# LESSONS LEARNED FROM DESIGNING HIGH-RISE BUILDING FOUNDATIONS

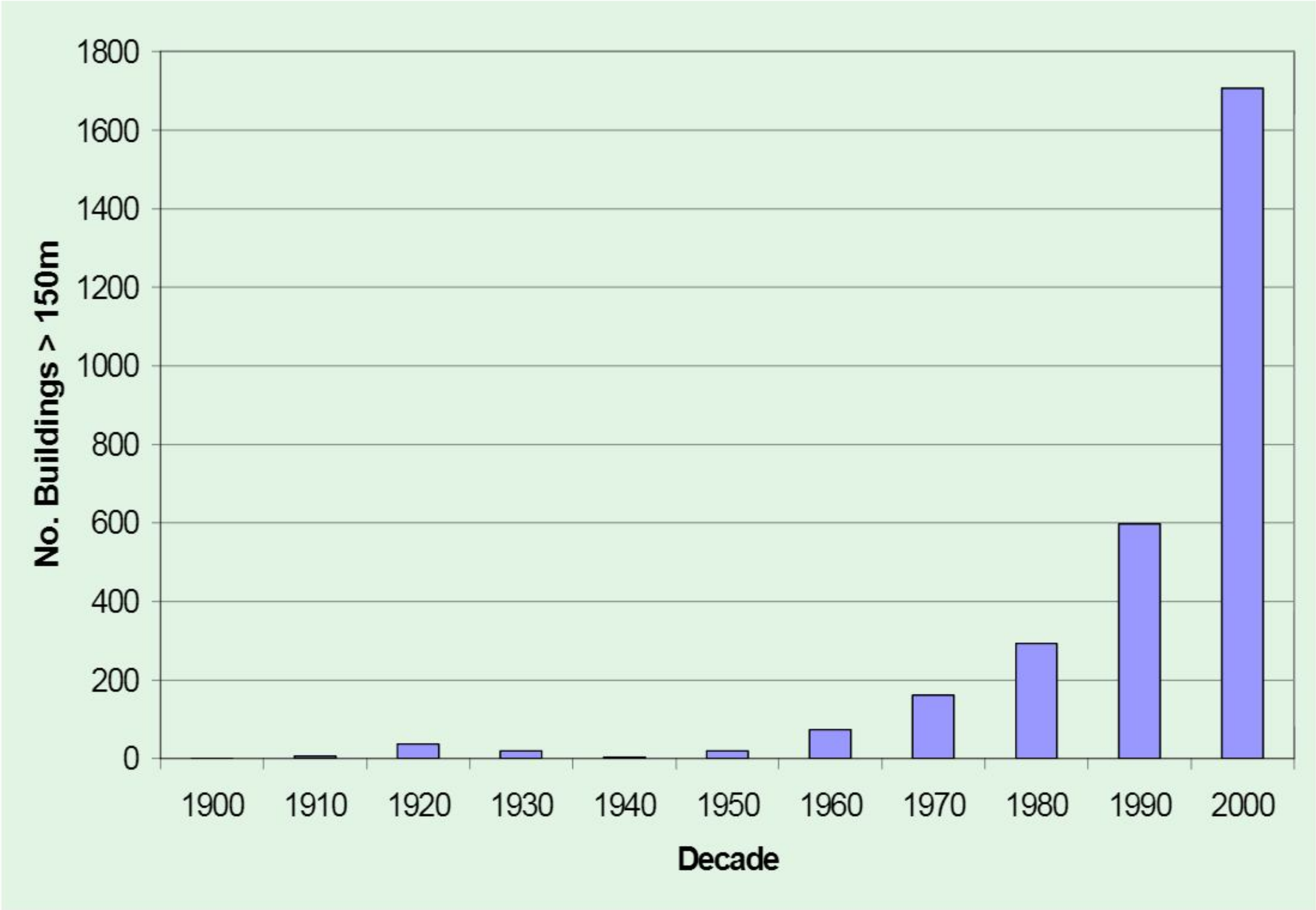
**Harry Poulos**

Coffey Geotechnics

# Outline

- Tall building challenges
- Foundation design requirements
- Foundation design process
- Case histories from which lessons learned:
  - Emirates Towers, Dubai
  - Burj Khalifa, Dubai
  - Incheon Tower, South Korea
- Summary of lessons learned

# Growth in Rate of Construction of Tall Buildings



# Some Challenges with Tall Buildings

- High vertical loads – non-linear increase with height
- Low-rise podium areas adjacent – differential settlements
- High lateral forces & moments from wind
- Cyclic nature of loading
- Seismic forces on foundations – inertial, kinematic
- Dynamic response issues

# Meeting the Challenges

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- Appropriate ground investigation
- Appropriate geotechnical model(s)
  - Stratigraphy
  - Parameters
- Appropriate design process & tools
- Load testing
- Performance measurements

# Site Investigation & Characterization

## A critical aspect!!

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

# Key Parameters to Assess

- Ultimate shaft friction
- Ultimate end bearing
- Soil stiffness/modulus for vertical loading
  - *Long-term (dead plus live loading)*
  - *Short-term (wind, seismic loading)*
- Ultimate lateral pressure
- Soil stiffness/modulus for lateral loading
- Dynamic soil stiffness & damping

# Foundation Design Process

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## Foundation Type & Layout.

– Usually piles or piled raft

Based on:

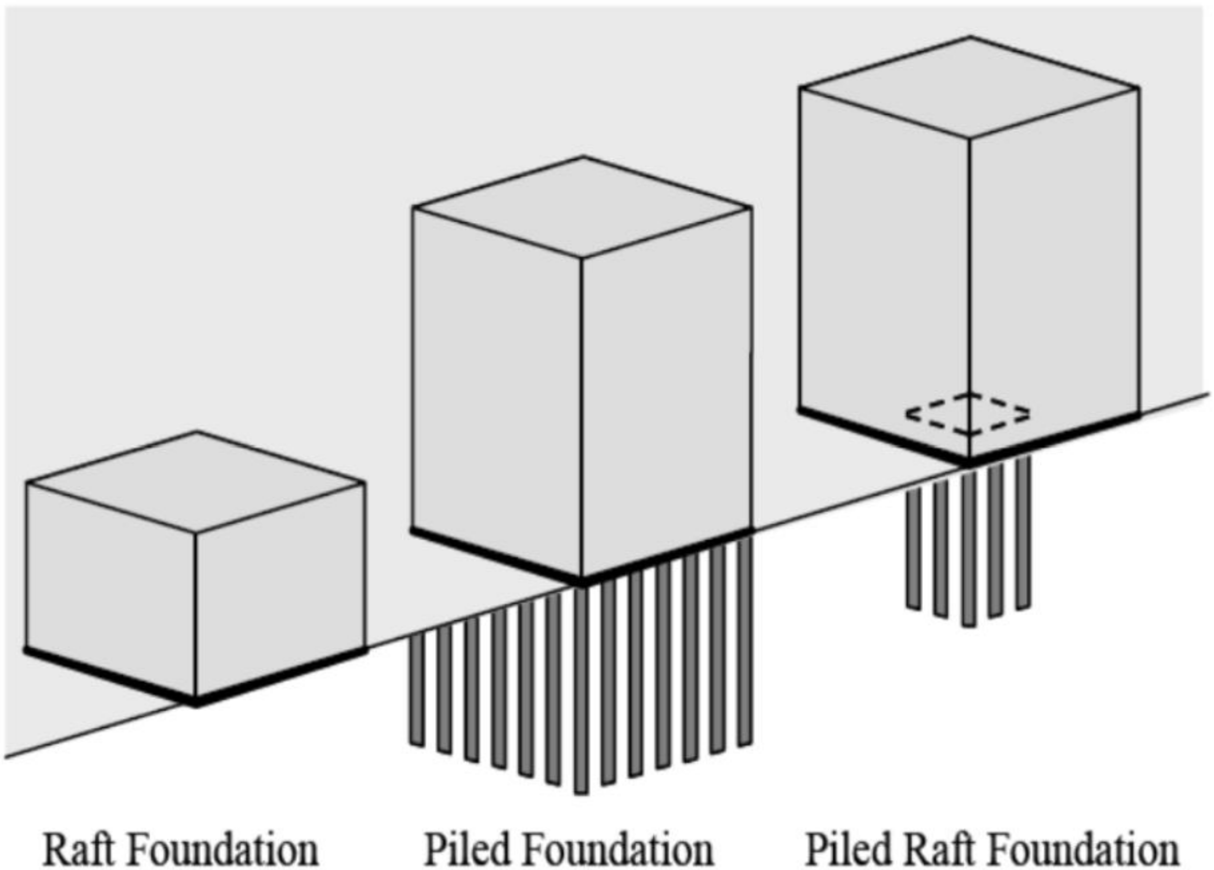
Foundation loadings

Design criteria

Construction issues

Material availability

# Foundation Options




Piled raft provides

**REDUNDANCY**

# Key Foundation Design Issues

1. Ultimate capacity & overall stability
2. Cyclic loading effects (wind, seismic)
3. Settlement
4. Differential settlement & tilt
5. External ground movement effects
6. Dynamic behaviour (wind)
7. Earthquake response & liquefaction
8. Structural strength of foundation elements
9. Durability

# Cooperation Between Geotechnical & Structural Designers

- Essential for a successful outcome
- A key geotechnical output is the values of pile stiffness (axial, lateral, rotational) for each pile within the group
- Incorporated into the structural analysis to obtain structural design actions and also to take account of structural stiffness for settlements and differential settlements
- The stiffness values MUST take into account pile group interaction effects

# THE EMIRATES PROJECT, DUBAI

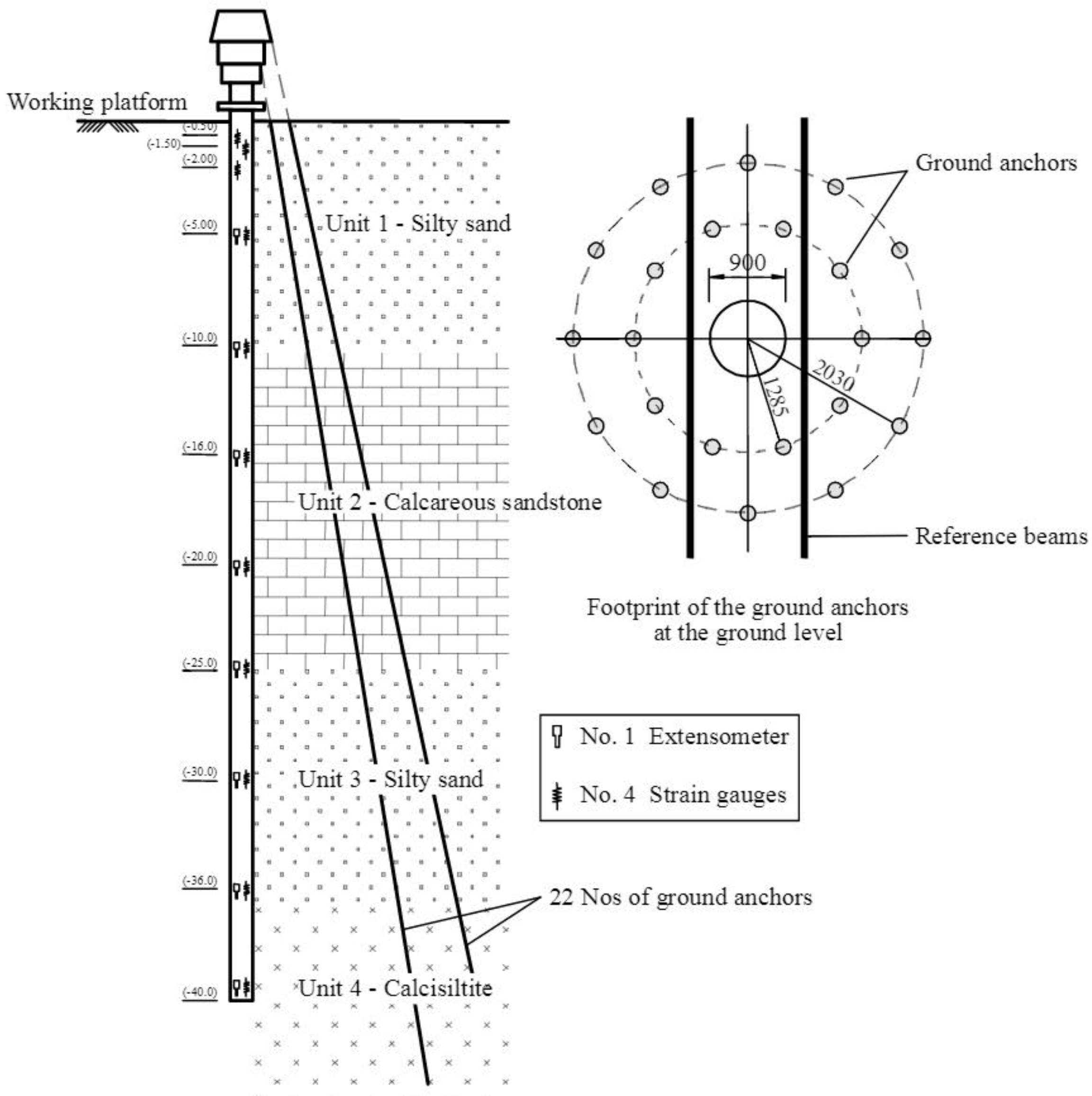
# INVESTIGATION PROGRAM

- 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 FOR EMIRATES SITE

| | $E_u$ MPa | $E'$ MPa | $\nu'$ | $f_s$ kPa | $f_b$ MPa | $p_u$ MPa | Unit |
|---|---|---|---|---|---|---|---|
| SILTY SAND, some calcarenite bands | 40 | 30 | 0.2 | 18 | 0.15 | 0.1 | 1 |
| As above | 125 | 100 | 0.2 | 73 | 1.5 | 1.5 | 2 |
| CALCAREOUS SANDSTONE | 700 | 500 | 0.1 | 200 | 2.3 | 2.3 | 3 |
| SILTY SAND | 125 | 100 | 0.2 | 150 | 1.9 | 1.9 | 4 |
| CALCISILTITE | 500 | 400 | 0.2 | 450 | 2.7 | 2.7 | 5 |
| As above | 90 | 80 | 0.3 | 200 | 2.0 | 2.0 | 6 |
| As above | 700 | 600 | 0.3 | 450 | 2.7 | 2.7 | 7 |

