Geotechnical lessons learned from COWI Mega-projects

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Outline - introduction

• Mega-projects
  - definition
  - why interesting?

• Associated problems?
  - cost and time escalation
  - projects or geotechnicians

• Case histories
  - Fixed Links (general)
  - Ship protection modelling
  - Pylon cavity remediation
Megaprojects?

- Large-scale investment projects (> US$ 1 billion)
- Alternatively: "initiatives that are physical, very expensive and public"
- Bridges, tunnels, highways, railways, airports, seaports, buildings, energy extraction projects, power plants, IT systems, aerospace projects, weapons systems
Megaprojects?

- Extremely large-scale investment projects (> US$ 1 billion)
- Alternatively: "initiatives that are physical, very expensive and public"
- Bridges, tunnels, highways, railways, airports, seaports, buildings, energy extraction projects, power plants, IT systems, aerospace projects, weapons systems
- Escalation in project costs - failures
  - poor/problematic soil conditions?
  - poor ground investigations?
  - poor geo-professionals?
  - poor interplay
  - poor management
Postulate: problematic = failure to recognize or understand

- Local, comparable experience
- Importance of adequate and timely ground investigations
- Difficulties in specifying, testing and interpreting lab. and field tests
- Confusion of measured, derived, characteristic & design values
- Geological set-up and stratification
- Application of proper theoretical framework
- Abuse of numerical tools (garbage in ⇒ garbage out)
Problematic = Euphemism for geo-professionals?

- Problematic soils? No!
- Problematic geo-professionals? Yes!
- Megaprojects? Learn!
Challenge should be our middle name - not problematic

Case histories
(1) Fixed Links and Landmark structures exemplify Mega-project challenges

- by nature cross border
- ability to grasp & communicate
  - non-tech issues
  - "soft demands" to sustainable solutions
- demonstrate need for cross pollination
  - geo, -structural, -hydraulic, -environmental,
  - surveyors, -architects, -traffic planners,
  - biologists, -bankers, -economists, -lawyers,
  - 3D animators, -NGO's, -politicians
- require
  - innovative but "controlled" mind-set
Concept to COWI track record for Fixed Links

- Practice runs with internal Links

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Length</th>
<th>Span</th>
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<tbody>
<tr>
<td>Little Belt</td>
<td>1970</td>
<td>600 m</td>
<td>42 m</td>
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<tr>
<td>Farø Bridges</td>
<td>1985</td>
<td>260 m</td>
<td>26 m</td>
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<tr>
<td>Great Belt</td>
<td>1998</td>
<td>1624 m</td>
<td>65 m</td>
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Concept - track record

- Practice runs with internal Links
- Trans-national Links
- Backbone for new challenges

<table>
<thead>
<tr>
<th>Øresund</th>
<th>Femern Belt</th>
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<tbody>
<tr>
<td>2000</td>
<td>2020?</td>
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<tr>
<td>490 m</td>
<td>700-2000 m</td>
</tr>
<tr>
<td>57 m</td>
<td></td>
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Concept - track record - new opportunities

- at truly international scope & scale
- forerunner in pre-cast caisson solutions
- always invited to bid
(2) Ship impact protection– SIP (Korea)

COWI designer of SIP for Samsung C&T Corporation

Dolphins max Ø 30 m
Ground conditions

**Deposit**

- Marine clay, silt sand (0.27/0.13/0.50) 15.5 - 25.5
- Residual soils 0 – 16.5
- Weathered rock (D4 to D5) 2.5 –>11.5
- Soft rock (Biotite Granite, D3 to D5)

*Irregular sequence – considerable variation between SIPs*
Ø20 - 30 m dolphin structures (flat sheet piles)

- Sheet piles driven to sand/residual soil/weathered rock with SPT-N>40
- Dolphins filled with crushed rock (replacement of soft soil)
Ship impact protection structure modelling

- Borings with SPT - provide layering, $\varphi'$, $c'$, $c_u$
- 9 design profiles and numerous design cases
- Verification of bearing capacity by 2D PLAXIS - strength limit & extreme seismic
- Structural by 3D ABAQUS dynamic

2D deformed mesh

Hoop stresses
Ship impact load case

• Imperative to quantify/qualify behaviour
  3D dynamic analyses (ABAQUS software)

• Rationale for physical modelling
  ▪ representative stresses ➔ centrifuge
  ▪ modelling of models at reduced scale
  ▪ simplified geometry and stratification

To provide insight into:

▪ relevant failure modes
▪ soil-structure-water interaction at real time modelled impact
▪ backbone data for 3D dynamic FEM with "real" stratification and geometry
Centrifuge modelling (Deltarens)

- Scale 1:200 @ 200 g
  Ø20 and 30 m dolphins

- Baskarp sand
  (very/medium dense)

- Quasi-static tests for FEM
  300 mm/h

- Dynamic impact (18.1 kg)
  145000 t @ 3 m/s

**aluminium with requisite bending and axial stiffness**
The full scale dolphins
Quasi-static test (300 mm/h)

F_{contact}

F

Test 05

ABAQUS - Test 5/9

u_{contact}
Dynamic tests (145 000 t @ 3 m/s)

Energy dissipation (MJ)

- Test 05
- Test 09

Dynamic

Quasi-static
Conclusion SIP physical modelling

- Model tests verify use of ABAQUS 3D FEM
difference in quasi-static ~ tests experimental accuracy

