SEISMIC DESIGN OF FOUNDATIONS IN DIFFICULT SOIL CONDITIONS
Examples of solutions

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SCOPE OF PRESENTATION

- Soft soil conditions : soils susceptible to generate large displacements
  - Clays (cyclic degradation, consolidation…)
  - Loose sands (settlements)
  - Saturated sands (liquefaction, lateral spreading)
- Foundations types
  - Piles
  - Shallow foundations
- Illustrations on actual projects
  - Piles and/or Shallow foundation + Soil improvement

SHALLOW FOUNDATION

- Advantages
  - Low cost
  - Easy to construct
  - Simple to design
  - Efficient in seismic areas when advantage of sliding and uplift is taken into account in design

    ⟹ Reduction of actions on foundation

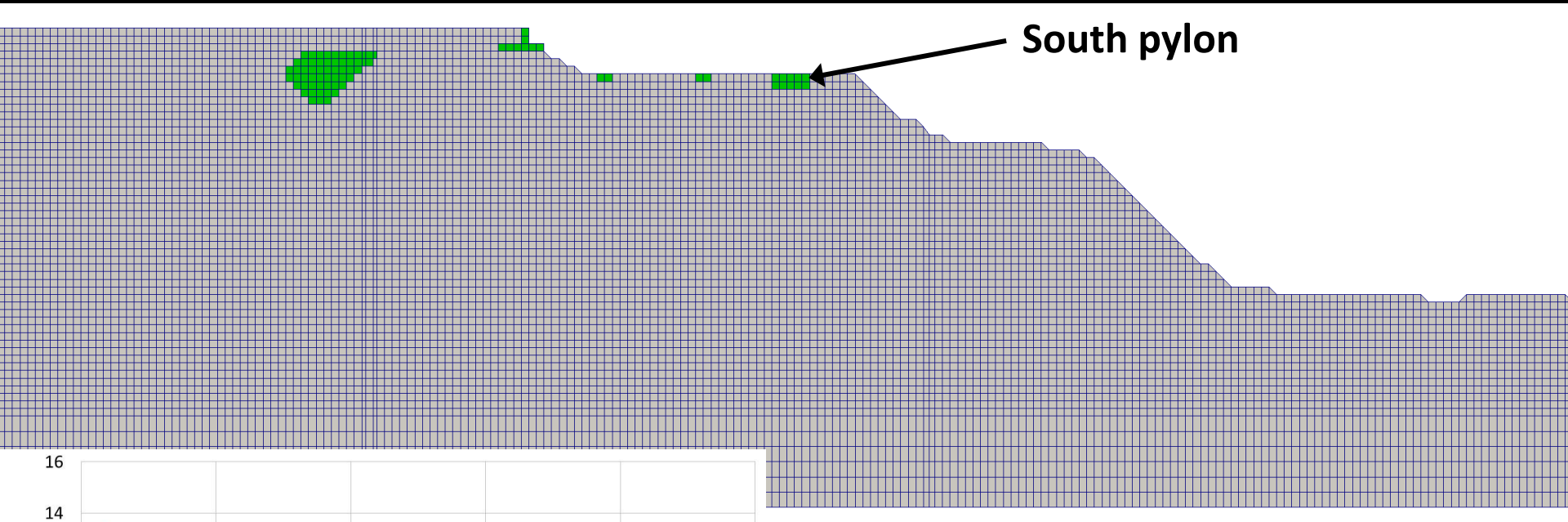
SHALLOW FOUNDATION

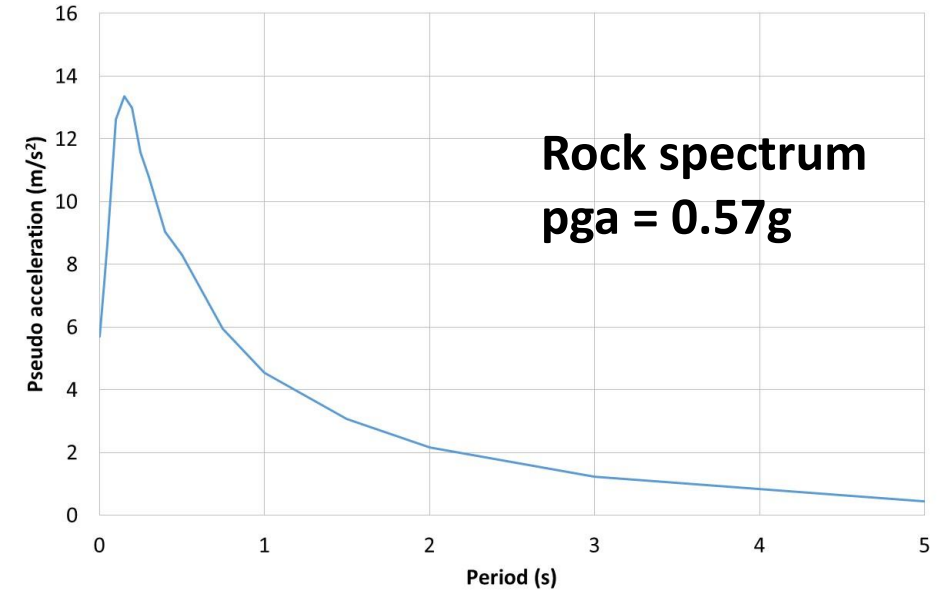
- Drawbacks
  - ➢Current practice in building codes does not allow for permanent displacements/rotations which imply yielding of the foundation system
  - ➢Sensitive to settlements due to ground response
  - ➢Inadequate in liquefiable environment

    ⟹ lateral spreading

CHACAO BRIDGE (CHILE)

