

TALL BUILDINGS, DEEP FOUNDATIONS; MIDDLE EAST EXPERIENCES

The 2009 Terzaghi Oration

Harry Poulos

Coffey Geotechnics

OUTLINE

- Design Process for High-Rise Buildings
- Emirates Twin Towers Project
 - Investigations
 - Design
 - Load tests
 - Tower foundation performance
- Burj Dubai
 - Foundation design
 - Load tests
 - Foundation performance
- Gold Coast Building

Henry David Thoreau – Walden (1854)

“If you have built castles in the air,
Your work need not be lost;
That is where they should be.
Now put the foundations under them.”

FOUNDATION DESIGN PROCESS

- **Site characterization**
 - Geology
 - Stratigraphy
 - Quantification of relevant geotechnical parameters.
Based on:
 - In-situ testing
 - Laboratory testing
 - Load testing

FOUNDATION DESIGN PROCESS

- Foundation Type & Layout.
 - Usually piles or piled raft

Based on:

- Foundation loadings
- Design criteria
- Construction issues
- Material availability



FOUNDATION DESIGN PROCESS

Design Issues

1. Ultimate capacity
2. Settlement
3. Differential settlement & tilt
4. Dynamic behaviour
5. Earthquake response
6. Structural strength of foundation elements
7. Durability

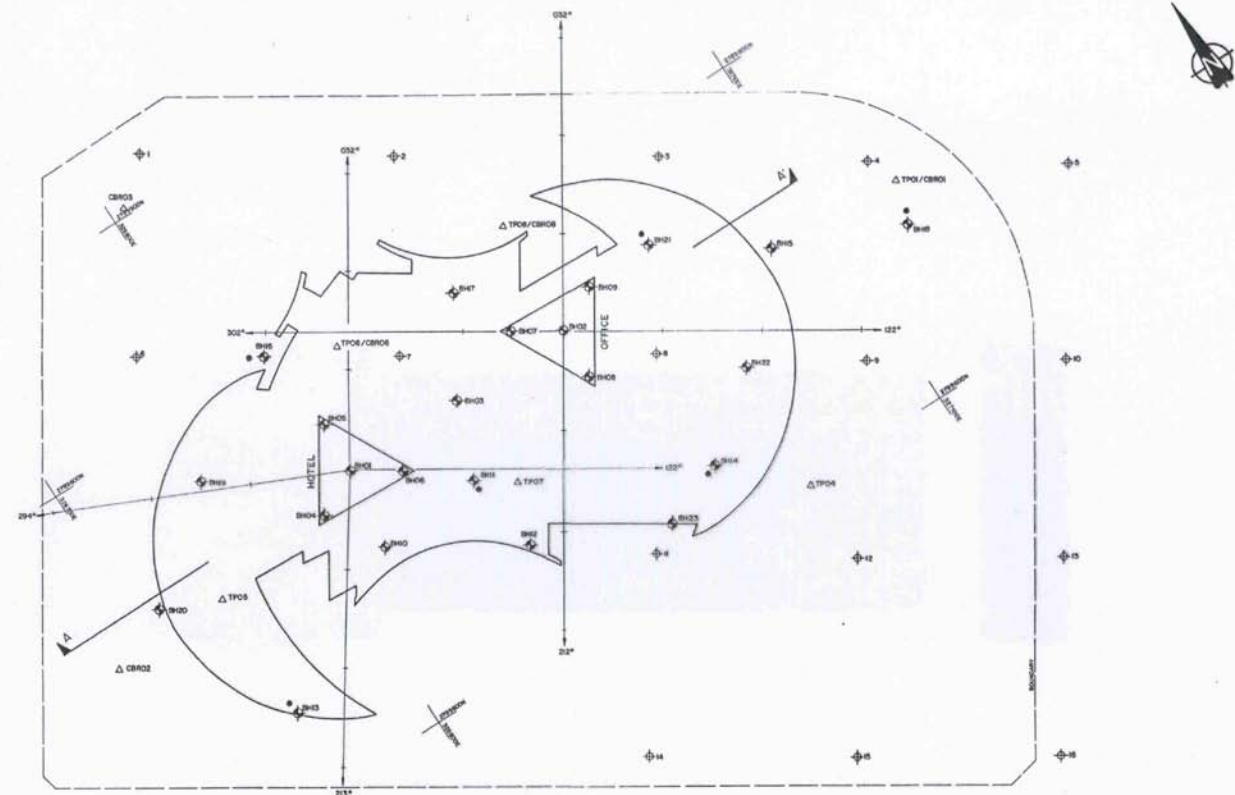
LOCATION OF DUBAI PROJECTS



Emirates Site - 1996



SITE PLAN & BOREHOLES



- LEGEND**
- STRONGPIE PIEZOMETER, INSTALLED IN BOREHOLE ADJACENT TO MAIN BOREHOLE
 - ◆ BOREHOLE (CURRENT INVESTIGATION)
 - ◆ BOREHOLE (PAST BORING - 1994)
 - PROPOSED DEVELOPMENT
 - △ TEST PIT
 - △ IN-SITU CBR TEST
 - SEISMIC SURVEY LINES

Coffey Partners International Pty Ltd		ACER FREEMAN FOX INTERNATIONAL LTD	
The Emirates Project		DUBAI	
LOCATION OF BOREHOLES		SIO588/1-1	
Drawn	RWL/SW	Scale	1:1000
Approved		Scale	1:1000
Date	26/1/97	Scale	1:1000
Scale	1:1000	Scale	1:1000

INVESTIGATION PROGRAM

- 23 boreholes, up to about 80m depth (maximum)
- Trial pits
- SPT in upper layers
- Undisturbed sampling
- Water samples
- Permeability tests
- Pressuremeter tests
- Vertical seismic shear wave profiling
- Uniformity borehole testing

LABORATORY TESTING

- Conventional laboratory & field tests
- Specialized testing
 - Site uniformity testing (geophysical)
 - Cyclic triaxial testing
 - Effects of repetitive wind loading
 - Stress path triaxial testing
 - Deformation parameters
 - CNS testing
 - Ultimate shaft friction
 - Resonant column testing
 - Dynamic shear modulus & damping

GEOTECHNICAL PROFILE & MODEL FOR EMIRATES SITE

		Eu MPa	E' MPa	fs kPa	fb MPa	pu MPa
	Silty Sand	40	30	18	0.2	0.1
	Silty Sand	125	100	73	1.5	1.5
	Calcareous Sandstone	700	500	200	2.3	2.3
	Silty Sand	125	100	150	1.9	1.9
	Calcisiltite	500	400	450	2.7	2.7
	"	90	80	200	2.0	2.0
	"	700	600	450	2.7	2.7

FOUNDATION TYPES

Towers

- Piled raft foundations

Podium

- Piles, pile groups

LOAD TEST PROGRAM

- Below each tower:
- Compression test to 3000t, L=40m, d=0.9m
- Static tension test: L=25m, d=0.6m or 0.7m
- Cyclic tension test
- Lateral load test

Class “A” predictions made using assessed design parameters

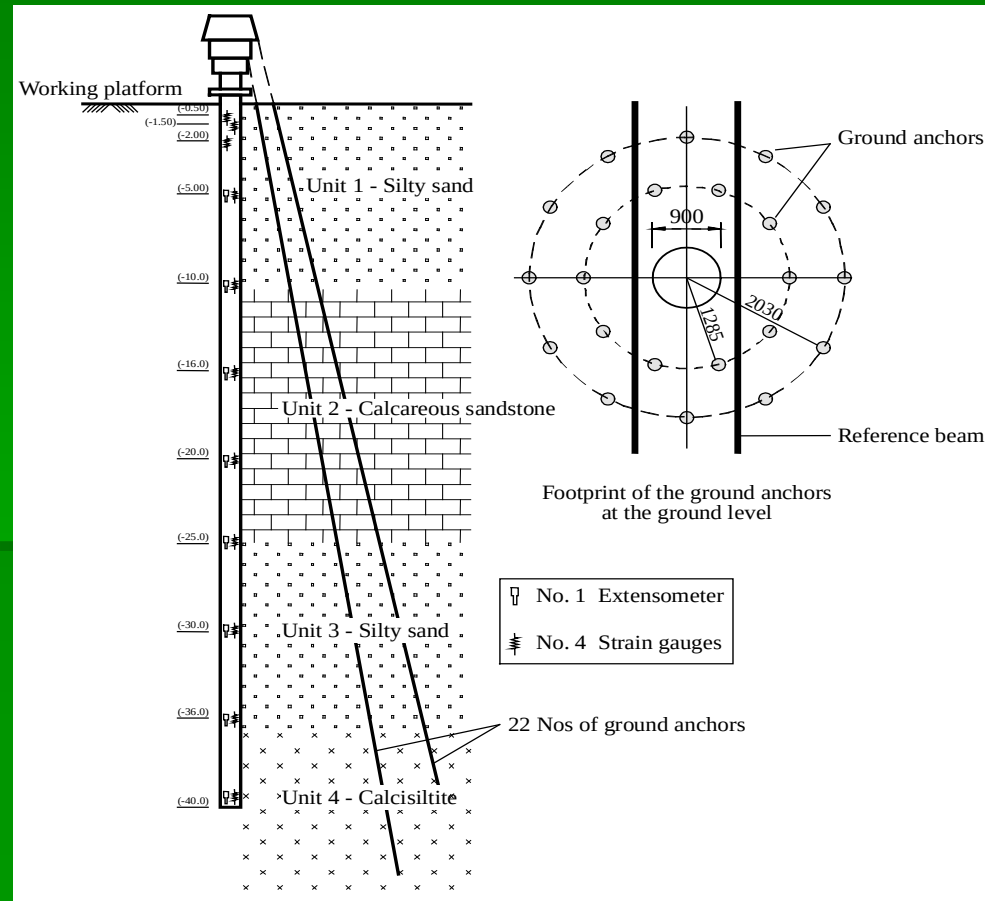
PREDICTION METHODS

- Axial Response
 - Non-Linear boundary element analysis
 - PIES program
- Lateral Response
 - Non-Linear boundary element analysis
 - ERCAP program
- Cyclic Tension Test
 - Non-Linear boundary element analysis
 - SCARP program