# SETUP FOR COMPRESSION PILE TESTS



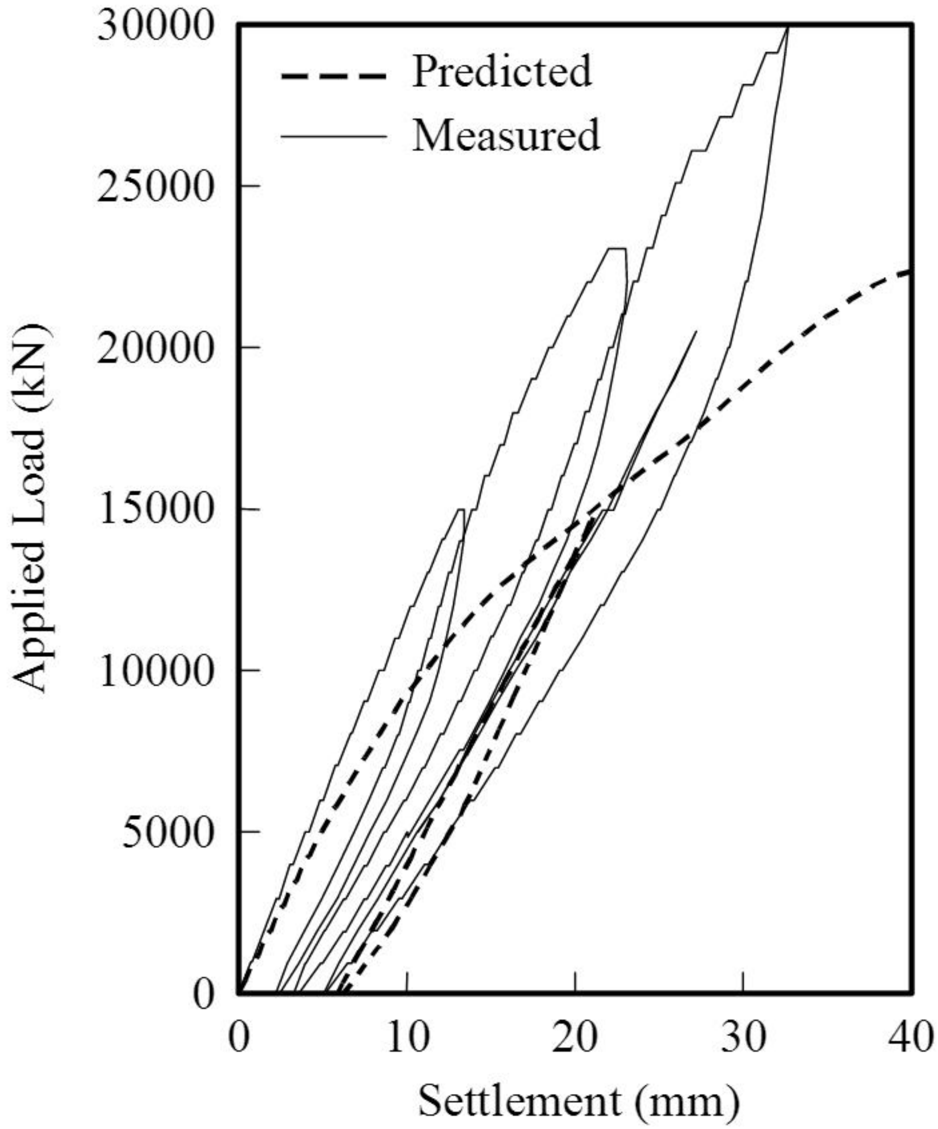
# 3000t LOAD TEST WITH REACTION ANCHORS


Emirates Project, Dubai

# 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

# LOAD-SETTLEMENT CURVES FOR PILE P3(H)



# PREDICTED & MEASURED AXIAL LOAD DISTRIBUTIONS

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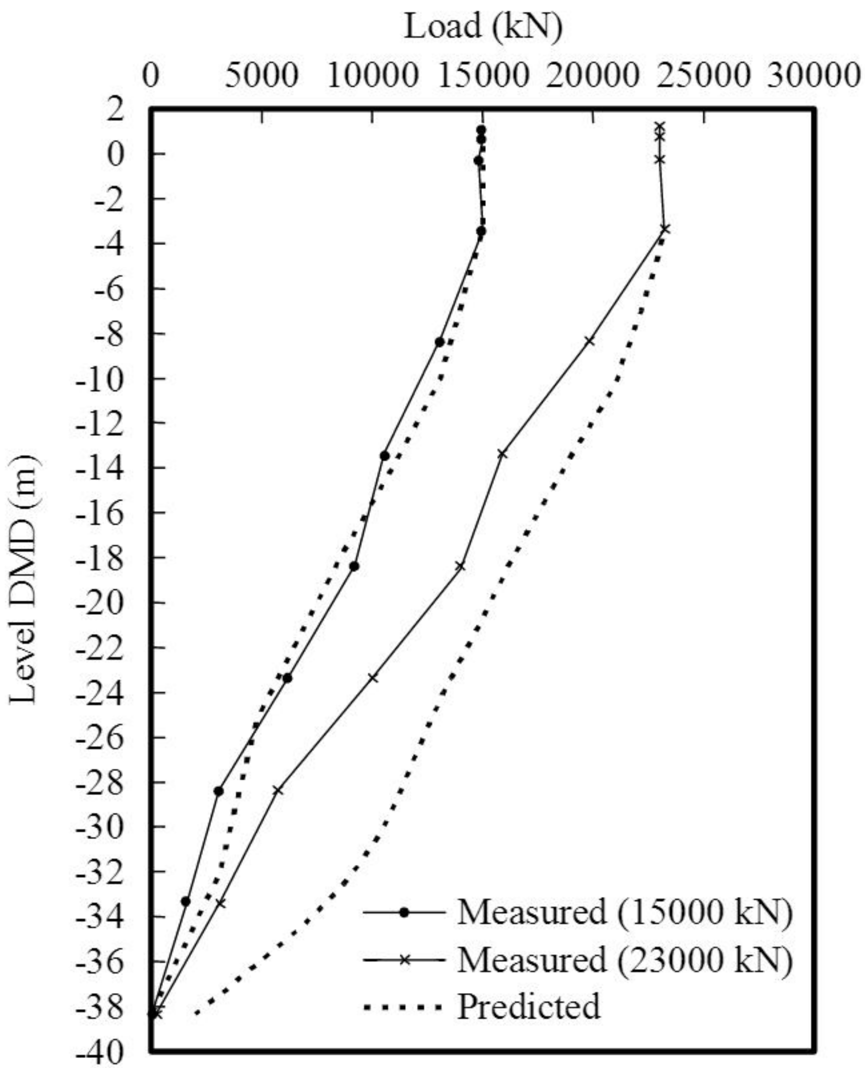
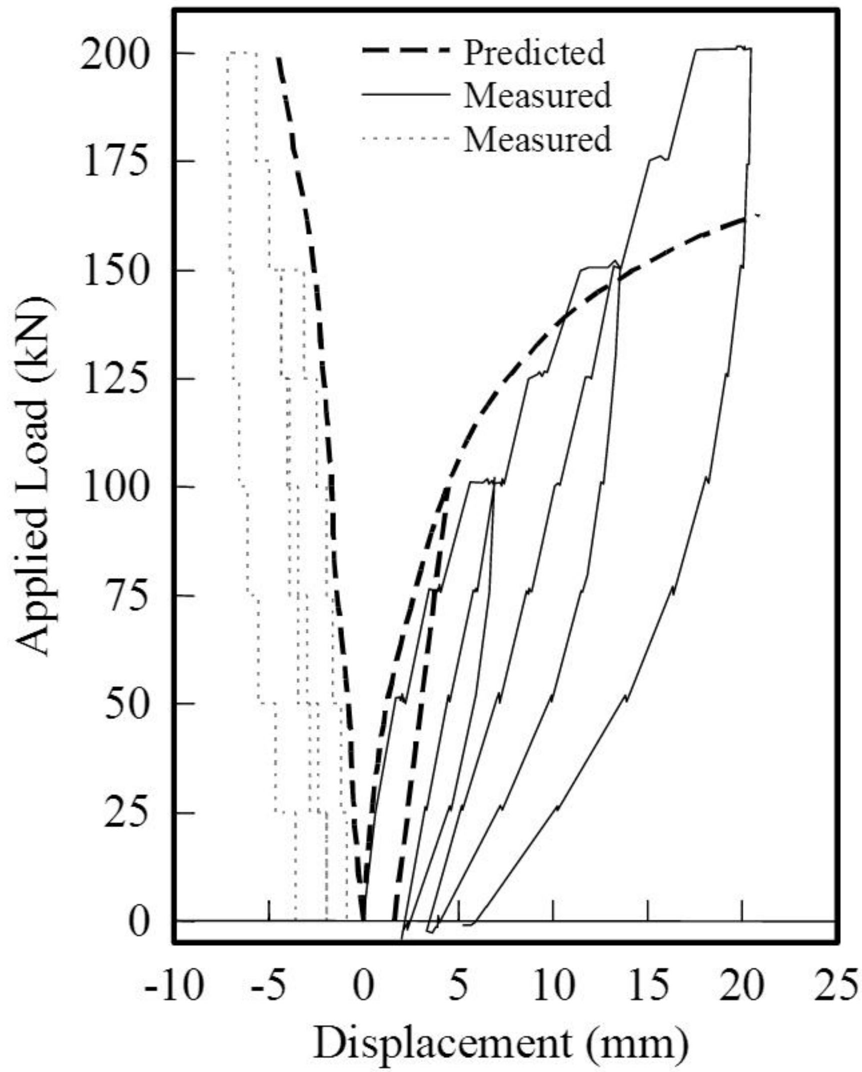


# MEASURED & PREDICTED LATERAL LOAD-DEFLECTION CURVES



# ASSESSMENT OF PREDICTIONS

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

# 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

# EMIRATES TOWERS - PREDICTION METHODS

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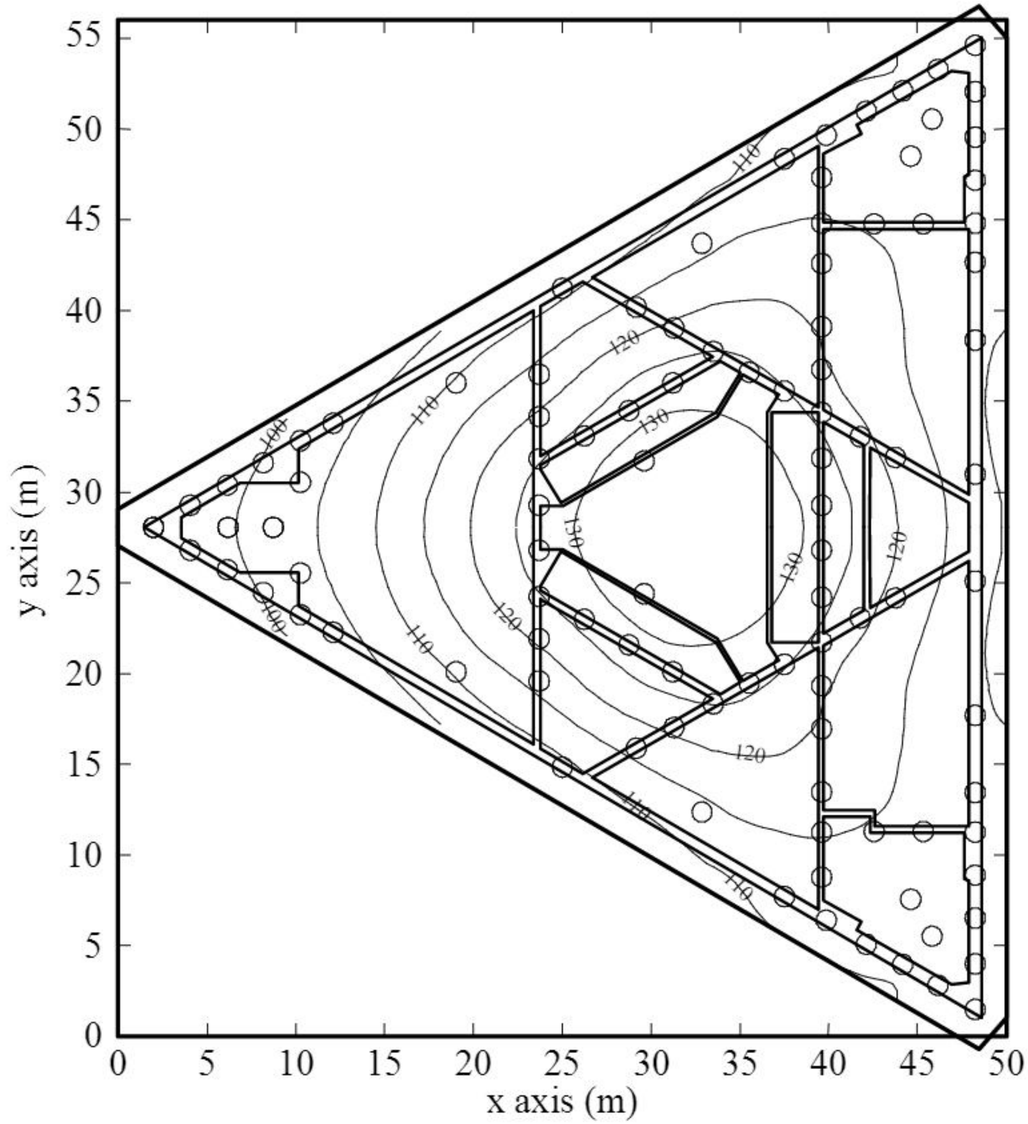
- Piled raft foundations
- Conventional analysis for capacity of raft & piles
- Settlement & pile loads via piled raft analysis
- GARP program
  - Finite difference representation of raft
  - Piles as interaction non-linear springs
  - Interaction factors via DEFPIG analysis
- Parameters as for single piles

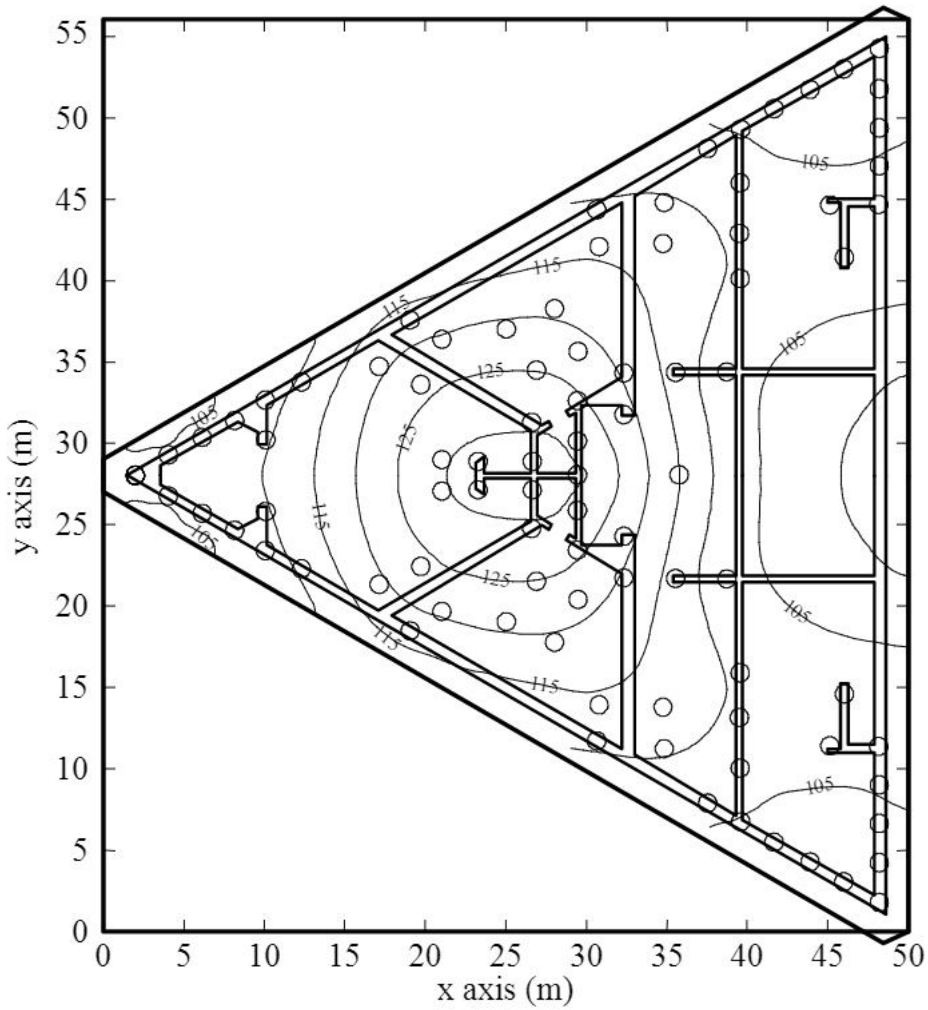
# PREDICTED SETTLEMENT CONTOURS FOR OFFICE TOWER




Predicted Max.