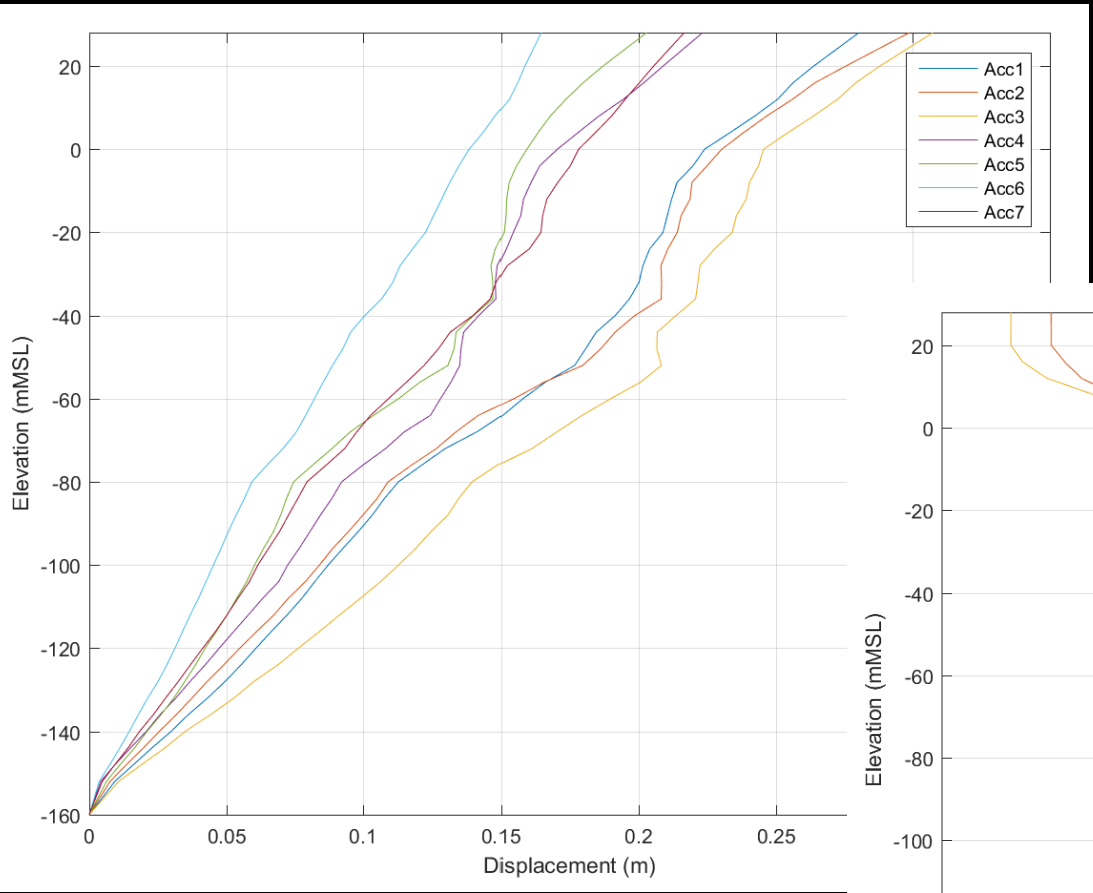
SOUTH BANK

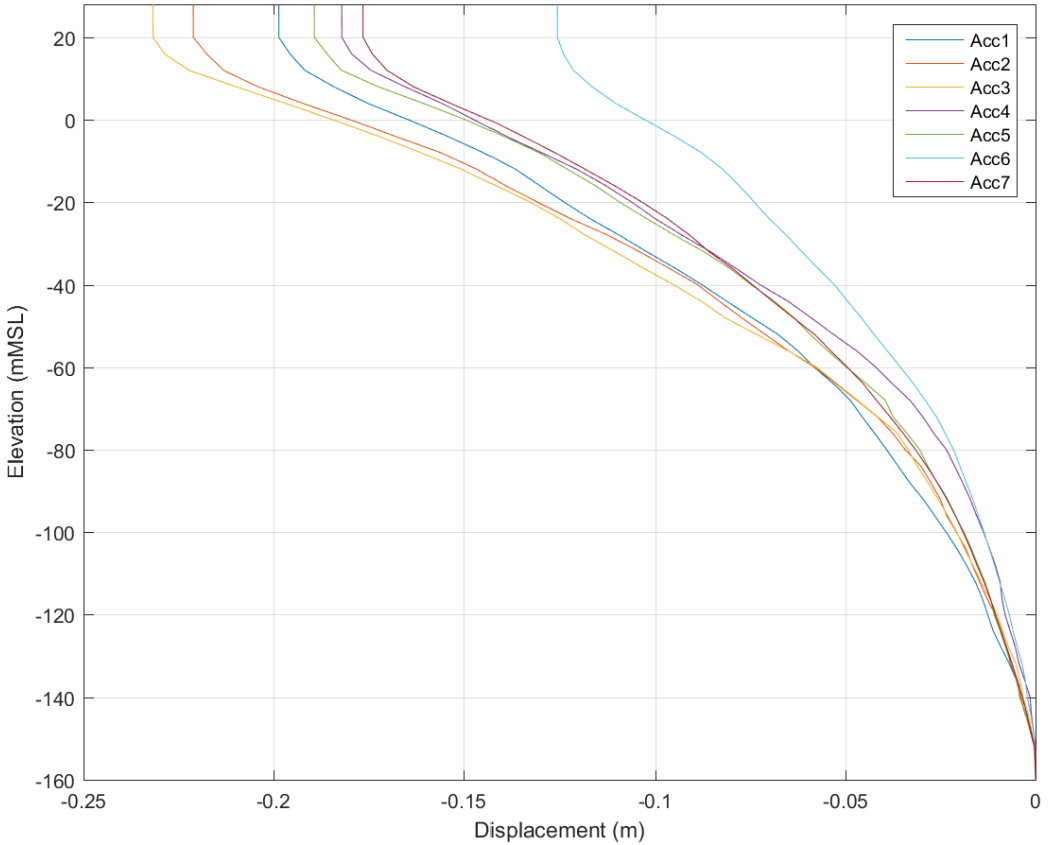




Rock spectrum
pga = 0.57g

RESIDUAL FOUNDATION DISPLACEMENTS





ARE PILES THE ULTIMATE SOLUTION ?

- Advantages
  - ➢Limitation of foundation displacements in absence of ground displacement
  - ➢Safe solution with end bearing piles
- Drawbacks
  - ➢Floating piles may be subjected to loss of skin friction (cyclic degradation, gapping…)
  - ➢High internal forces may be developed by ground displacement (kinematic interaction)

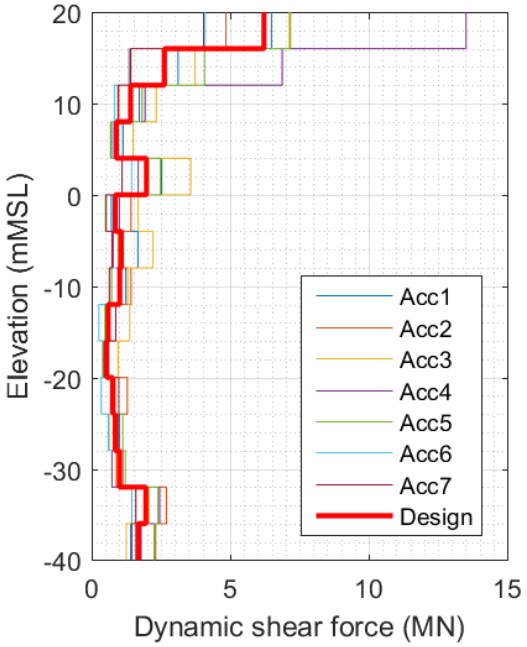
⟹ Excessive reinforcement ratio

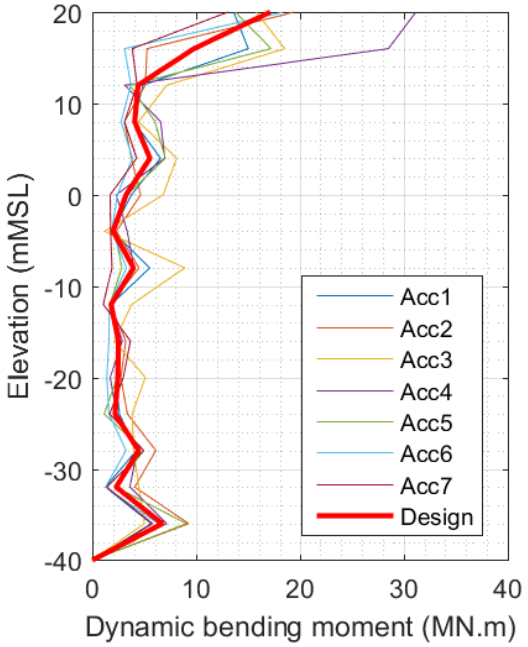
MEXICO CITY (1985)