THE EMIRATES PROJECT, DUBAI



SETUP FOR COMPRESSION PILE TESTS

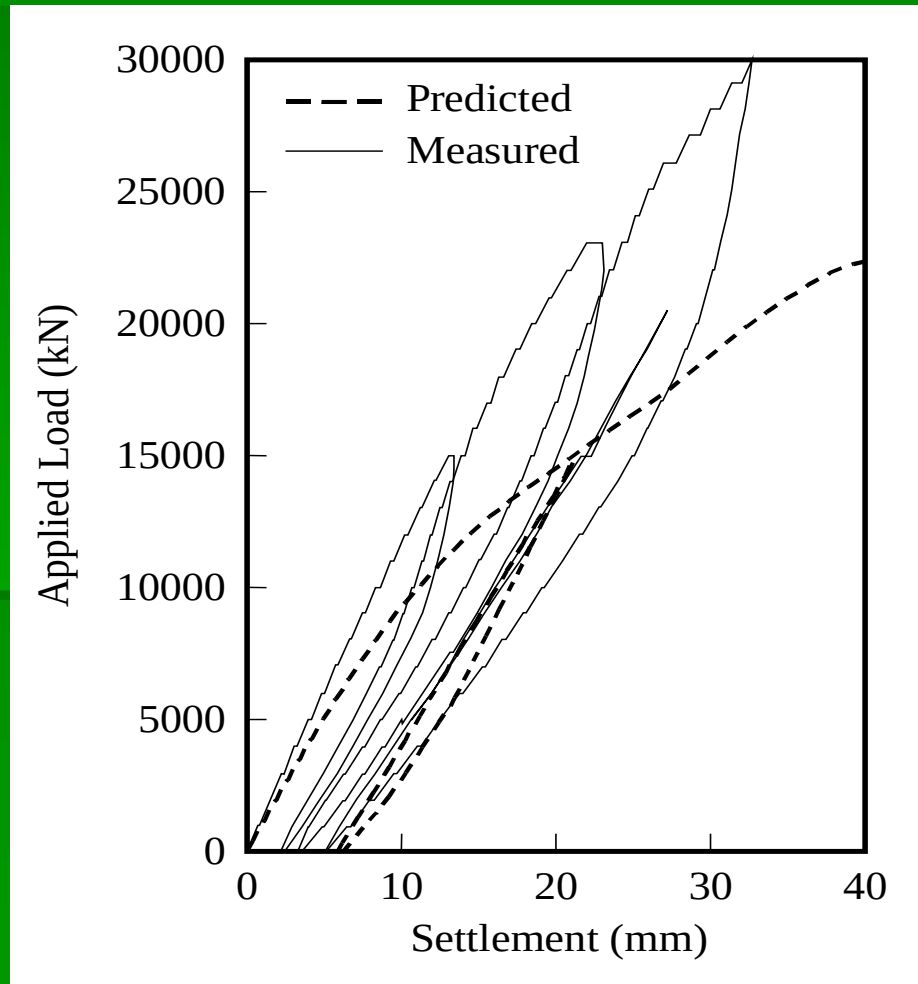


3000t LOAD TEST WITH REACTION ANCHORS

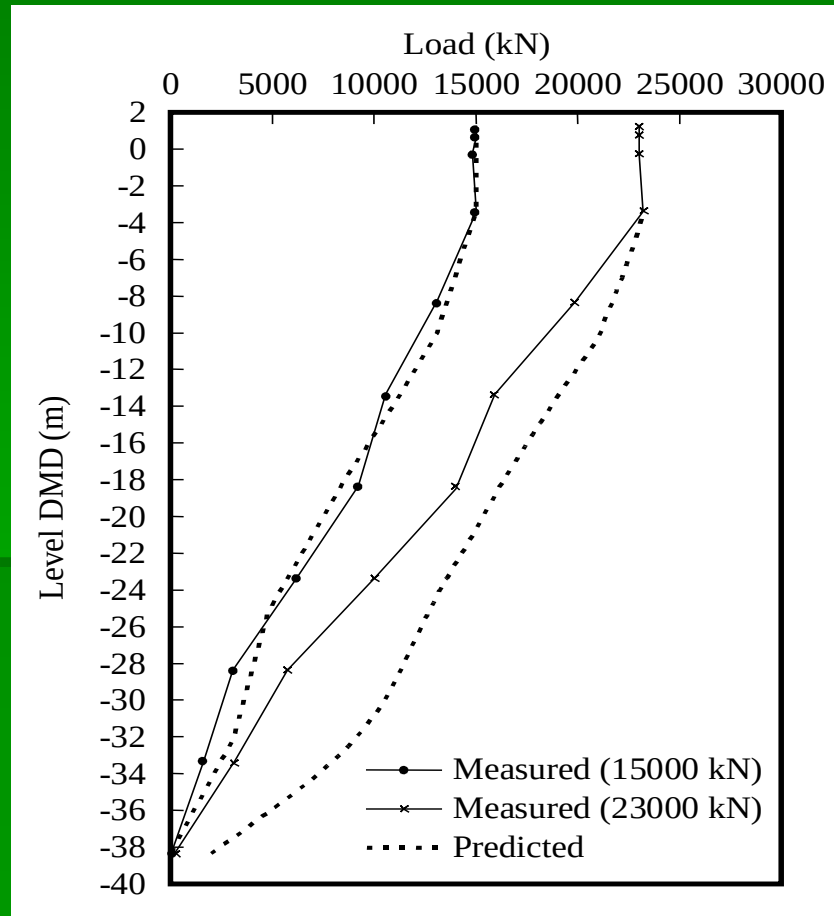


Emirates Project, Dubai

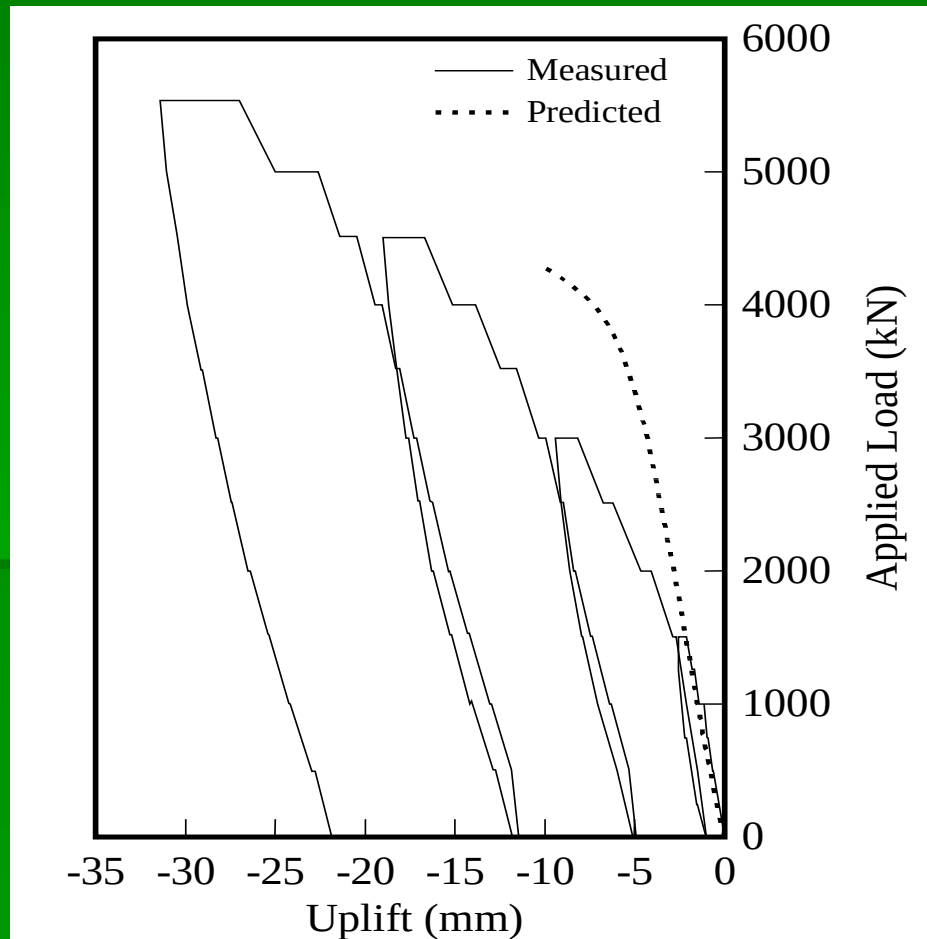
LOAD-SETTLEMENT CURVES FOR PILE P3(H)



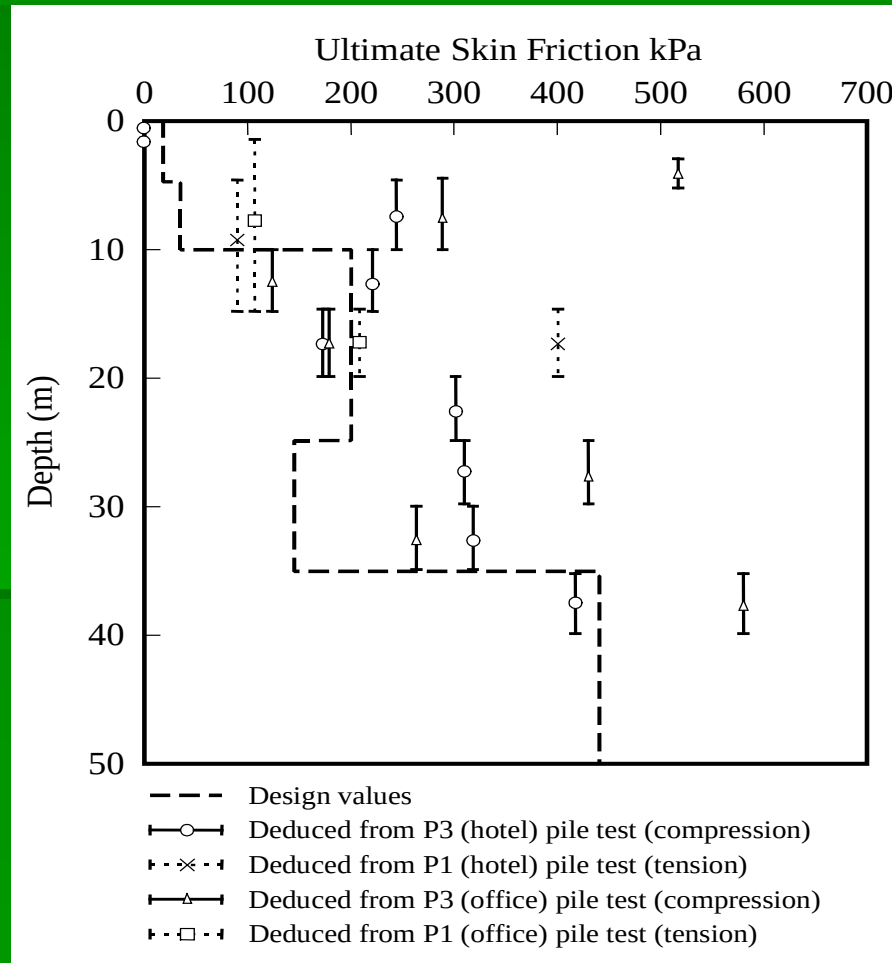
PREDICTED & MEASURED AXIAL LOAD DISTRIBUTIONS



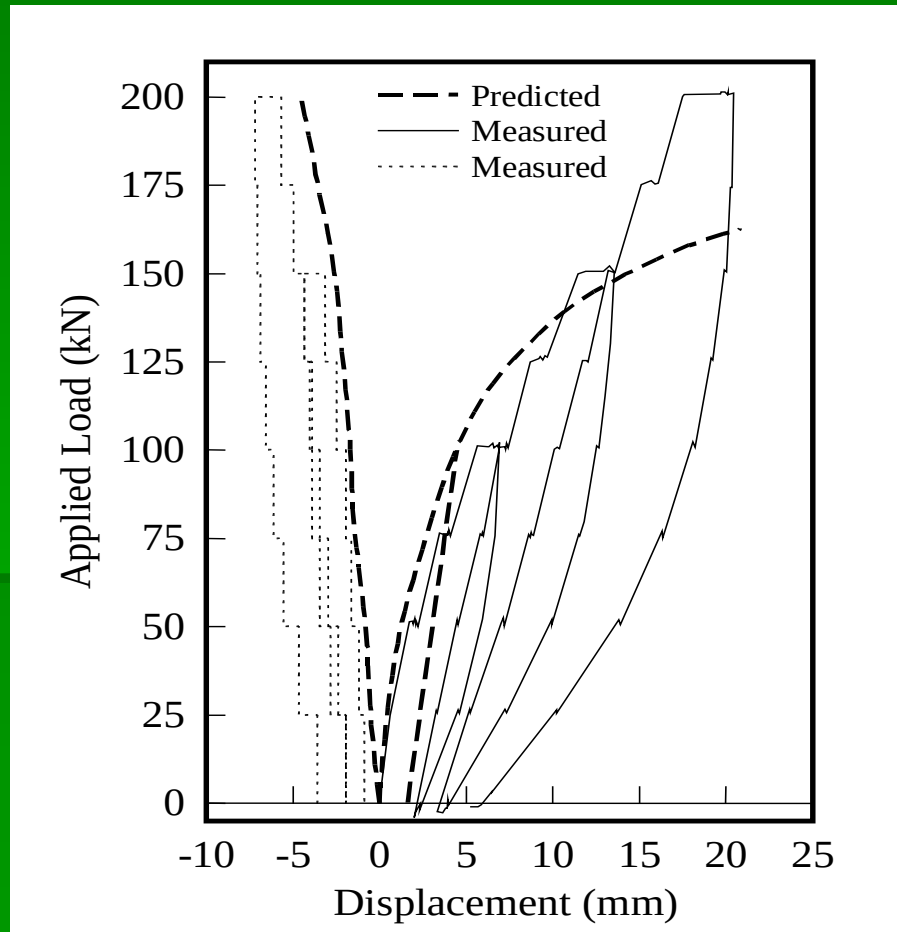
LOAD-MOVEMENT CURVES FOR UPLIFT TEST



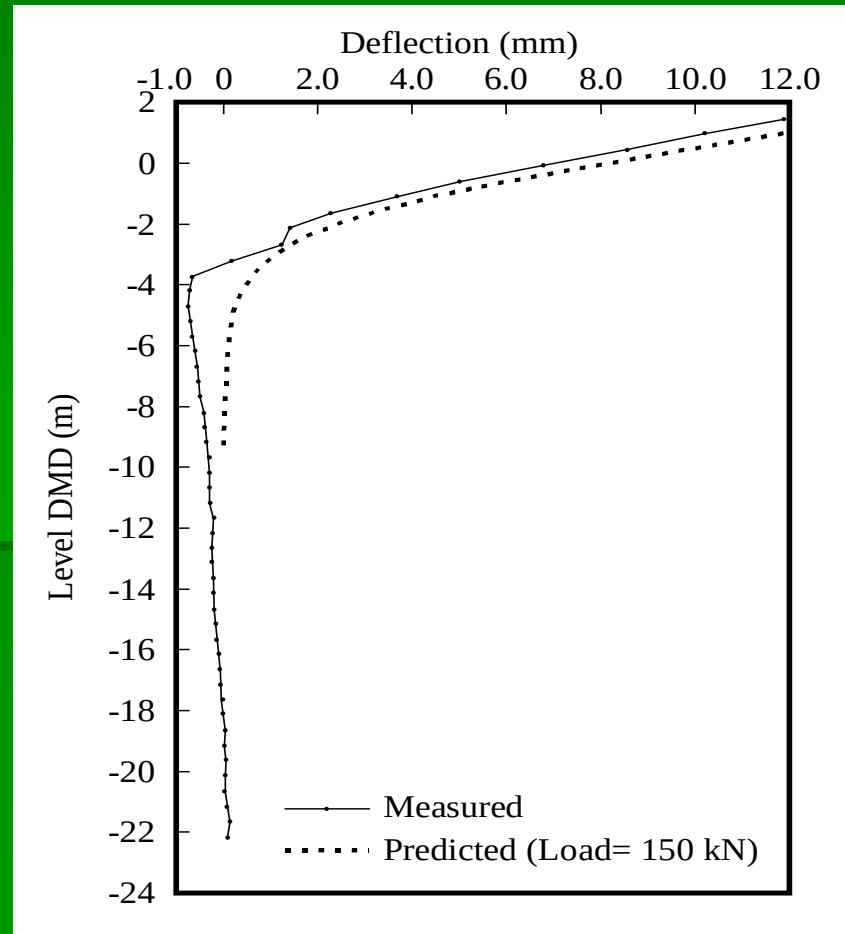
ULTIMATE SHAFT FRICTION FROM TESTS



MEASURED & PREDICTED LATERAL LOAD-DEFLECTION CURVES



MEASURED & PREDICTED LATERAL DEFLECTION vs DEPTH



ASSESSMENT OF PREDICTIONS

- Class A predictions were in fair agreement
- Cyclic loading effects not well-predicted
- Assisted by:
 - Comprehensive investigation data
 - Modern methods of lab & field testing
 - Straight-forward mechanisms of behavior

