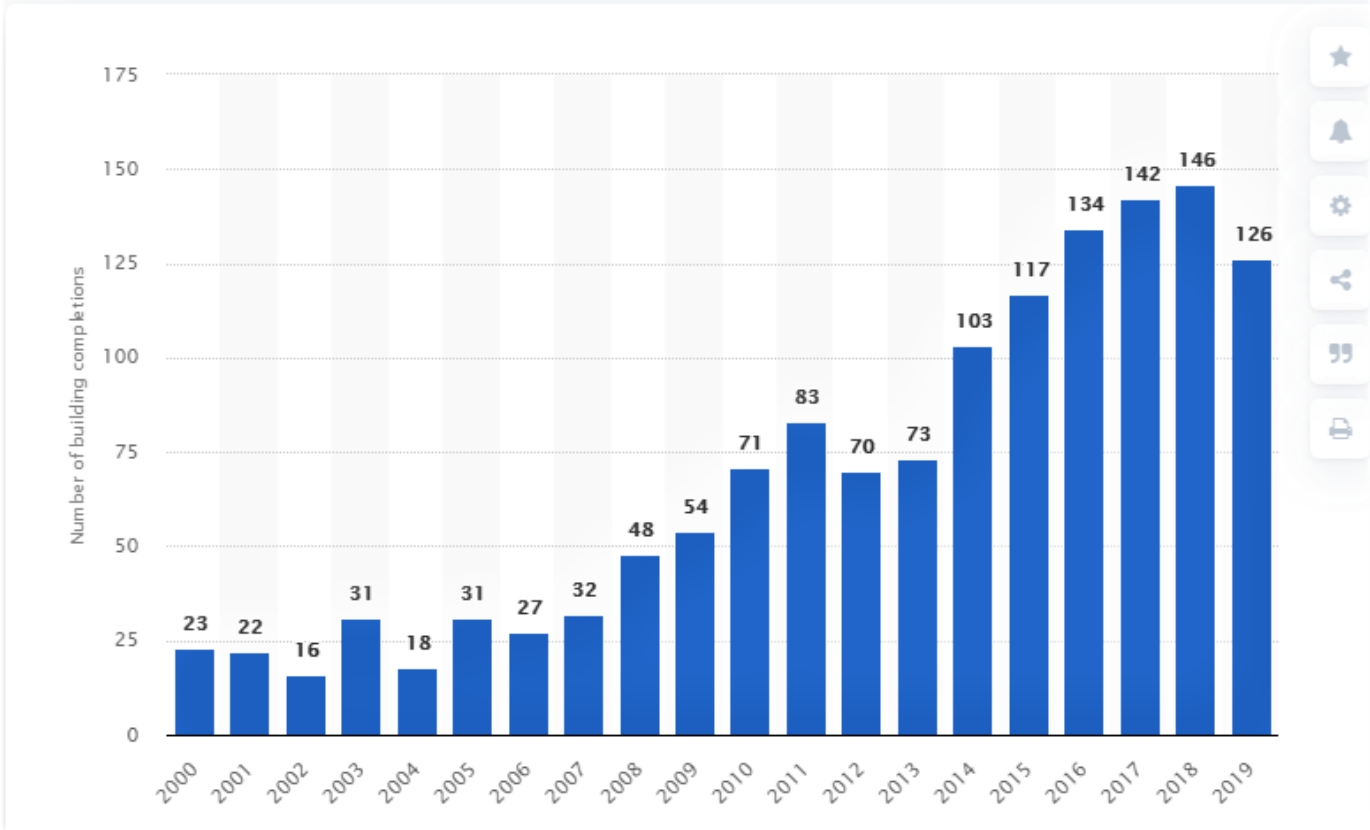
OUTLINE

- A design process for high-rise building foundations
- Risks associated with tall building foundations
- Potential problems and solutions
- Examples
  - Burj Khalifa
  - Dubai Creek Tower
  - Millennium Tower