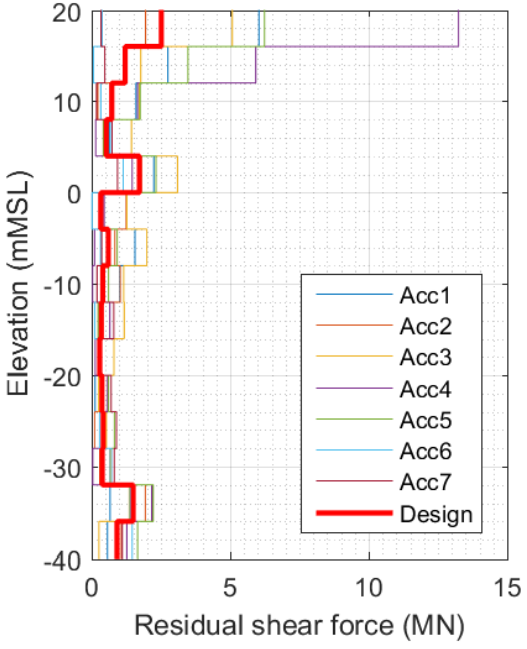
FLOATING PILES

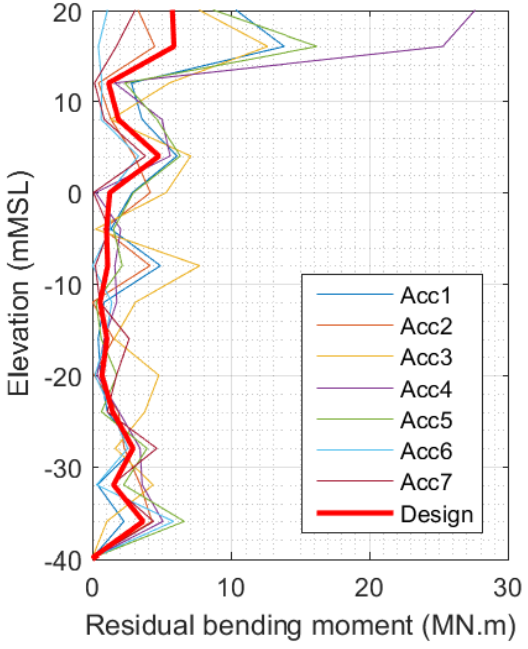
CHACAO BRIDGE

PILED FOUNDATION
South Pylon









LNG TANKS – WHEATSTONE (AUSTRALIA)

Vinci – Entrepose Contracting

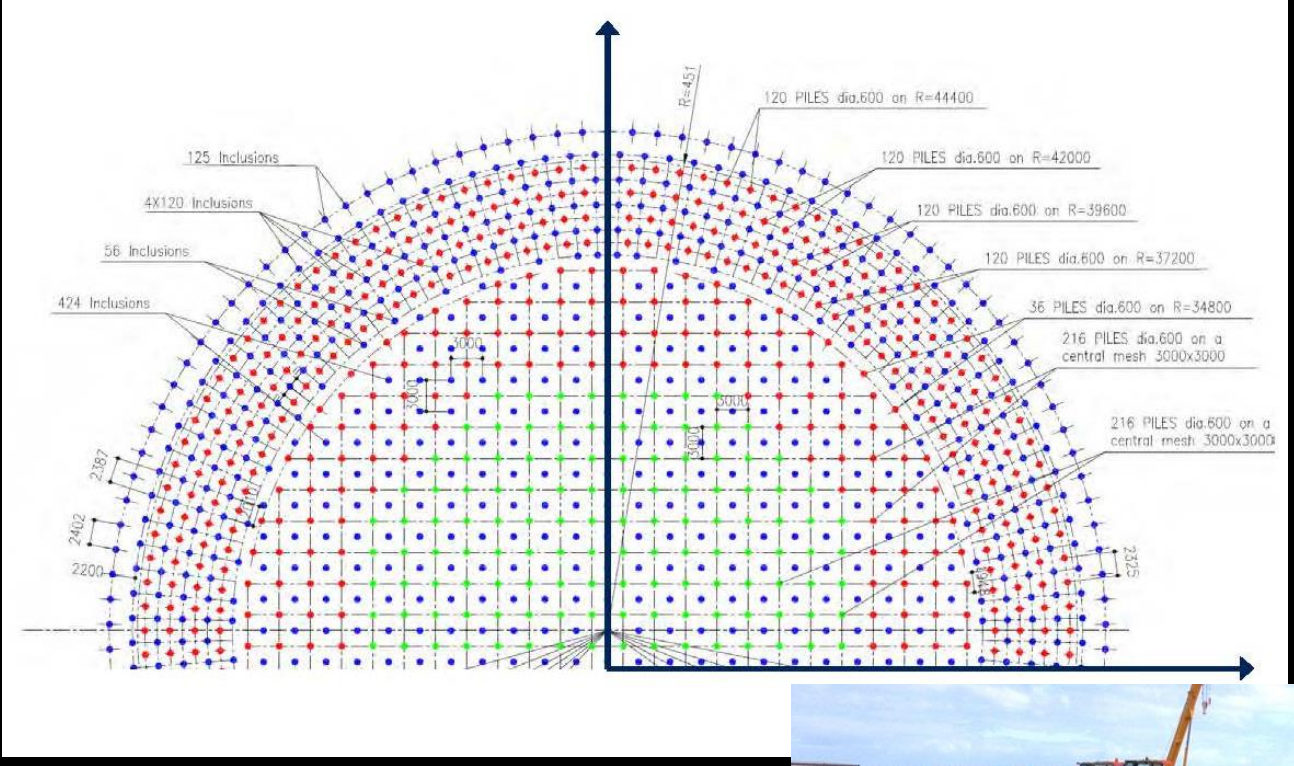
Capacity 180 000m^3
Diameter 90m

Challenges

- Thick layers of cohesionless soils
- 3.3m liquefiable layer @ 3.5m below grade
- Lateral spreading possible

ADOPTED SOLUTION

- 948 driven steel piles ($\phi = 0.6$m, L = 25m)
- 5m long steel inclusions, driven closed-ended in-between piles
- Achievements
  - Minimization of settlements
  - Decrease of the kinematic forces induced by liquefied layer
  - Self-stable "caisson" resisting displacements due to lateral spreading
  - Minimum additional cost


R=451
120 PILES dia.600 on R=44400
125 Inclusions
120 PILES dia.600 on R=42000
4X120 Inclusions
120 PILES dia.600 on R=39600
56 Inclusions
120 PILES dia.600 on R=37200
424 Inclusions
36 PILES dia.600 on R=34800
216 PILES dia.600 on a central mesh 3000x3000
216 PILES dia.600 on a central mesh 3000x3000
3000
3000
3000
3000
2387
2402
2200
2325