EMIRATES TOWERS- FOUNDATION SYSTEMS

- 1.5m thick raft
- 102 piles for office
- 91 piles for hotel
- 1.2 & 1.5 m piles to 40-45 m

DESIGN METHODOLOGY

Limit State Approach

- **Ultimate Limit State:**
 - Static loads
 - Repetitive wind loads
- **Serviceability Limit State:**
 - Settlements : max. 150mm
 - Angular rotation: max. 1/350 long-term

TOWER FOUNDATION ANALYSES

- GARP program for piled rafts
- **Ultimate Limit State:**
 - Used both factored & unfactored pile capacities
 - Many load combinations
- **Serviceability Limit State**
 - Long-term settlements - GARP
 - Short-term movements (wind) – DEFPIG for axial & lateral stiffness of individual piles in group
 - Passed on to structural engineer for overall analysis

LOAD COMBINATIONS

- Ultimate Limit State:

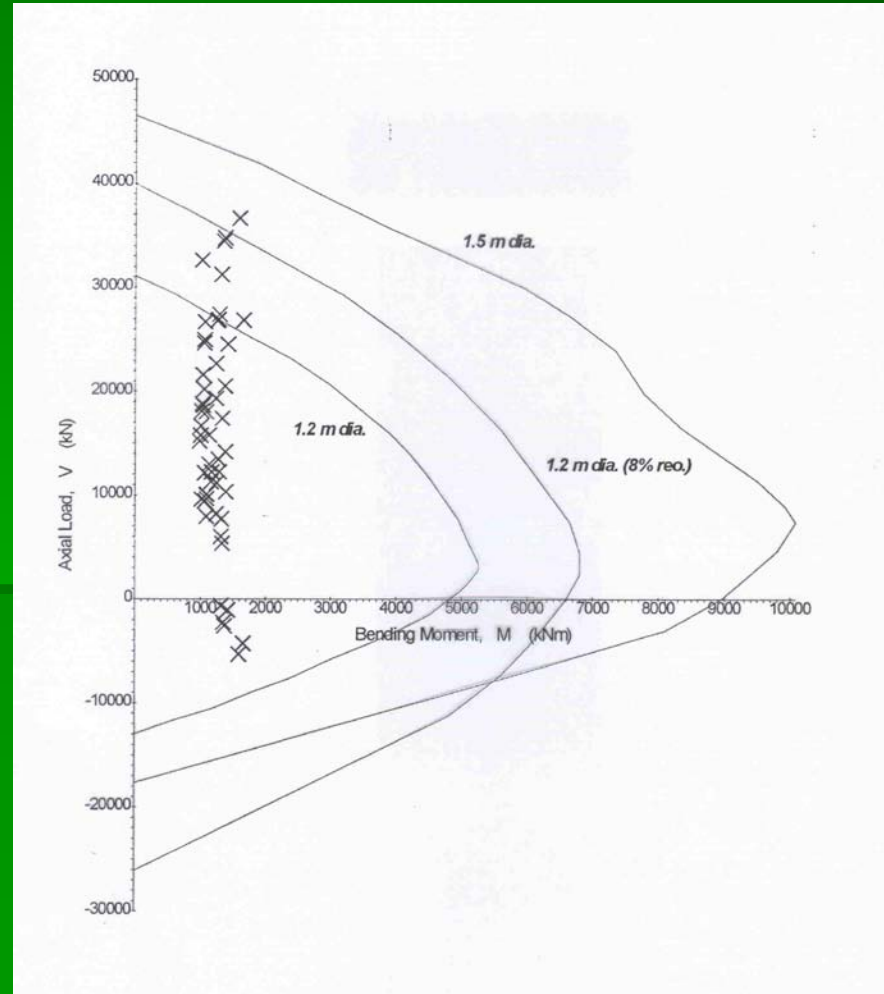
- $1.25G + 1.5Q$
- $1.2G + 0.4Q + W_u$
- $0.8G = W_u$

- Serviceability Limit State:

- $G + 0.4Q$

Total of 18 load cases per tower

PILE INTERACTION DIAGRAM : OFFICE TOWER



DYNAMIC FOUNDATION RESPONSE

- Required for seismic & wind response
- Dynamic stiffness & damping from dynamic pile group analysis via Gazetas' approach
- MATLAB program developed for evaluation

SEISMIC EFFECTS

Liquefaction:

- Low – very low risk

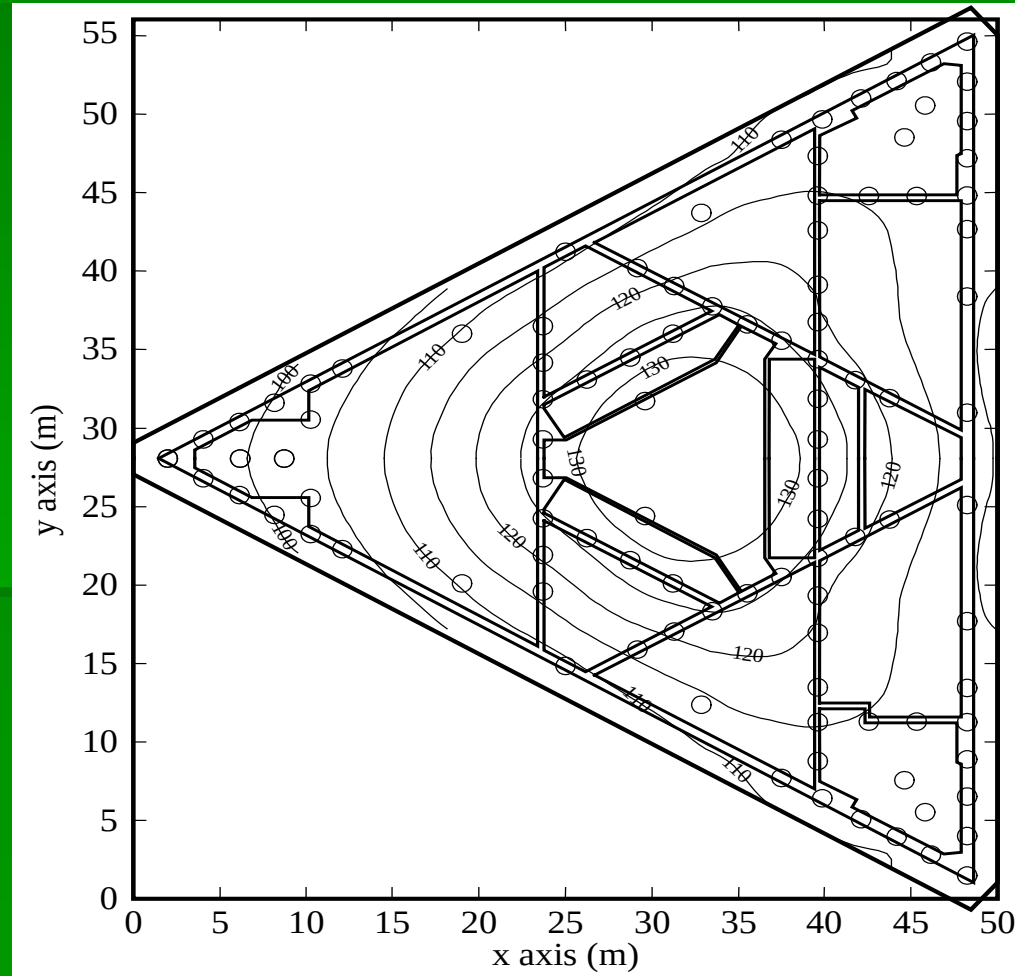
Ground Amplification of seismic motions:

- Category B assessed – modest amplification

Potential for Site Settlements:

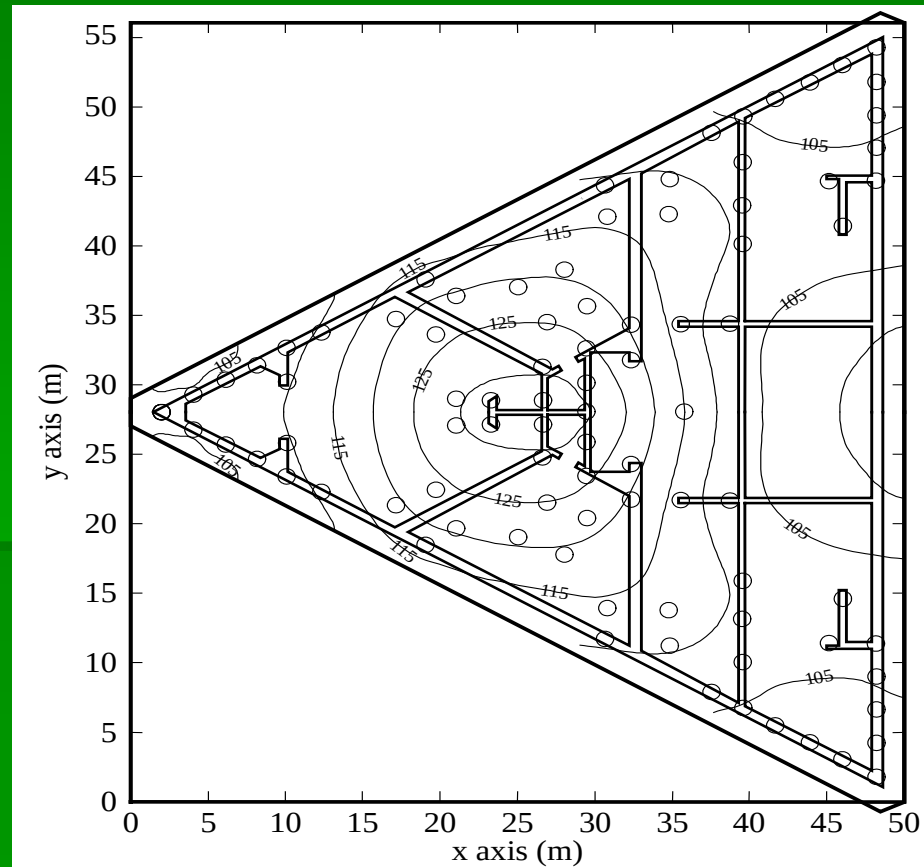
- Assessed to be low, 5-10mm under design earthquake, unlikely to cause excessive downdrag loads on piles.

