Presentation outline

• Brief project description
• Geology & ground investigations
• Requirements - seismicity
• Foundation challenges & (elegant) solutions
• Conclusion - Lessons learned
Project rationale and history

- Part of 420 km infrastructure project Gebze-Izmir
- 50% reduction in travel time
- BOT project
  - total cost $11 billion
  - bridge $1.1 billion
- Project considered since 90'ies
  - Sep. 2010 tender submission
  - Sep. 2011 start DD
  - Sep. 2012 prep. site works
  - Jan. 2013 permanent works
- Mar. 2016 bridge completion

Project organisation

- Owner: KGM – Turkish Ministry of Traffic
- Employer: OYTOL/NÖMAYG Joint Venture
- Bridge Contractor: IHI, Japan
- Bridge designer: COWI, Denmark
General layout of Izmit Bay Suspension Bridge

Navigational clearance: 64.3 m x 1000 m
40-65 m water depth

Detailed Design; layout of foundation structures

NA gravity structure
Tower foundation with base isolation
SA gravity structure
Geological setting & ground investigations

• GIR prepared Based on ground investigations:
  2009-2011 Phase 1
  2011-2012 Phase 2 supplementary

• 56 boreholes (depth 32 - 200 m)
  - sampling, down the hole CPTU, Field vane,
  - suspension and caliper logging, (acoustic & optical telev.)

• 100+ CPTUs (max depth 42 m)

• Near-shore and offshore geophysics

• Standard classification testing

• Advanced static & dynamic laboratory testing
  - CRS and IL oedometer; CAU triax, DSS
  - rapid direct simple shear, reasonant column,
  - strain and stress controlled cyclic direct simple shear

North Anatolian Fault - seismicity

• Bridge site close to North Anatolian Fault

• Koecali 1999 EQ: M= 7.5
  - catastrophic

• Progression ominous along the 1600 km NAF
Inferred seismicity risks along alignment

- North anchor block: no faulting
- Towers: no faulting
- South anchor block: initially none
- Reinterpretation during DD: possible secondary fault zone
- Relocation of SA by 160 m and towers by 80 m

Design profile & issues South anchor block

Possible secondary fault below Unit 4
Possible liquefaction top 10 m
**Design profile North anchor block & side span pier**

- Layer with liquefaction potential
- Non liquefiable rock fill

**Design profiles North & South towers**

- Deep seated competent soils
- Conditions similar to Rion–Antirion
- EQ and ship impact also roughly similar
- Piles & Base isolation
Performance criteria – seismic most onerous

<table>
<thead>
<tr>
<th>Seismic Event</th>
<th>Ground Motion Return Period</th>
<th>Service Performance Level</th>
<th>Damage Performance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Evaluation Earthquake (FEE)</td>
<td>150 years (50% in 100 years)</td>
<td>Immediate Access</td>
<td>No damage</td>
</tr>
<tr>
<td>Safety Evaluation Earthquake (SEE)</td>
<td>1000 years (10% in 100 years)</td>
<td>Limited Access</td>
<td>Repairable damage</td>
</tr>
<tr>
<td>No Collapse Earthquake (NCE)</td>
<td>2475 years (4% in 100 years)</td>
<td>-</td>
<td>No collapse, no casualties Significant damage</td>
</tr>
</tbody>
</table>

Rock outcrop PGAs: FEE 0.25g, SEE 0.65g and NCE 0.87 g

Foundation challenges and solutions

North anchor block & side span pier
Changes in assumptions – IDC worries

Tender Design & pre-Detailed Design:
• Competent limestone in one domain
• Stair-step wedge failure
• Rock strength based on "global strength"

Detailed design assumptions
• Possibly more than one rock domain
• Continuous bedding plane assumed
• Joints to form release mechanism assumed
• Limestone-limestone contact

Conservative and robust assumptions

Proof: Trial excavations in NA footprint

Plan dimensions of NA
Updated geological model for NA

Design impact:

• Detailed Design based on continuous bedding with lower bound strength

• Site inspection verified discontinuous & incipient bedding ➔ Detailed Design approach valid and conservative

• Micro-fractured rock described as Fault 1 ➔ no influence on geotechnical verification; change in stiffness insignificant for global behaviour

• East front pad partially within Fault 2 regime ➔ material excavated and replaced with concrete

• Karst features of very minor impact - filled with concrete

Kinematic analysis for North anchor block

Lower bound $\varphi = 40^\circ$ in bedding plane

• ULS + FEE, $\text{FoS} = 1.8$ to $2.4$

• SEE + NCE, $\text{FoS} < 1.0$, ➔ possible
  $\delta_{\text{SEE}} = 50 \text{ mm}$
  $\delta_{\text{NCE}} = 110 \text{ mm}$
Stages in excavation of North anchor block

- Grout curtain around excavation + pumping
- Grouting at points of ingress or plates bolted on
- Sheeting to avoid casting against wet rock

Water ingress at North anchor block
North side span pier

- Bored rock socket foundation (Ø1.85 m)
- Pile cap below sea level and liquefaction risk
- Confinement jet grout wall 56 by 80 m
- Jet grouting to improve soil volume
- O-cell test on pile with minimum load

Foundation challenges and solutions

Tower foundations
**Tower foundations**

- 195 Ø2 m steel pile inclusions to improve soil
- Gravel bed fuse as base isolation measure
- "Ground work" done by Rion-Antirion!