F34

PREFECTURE FORT de FRANCE (CARIBBEAN)

Solétanche-Bachy

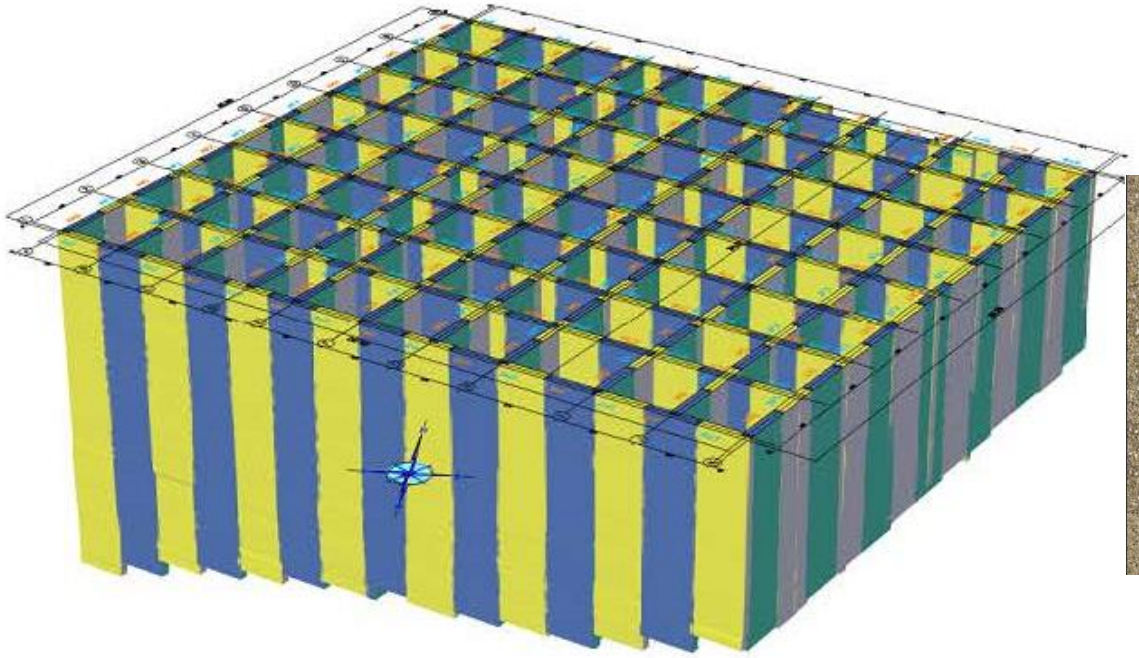
Challenges

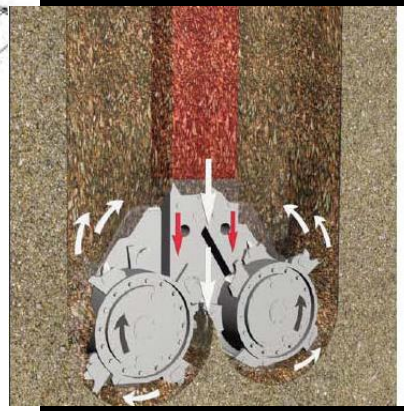
- Reclaimed hydraulic fill (9-17m)
- Sloping rock surface towards the sea ➡ lateral spreading
- Highly seismic area : M=7.5, pga=0.36g

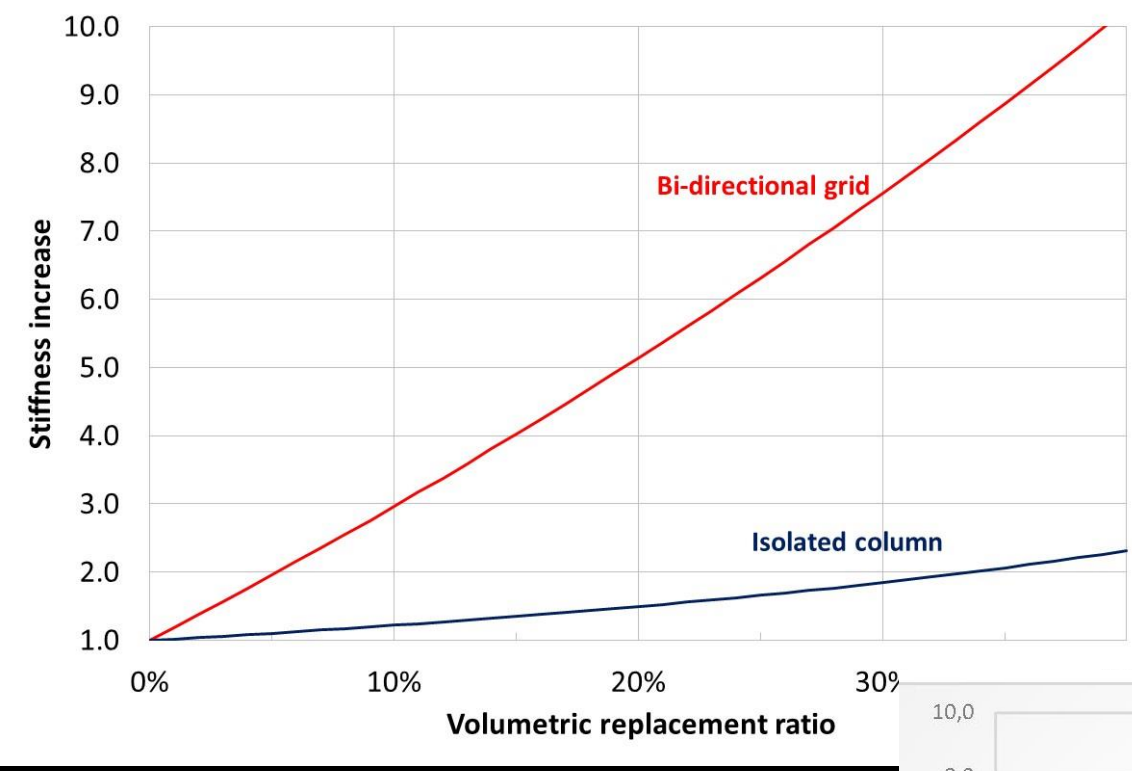
ADOPTED SOLUTION

- Caissons in Deep soil mixing (Geomix®)
- Gravel layer on top of the grid

- Achievements
  - ➢Shallow foundation
  - ➢Minimization of settlements
  - ➢Self-stable "caisson" resisting displacements due to lateral spreading
  - ➢Ease of construction