PREDICTED SETTLEMENT CONTOURS FOR OFFICE TOWER



Predicted Max.
Settlement =
134 mm

PREDICTED SETTLEMENT CONTOURS FOR HOTEL TOWER



Predicted Max.
Settlement = 138
mm

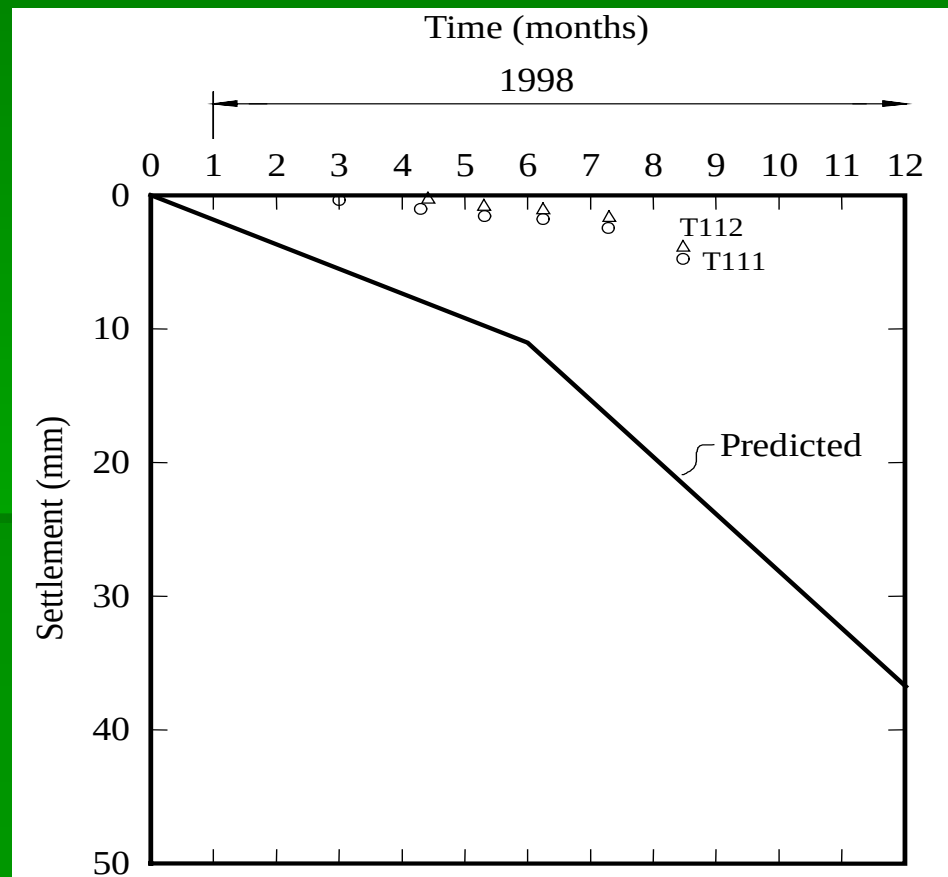
THE EMIRATES PROJECT, DUBAI



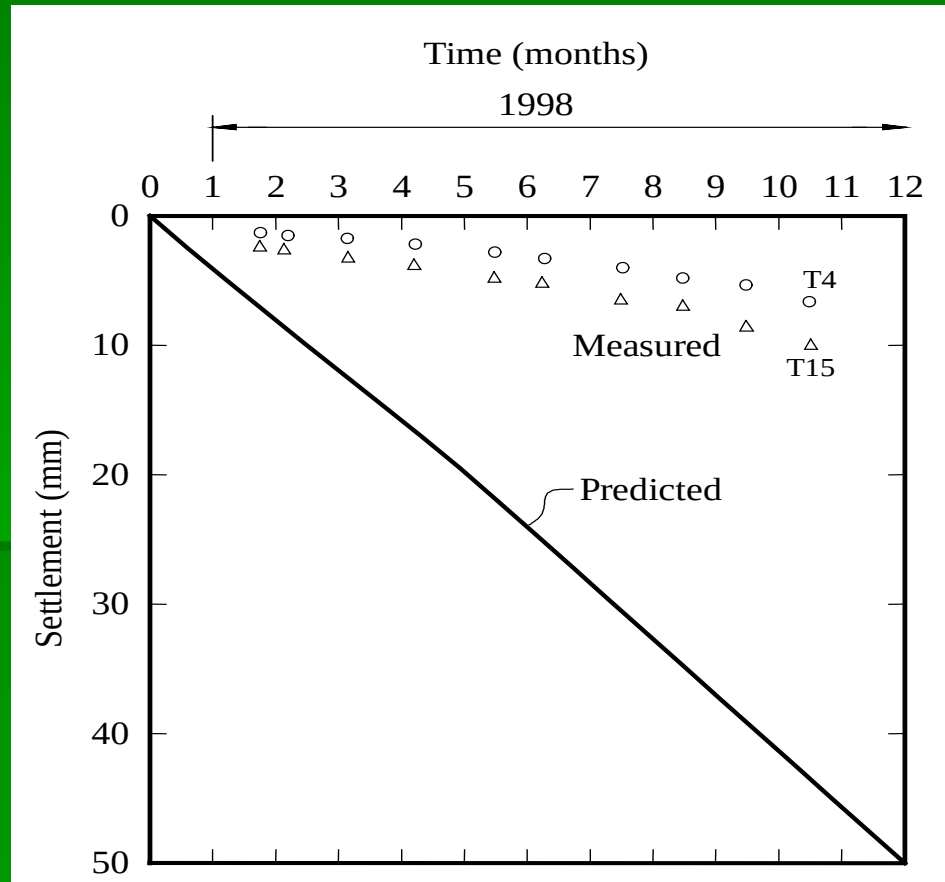
THE EMIRATES PROJECT, DUBAI



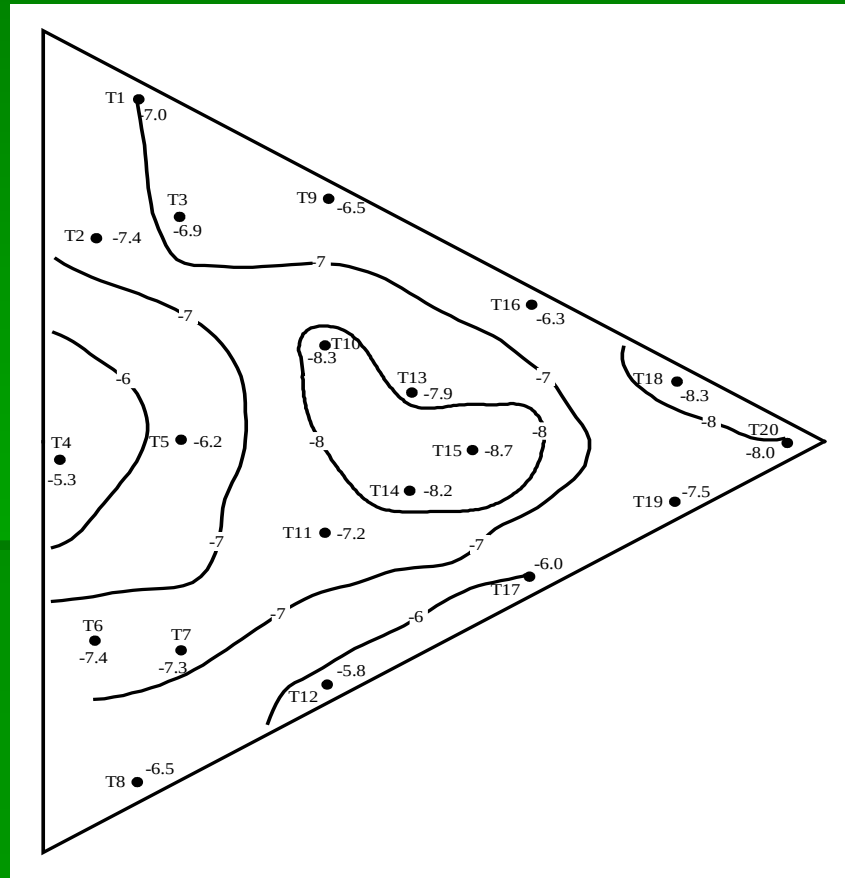
MEASURED & PREDICTED TIME-SETTLEMENT BEHAVIOR – OFFICE TOWER



MEASURED & PREDICTED TIME-SETTLEMENT BEHAVIOR – HOTEL TOWER

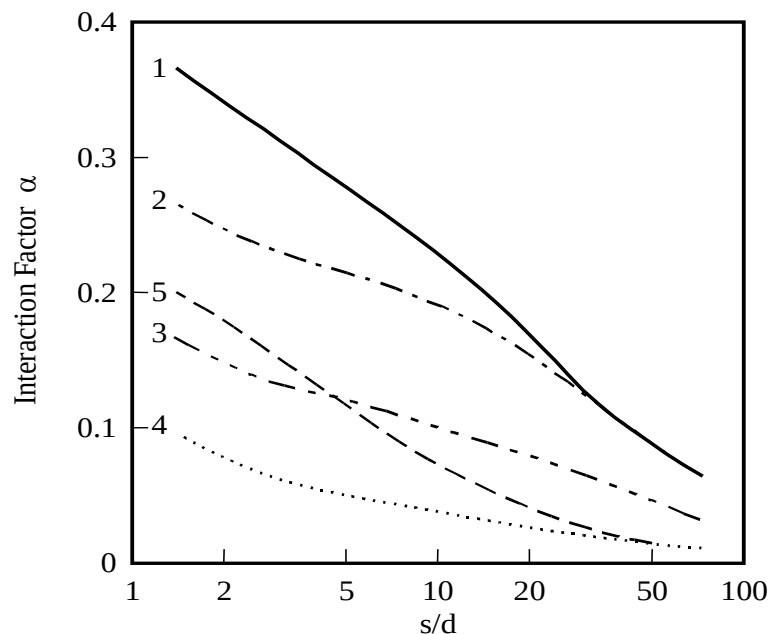


MEASURED SETTLEMENT CONTOURS – HOTEL TOWER



SENSITIVITY OF INTERACTION FACTORS TO ANALYSIS ASSUMPTIONS

Curve No.	Modulus of Layer below MPa	Modulus of Soil between Piles to Near-Pile Values
1	90	1.0
2	90	5.0
3	200	5.0
4	700	5.0
5	700	1.0



Allowances made for:

- Stiffer soil between piles
- Stiffer soil below pile tips

Interaction is generally reduced
Markedly.

Assumptions have a MAJOR
influence on computed
interaction effects.

EFFECT OF ANALYSIS ASSUMPTIONS ON COMPUTED SETTLEMENT



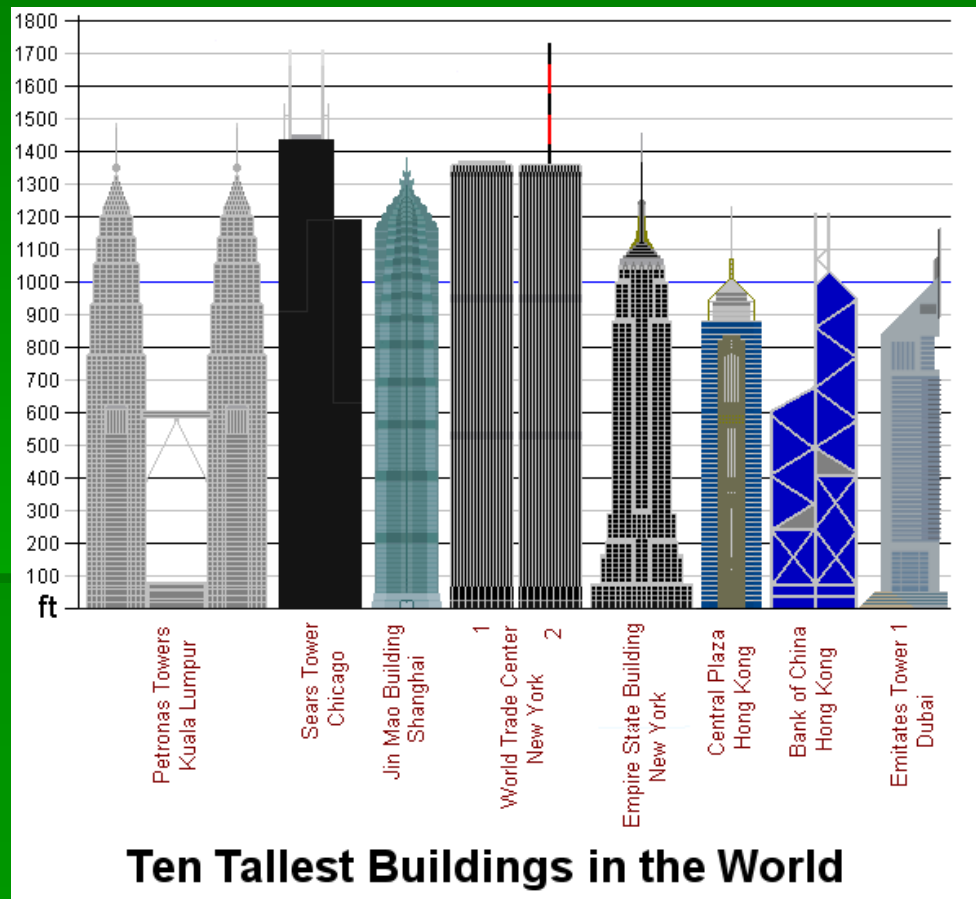
THE EMIRATES PROJECT, DUBAI



SOME COMMENTS

- Major efforts to obtain good site characterization
- Design values of skin friction higher than previously used in UAE
- CNS direct shear testing proved very useful
- Test pile behaviour reasonably well-predicted
- Foundation behaviour not well-predicted, but at least conservative

TALLEST BUILDINGS (2000)



Dubai - 2006



BURJ DUBAI TOWER



Site Photograph – September 2003



EARLY CONSTRUCTION – July 2005



GEOTECHNICAL PEER REVIEW - SCOPE

- Review geotechnical information
- Develop geotechnical model independently
- Independent review of Hyder foundation design
- Independent calculations for foundation stability, settlement, differential settlement
- Assessment of pile load test data and final design parameters.

Close cooperation between Coffey & Hyder maintained.
Site visits, examination of site and borehole cores.