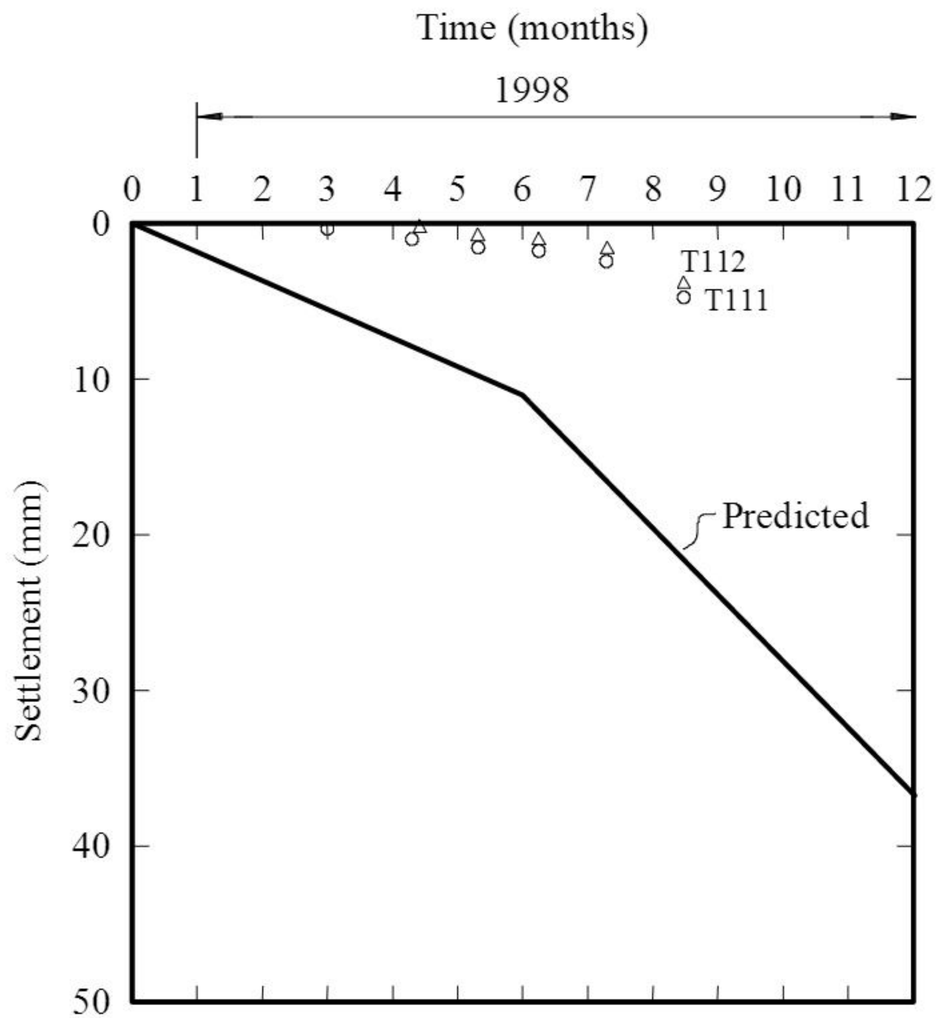
Settlement = 134 mm

# PREDICTED SETTLEMENT CONTOURS FOR HOTEL TOWER

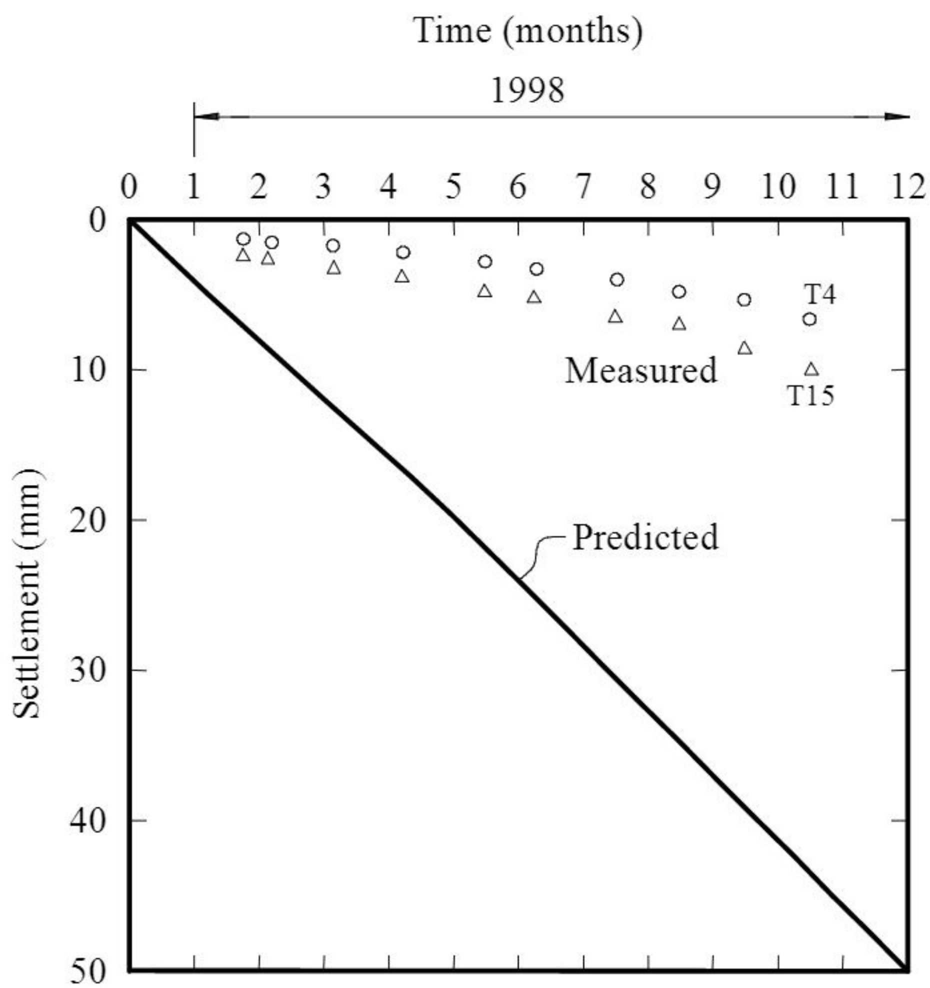



Predicted Max. Settlement = 138 mm

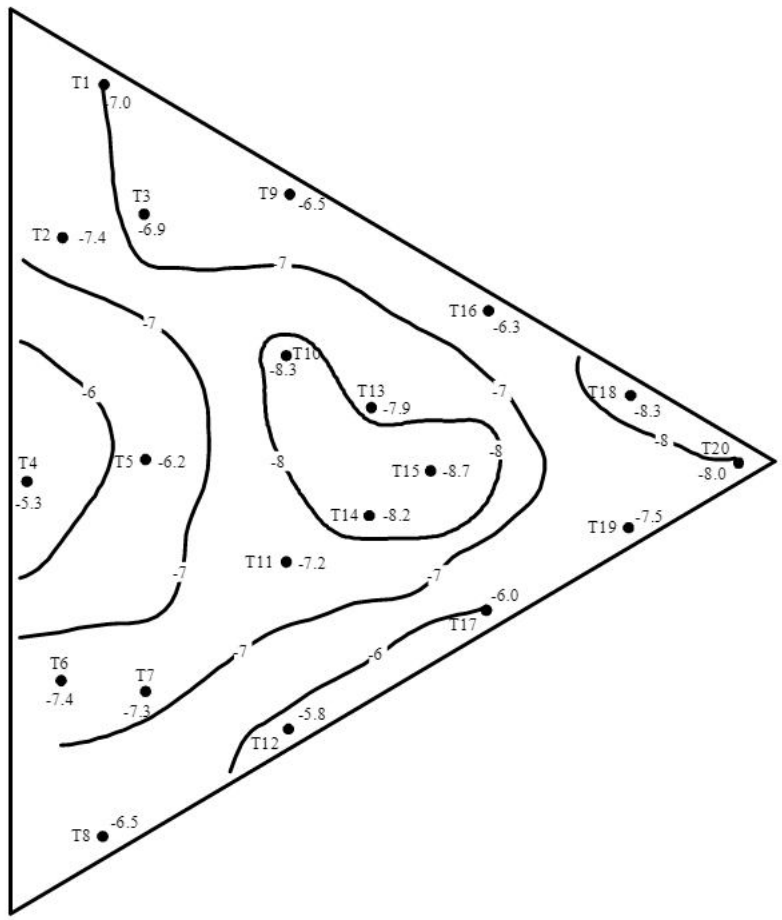
# MEASURED & PREDICTED TIME-SETTLEMENT BEHAVIOR – OFFICE TOWER



# MEASURED & PREDICTED TIME-SETTLEMENT BEHAVIOR – HOTEL TOWER

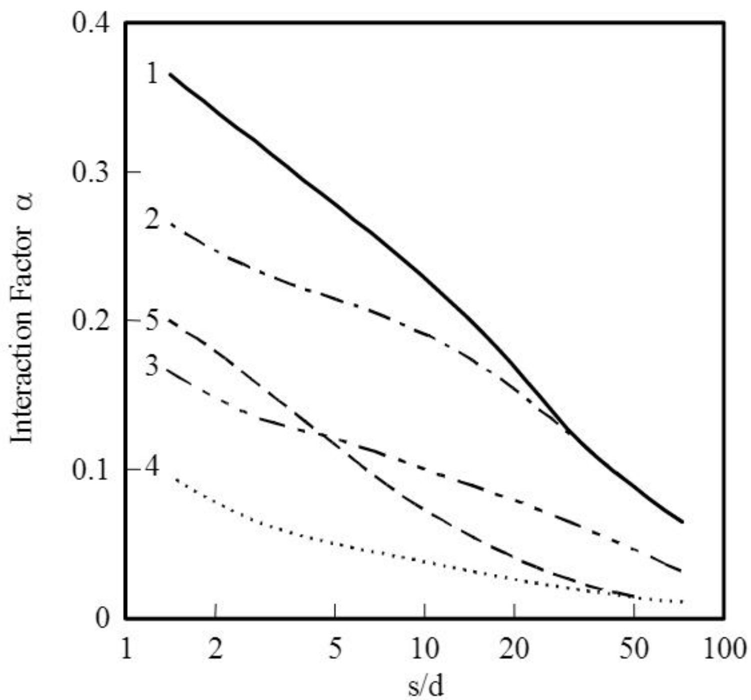


# MEASURED SETTLEMENT CONTOURS – HOTEL TOWER



# 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 |

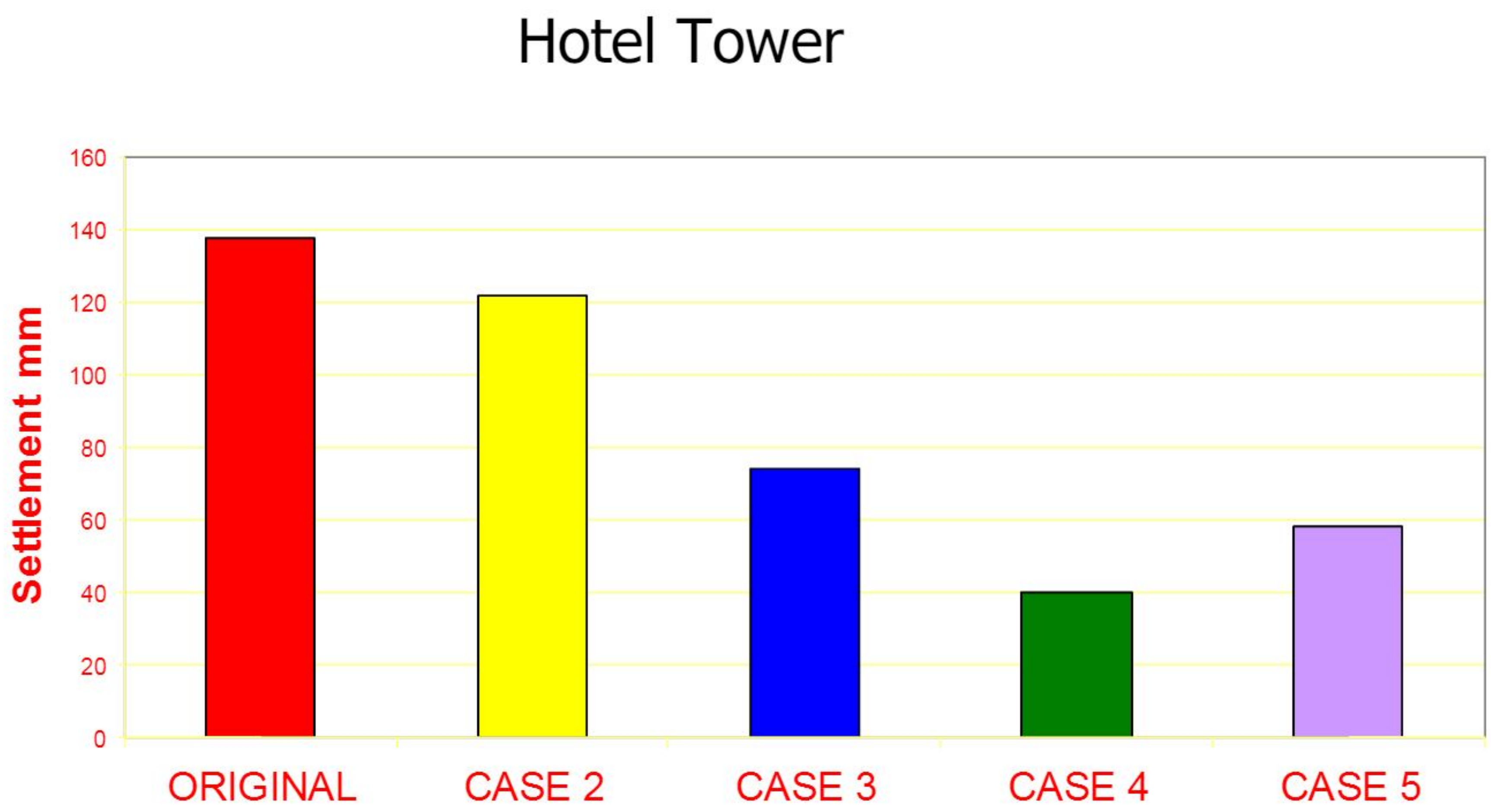



Allowances made for:
- Stiffer soil between piles
- Stiffer soil below pile tips

Interaction is generally reduced Markedly.

Assumptions have a MAJOR influence on computed interaction effects.