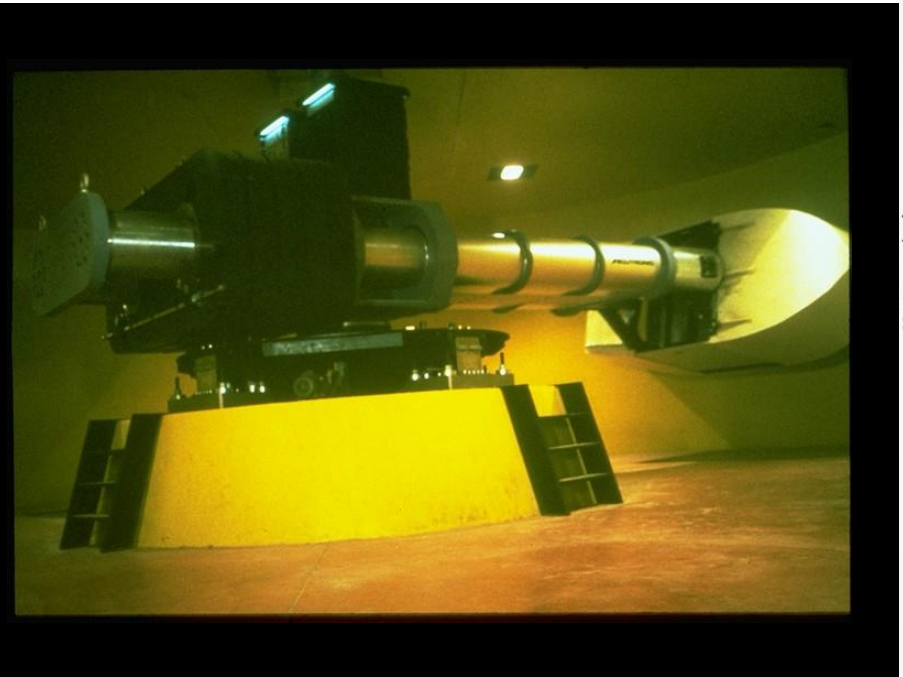
Stiffness increase

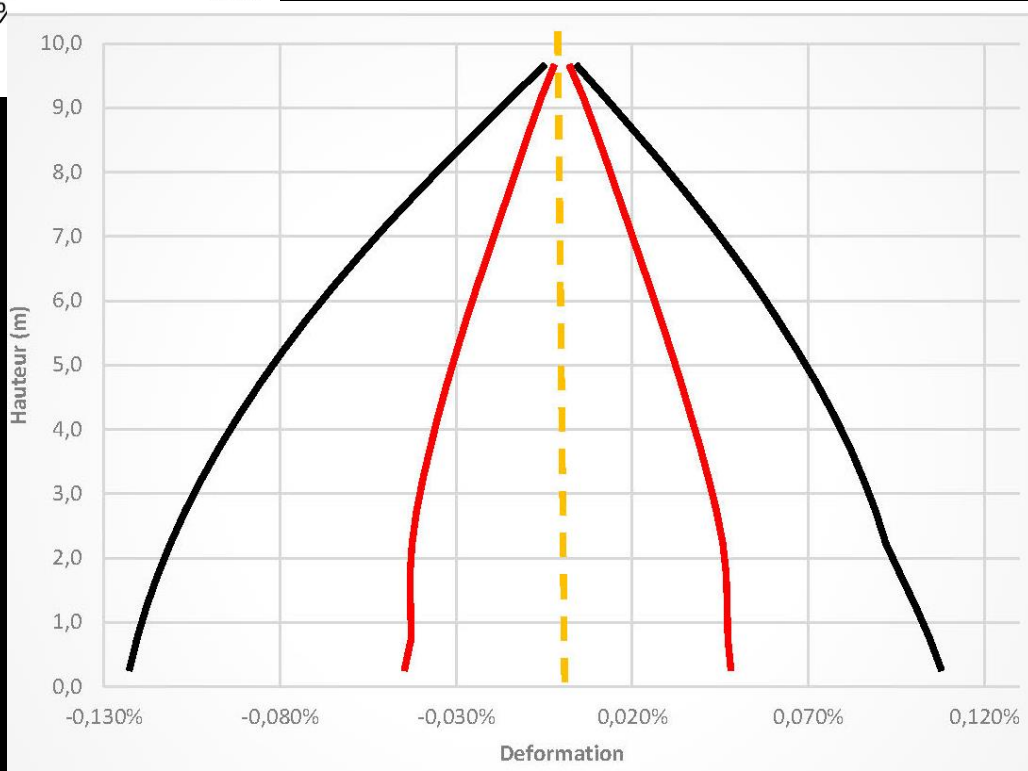
↓

Smaller shear strains

↓

Smaller pore pressure





RION ANTIRION BRIDGE (GREECE)

Vinci + Greek companies

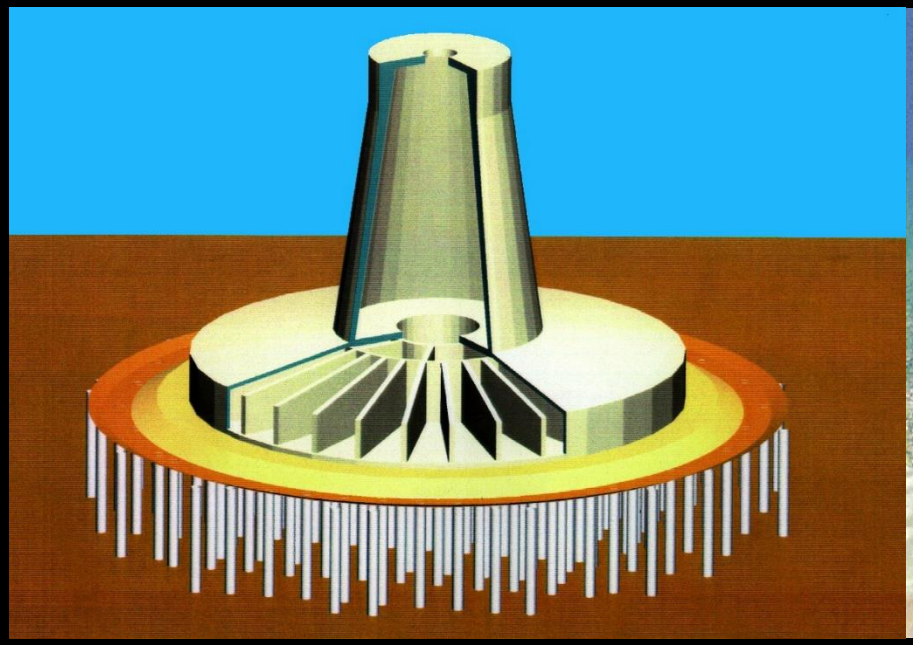
2.2km Cable stayed bridge
3 main spans 560m

Challenges

- More than 600m alluvial deposits
- Water depth 65m
- Highly seismic area (pga = 0.48g)

ADOPTED SOLUTION

- Large diameter shallow foundations (90m)
- 30m long steel inclusions, driven closed-ended (200 per foundation)
- Top gravel layer (3m thick)
- Achievements
  - ➢Shallow foundations easier to construct
  - ➢Capacity design strategy
  - ➢Limitation of forces in pylon by allowing sliding and uplift of foundation
  - ➢The bridge successfully survived the Achaia-Ilia earthquake (2008)