SITE CHARACTERIZATION

- 30 boreholes
- SPT
- 60 PMT tests in 5 boreholes
- 6 standpipe piezometers
- Geophysics – cross-hole tomography

SIMPLIFIED PROFILE

	4	Silty Sand
	6	Calcareenite
	17	Calcareous Sandstone
	4.5	Gypsiferous Sandstone
	40	Conglomeritic Calcisiltite
	22.5	Calcareous/Conglomeritic
	>47	Claystone/Siltstone

Base of Tower Raft

Base of Tower Piles

Typical Cores – 66m depth



Typical Cores – 88m depth



LABORATORY TESTING

Conventional tests:

- Classification (various)
- UCS
- Point Load Index
- Modulus
- Chemical

LABORATORY TESTING

Advanced tests:

- Stress path triaxial
- Resonant column
- Cyclic undrained triaxial
- Cyclic simple shear
- CNS

HYDER PILE DESIGN – PARAMETER ASSESSMENT

- Skin friction via UCS correlations & CNS test data
- Modulus value for settlement prediction via correlations with SPT & UCS, pressuremeter, shear wave velocity (with allowance for strain levels)
- Non-linear behaviour via stress path tests
- Judgement employed

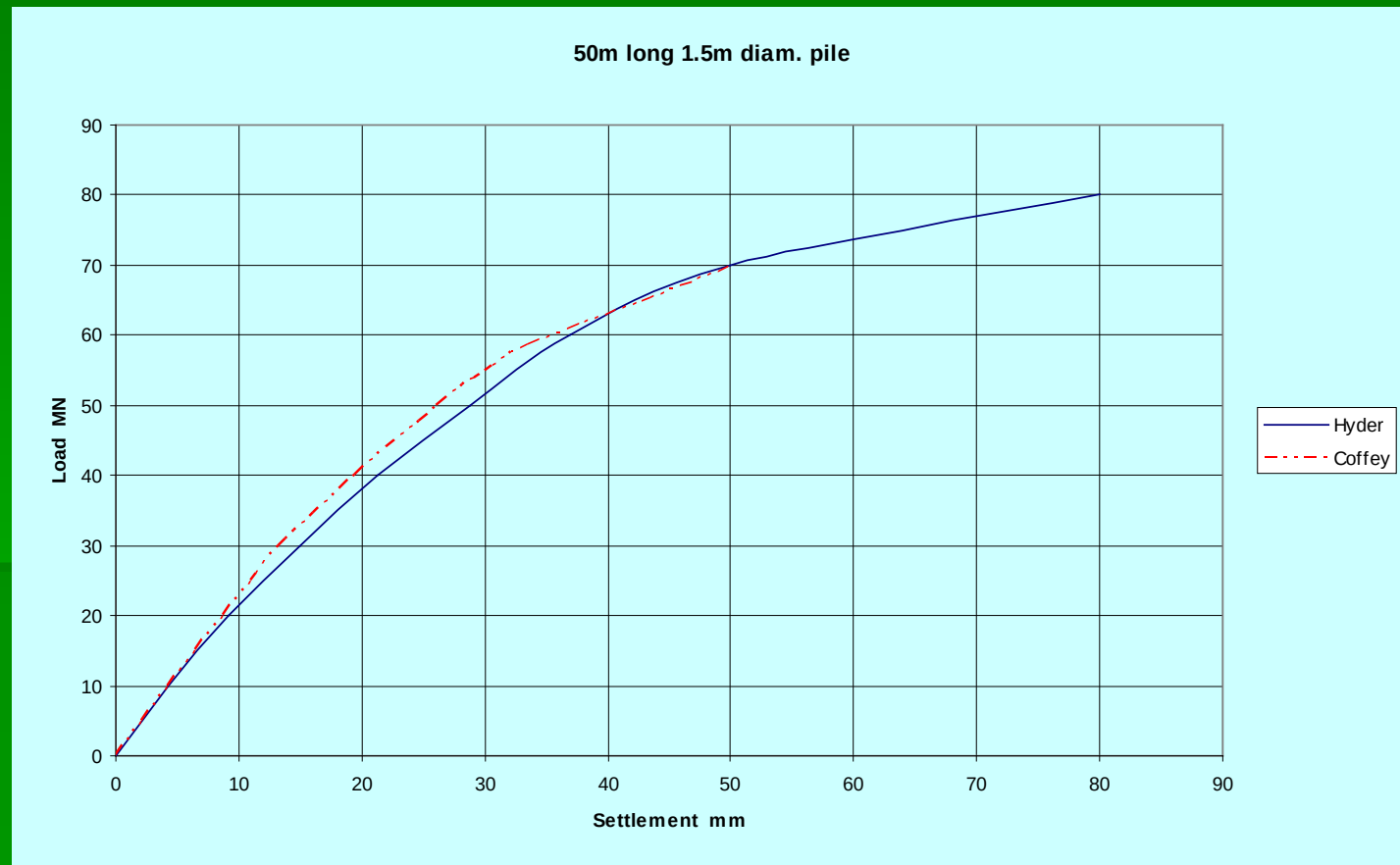
INITIAL PILE DESIGN

- **Tower:**
 - 196 piles, 1.5m diameter, 47.5m long
- **Podium:**
 - 750 0.9m diameter piles, 30m long
- **Raft:**
 - 3.7m thick (tower)

HYDER SETTLEMENT PREDICTIONS

- REPUTE – linear
- PIGLET - linear
- VDISP - linear & non-linear
- ABAQUS – non-linear 3D FEA

PREDICTED LOAD-SETTLEMENT CURVES



HYDER - INITIAL TOWER SETTLEMENT PREDICTIONS

Analysis	Settlement mm (Flexible cap)	Settlement mm (Rigid cap)
REPUTE	66	56
PIGLET	-	45
VDISP	-	62
ABAQUS	72	46

COFFEY – INITIAL TOWER SETTLEMENT ESTIMATES

- FLAC (Axisymmetric)
 - 73 mm
(maximum)
- PIGS
 - 74 mm (maximum)

LOAD TEST PROGRAM

- 3 static compression tests (1.5m dia.)
 - Various toe levels (35-55m long)
- 1 static compression test (0.9m dia.)
 - Shaft grouted
- 1 cyclic compression test (0.9m dia.)
- 1 static tension test (0.9m dia.)
- 1 lateral load test

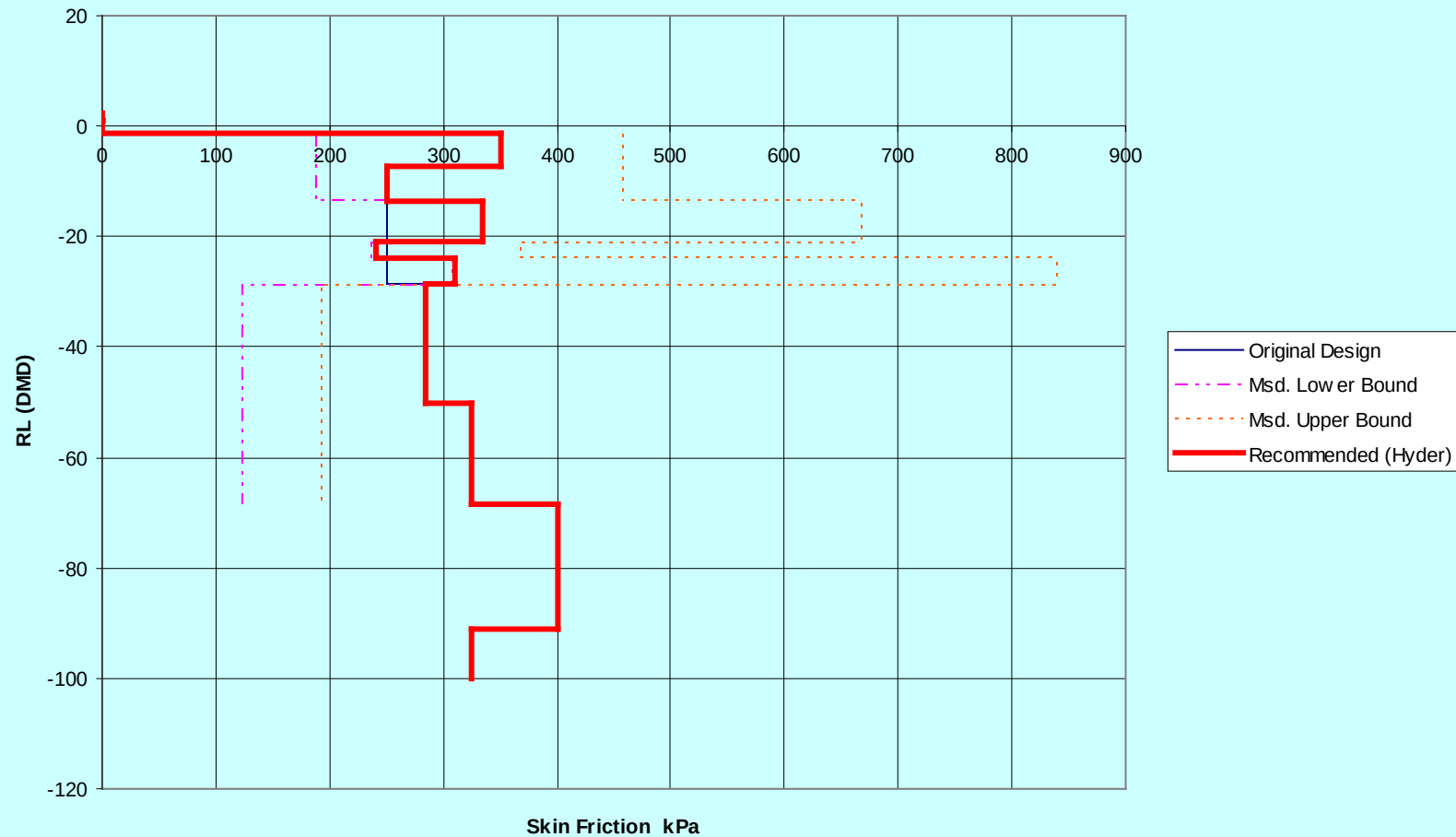
LOAD TEST PROGRAM- OUTCOMES

1.5m piles loaded to 2 times WL

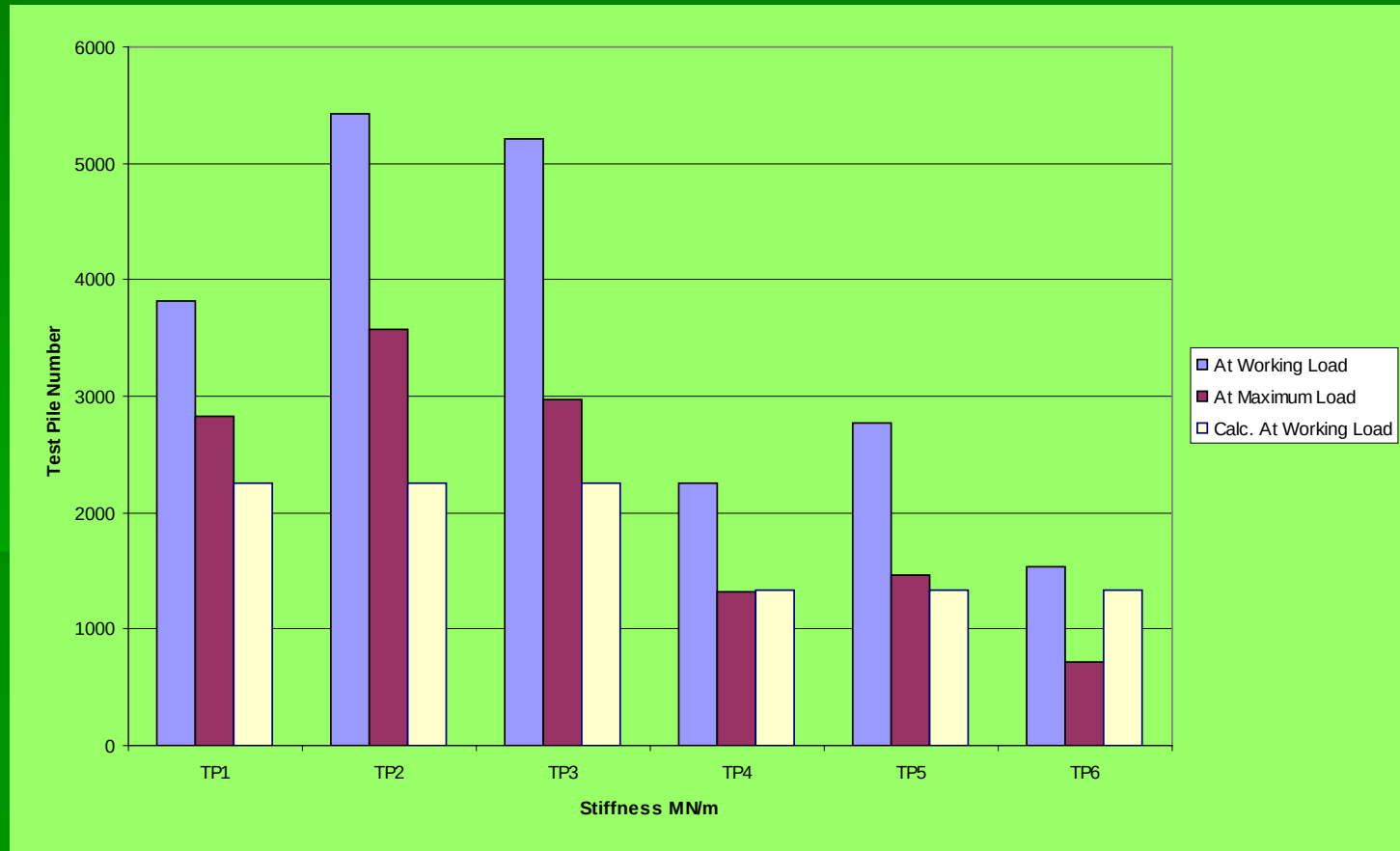
0.9m piles to 3.5 times WL

- No piles appeared to be approaching failure
- Skin friction values in excess of design assumptions
- Shaft grouting effective, but not necessary
- End bearing resistance not fully mobilized
- Axial stiffness greater than predicted
- Cyclic axial loading had little effect
- Lateral stiffness greater than predicted