# EFFECT OF ANALYSIS ASSUMPTIONS ON COMPUTED SETTLEMENT



# LESSONS LEARNED

- Is critical to appreciate real aspects of behavior

- Potential problems in applying interaction factors to large groups without account of:
  - intervening piles
  - Stiffer soil between piles

- Inadequate ground model – uniform soil stiffness below pile tips

- Success in predicting test pile behavior does not guarantee success for overall foundation behavior

# Burj Khalifa, Dubai

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# Main Challenges

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- World's tallest building
- Foundation capacity for piles in carbonate soils/rocks
- Concerns re cyclic loading of piles
- High-rise to low-rise differential settlements

# Site Photograph – September 2003

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# Early Construction – July 2005

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# Geotechnical Peer Review - Scope

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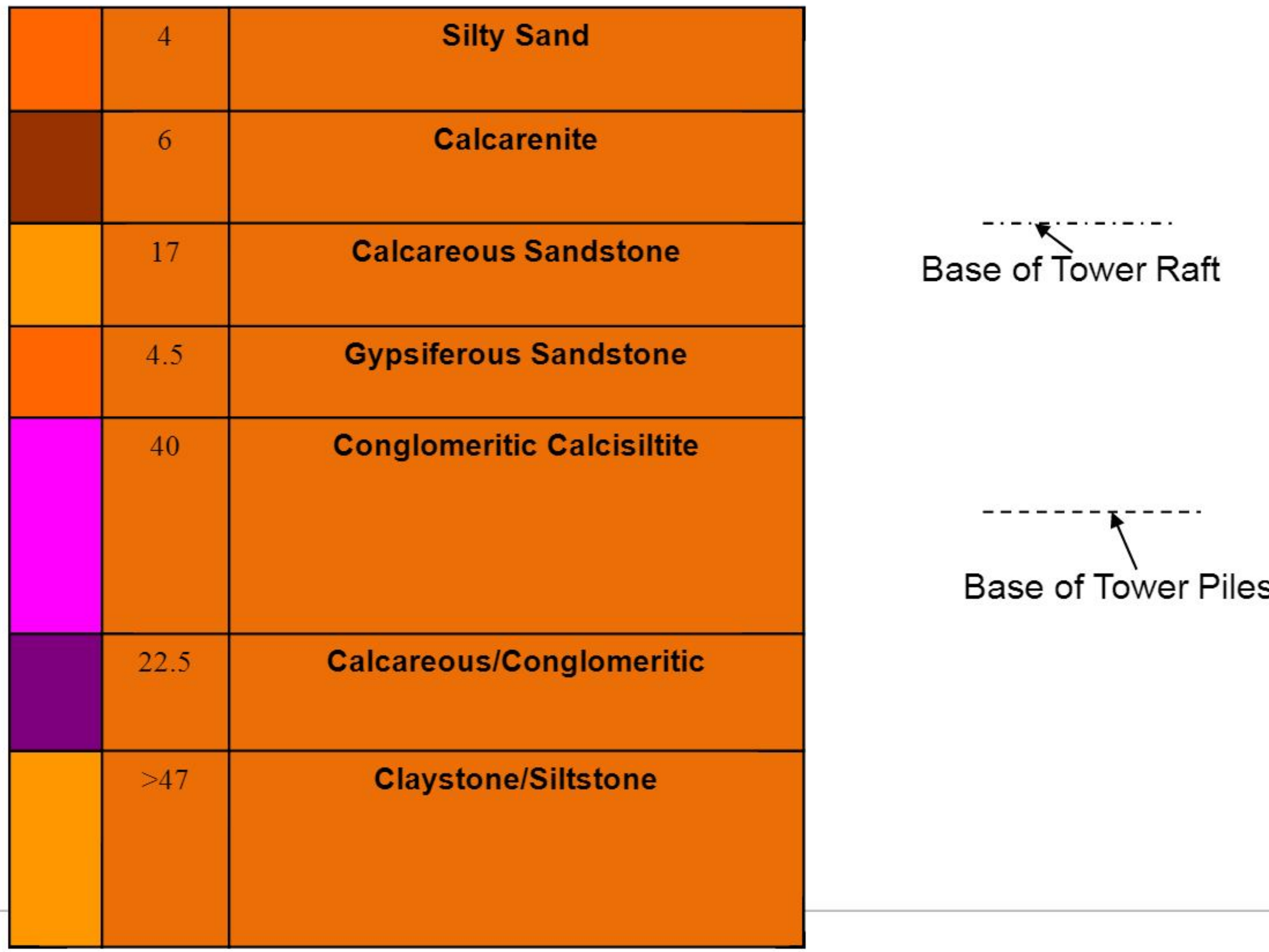
- Review geotechnical information
- Develop geotechnical model independently
- Independent review of Hyder foundation design
- Independent calculations for foundation stability, settlement, differential settlement
- Assessment of pile load test data and final design parameters.
- Close cooperation between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



# Typical Cores – 66m depth

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# 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 - Initial Tower Settlement Predictions

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

# Coffey – Initial Tower Settlement Estimates

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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

# Tower Pile Layout

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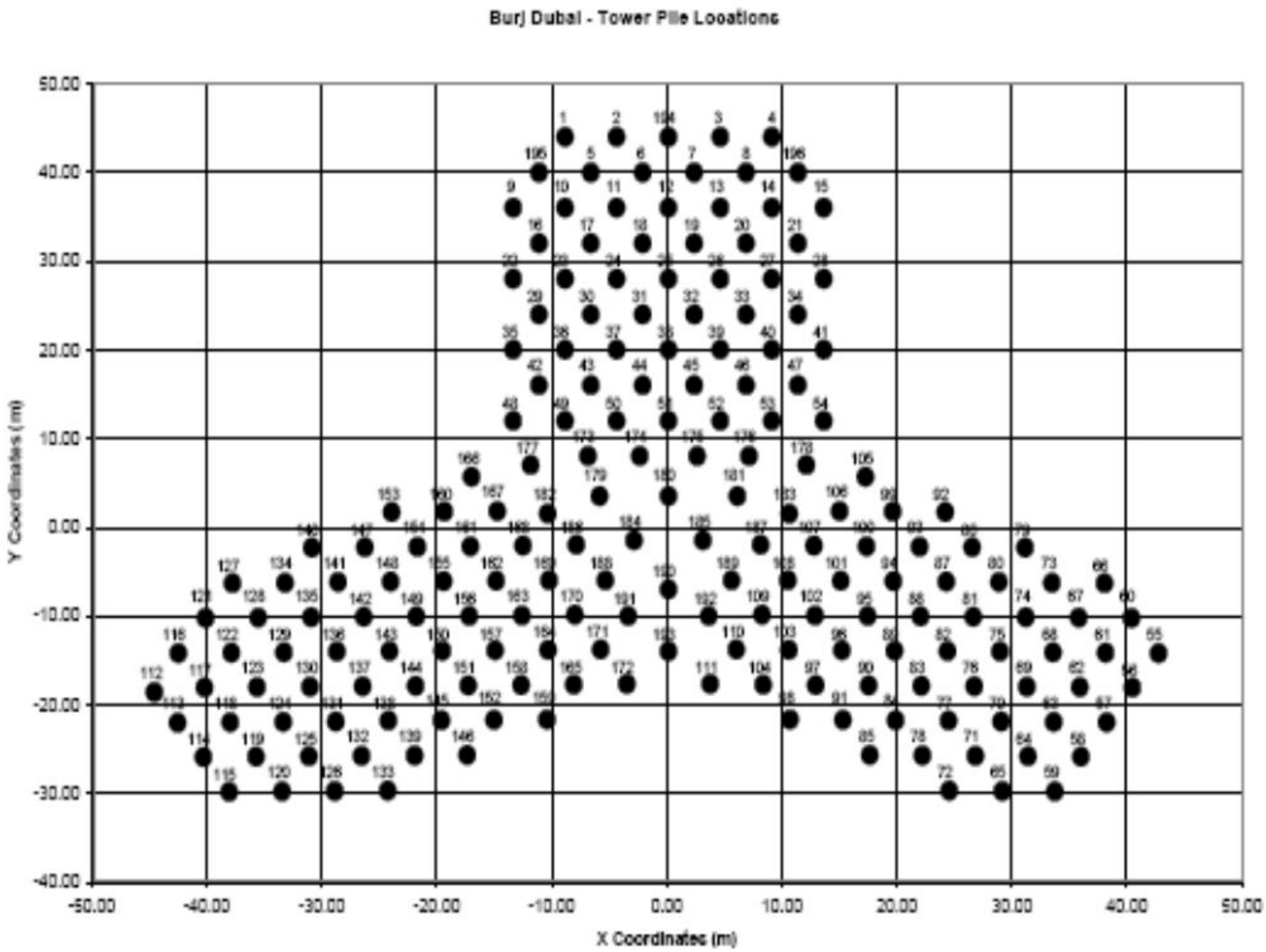
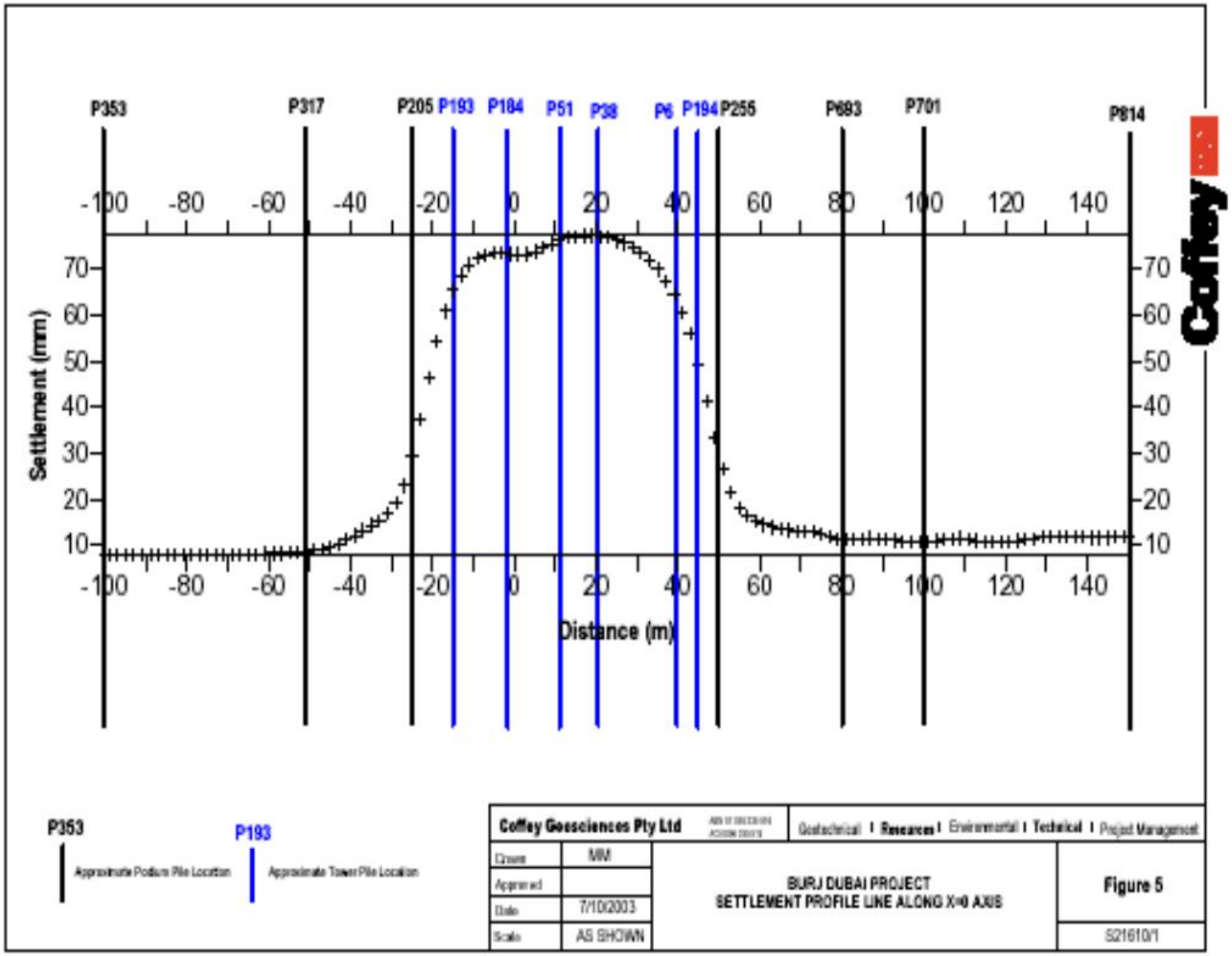
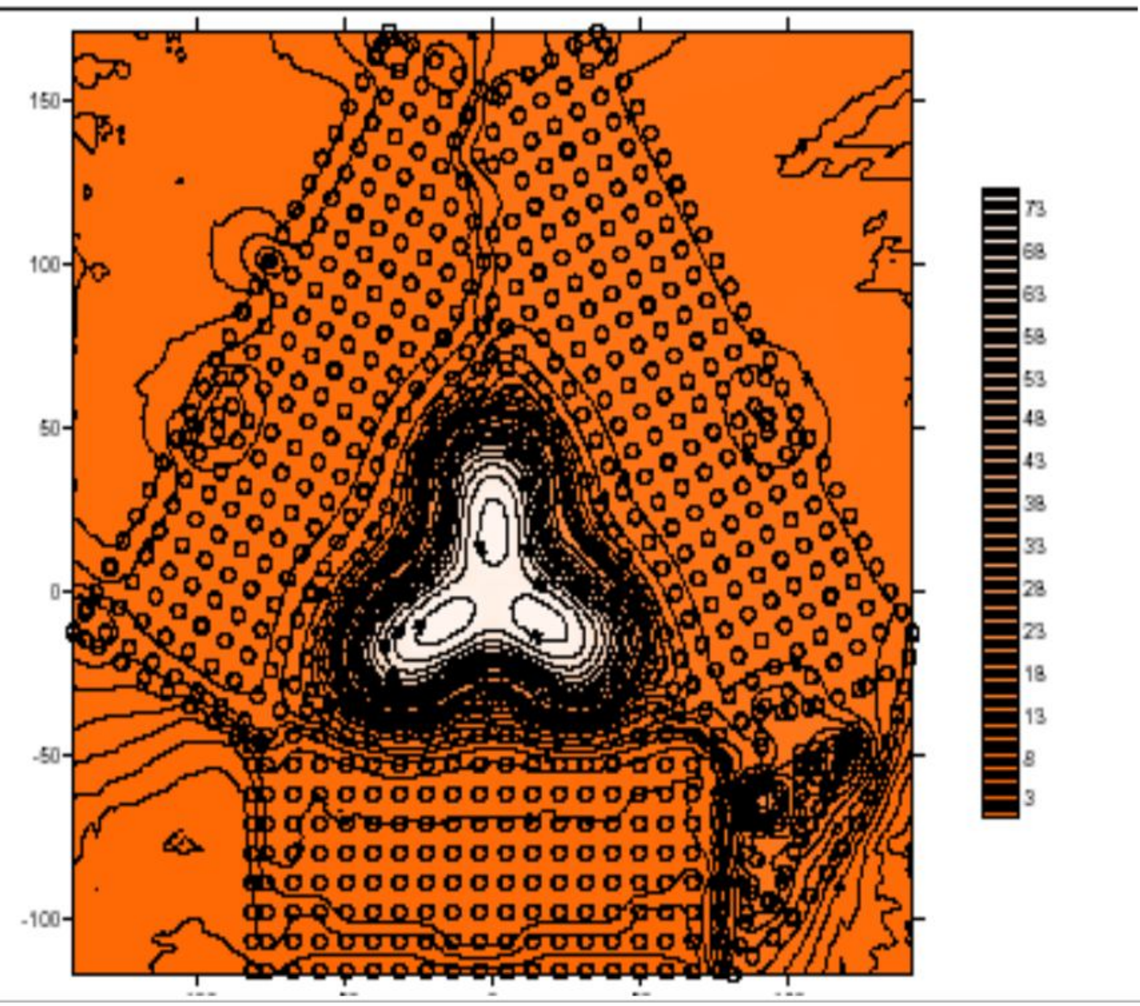