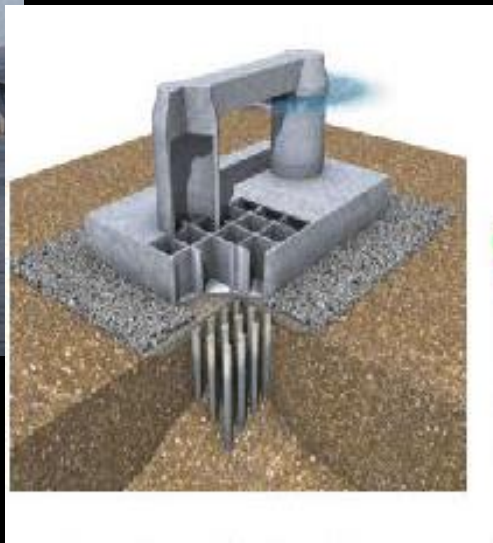


SIGNIFICANT MILESTONE

- First major civil engineering project in which yielding (sliding) and uplift at the foundation has been accepted

- Since its completion at least 2 major projects used the same concept

IZMIT BRIDGE (TURKEY)
Cowi



NUCLEAR WASTE STORAGE BUILDING ICEDA

EDF

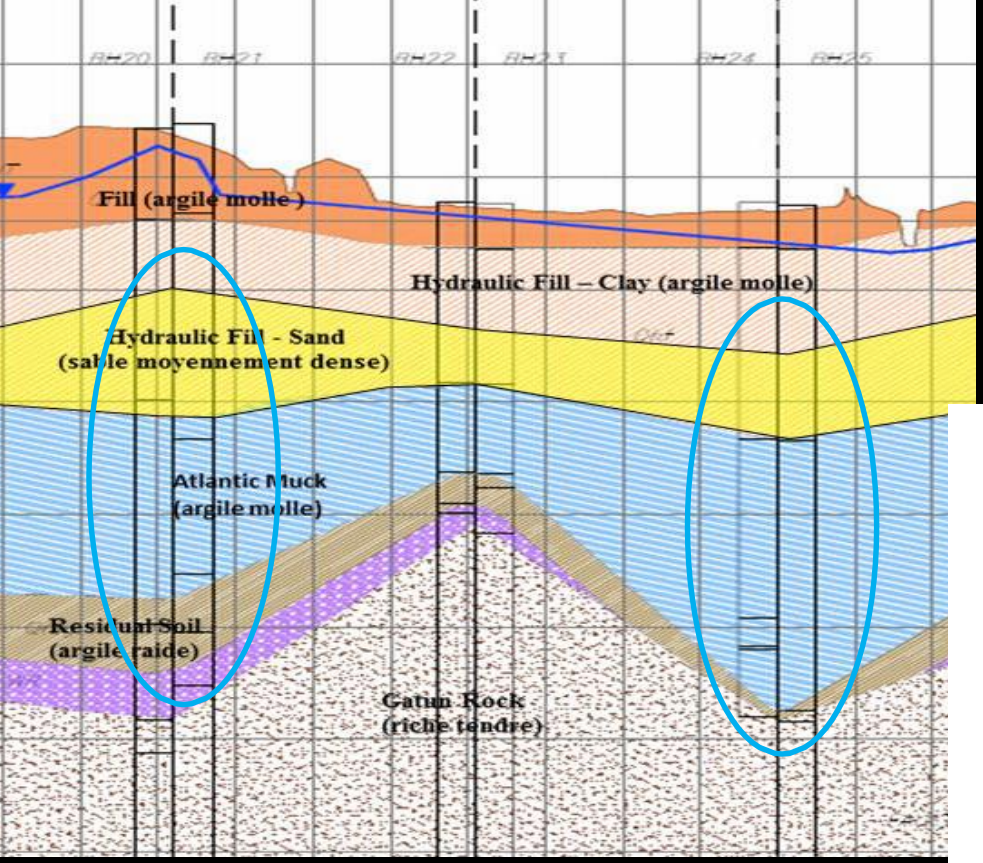
ATLANTIC BRIDGE (PANAMA)

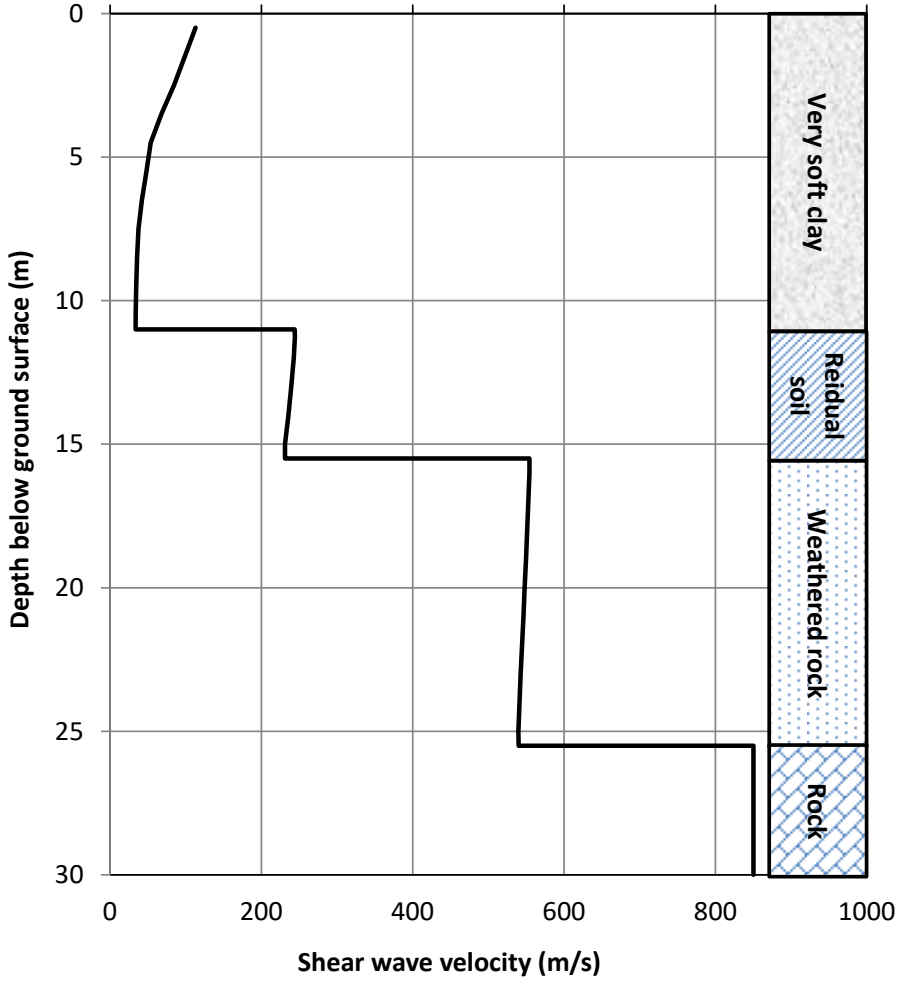
Vinci

Cable stayed bridge
Main Span 530m

Challenges for foundation of 2 piers of access viaducts

- Hydraulic fill, 10m thick overlying very soft clay (12m)
- High seismic area (pga 0.57g)
- Large kinematic forces