COMPARISONS – SKIN FRICTION



MEASURED & PREDICTED PILE HEAD STIFFNESSES

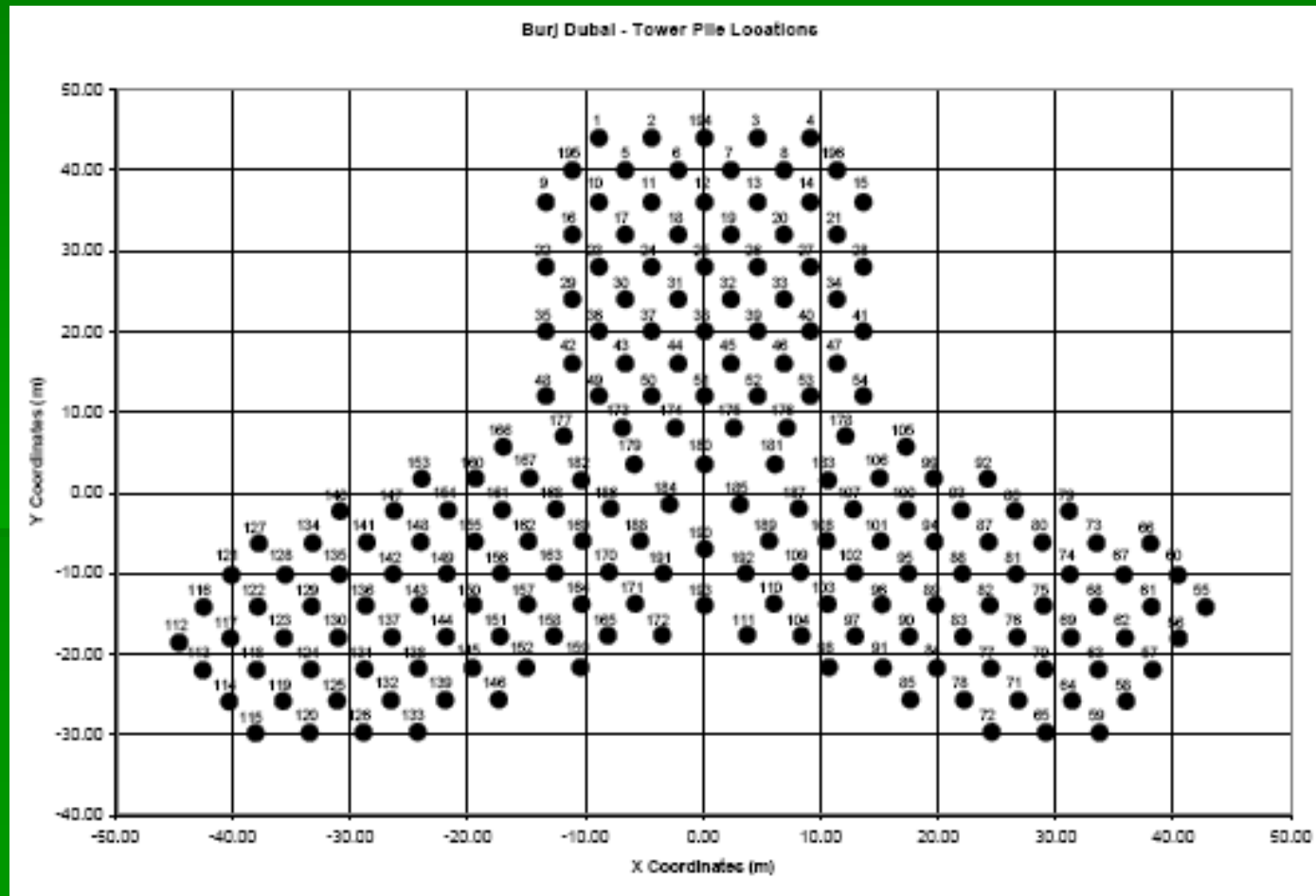


MEASURED & PREDICTED PILE HEAD STIFFNESSES

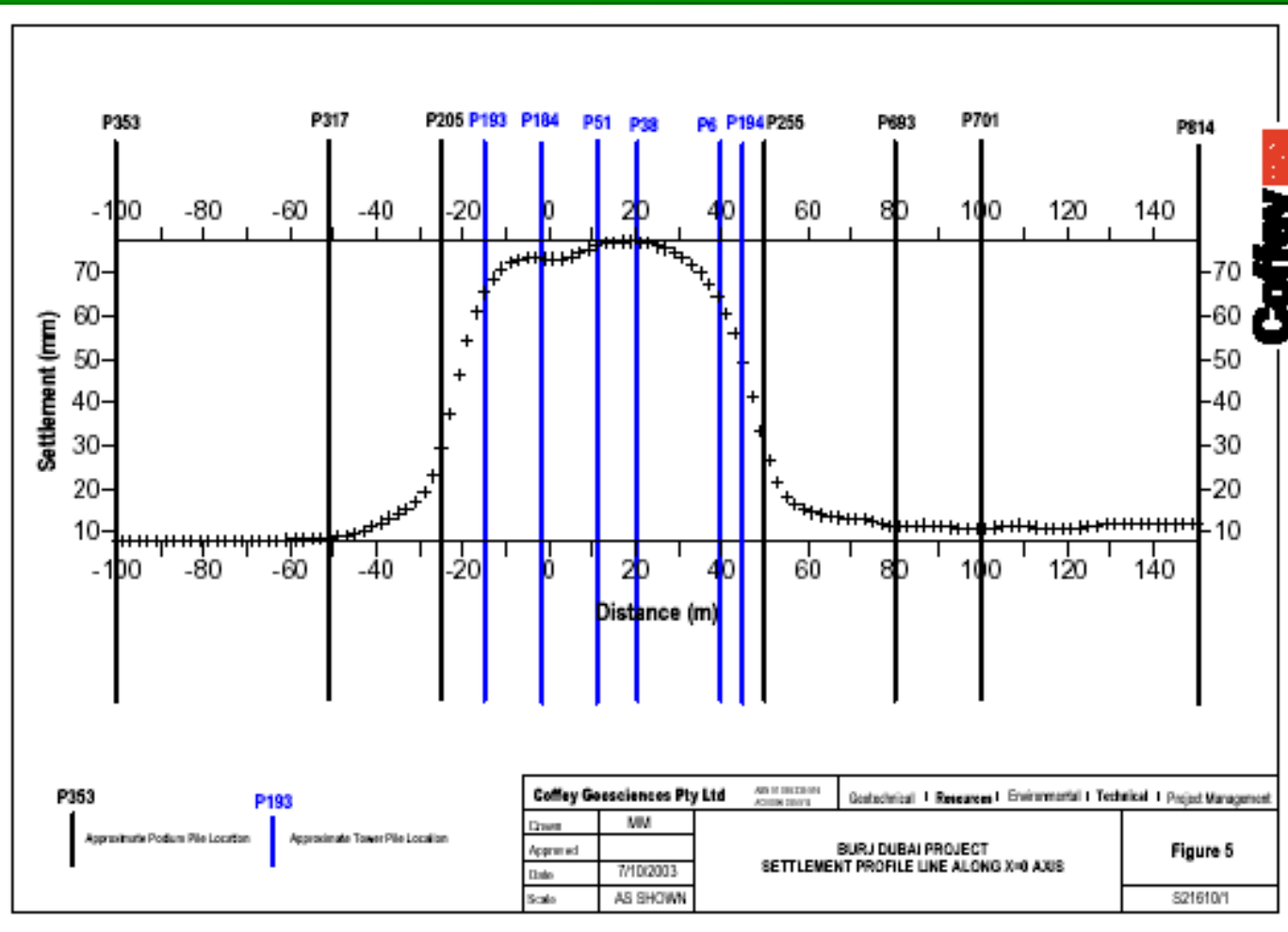
Possible reasons for stiffer than expected behaviour:

- Use of polymer drilling fluid.
- Interaction between test pile & reaction piles:
 - Analysis estimated that this interaction could cause a reduction in test pile settlement of about 30%
 - With this allowance, axial stiffness more consistent with Emirates experience

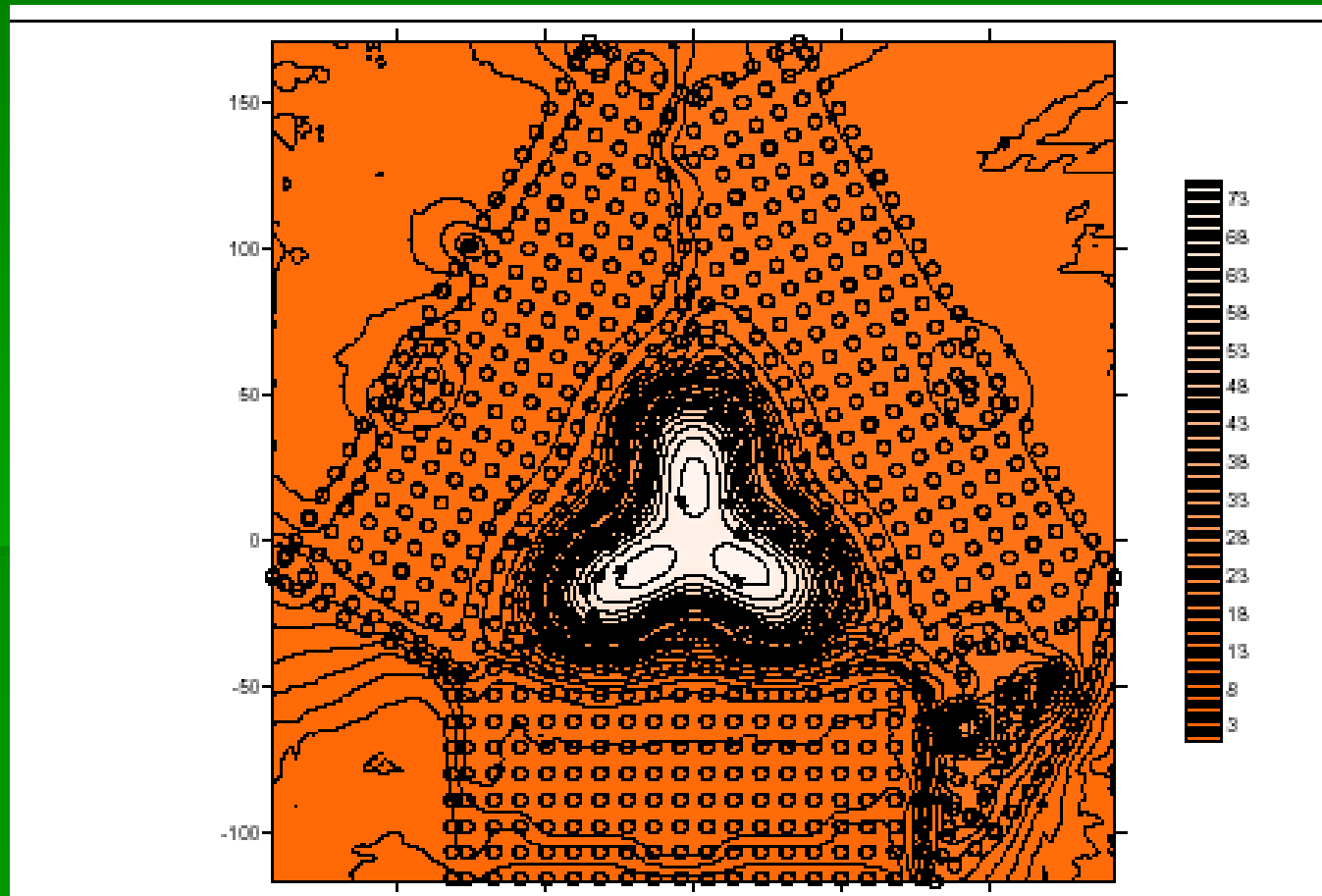
TOWER PILE LAYOUT



PREDICTED SETTLEMENT PROFILE



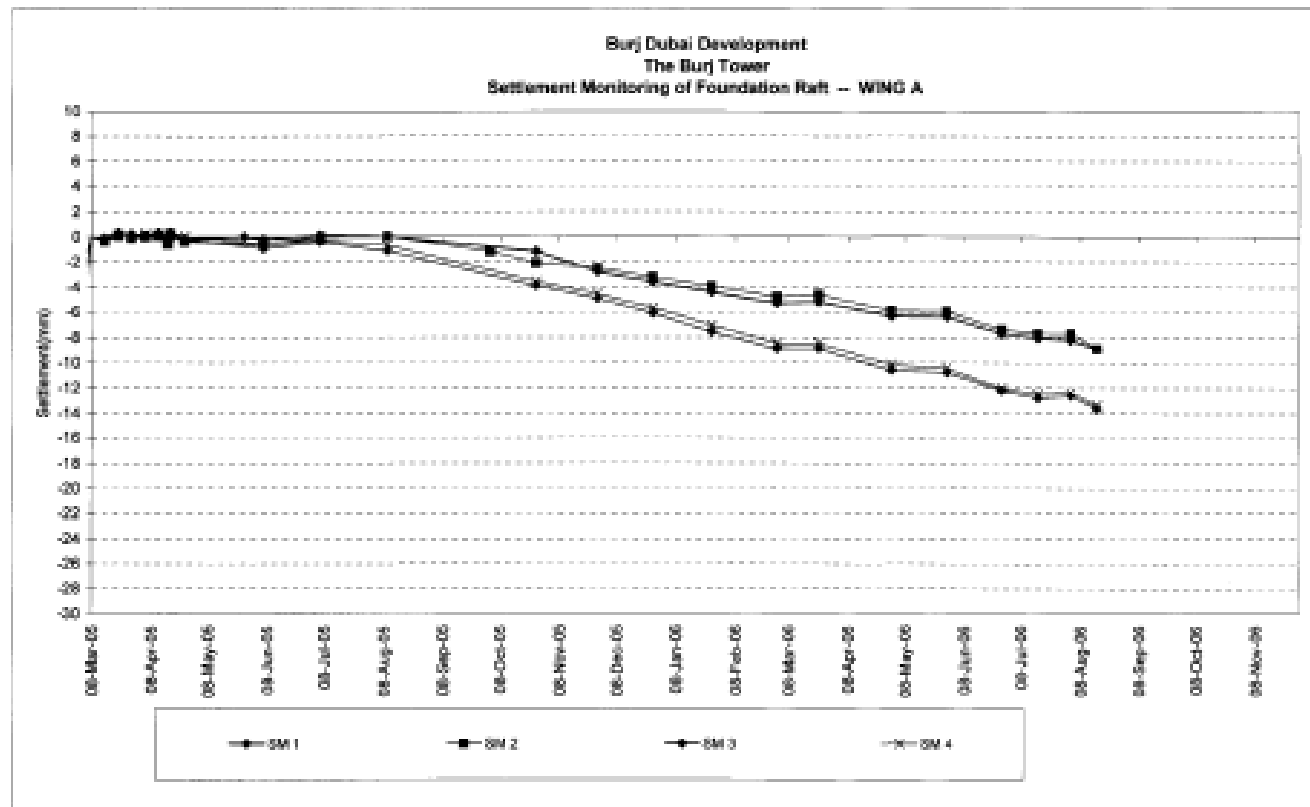
PREDICTED SETTLEMENT CONTOURS – PIGS ANALYSIS