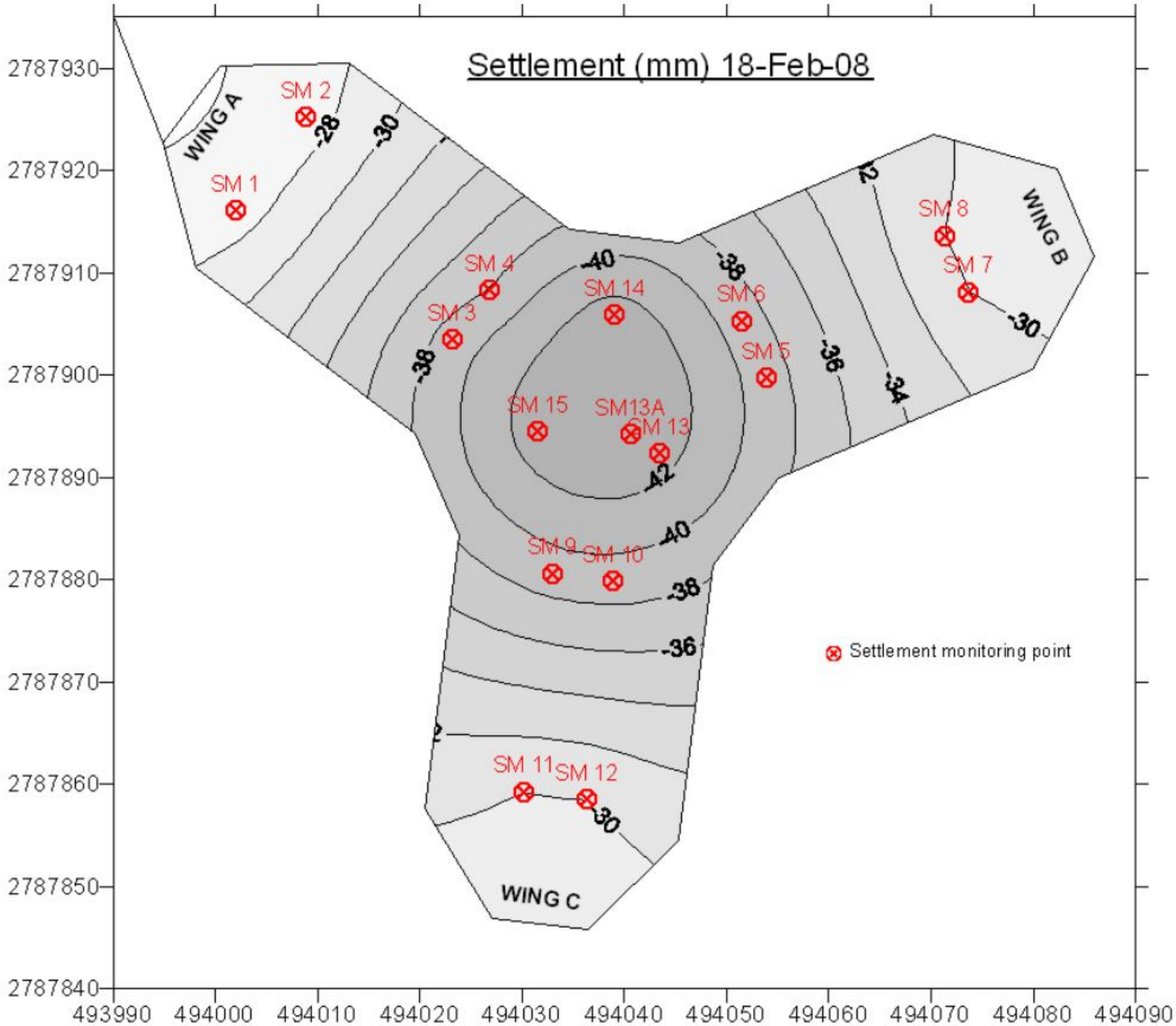
# Predicted Settlement Profile



# Predicted Settlement Contours – PIGS Analysis

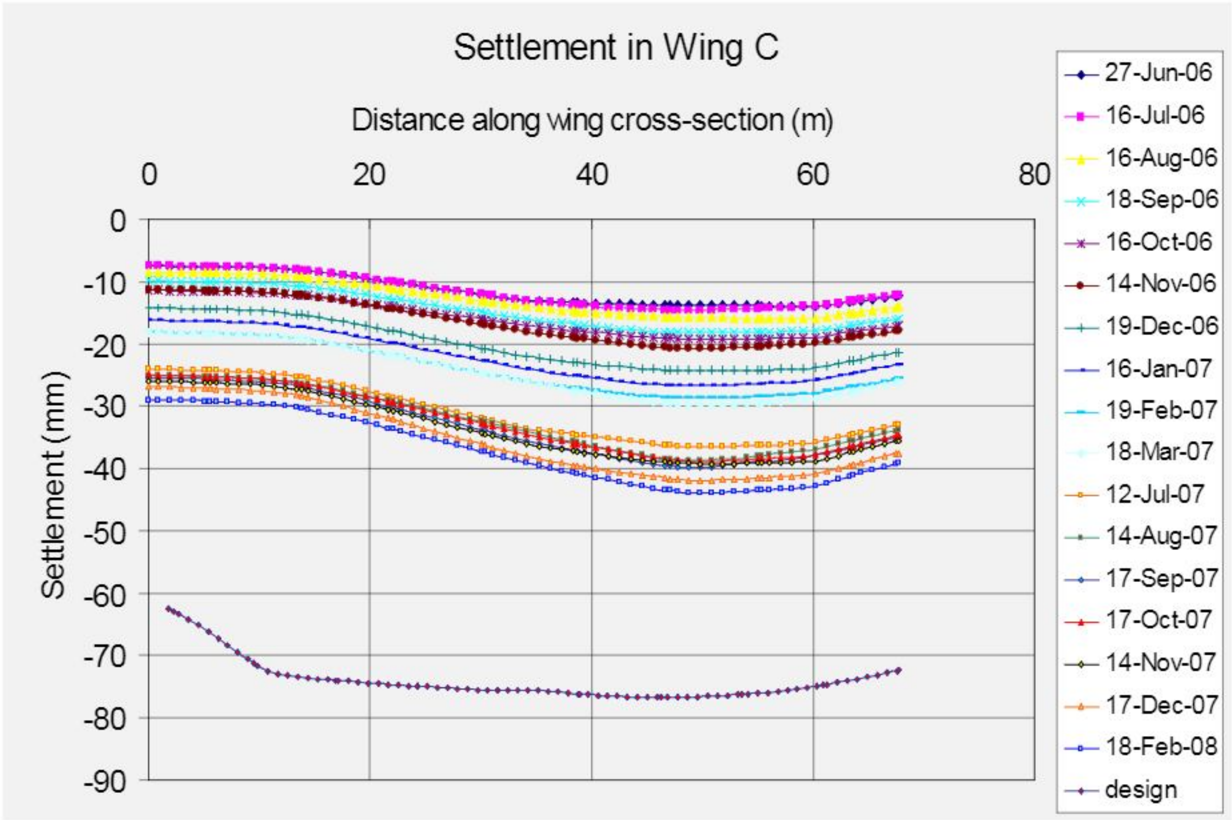


# Measured Settlement Contours – February 2008



# Measured Time-settlement – Wing C

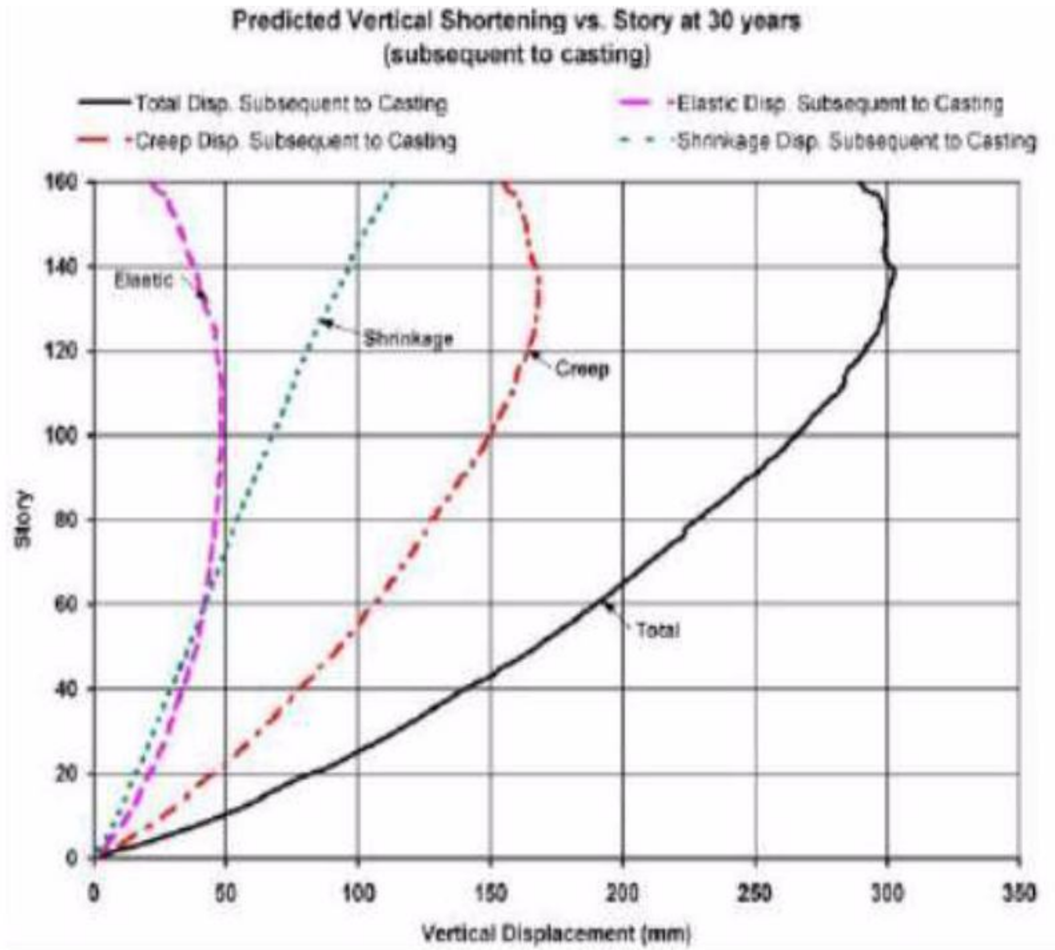
- Predicted approx 75-80mm
- To February 2008 43mm measured for 80% of dead load
- Estimated 50 to 55mm final settlement
- Within design tolerances
- Monitoring ongoing



# Comparison With Predictions

Maximum measured settlement towards the end of construction is about **45mm**

# Perspective – Structural Shortening Of Tower



# Burj Dubai – Re-named Burj Khalifa on 4th January 2010

Early 2008

December 2008


January 2010

# Lessons Learned

- Experience from previous case histories can be very valuable
- Be aware of how investigation drilling was done – do not accept core that is not consistent with the geology
- Pile testing is essential, for both design verification and quality assurance
- Simple analysis methods should be used to verify complex design analyses

# Incheon 151 Tower, South Korea

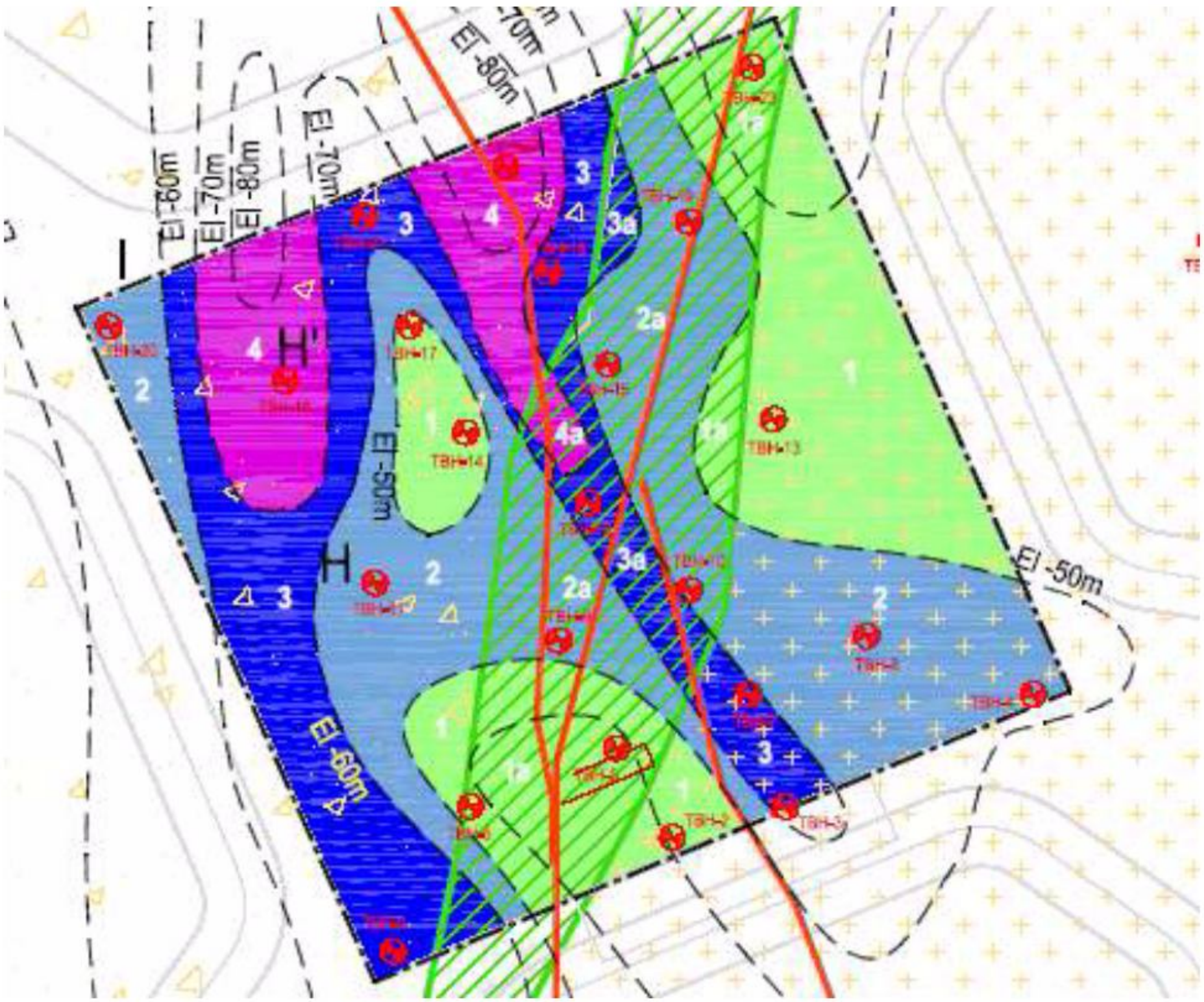
Incheon Tower

# Key Challenges

- Reclaimed land
- Complex geology
- 600m tall building
- Limited tolerance to differential settlements

# Site Conditions

# Geotechnical Conditions




Contours of depth to bedrock

**8** separate soil profiles modeled within building footprint

# Typical Geotechnical Model

| Strata | $E_v$ (MPa) | $E_h$ (MPa) | $f_s$ (kPa) | $f_b$ (MPa) |
|---|---|---|---|---|
| UMD | 7 - 15 | 5 -11 | 29 - 48 | - |
| LMD | 30 | 21 | 50 | - |
| Weathered Soil | 60 | 42 | 75 | - |
| Weathered Rock | 200 | 140 | 500 | - |
| Soft Rock (above EL-50m) | 300 | 210 | 750 | 12 |
| Soft Rock (below EL-50m) | 1700 | 1190 | 750 | 12 |

$E_v$ = Vertical Modulus

$E_h$ = Horizontal Modulus

$f_s$ = Ultimate shaft friction

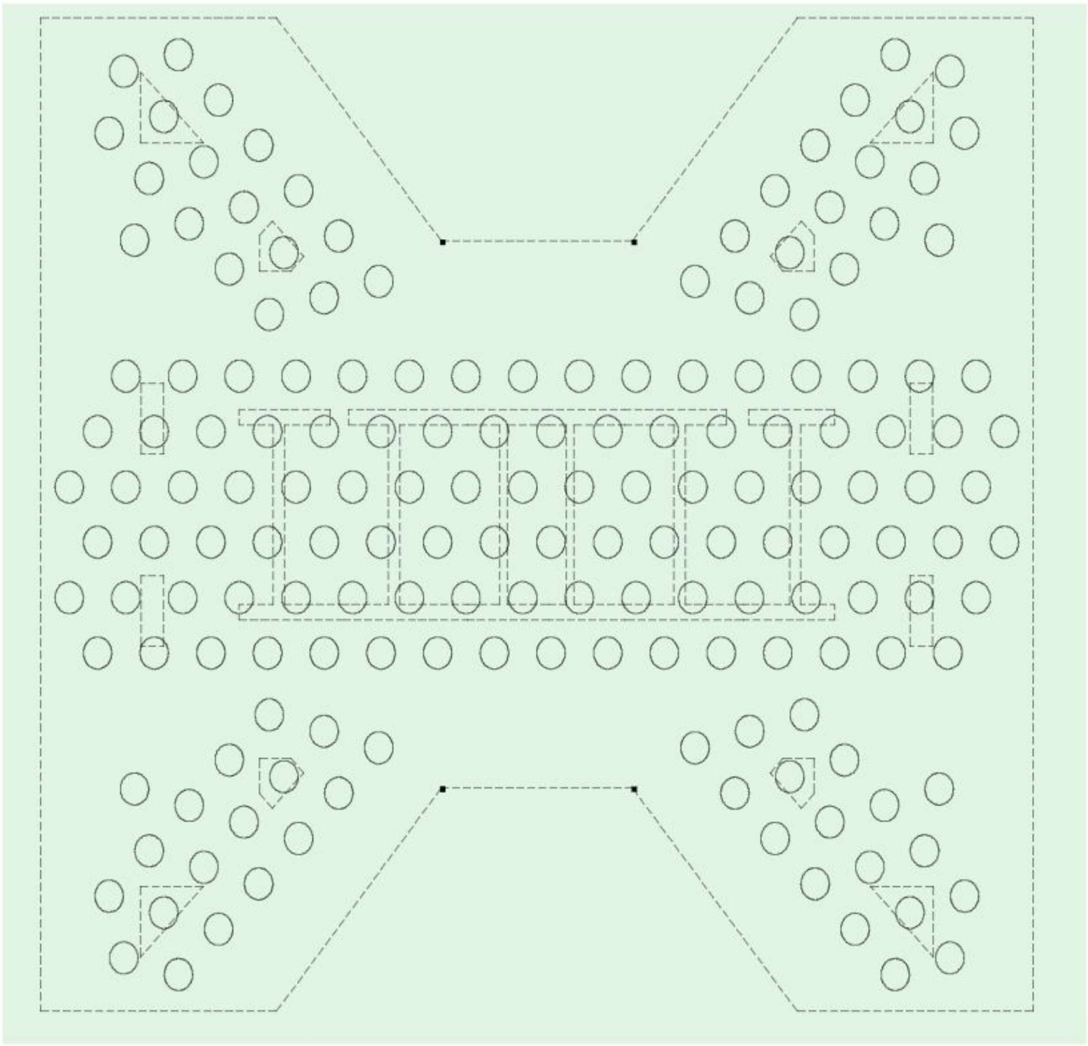
$f_b$ = Ultimate end bearing

# Typical Core

# Foundation System

- Piles: 172
- Pile size : 2.5m dia.
- Founded minimum 2 pile diameters into soft rock or below EL-50m
- Mat Thickness : 5.5m