Number of tall buildings completed from 2000 to 2019



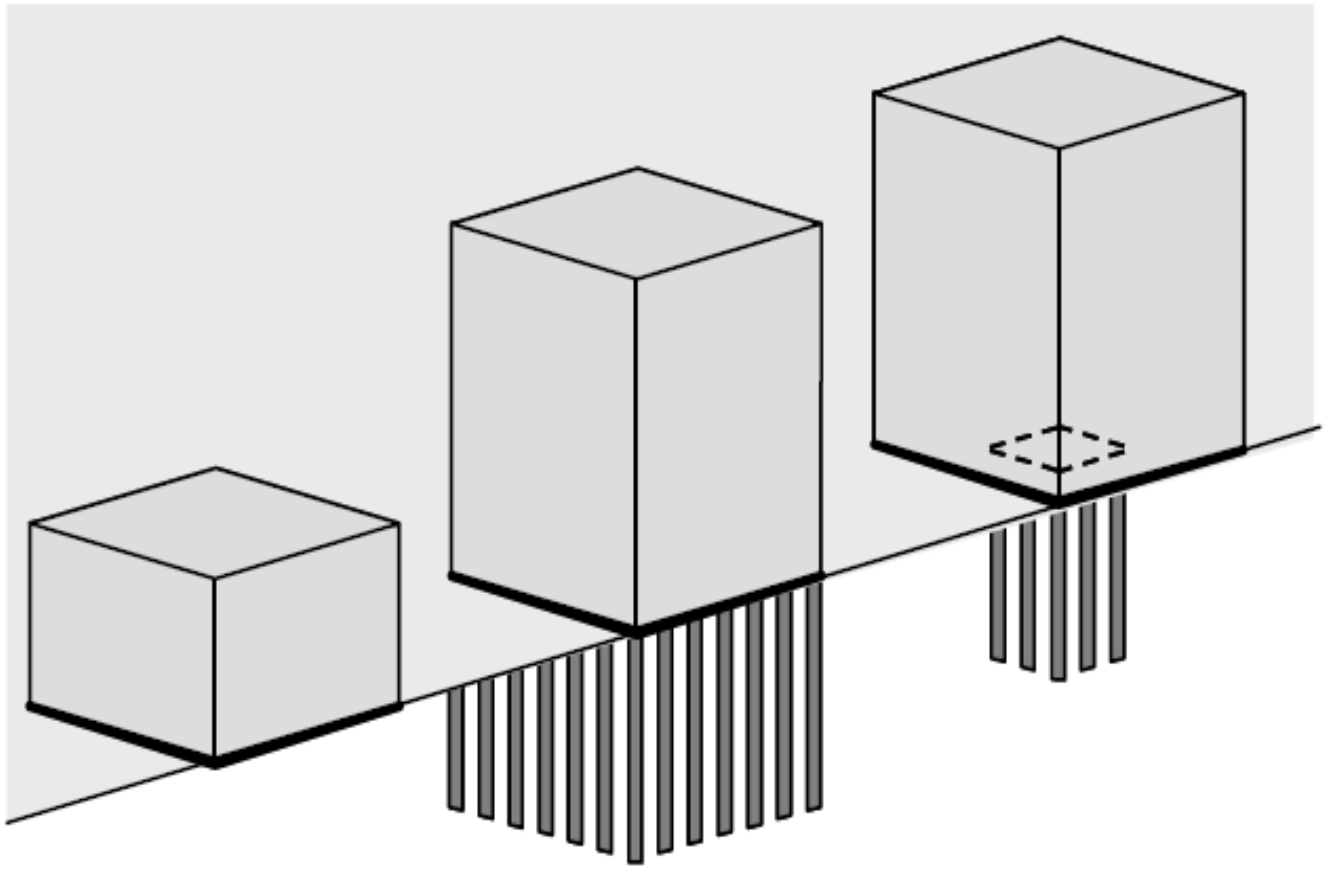
SOME CHALLENGES WITH TALL BUILDINGS

- 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 – human comfort

SOME INGREDIENTS FOR ECONOMIC FOUNDATIONS

- Appropriate foundation concept
- Appropriate design criteria & methods
- Appropriate ground data and design parameters
- Quality construction
- Appropriate foundation element (pile) testing
- Performance monitoring

FOUNDATION OPTIONS



Raft Foundation Piled Foundation Piled Raft Foundation

FOUNDATION DESIGN ISSUES

1. Ultimate capacity
2. Settlement
3. Differential settlement & tilt
4. Response to lateral loads and moments
5. Dynamic behaviour
6. Earthquake response
7. Structural strength of foundation elements
8. Durability

DESIGN PROCESS

- **Preliminary stage** – basis for concept development

- **Detailed stage** - develop and optimize design. Interaction with structural engineers.

- **Final stage** – analysis, parameters and design are finalized and checked with alternative analyses, and/or via peer review.

  Design tools should be consistent with the stage of design

  Complex analyses should be checked with simpler methods!!

DESIGN ANALYSES

- **Ultimate limit state** – overall stability & geotechnical capacity
- **Cyclic loading** – limit to 50% shaft friction capacity
- **Serviceability** – limit settlements and angular rotations – typically < 100mm, 1/500 for tall buildings
- **Dynamic loading** – foundation natural frequency and damping affect structural response and wind loads
- **Earthquake loading**:
  - Inertial loads
  - Kinematic loading through soil movements

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

SOIL-STRUCTURE INTERACTION ISSUES

- **Geotechnical resistances** – should be factored down for geotechnical stability, but NOT for structural check analyses

- **Superstructure stiffness** – will affect settlement and differential settlement. Best taken into account in structural analysis

- **Pile load distribution** – Beware of the assumption of a rigid raft. Can lead to serious over-estimation of pile loads near outer edges! Account for actual raft flexibility.

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
- These stiffness values MUST take into account pile group interaction effects
- Incorporated into the structural analysis to obtain structural design actions and also to take account of superstructure stiffness for settlements and differential settlement predictions

SOME RISK FACTORS

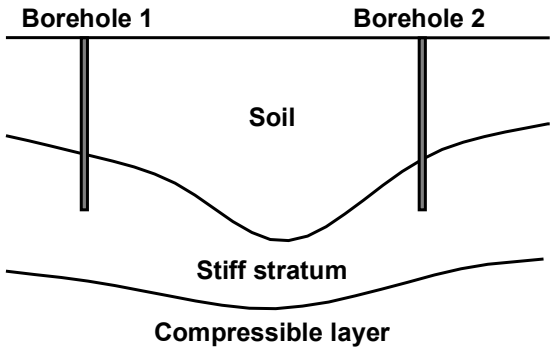
- Inappropriate design approach &/or parameters
- Inadequate investigation
  ⇒ Inappropriate ground model
- Geological “imperfections”
  - Soft layer below piles
  - Sloping bedrock/uneven layer thickness
  - Presence of boulders
- Construction deficiencies/imperfections

MEASURES TO REDUCE RISKS

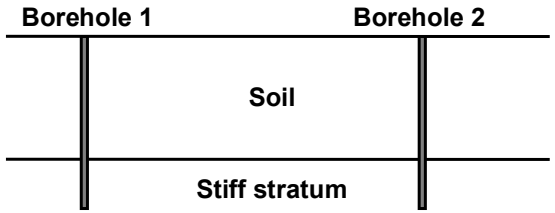
- Independent peer review of ground investigation report
- Independent peer review of foundation design
- Independent supervision of foundation construction
- Foundation element (pile/barrette) testing
- Monitor settlements during construction
  - Compare measured versus predicted performance