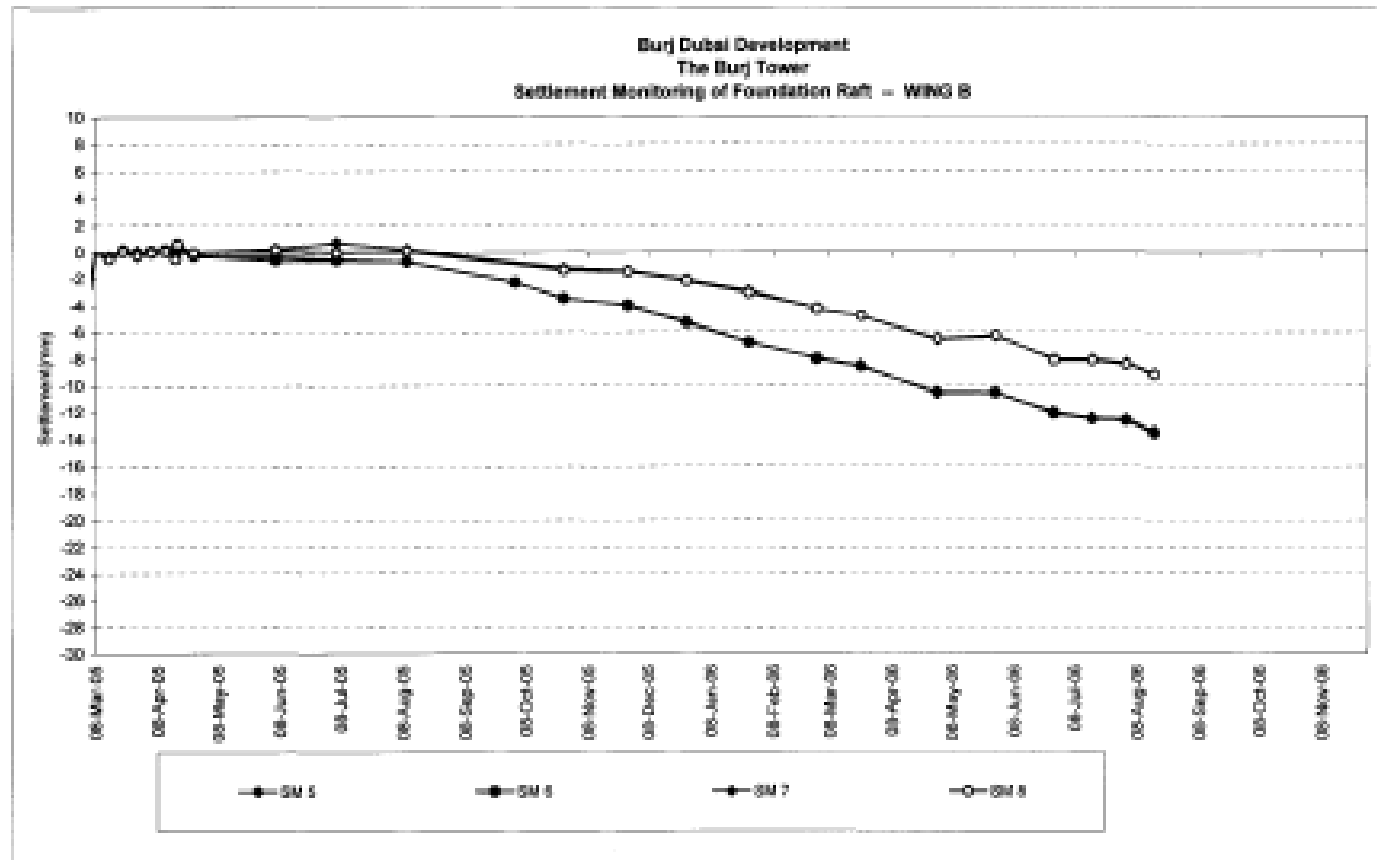
LOAD TESTS ON WORKS PILES

- Load tests carried out on some works piles
- Behaviour (axial) even better than test piles
- Predicted settlements could be conservative, although group settlement depends on stiffness of underlying layers