# Foundation Layout



# Overall Stability Analysis

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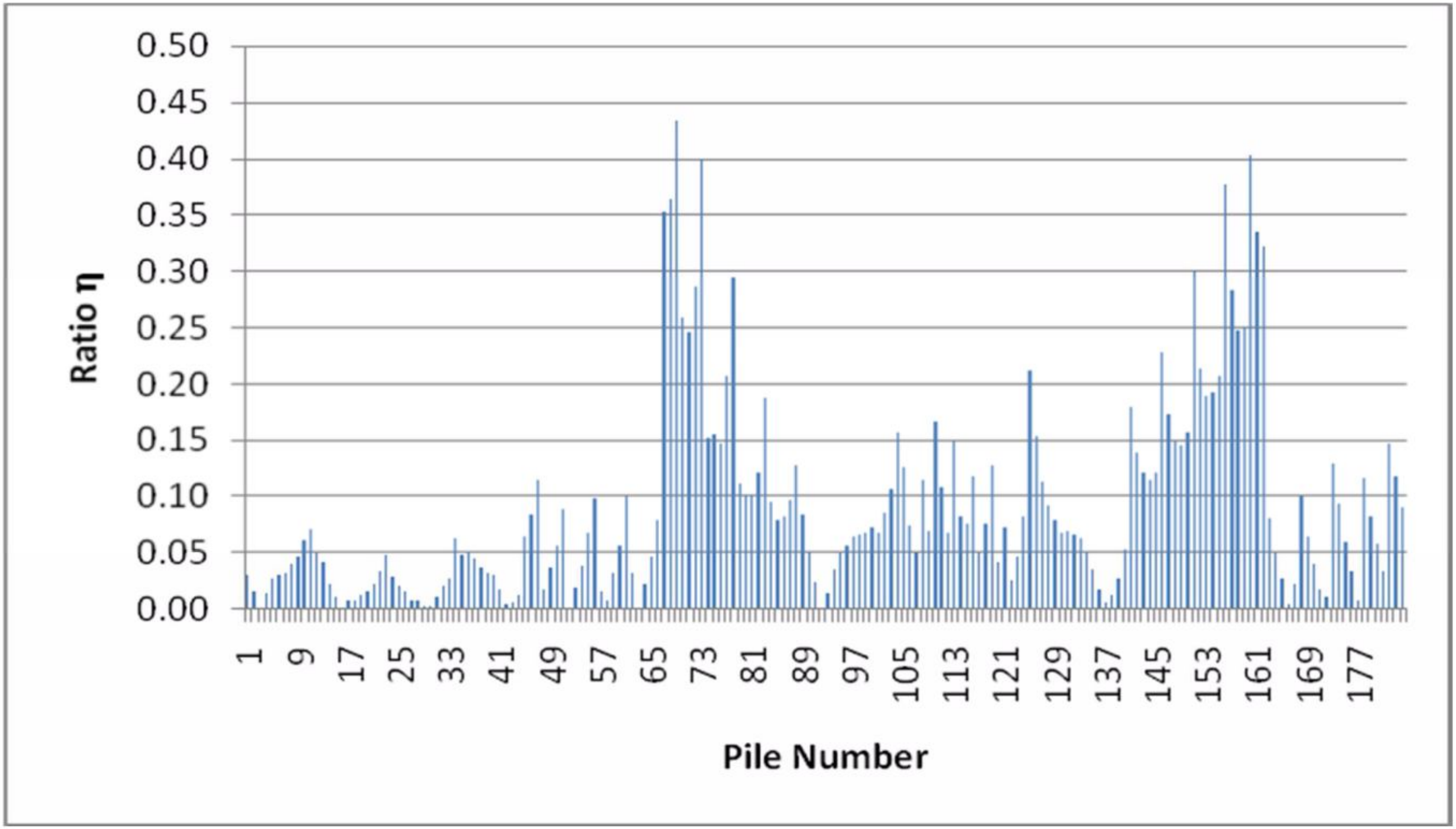
•Geotechnical reduction factors (0.65 for axial load, 0.40 for lateral load).

•The smaller factors for lateral load reflected the greater degree of
uncertainty for lateral response.

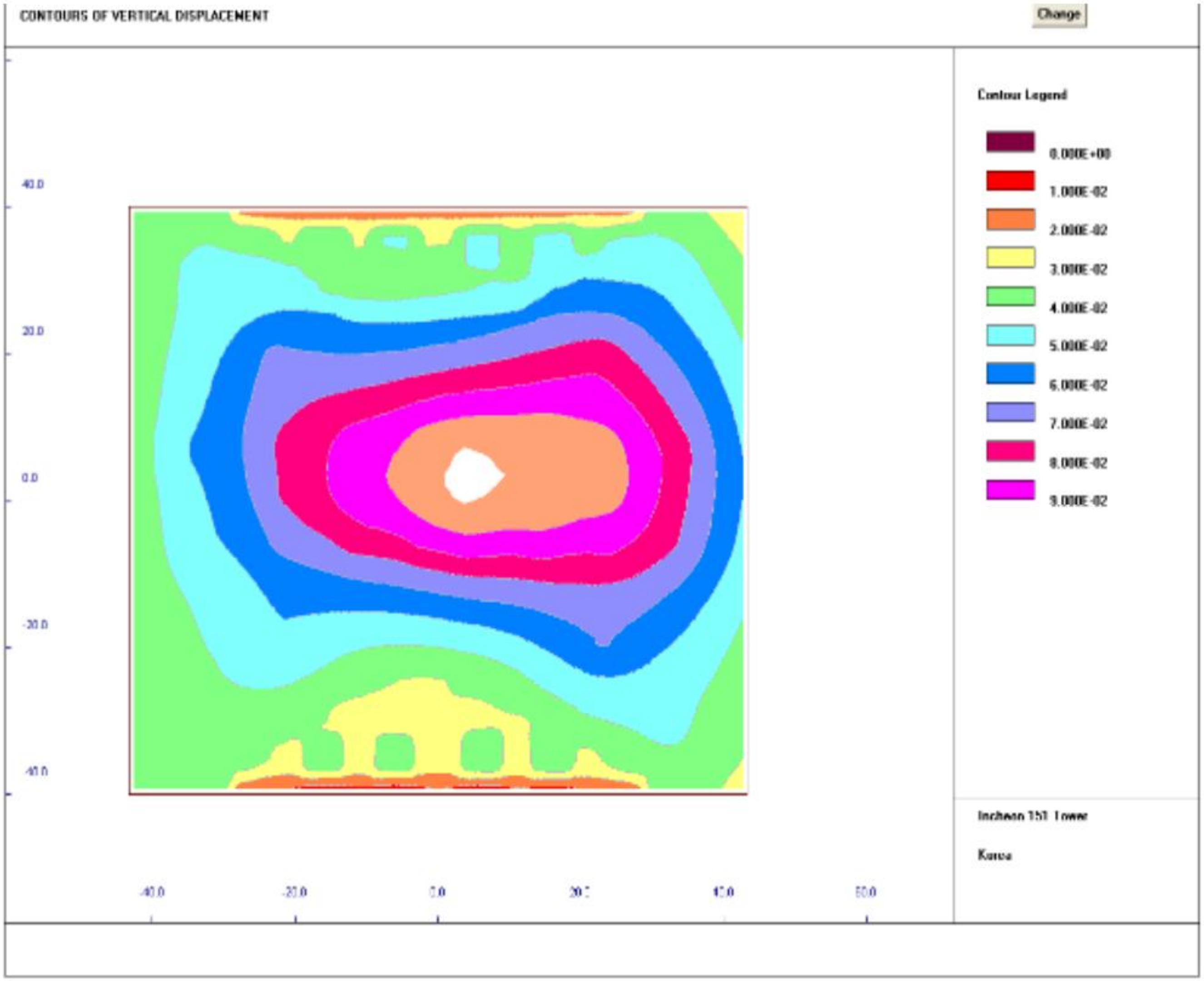
•Maximum computed settlement under the ULS loadings <100mm

•In all cases, the foundation system was found to be stable,
i.e. the computed foundation movements were finite.

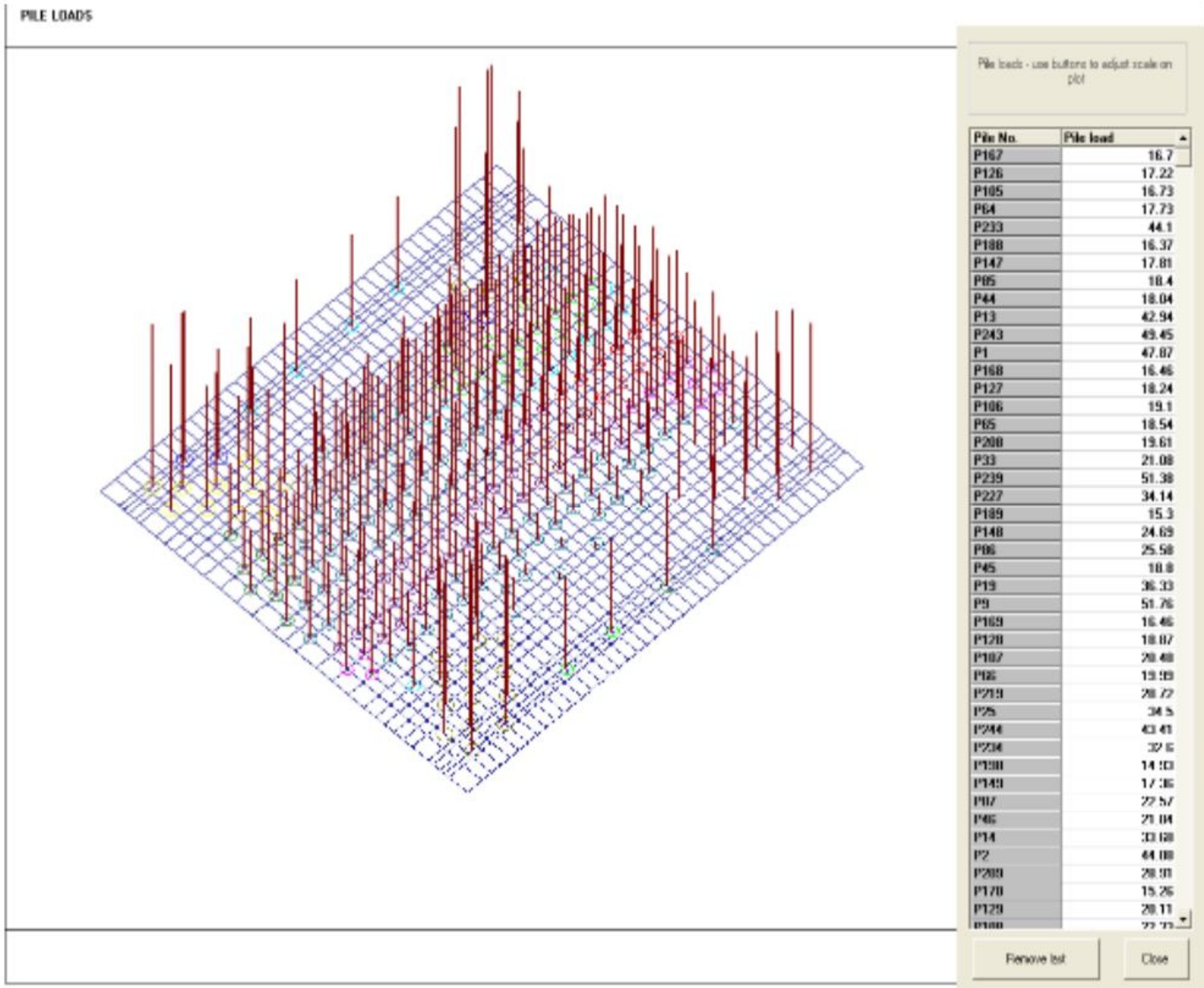
# ULS Cyclic Loading Analysis



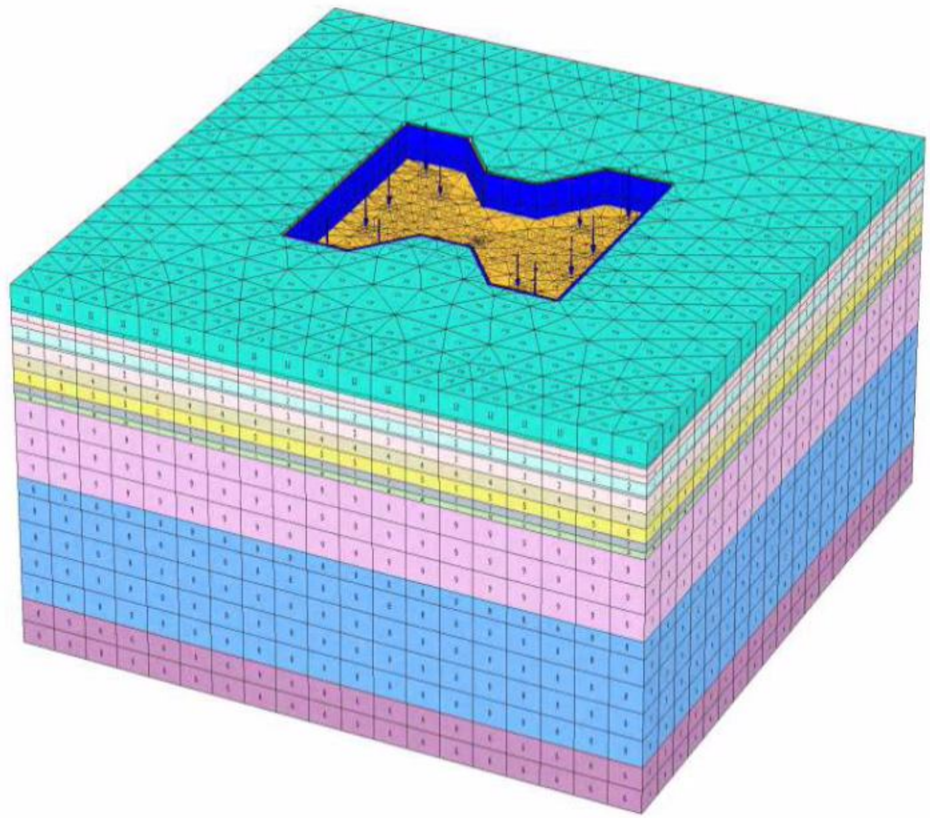
# Serviceability Analysis– Settlement Contours