- Treat these measures as **INSURANCE INVESTMENTS**

INADEQUATE INVESTIGATION



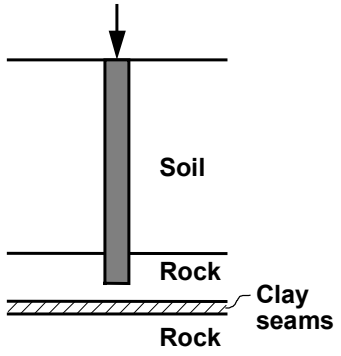
(a) Real profile with two boreholes to inadequate depth



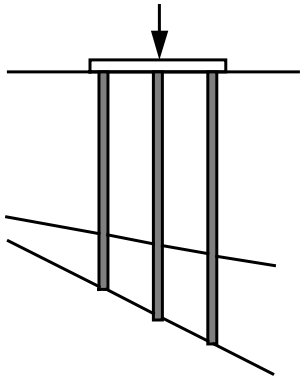
(b) Incorrect inferred ground profile

- Insufficient boreholes or probes
- Assumptions made regarding information between and below boreholes
- Can lead to inaccurate ground characterization

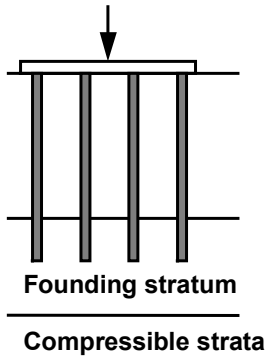
GEOLOGICAL “IMPERFECTIONS”



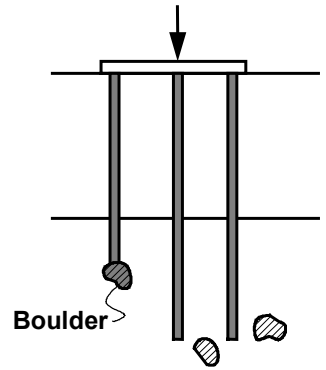
(a) Clay seams below rock socket



(b) Strata of variable thickness, sloping bedrock



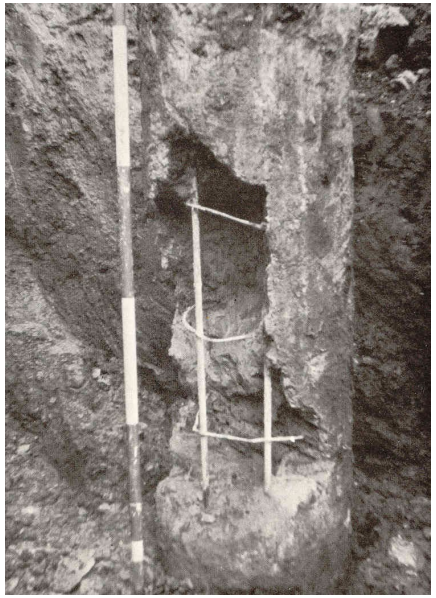
(c) Compressible strata below founding stratum



(d) Pile(s) founding on a boulder

IMPERFECTLY CONSTRUCTED BORED PILES

In design, we assume perfect homogeneous vertical cylinders!







COPING WITH CONSEQUENCES OF IMPERFECTIONS

- **Investigation issues**
  - Care required to avoid additional disturbance & settlement
  - SPT testing must be done carefully
  - Balance fluid pressures in drill holes or cores

COPING WITH CONSEQUENCES OF IMPERFECTIONS

- **Design issues**
  - Correction of settlements – “hard” and “soft” methods
  - Design of remedial/enhancement works
  - Load sharing between old & new elements

CORRECTION OF UNEVEN SETTLEMENTS

- **“HARD” METHODS**

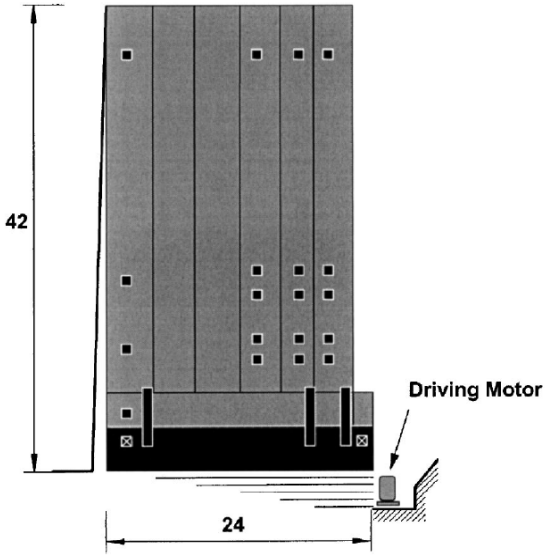
  - Anchor stressing
  - Additional loading
  - Cutting of piles
  - Jetting of soil below pile tips
  - Jacking of foundation on low side
  - Fracture grouting

CORRECTION OF UNEVEN SETTLEMENTS

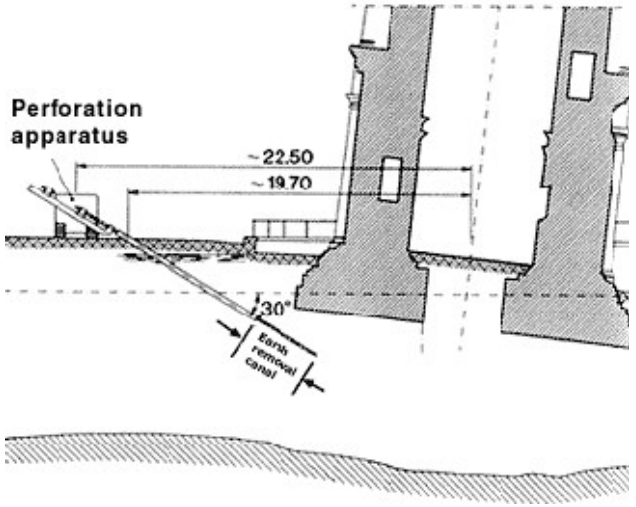
- **“SOFT” METHODS**
  - Soil extraction
  - Dewatering
  - Compensation grouting
  - Removal of soil support (RSS)