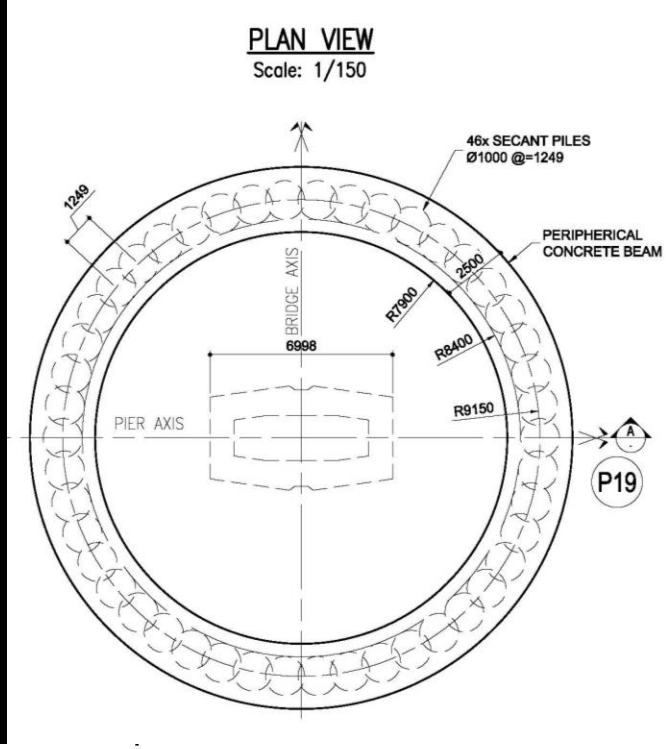

Fill (argile molle)
Hydraulic Fill – Clay (argile molle)
Hydraulic Fill - Sand
(sable moyennement dense)
Atlantic Muck
(argile molle)
Residual Soil
(argile raide)
Gatun Rock
(riche tendre)

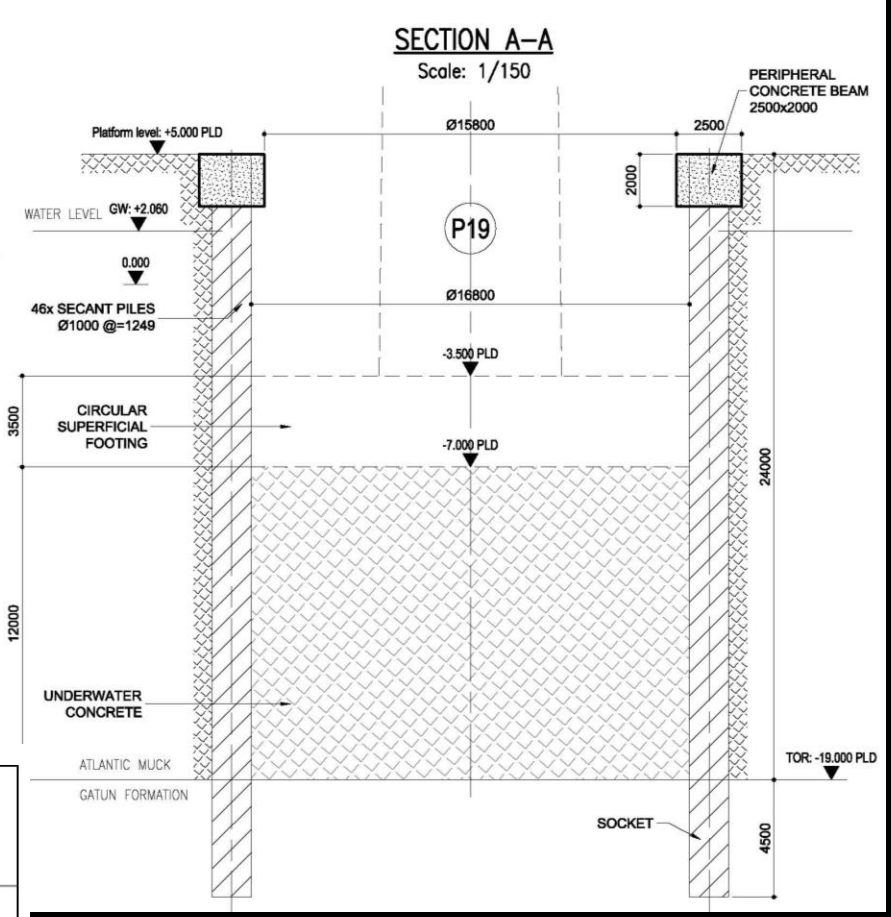

Depth below ground surface (m)
0
5
10
15
20
25
30
0
200
400
600
800
1000
Shear wave velocity (m/s)
Very soft clay
Reidual soil
Weathered rock
Rock