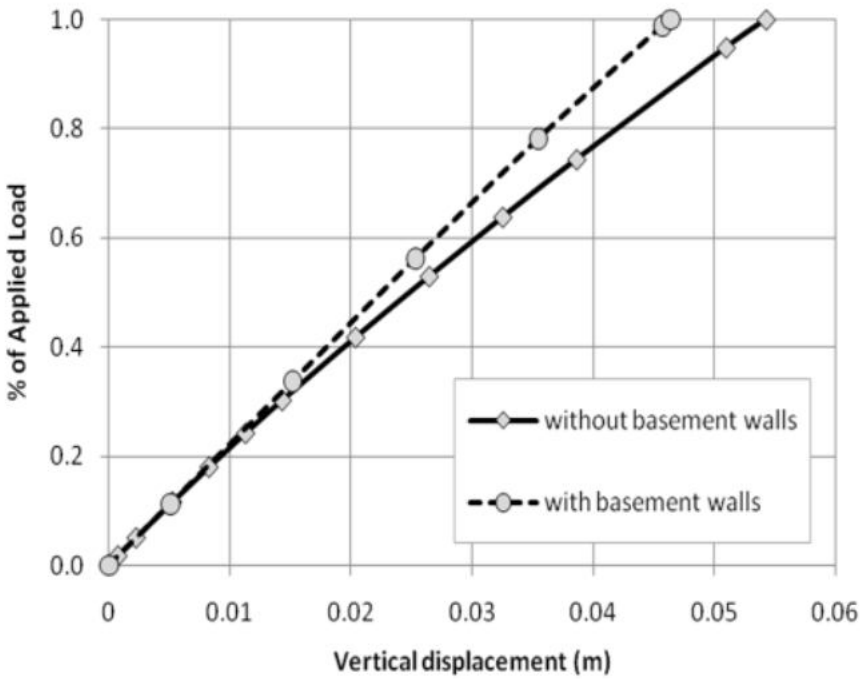
# Serviceability Analysis: Computed Pile Loads

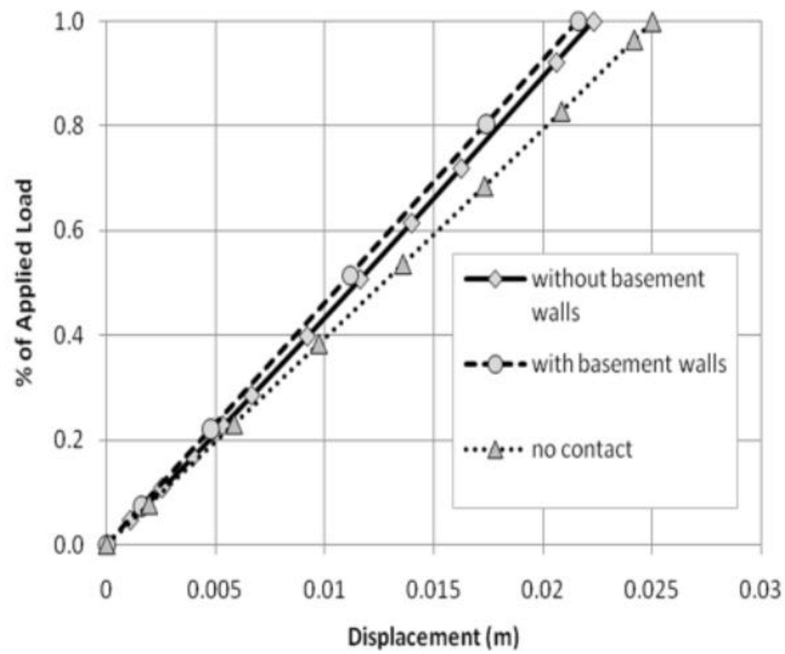


# Final Design Check – 3D FE Analysis



# Final Design Check - Effect of Basement Walls

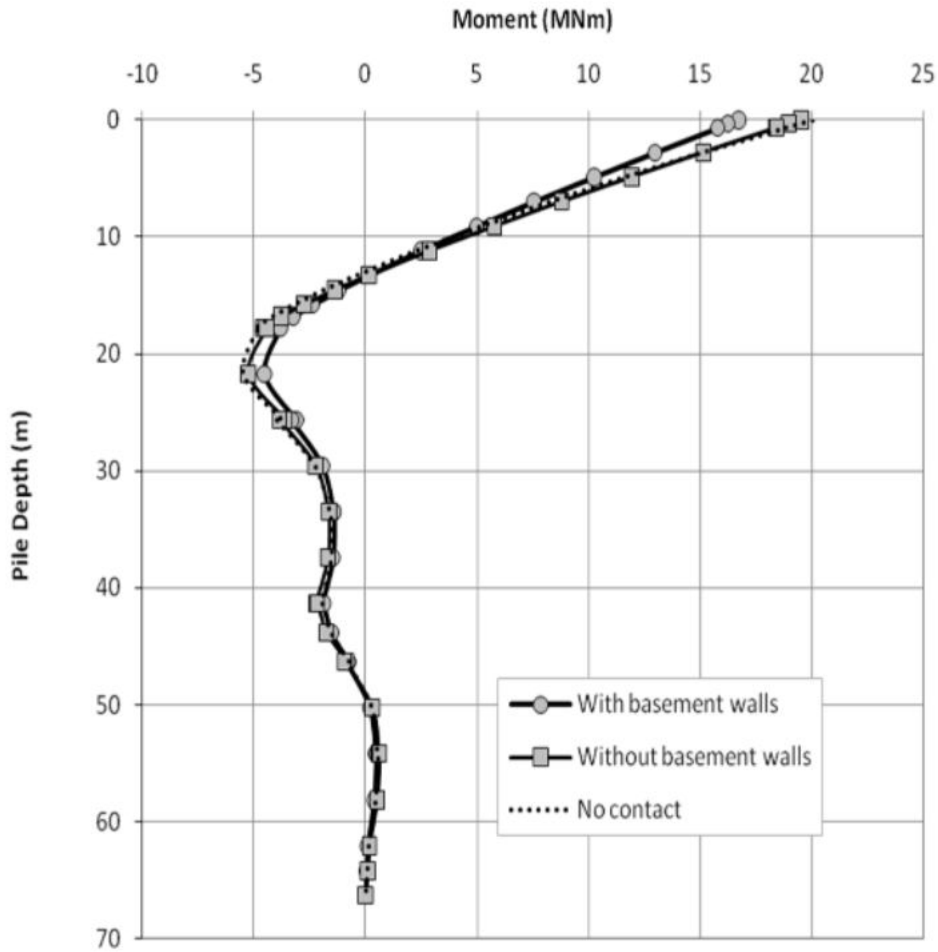



Load - Settlement

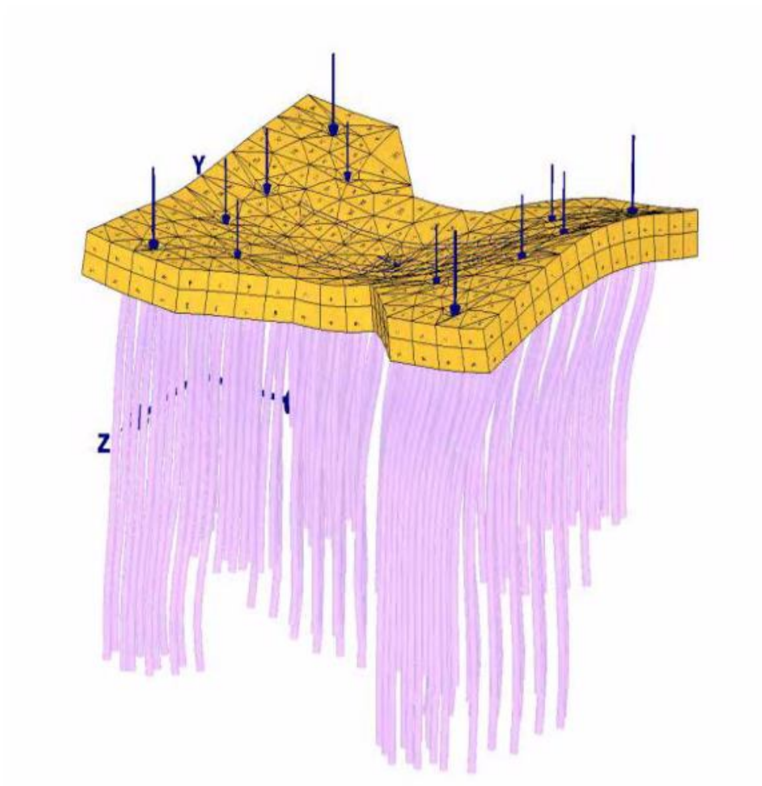
Lateral Load - Deflection

# Final Design Check- Effect of Basement Walls

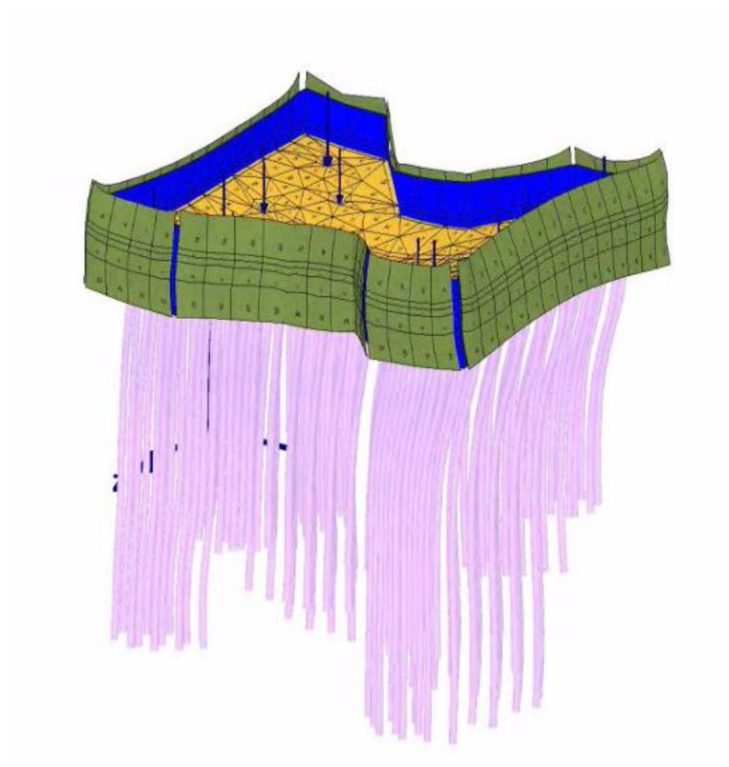



Bending Moments Along Typical Leading Pile

# Final Design Check– Visualization




No basement contact



With basement contact

# Comparison of Computed Settlements

- Preliminary (equivalent pier):
  - **75mm (average)**
- Detailed Design (GARP):
  - **67mm (maximum)**
- Final Design Check (PLAXIS 3D):
  - **56mm (maximum)**

# PILE LOAD TEST PROGRAM

- 4 axial pile tests – O-Cell procedure
- 3 were successful – results indicated that design values of shaft friction, end bearing & stiffness could be increased
- 1 pile (TP03) indicated problems via as-built records.
- Further investigation carried out on TP03

# O-Cell Testing

# Pile Load Test Results

**Table 7. Assessed Average Performance of Three Test Piles**

| Location | Parameter | Ultimate Design Value | Average Mobilized & Range |
|---|---|---|---|
| Soft Rock | End Bearing (MPa) | 12.0 | 24.3 (18.9-37.6) |
| | Shaft Friction (kPa) | 750 | 1534 (1326-1994) |
| Weathered Rock | Shaft Friction (kPa) | 500 | 708 (356-1054) |

- Design parameters are conservative
- Scope exists for foundation economy (if project resumes)

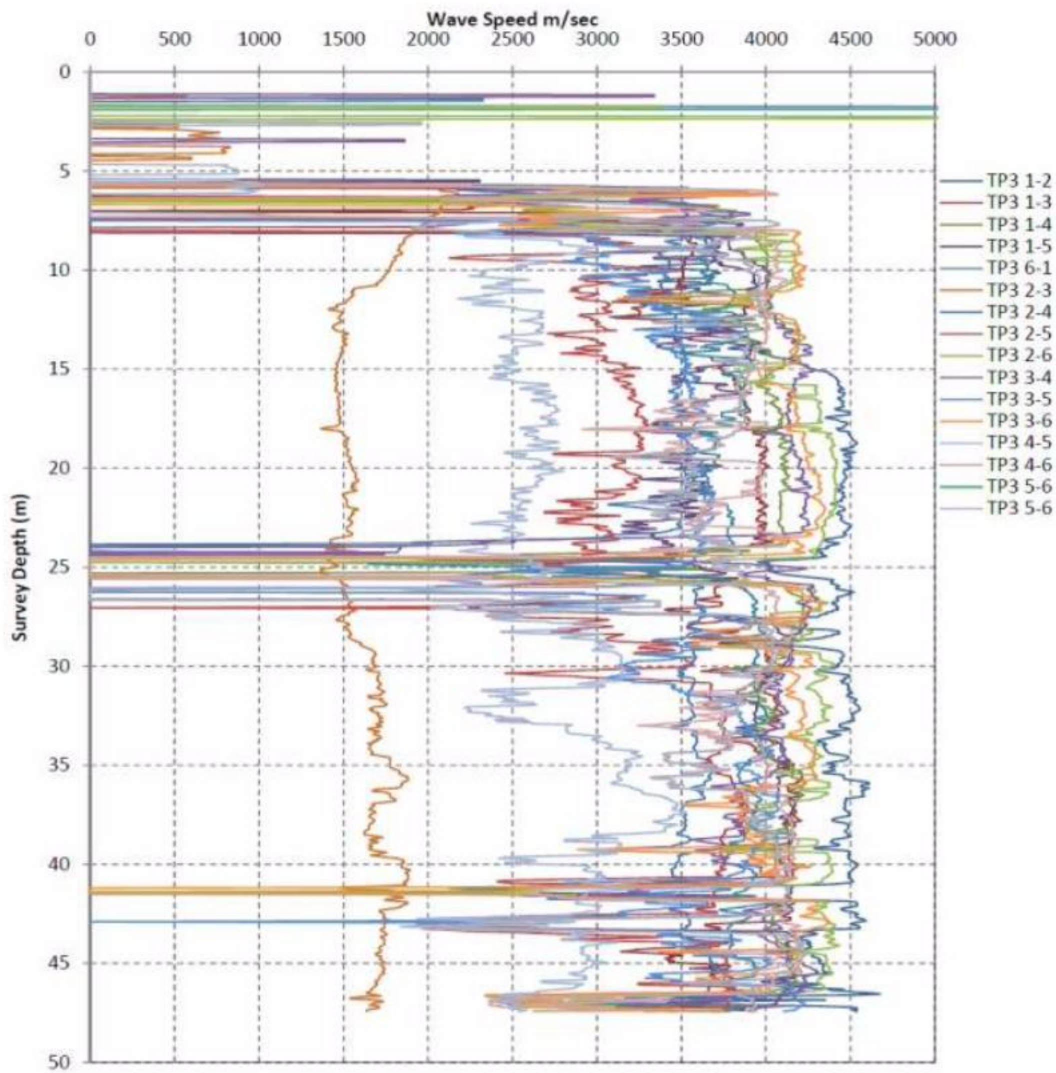
# AS-BUILT ASSESSMENT OF TP03 - Methods

- Koden survey of pile profile
- Pile concreting summary
- Sonic logging survey

# AS-BUILT ASSESSMENT OF TP03 - Findings

- Nominal pile diameter = 2.35m
- Nominal length = 47m
- Pile diameter variation from 2.5 to 3.2m
- Pile profile inflection at 37m from near-vertical to 1(H) to 10 (V)
- Socket profile overbreak with wavelength variation of 0.4m over ≈ 4m lengths
- Nominal concrete volume = 204m$^3$
- Actual concrete volume = 282m$^3$ **(38% more)**