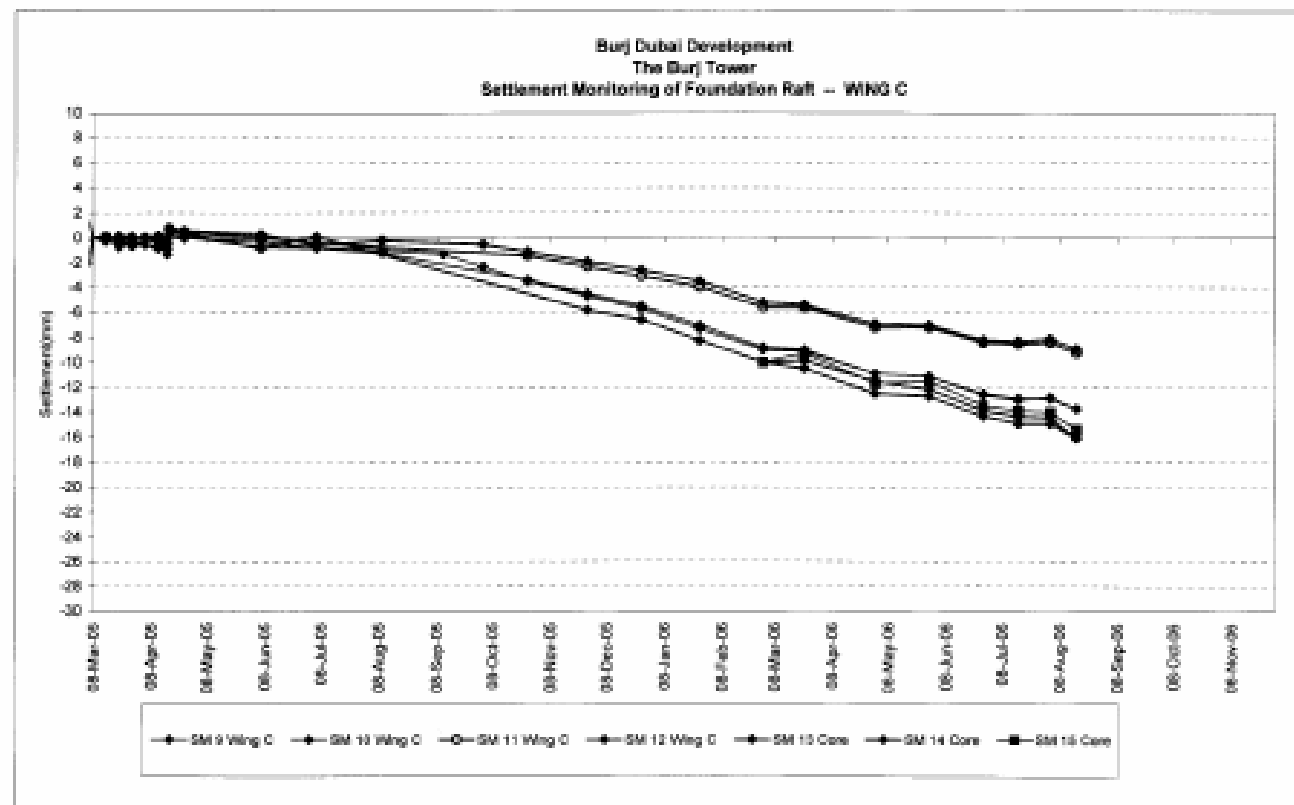
Measured Time-Settlement – Wing A



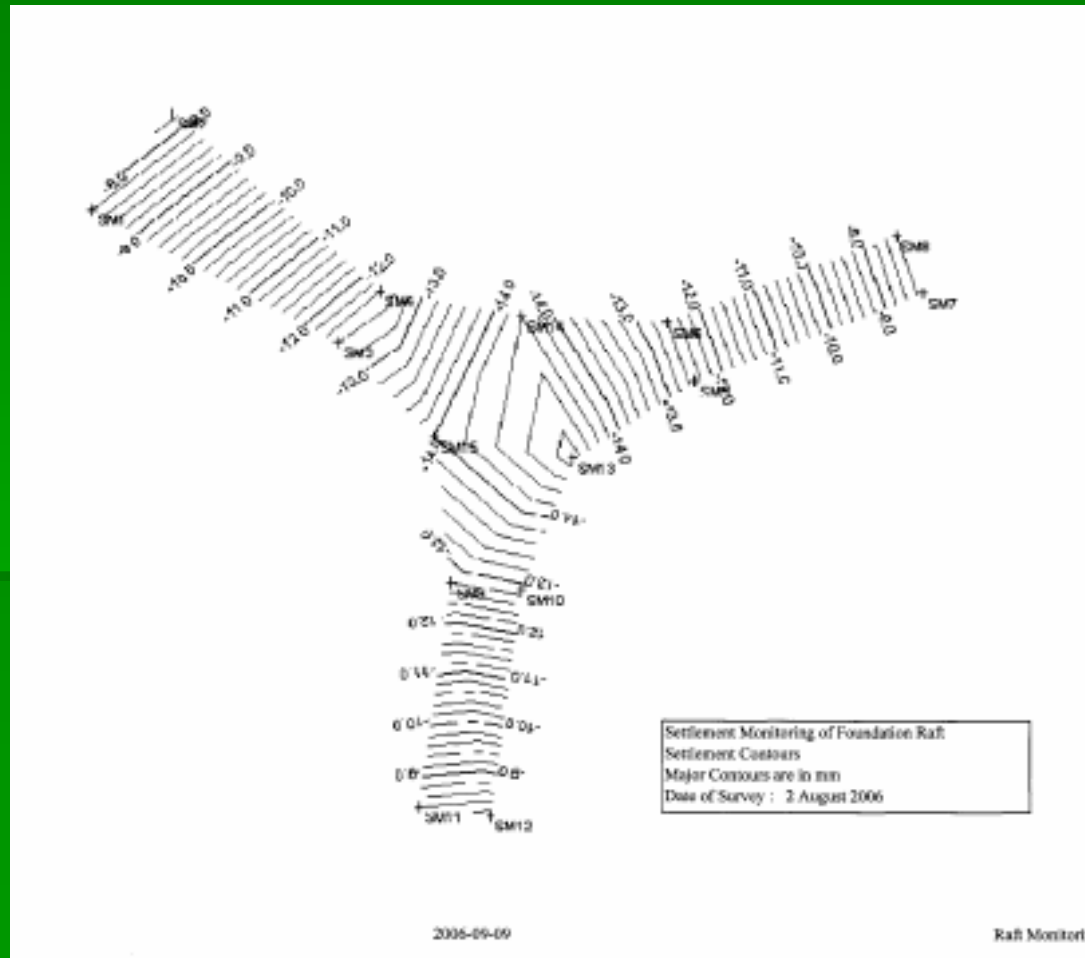
Measured Time-Settlement- Wing B



Measured Time-Settlement – Wing C



Measured Settlement Contours - August 2006



Comparison with Predictions

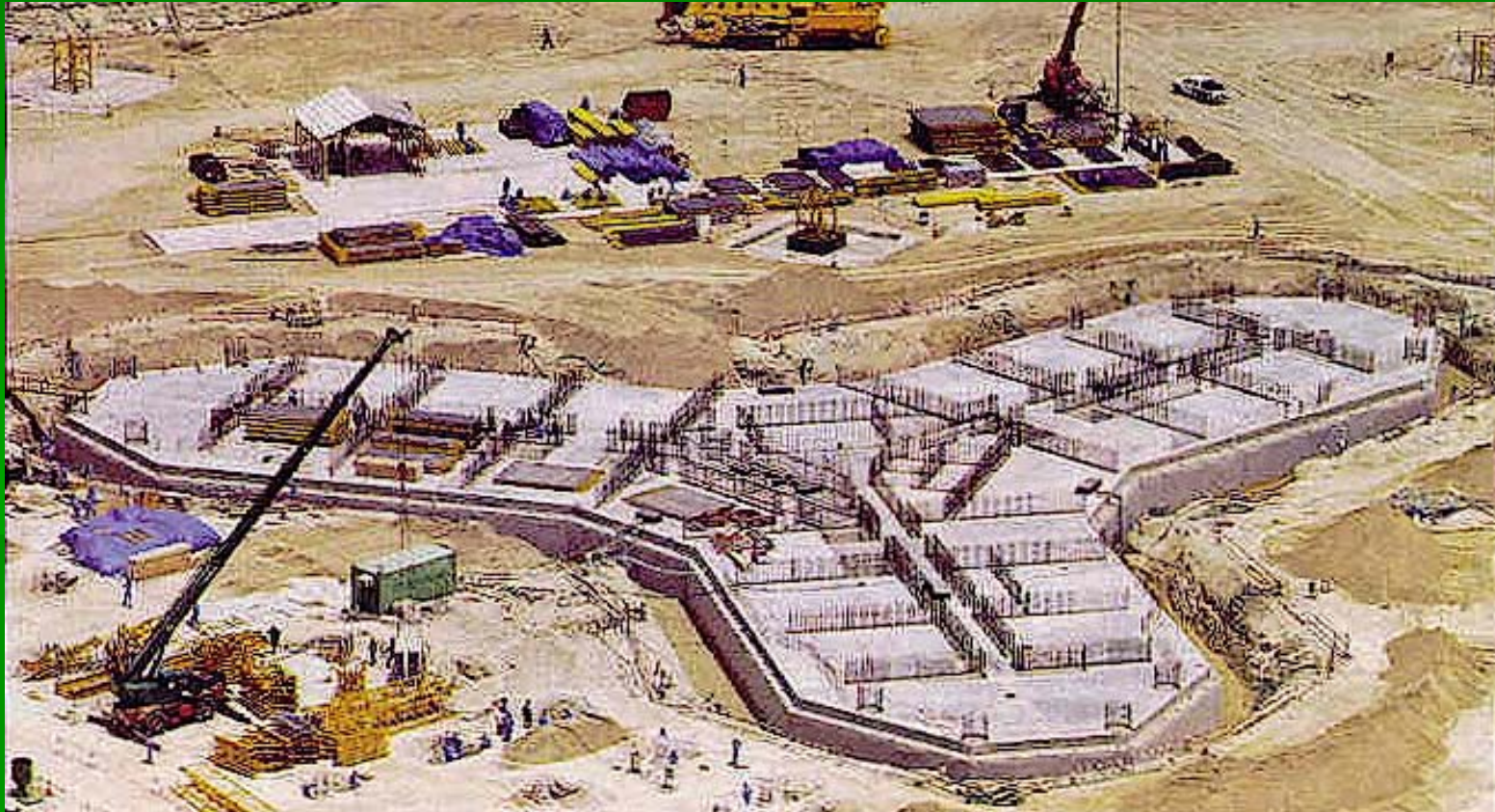
- Assuming 40% DL and LL = 20% of DL, in August 2006, applied load is about 33% of design load
- For linear behaviour, maximum predicted settlement is:
 - Hyder 22 mm
 - Coffey 25 mm
- Measured 16 mm

Comparison with Predictions

- Latest measurements:

Maximum measured settlement towards the end of construction is about **40mm**

COMPLETED RAFT



CONSTRUCTION PROGRESS



Early 2006



Early 2007



September 2007

Gold Coast Project - Artique

- A 28 storey building on the Gold Coast
- Structural Engineer designed a fully piled to rock foundation system
- Piling contractor engaged Coffey to assess feasibility of piled raft
- Based on results of feasibility, piling contractor engaged Coffey to optimize piled raft design



Analysis of Piled Raft

- Feasibility
- Detailed Design – Serviceability
- Optimization
- Detailed Design – Strength

Original Design



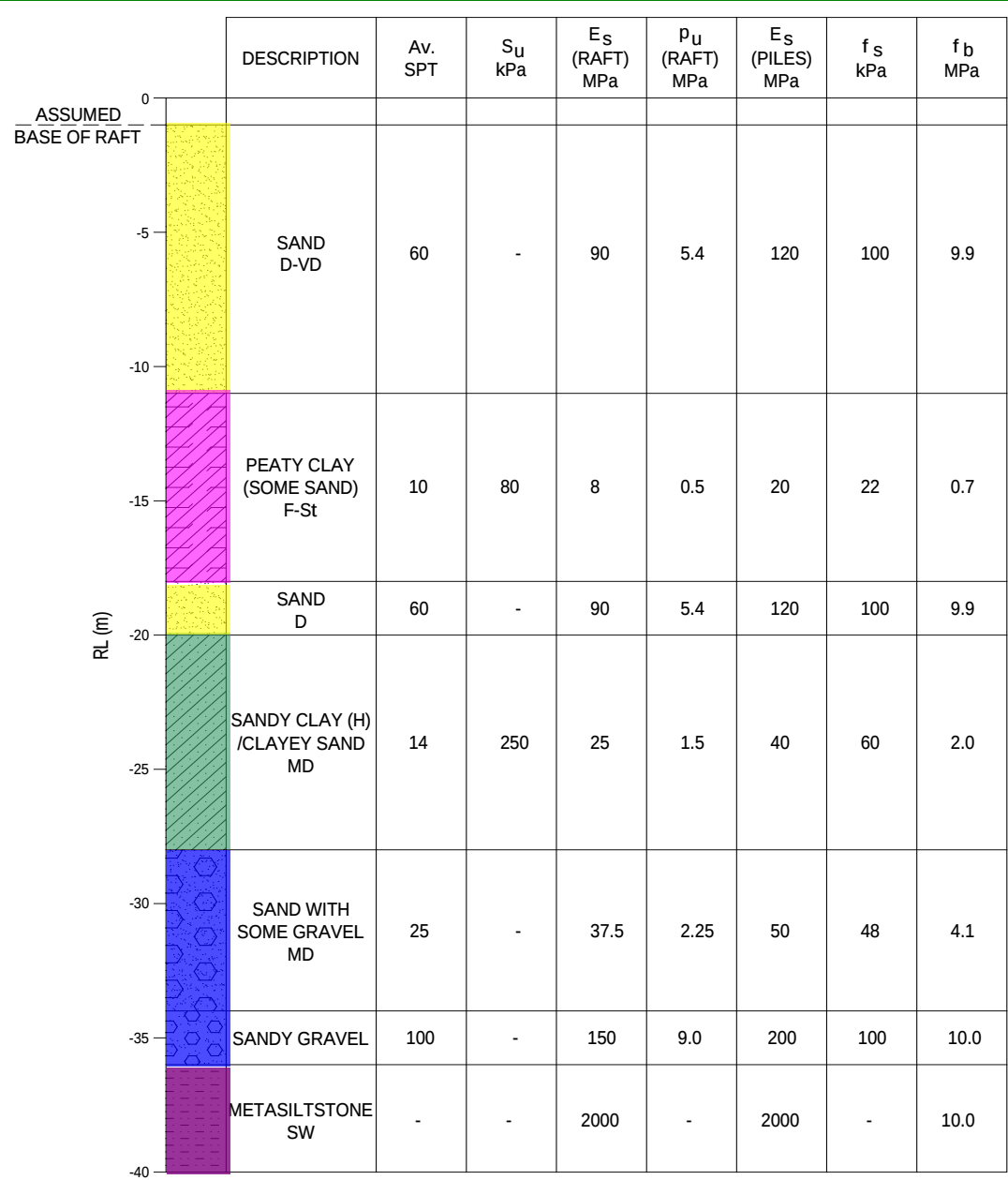
136 piles
founded
on rock

Slab
0.7m
thick

Contiguous bored pile wall

Shear joint between core and podium

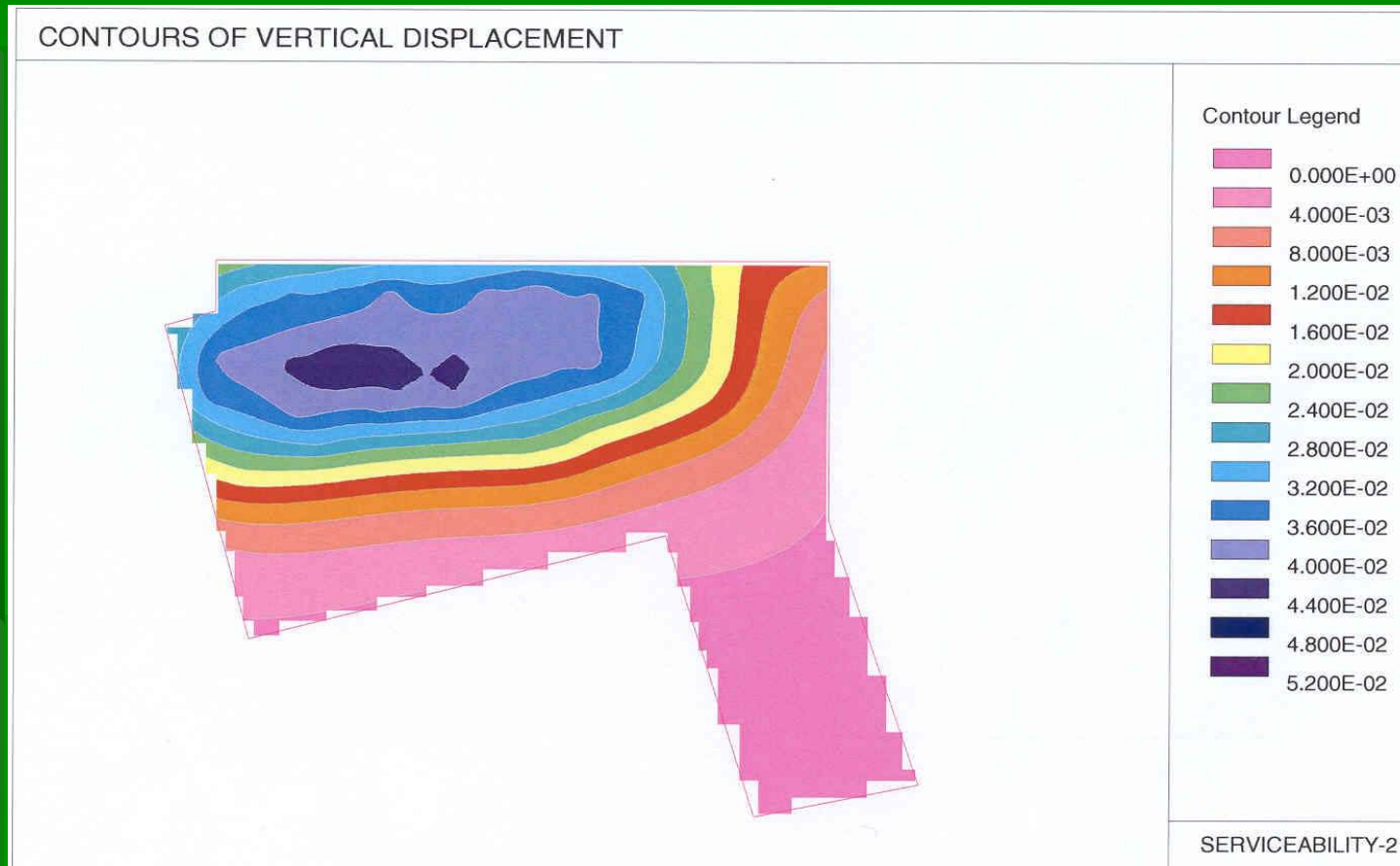
Geotechnical Model



Feasibility Results

- Indicated that a raft foundation alone would have a factor of safety of approximately 10 for ultimate loading
- Settlements would govern. Estimated to be of the order of 35mm to 60mm
- The number of piles would be of the order of 140 – as per the foundation design supplied by contractor. However, piles only 18m long not 35m

Serviceability Case



- 123 piles (13 less)
- Maximum raft settlement of 44mm
- Maximum differential settlement of 10mm (1/400)

Outcomes

- Number of piles reduced by 10% (13 piles)
- Pile length reduced from 35m to 18m
- Total pile length reduced by 2767m
- Settlement criteria (both total and differential) satisfied
- Potential variations in pile stiffness compensated for by raft

CONCLUSIONS

- Ground conditions in Dubai are challenging for very tall buildings
- Modern methods are being employed for:
 - In-situ testing
 - Laboratory testing
 - Analysis & design methods
- Simpler methods essential for checks on advanced numerical analyses
- Use of piled rafts can lead to foundation economy
- With benefit of experience, predictive capabilities are improving
- BUT, reluctance remains to measure foundation performance

ACKNOWLEDGEMENTS

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 - Frances Badelow
 - Muliadi Merry
 - Patrick Wong