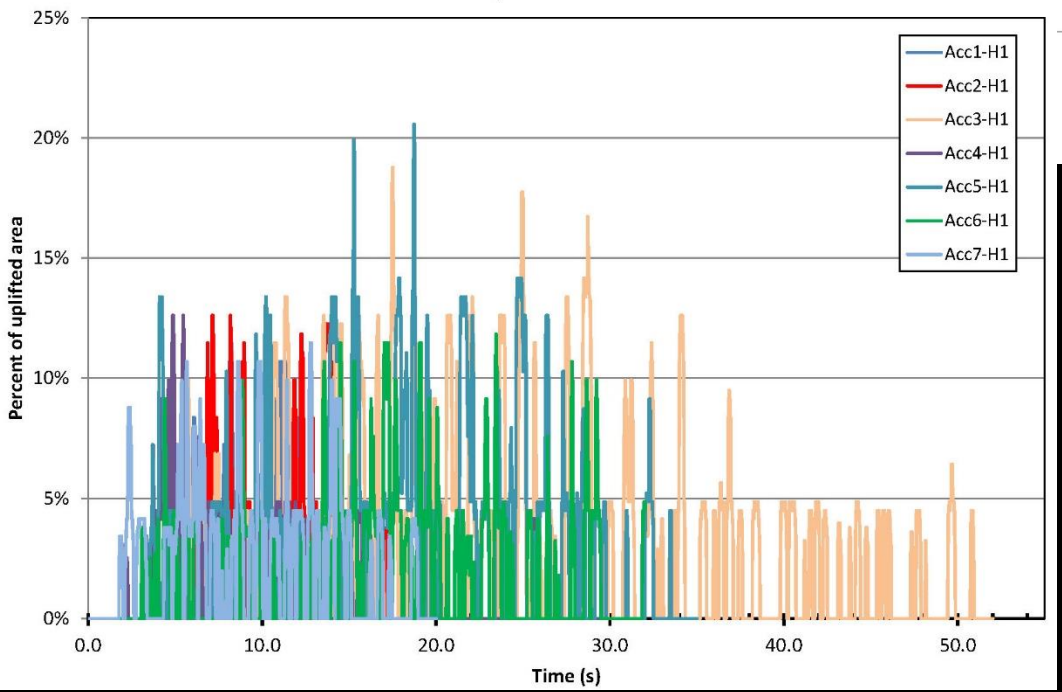
ADOPTED SOLUTION

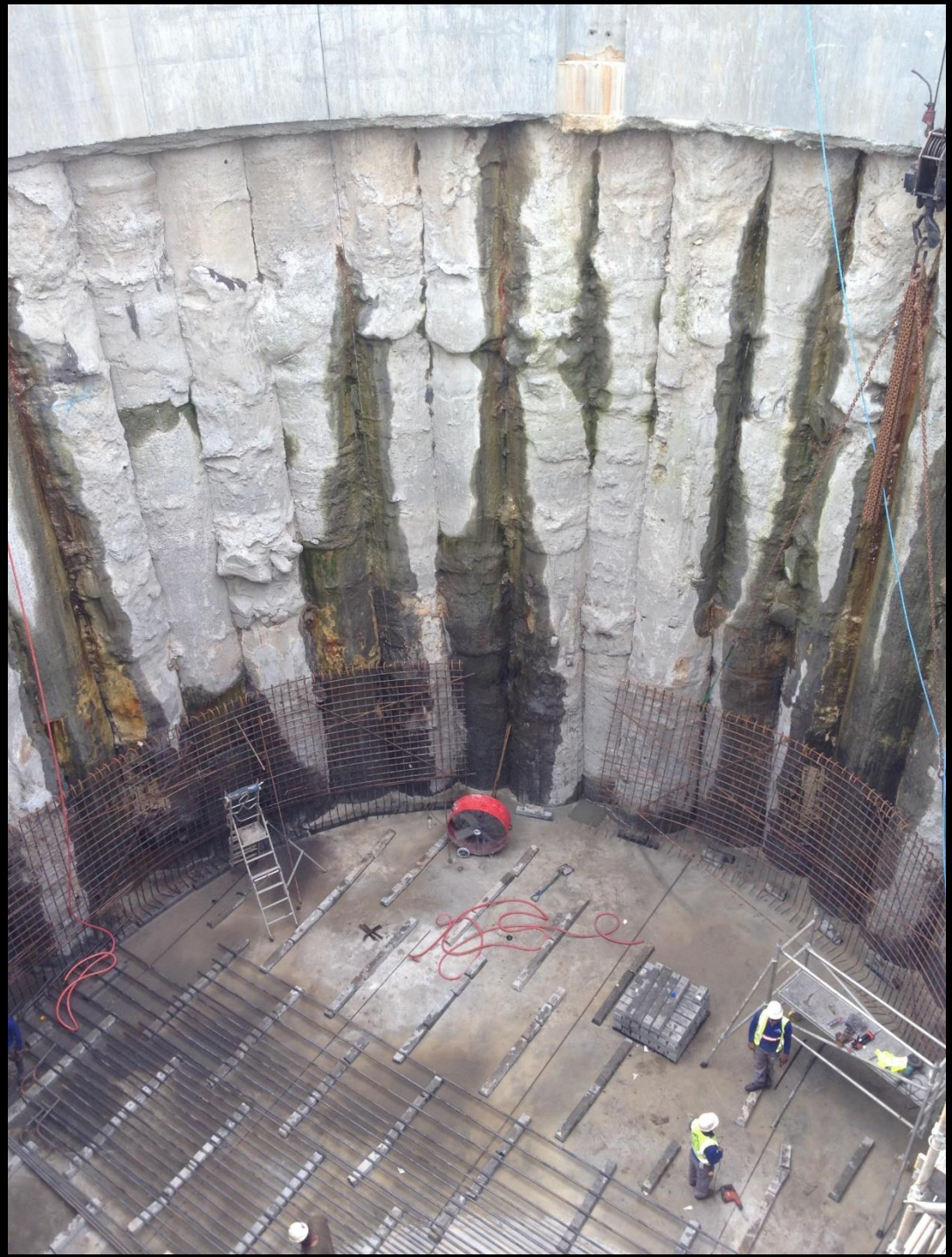
- Peripheral wall made of secant concrete piles
- Substitution of soft clay with mass concrete
- Shallow foundation simply cast on top of mass concrete (no connection)
- Achievements
  - ➢Shallow foundation with possible uplift to bound the overturning moment
  - ➢Peripheral wall to protect the foundation from the soil displacements

→ limitation of forces due to kinematic interaction


PLAN VIEW
Scale: 1/150
46x SECANT PILES
Ø1000 @=1249
1249
PERIPHERICAL
CONCRETE BEAM
2500
BRIDGE AXIS
R7900
R8400
6998
R9150
PIER AXIS
A
P19


SECTION A–A
Scale: 1/150
PERIPHERAL
CONCRETE BEAM
2500x2000
Platform level: +5.000 PLD
Ø15800
2500
2000
WATER LEVEL GW: +2.060
P19
0.000
Ø16800
46x SECANT PILES
Ø1000 @=1249
-3.500 PLD
3500
CIRCULAR
SUPERFICIAL
FOOTING
-7.000 PLD
24000
12000
UNDERWATER
CONCRETE
ATLANTIC MUCK
GATUN FORMATION
TOR: -19.000 PLD
SOCKET
4500

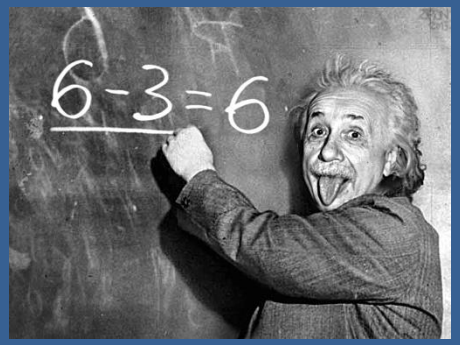

25%
20%
15%
10%
5%
0%
Percent of uplifted area
0.0
10.0
20.0
30.0
40.0
50.0
Time (s)
Acc1-H1
Acc2-H1
Acc3-H1
Acc4-H1
Acc5-H1
Acc6-H1
Acc7-H1



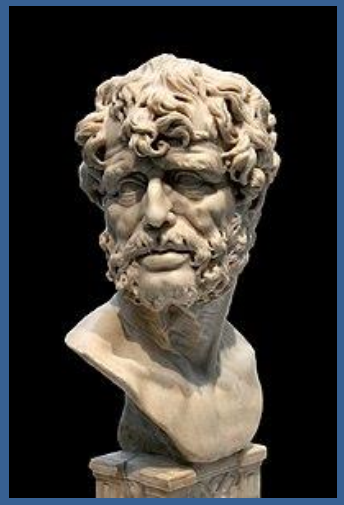
CONCLUSIONS

- There is no unique solution for foundation in difficult soil conditions
- Combination of at least 2 different solutions may be effective : piles + inclusions, shallow foundation + soil improvement, shallow foundation + caisson….
- Efficiency of a solution, should be judged with respect to feasibility, reliability, ease of construction, quality control and cost

WE SHOULD REMAIN CONFIDENT IN OUR CAPABILITIES TO FIND SOLUTIONS



A problem without a solution is a ill-posed problem (*Albert Einstein*)



It's not because things seem difficult that we do not dare, it's because we do not dare that they seem difficult (*Seneque the Younger)*

THANK YOU FOR YOUR ATTENTION