SOIL EXTRACTION

(Amirsoleymani, 1991)

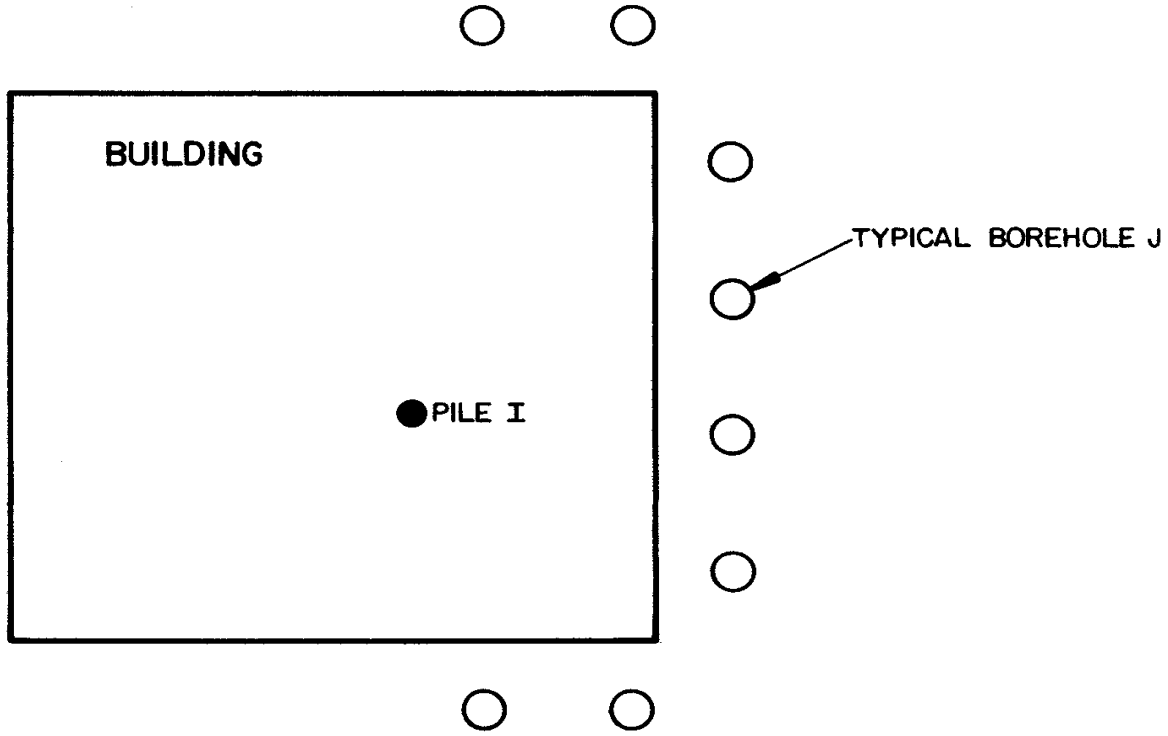


Pisa Tower process



ANOTHER METHOD OF FOUNDATION CORRECTION –

Removal of Soil Support ("RSS METHOD")



FOUNDATION ENHANCEMENT WORKS

- Repair of existing piles
  to enhance capacity / stiffness
- Extension of existing pile caps to strengthen / stiffen foundation
- Addition of new piles to strengthen / stiffen existing foundation

POSSIBLE SIDE EFFECTS OF REMEDIAL CONSTRUCTION

- Ground movements due to pile installation
- Ground movements due to pile cap excavation
- In both cases, highly stressed ground is disturbed below the building.
- Effects are much more severe than for a “greenfield” site