**General basis of seismic analysis method**

- Global in-house IBDAS 3D FE software
- 7 sets of earthquake time histories,
  at each of the 4 foundations,
  for each of the 3 design earthquake return periods (FEE, SEE, NCE),
  each comprising 3 components
  (two horizontal (FN, FP) and one vertical)
- 252 in total –
  (very time consuming – excessive amount of output)
**Tower foundation verification**

**Soil-structure interaction:**
- Equivalent non-linear soil-foundation spring stiffness and damping coefficients
- Gravel bed springs and "soil" springs
- Single point (global) and distributed springs (design)
- (SSI is handled this way for all foundations!)

**Geotechnical verification comprised**
- Strength analysis (Ultimate limit state)
- Strength analysis (Ship collision)
- Force based seismic verification (FEE)
- Displacement based verification (SEE+NCE)
- Settlement analysis
Tower foundation verification - results

Permanent displacement as a result of the fuse

<table>
<thead>
<tr>
<th>δ (m)</th>
<th>Tower</th>
<th>Transient (max)</th>
<th>Permanent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SEE</td>
<td>NCE</td>
</tr>
<tr>
<td>longitudinal</td>
<td>north</td>
<td>0.20</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>south</td>
<td>0.45</td>
<td>0.87</td>
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<tr>
<td>transverse</td>
<td>north</td>
<td>0.14</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>south</td>
<td>0.24</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Long-term settlements at full bridge load

- Settlement occurring during 100 years lifetime (m)

<table>
<thead>
<tr>
<th>Settlement (m)</th>
<th>North tower</th>
<th>creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>-160</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>-140</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>-120</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>-100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>-80</td>
<td>100</td>
<td></td>
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<td>-60</td>
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<td>100</td>
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<td>-20</td>
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<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

+ "δ init" up to completion (adjustment before "steel")

Predictions accepted ➔ over-height for clearance ➔ monitoring of all major events and long term

North tower foundation settlements

- Long term settlements after completion at ~ 250 kPa

  South tower: 700 to 1000 mm
  North tower: 340 to 640 mm

- After placing of Plinth 3rd lift at 101 kPa (2014-07-18)

<table>
<thead>
<tr>
<th>Tower</th>
<th>Prediction (mm)</th>
<th>Actual (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>140</td>
<td>138</td>
</tr>
<tr>
<td>South</td>
<td>280</td>
<td>237</td>
</tr>
</tbody>
</table>
North tower foundation settlements

- Factor 0.85 on South Tower
  2015-01-29

South tower: 595 to 850 mm
North tower: 340 to 640 mm

- Break after free standing tower at 127 kPa (2015-04-27)

<table>
<thead>
<tr>
<th>Tower</th>
<th>Prediction (mm)</th>
<th>Actual (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>184</td>
<td>184</td>
</tr>
<tr>
<td>South</td>
<td>335</td>
<td>339</td>
</tr>
</tbody>
</table>

Tower foundation verification - challenges

- Placing the 3 m thick gravel bed with piles in place by fall pipe
- Levelling gravel bed
- Verification of stiffness achieved by plate loading tests (on retrieved box filled in situ)
Foundation challenges and solutions

South anchor block

Tender design solution – challenging!
**Tender design solution – challenging!**

- Pile foundation as H/V >> 1
- Barrettes not an option for sub-contractor
- Front and rear pads
- Diaphragm wall for construction and permanent condition
- How to handle anchors?
- Side span pier separate

**Alternative design**

- Development of DD ➔ increasing V (+ issues with the secondary fault) ➔
- H/V < 1 & competent sand layer at 15 m depth
- Why not use a direct foundation?
- and solve problem with anchors and side span pier
Elegant alternative

- Ø58 m overlapping diaphragm walls capping beam
- 3 temporary pile supported struts
- Internal struts at front
South anchor block geotechnical verification

- Analysis of secondary fault issue
- Strength analysis
- Settlement analysis
- Force based seismic verification, FEE
- Displacement based verification, SEE+NCE

Analytical approach + Plaxis 3D + IBDAS

SA geotechnical verification results

Strength analysis FOS:
- ULS-GEO = 3.84; NCE = 1.56

Settlements/displacements:
- $\delta_v$ (SLS) = 140 mm (during construction)
- $\delta_H$ (NCE) = 60 – 80 mm (~ elastic; sliding)
Conclusions & lessons learned

- Expect to meet the unexpected
- Fruitful co-operation and understanding between IHI & COWI
- Challenges overcome by elegant & innovative solutions
- Use of well winnowed techniques
- Readiness to accept changing design conditions due to
  - changes in ground conditions
  - construction programme
  - economy
  - availability of "tools"