards SA CFA Piling Specification](#)



Thorough site investigation, design approach and constructability planning and execution allowed successful delivery of piling works.

▶ Concluding Remarks

- CFA piles have become a common choice of foundation type on both building and infrastructure projects
- Differences between approach to project execution and allocation of responsibility on building vs infrastructure projects should be understood and incorporated in practice
- Widespread application of CFA pile type necessitates broader understanding of key principles and issues within design, procurement, installation and verification
- Geotechnical industry needs to advance their understanding and participation in delivering good outcomes
- More readily accessible guidance is required for practitioners
- Codes and standards need to be developed to align with industry capability and consolidated good practice guidelines



▶ Superway Acknowledgements

Client:



Designers:

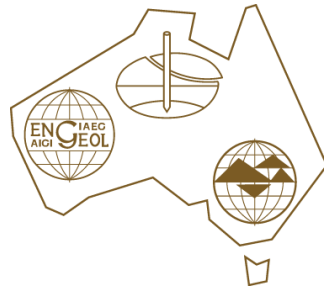


Owner:



Government of South Australia
Department of Planning,
Transport and Infrastructure

Thanks to AGS SA Chapter!



AUSTRALIAN GEOMECHANICS SOCIETY

**THANK YOU
FOR YOUR TIME**