TWO SUCCESSFUL CASES

- Burj Khalifa, Dubai
- Dubai Creek Tower, Dubai

BURJ DUBAI (KHALIFA)TOWER







MAIN CHALLENGES

- 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

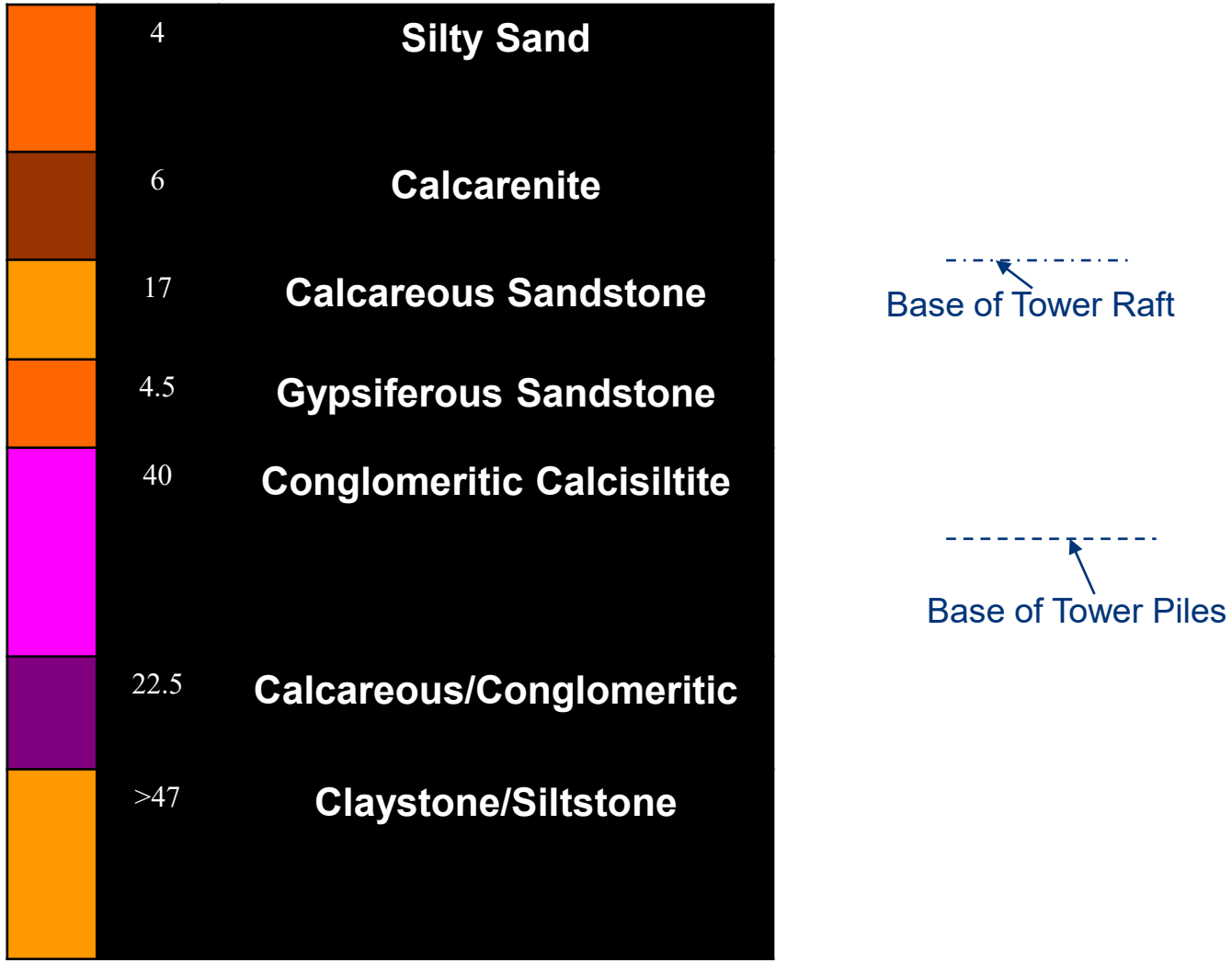
SITE PHOTOGRAPH – September 2003



SITE CHARACTERIZATION

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

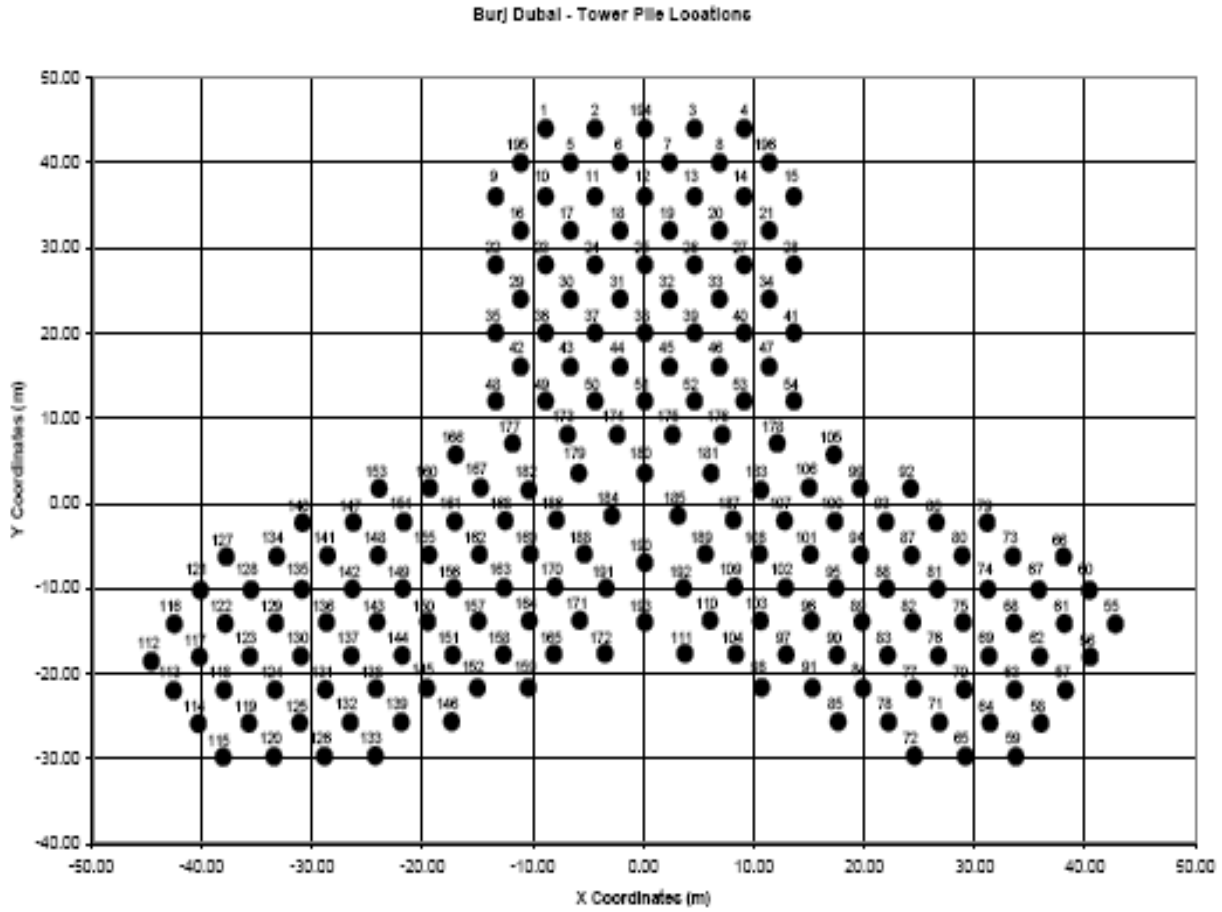
SIMPLIFIED PROFILE



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)

TOWER PILE LAYOUT



Initial Tower Settlement Predictions

Analysis	Settlement mm (Flexible cap)
HYDER - REPUTE	66
HYDER - ABAQUS	72
COFFEY – FLAC (axisymmetric)	73
COFFEY - PIGS	74