**General findings**

- quasi-static is conservative (30-50%)
- dissipation capacity increases with increasing fill density
- low level impact (higher risk of membrane penetration) counteracted by reduced moment (higher dissipation)

**Physical modelling allowed confidence in**

- force-displacement and dissipation response
- modelling "real" stratification and geometry of SIPS
- ability to provide cost efficient design at acceptable risk
(3) Cavity remediation of pylon foundation

Owner: Direction des Travaux Publics de la Wilaya de Constantine – DTP (Algeria)
Contractor: Andrade Gutierrez – AG (Brazil)
Designer: COWI (Denmark)
Project extent & description

[Map showing project extent and description]
Project extent & description

Sidi M’Cid

Sidi Rached
Project extent & description

- 756 m cable stayed bridge
  main span 259 m (80 m clearance)
- 10 km roads incl. accesses
  (13 over & underpasses)
- 4 km retaining walls
  1 km with ground anchors
  (up to 33 m retained height)
- Extensive cuts (up to 45 m)
  (ground anchors & soil nails)
- Embankments and slopes
  (ground anchors & soil nails)
Recent deposits, Travertine; Continental deposits
Weathered Marl; Marl; Marlstone
Limestone
Faults; creeping soils; cavities?
Geology and ground conditions

• Seismic area; confusing geology

• 150 boreholes; 20 inclinometer tubes
  - SPT & pressuremeter testing
  - ambiguous or misleading laboratory testing

• Property characterisation of Marls
  - exposed or buried; with or without water
  - drained/undrained for static/seismic actions
  - site data ambiguous &
  - local comparable experience inaccessible
  - parameters for slopes and cuts a hot & difficult issue

• Pylon pile design
  - undr. strength of Marl based on PMT/SPT ("soil")
  - strength of Marlstone/Limestone based on UCS (rock)
  - shaft and toe bearing (mobilisation degree)
  - influence from fault
Pylon P4 moved due to fault presence
- very slow progress of bored piles in Limestone

Pre-drilling holes Ø178 mm (5 per pile)
- water loss or cavity by drop of drill string
- mapping of Limestone & Marlstone top by borehole data
- cavity feature needs to be considered

Pre-drilling no benefit for progress
- re-think design with pile toe in Marlstone above cavity
- remedial measures to handle cavity feature
Fault and cavity feature

Geophysical survey

Boreholes

50 m drop

F1
Pylon P4 foundation – 14 Ø2 m bored piles

Hypothetical extent of cavity feature

water loss

cavity inferred

Hypothetical extent of cavity

water loss
Remedial measures – required

- Rock socket min. 5 m into Marlstone
  - max: 45 MN load; 11.9 MN toe bearing
- Excessive or variable pile settlement
  - weathered Limestone and cavity feature
- Cavity extending outside foundation footprint
  - excessive foundation settlement
- Pre-drilling holes both a blessing and a curse?
  - Transfer of pile loads through cavity
  - Grouting of cavity in foundation footprint++
Remedial measures – piles schematically

Marlstone
Weathered Limestone
Cavity
Limestone
Remedial measures – for piles

- Re-drill pre-drilling holes
- Install reinforcement (12 m)
- Grout to bored pile toe level
- Execute Ø2 m bored pile
Remedial measures – foundation per se

- Drill "destructively" 40 m total length
  - Ø141 mm casing in Marl
  - Ø105-115 mm uncased
- Pressure grout staggered
  - bottom part (12 bar)
  - cased part (gravity)
- 20 primary holes
- 26 secondary holes
- Monitor excess grout take
- Tertiary grouting?
Evaluation: grouting of cavity

- Discontinuous feature
- Pile P4/3 most onerously affected
- Max pressure grout take coincide with max micropile take
- Primary: $1.9 \pm 3.8 \text{ m}^3$
- Secondary: $1.1 \pm 2.6 \text{ m}^3$
- Tertiary not needed

Primary:
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- Tertiary not needed
Grouting result – versus hypothesis
Axial pile load test using O-cells

O-cell

Top down

O-Cell

\[
N \quad (1-x)N
\]

End bearing
Pile load test: verification of axial capacity

- upper 26.1 m test pile (Ø2 m)
- O-cells (Ø870 mm)
- break in concrete
- lower 1 m test pile (Ø2 m)
- cavity feature 1-2 m high?
Pile load test: test location and set-up
Pile load test: verification of axial capacity

Gross O-cell load [MN]

\[ \delta \text{ [mm]} \]

Max load toe

End of creep O-cell down
Pile load test: verification of axial capacity

\[ \delta \text{ [mm]} \]

\[ \text{Gross O-cell load [MN]} \]

Max load shaft

End of creep O-cell up
Conclusions

- No evidence of detrimental effect from cavity
- Pile behaviour largely linear to max applied load
- Extrapolated loads
  - 200 mm toe and >5 mm shaft → 110 MN
  - at or above concrete capacity
- Close monitoring and observations → savings in time & money
..and the bridge is actually being built!
Closing remarks

• Facing challenges in Megaprojects we learn from
  - mistakes (not just our own!)
  - precedents
  - colleagues, competitors, mentors

• and gain insight from
  - other disciplines (cross pollination)
  - lateral thinking
  - open-mindedness

• A privilege to have be involved in Megaprojects
  - early and adequate ground conditions
  - transparent data/document handling
  - team approach
  - risk should be identified & managed