# AS-BUILT ASSESSMENT OF TP03 – Sonic Logging Survey



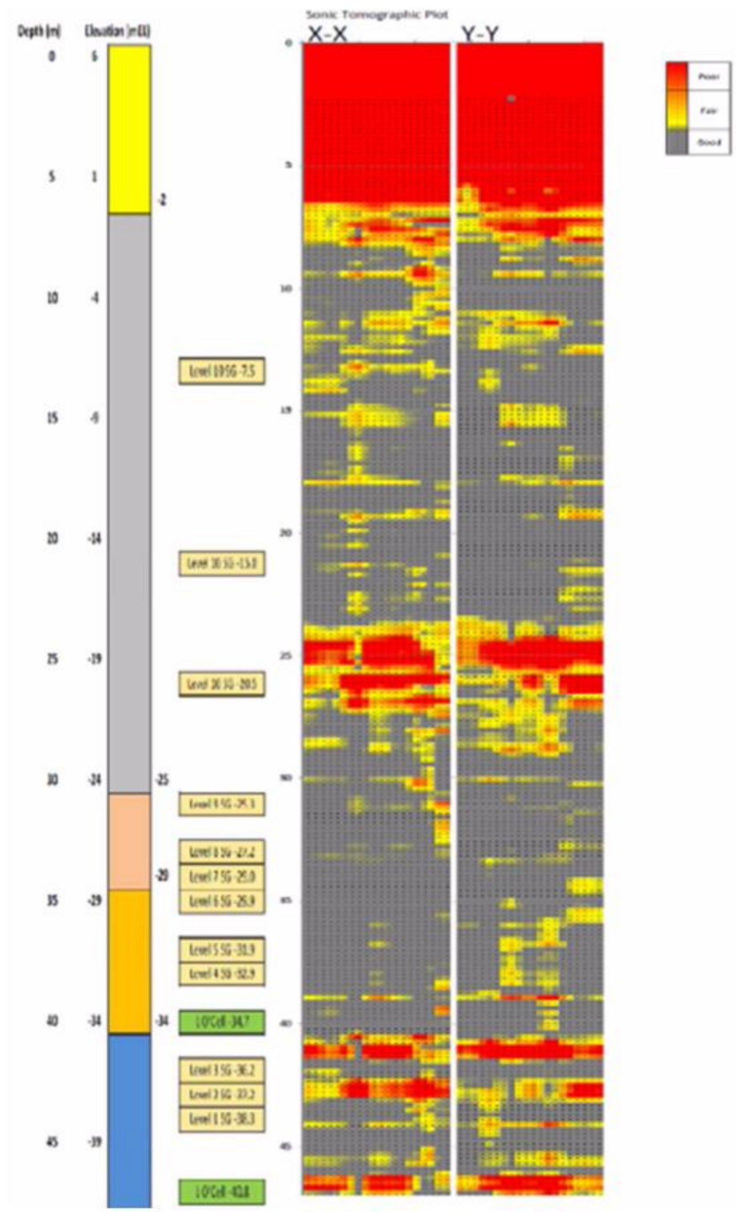

Testing 6 days after pouring

Variability in wave velocity

“Artefacts” in records
– irregular pipe spacing
- Poor pipe verticality
- Possible de-bonding

Iterative process to provide tomographic images

# AS-BUILT ASSESSMENT OF TP03 – Sonic Logging Survey




Red – poor quality concrete
Yellow – fair
Grey - good

# EFFECTS ON CONCRETE NON-HOMOGENEITY

PLAXIS analysis.

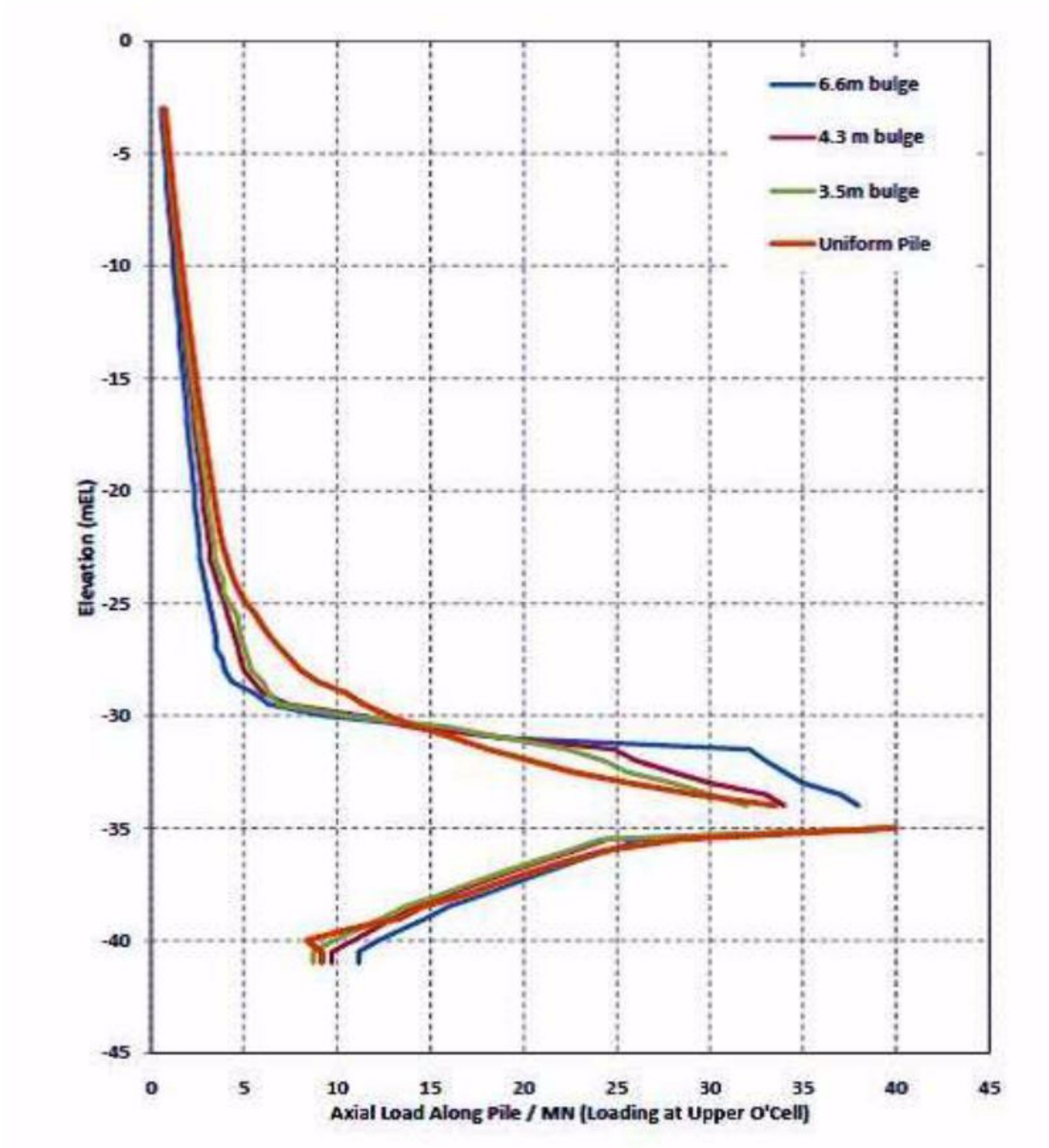
Parameters investigated:

- Effect of pile shape on strain measurements
  - Various overbreak diameters
- Effect of concrete quality

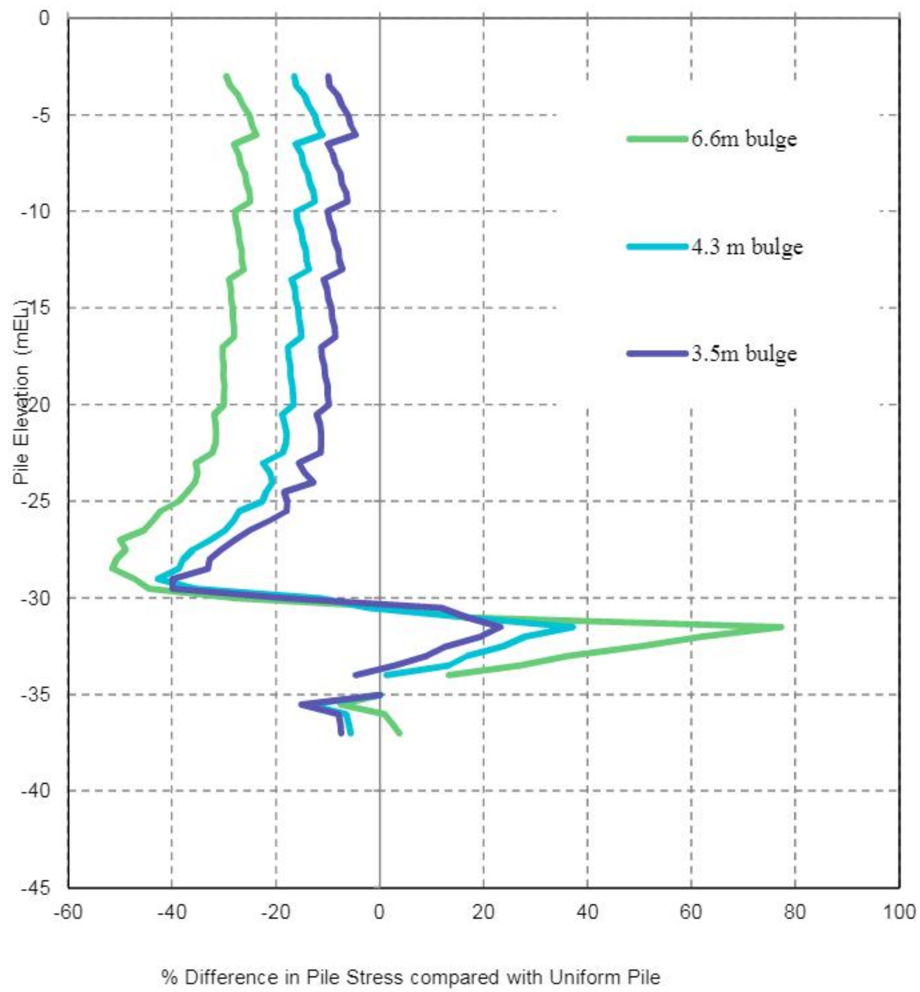
# EFFECTS ON CONCRETE NON-HOMOGENEITY

- Deduced stresses in pile depend on:
  - Pile area – affected by overbreak
  - Pile modulus – affected by poor quality concrete
- Deduced load distribution will therefore also be affected

# EFFECTS ON CONCRETE NON-HOMOGENEITY - Load Distribution



# EFFECTS ON CONCRETE NON-HOMOGENEITY
## Axial stress in pile – difference from uniform pile



# Lessons Learned

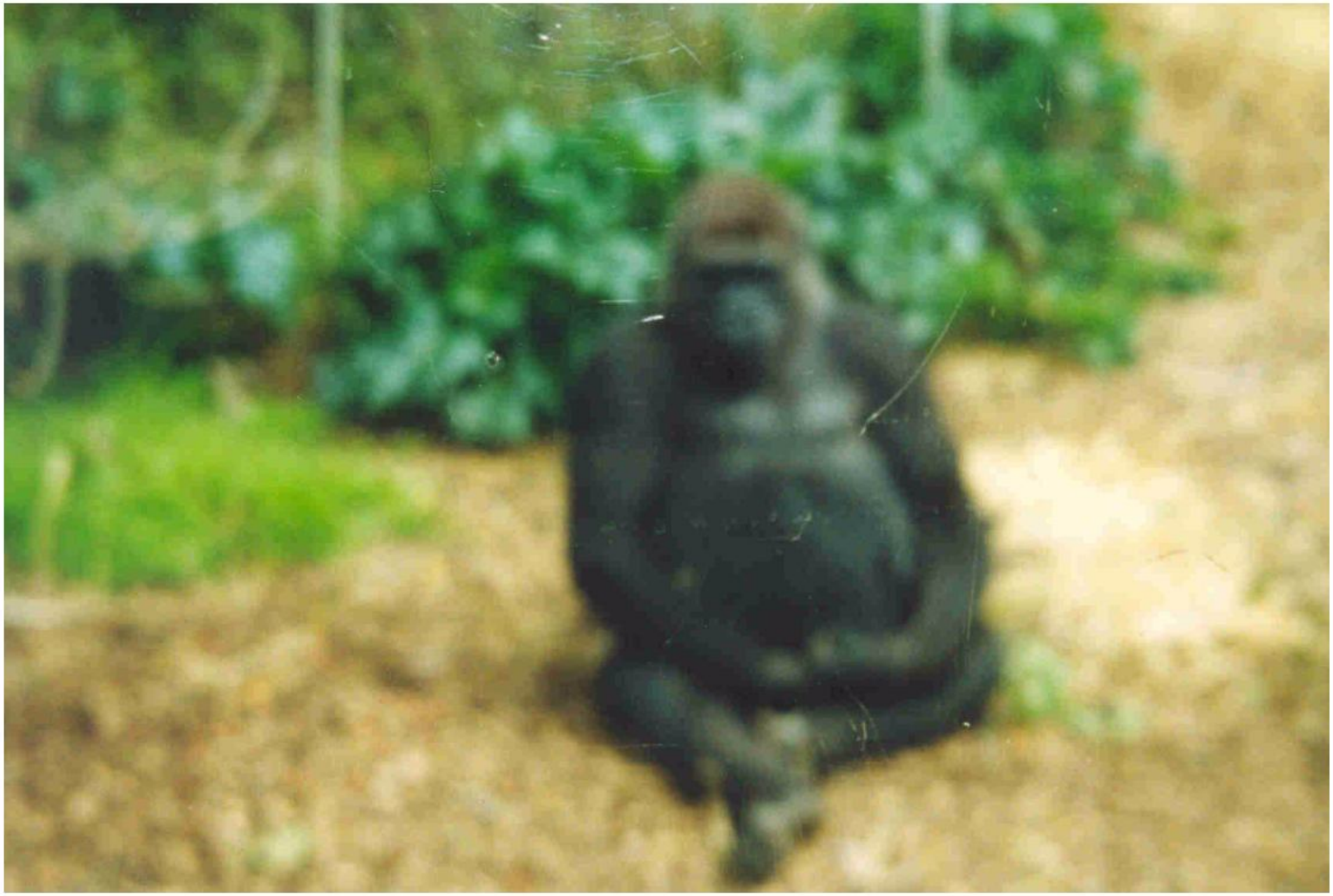
- Understanding site geology can be critical
- Involve competent engineering geologist in ground characterization
- Simple design calculations are valuable
- Pile load testing is essential to assess both performance & construction quality
- Sonic tomography can reveal variations in concrete quality
- Test interpretation for load & stress distribution is affected by both diameter variation & quality variation

# A KEY QUESTION

MUST WE HAVE NEW / MODERN TECHNOLOGY FOR SUCCESS?

# APPLICATION OF OLD TECHNOLOGY – Boissonas (1904)

# APPLICATION OF NEW TECHNOLOGY – Poulos (2004)



# Lesson Learned

- New technology is potentially valuable, BUT:
- It must be used correctly!

# Summary of Lessons Learned

- Proper ground investigation is essential (All cases)
- Engineering geology input can be critical (Incheon)
- Proper ground characterization is at least as important as advanced numerical analyses (Emirates)
- Soil-structure interaction issues must be considered (All cases)
- Always check computer analyses with simpler methods (All cases)
- Pile testing is essential (all cases)
- Learn from previous experiences (Burj Khalifa)

# CONCLUSIONS

- Lessons continue to be learned from case histories
- Much more is learned from failures than successes – we have to answer "why?"
- Cooperation between geotechnical and structural designers is essential
- With benefit of experience and performance measurements, our predictive capabilities are improving