Subsequent Equivalent pier check (Coffey): 73 mm

LOAD TEST PROGRAM

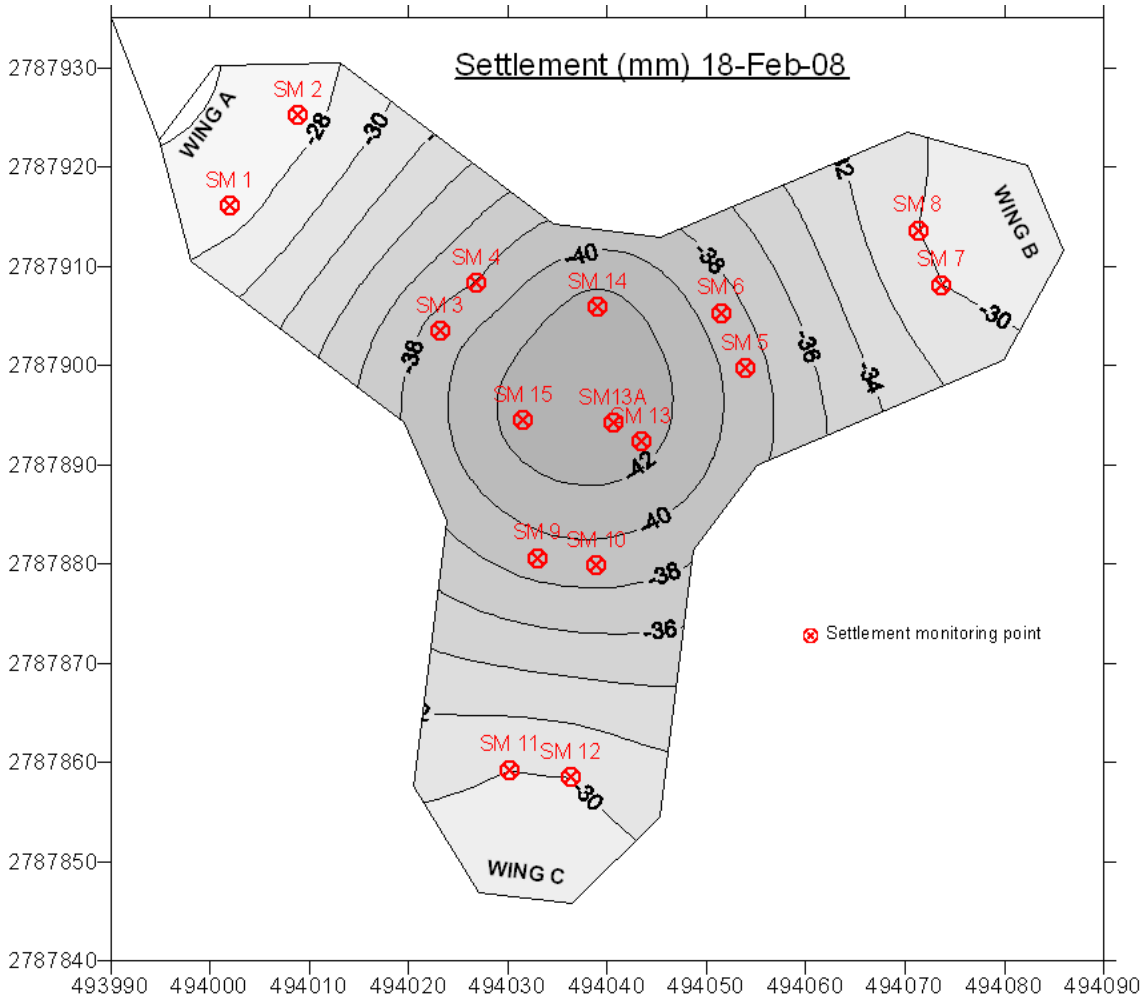
- 3 static compression tests (1.5m dia.)
  - Various toe levels (35-55m long)
- 1 static compression test (0.9m dia.)
  - Shaft grouted
- 1 cyclic compression test (0.9m dia.)
- 1 static tension test (0.9m dia.)
- 1 lateral load test



LOAD TEST PROGRAM - Outcomes

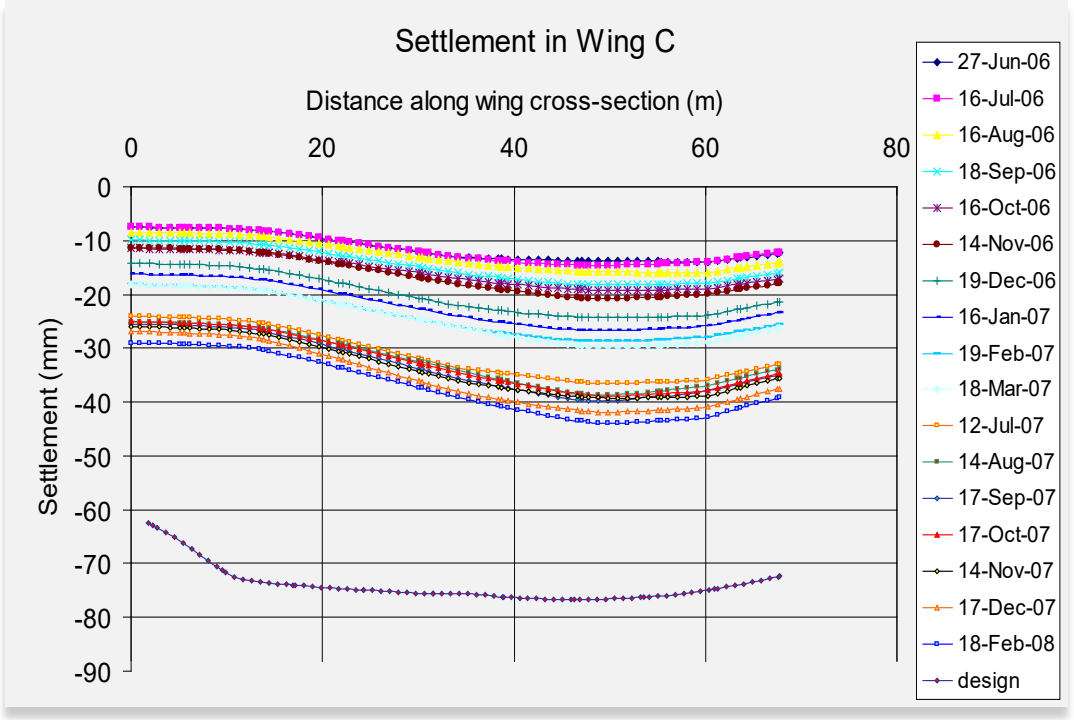
- 1.5m piles loaded to 2 times WL
- 0.9m piles to 3.5 times WL
- No piles appeared to be approaching failure
- Skin friction values in excess of design assumptions
- Shaft grouting effective, but not necessary
- End bearing resistance not fully mobilized
- Axial stiffness greater than predicted
- Cyclic axial loading had little effect
- Lateral stiffness greater than predicted

MEASURED SETTLEMENT CONTOURS – FEBRUARY 2008

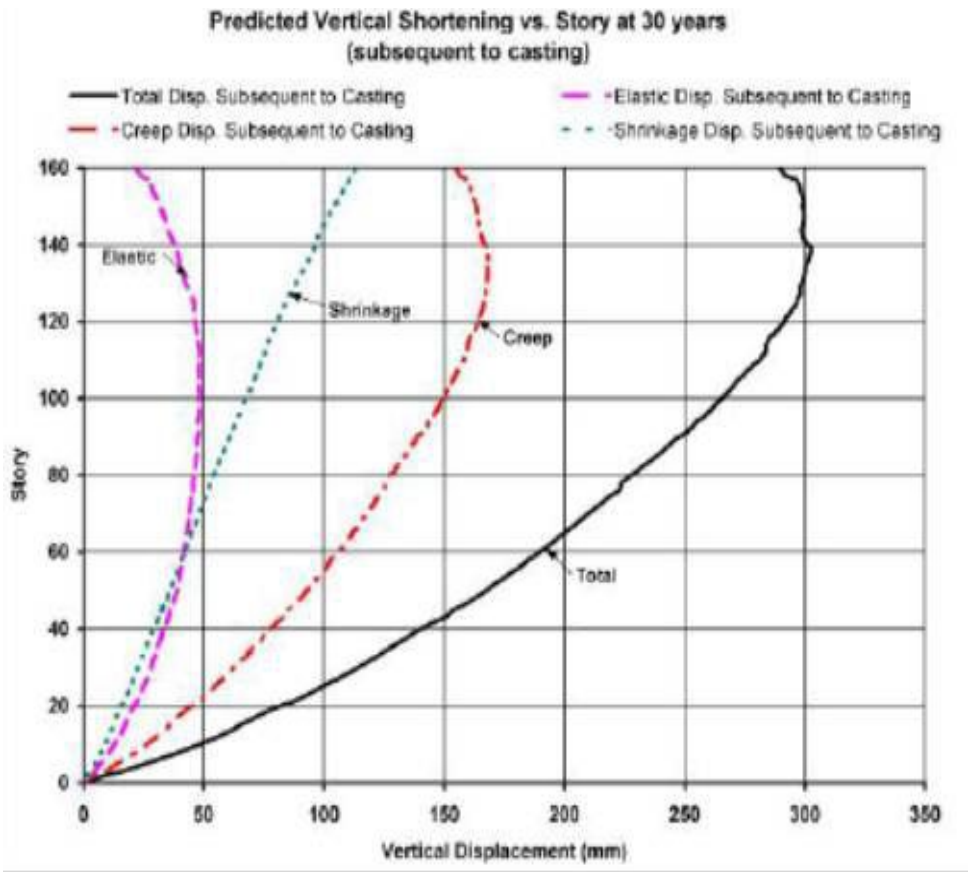


MEASURED TIME-SETTLEMENT – WING C

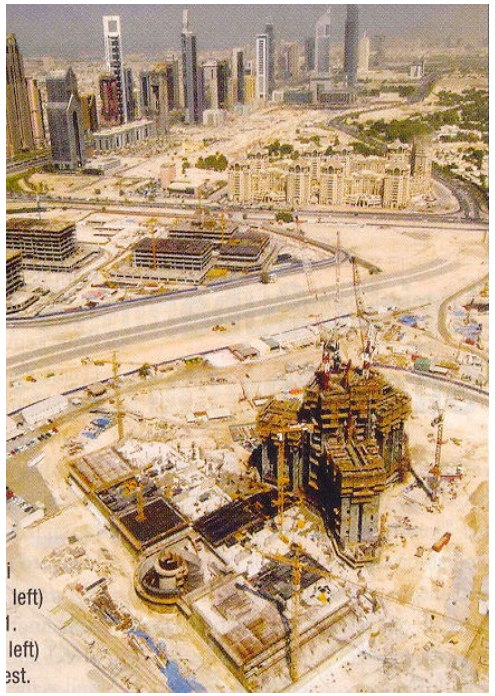
- Predicted approx **75-80mm**
- To February 2008 43mm measured for 80% of dead load
- Estimated 50 to 55mm final settlement
- Within design tolerances



PERSPECTIVE – STRUCTURAL SHORTENING OF TOWER



CONSTRUCTION PROGRESS



Early 2006



Early 2007



Grand opening, 4 January 2010

DUBAI CREEK TOWER, DUBAI



DUBAI CREEK TOWER – MAIN PARTIES

- Client – EMAAR
- Structural Designer – Calatrava International
- Structural & Foundation Design – Aurecon
- Foundation Contractor – Soletanche Bachy
- Foundation Testing - Fugro

MAIN CHALLENGES



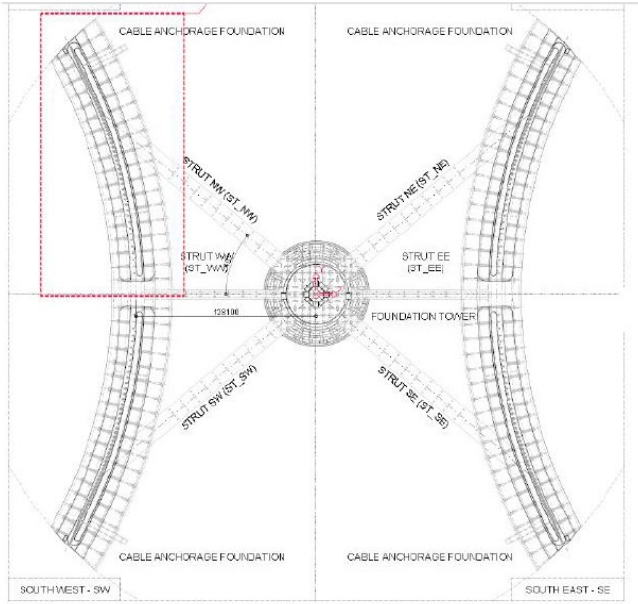
- Tower to be the world's tallest structure
- Fast track construction required
- Foundation capacity for piles in carbonate soils/rocks
- Large lateral & vertical loads

MEETING THE CHALLENGES

- Intensive ground investigation
- High-quality in-situ & laboratory testing
- High level final design analysis – 3D FE
- Design workshops
- Load testing program – O-cell on barrettes

FOUNDATION SOLUTION

- Barrettes
  - 145 below main tower, about 72 m long
  - 144 below each cable anchorage foundation



DUBAI CREEK TOWER







DUBAI CREEK TOWER – New World Record



GROUND ENGINEERING

Record-breaking testing completed on Dubai foundations

14 December, 2017 **By** Claire Smith

Fugro has announced that it has successfully completed the testing on the foundations for a complex new high rise building in Dubai and set a new world record in the process.

The slender structure for Emaar Properties' Dubai Creek Tower features a central concrete column supported by an array of steel cable stays.

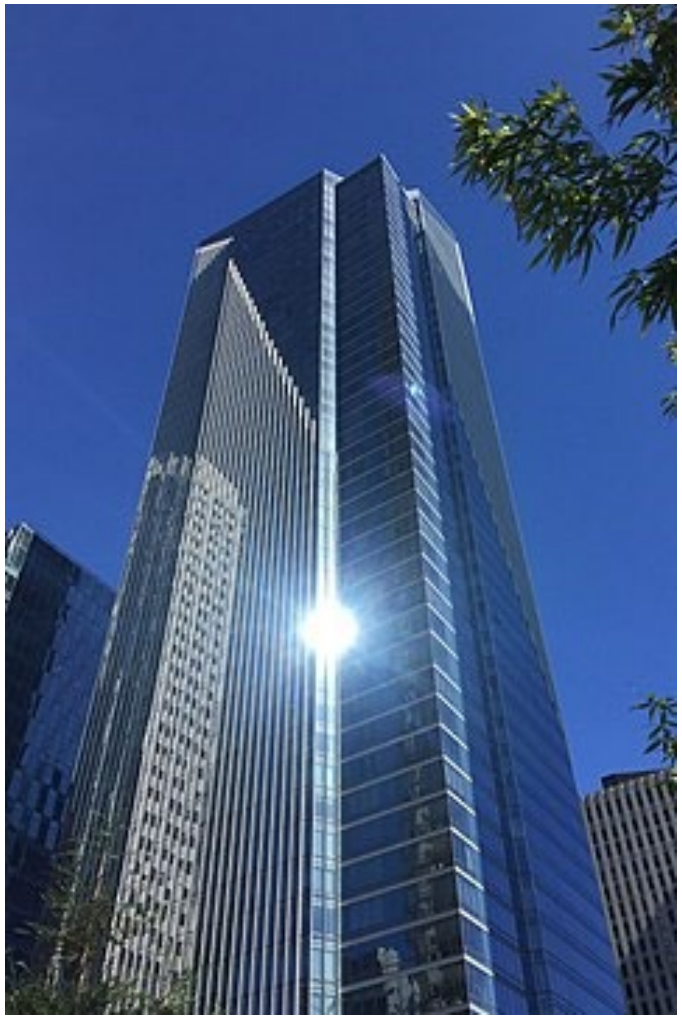
360 MN (80,930 kips) via O-cell on a single barrette!

20 years earlier – 60 MN (top loading) at Burj Khalifa

SOME POSITIVE ELEMENTS OF THESE PROJECTS

- Detailed ground investigation, incl. geophysics
- Advanced design methods
- Cooperative peer review process
- Detailed load testing
- Subsequent settlement monitoring

A LESS SUCCESSFUL PROJECT: MILLENNIUM TOWER, SAN FRANCISCO



- 184 m tall tower, 58 stories
- Tallest residential tower in SF
- Founded on 945 RC piles that do not extend to rock
- Construction activities also in vicinity
- Maximum Settlement > 450 mm
- Max differential settlement ~ 100 mm

- Remedial Plan: install 52 (later 18) additional piles to rock on the “low” side
- Additional 25 mm settlement recorded on low side during installation of the first few piles
- Work halted in September 2021, and resumed cautiously in December
- The tilt increased recently after excavation for foundation extension
- Scope for “soft” method for correction

CONCLUSIONS

- To meet the challenges of tall building foundation design, modern methods are being employed for:
  - In-situ testing
  - Laboratory testing
  - Analysis & design methods
  - Load testing – O-cell method

- Simpler methods essential for checks on advanced numerical analyses

- Cooperation between geotechnical and structural designers is essential

- Be aware of risks and possible sources of problems:
  - Investigations
  - Design
  - Construction

- Take appropriate risk reduction measures to address problems