DESIGN OF CHACAO BRIDGE

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Chacao Bridge – situation

Chiloé Island

Chacao Bridge
Chiloe Island as tourist attraction
2nd largest producer after Norway

But stabilization of production in 2007 due to a health problem

Evolution of the number of salmon farms between the 1980s and the 2000s

Salmon fish farm production
Chacao Bridge – introduction
Client/Owner: MOP
Contract: DB
Awarded: 2014
Contractor: CPC (Consorcio Puente Chacao)
Construction commencement: 2017
Finished: 2023
CAMPECHE, MÉXICO

**Designer (SAJ)**

SYSTRA + AAS-JAKOBSEN

50% 50%

**Contractor (CPC)**

HYUNDAI + OAS

Consorcio puente chacao

**Final Approval**

Final Client (MOP)

Ministerio de Obras Públicas

Gobierno de Chile

**Checker validation**

**Checker (AIF)**

COWI + R&Q INGENIERIA

Deliverables

Comments
CAMPECHE, MÉXICO

- Suspension bridge: 2 main spans and one suspended side span in North
- Approach bridge South: 220m
- 3 pylons: 199m, 175m, 157m
- Navigational clearance: 600x50m
- Chacao Bridge is a link between Chiloé Island and Chile mainland
  - Chanel depth can reach 120 meters along bridge axis
  - Central Pylon founded on Roca Remolinos in the middle of Chacao Chanel
Central Pylon (Roca Remolinos)

- **Caprock**: Medium to fine sand, well to high cemented, low to medium content of silt, fine to medium sized surrounded gravel, few rock fragments

- **Unit 3b2: 40°/150kPa**: Medium grained sand, well to low cemented mixed with sub-rounded gravel

- **Unit 3b1: 40°/15kPa**: Stiff or low cemented silt with few thin layers of fine to medium sand are embedded

- **Unit 2c: 41°/100kPa**
South Bank
South shore
North Bank
North shore
Environmental conditions

- Strong winds
- Strong currents
- High seismicity including Tsunami
Chacao Bridge is located in one of the most important seismic area in the world

- 3 of the 12 major seismic events ever recorded occur in Chile

<table>
<thead>
<tr>
<th>Rank</th>
<th>Date</th>
<th>Location</th>
<th>Country</th>
<th>Magnitude</th>
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<tbody>
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<td>1</td>
<td>1960 May 22</td>
<td>Valdivia</td>
<td>Chile</td>
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<tr>
<td>2</td>
<td>1964 March 27</td>
<td>Prince William Sound</td>
<td>Alaska, United States</td>
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<td>3</td>
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<td>Sumatra</td>
<td>Indonesia</td>
<td>9.3</td>
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<td>4</td>
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<td>Japan</td>
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<td>5</td>
<td>1952 November 4</td>
<td>Kamchatka</td>
<td>Soviet Union</td>
<td>9.0</td>
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<td>6</td>
<td>1868 August 13</td>
<td>Arica</td>
<td>Chile</td>
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<td>7</td>
<td>1700 January 26</td>
<td>Pacific Ocean</td>
<td>USA and Canada</td>
<td>9.0</td>
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<tr>
<td>8</td>
<td>869 July 9</td>
<td>Pacific Ocean, Tōhoku region</td>
<td>Japan</td>
<td>8.9</td>
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<tr>
<td>9</td>
<td>1762 April 2</td>
<td>Chittagong</td>
<td>Bangladesh</td>
<td>8.8</td>
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<tr>
<td>10</td>
<td>1833 November 25</td>
<td>Sumatra</td>
<td>Indonesia</td>
<td>8.8</td>
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<tr>
<td>11</td>
<td>1906 January 31</td>
<td>Ecuador – Colombia</td>
<td>Ecuador – Colombia</td>
<td>8.8</td>
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<tr>
<td>12</td>
<td>2010 February 27</td>
<td>Maule</td>
<td>Chile</td>
<td>8.8</td>
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</tbody>
</table>

- Seismic hazard
  - Subduction
  - Crustal
VALVIDIA EARTHQUAKE 1960

- Magnitude 9.6
- Most powerful earthquake ever recorded
- Cause of a tsunami with waves up to 25m

Plot of the maximum amplitude for the tsunami waves generated by the 1960 Valdivia Earthquake.
MAULE EARTHQUAKE 2010

- Magnitude 8.8
- In the top 12 of the most powerful earthquakes ever recorded

- Cause of a tsunami with waves up to 10m

Plot of the maximum amplitude for the tsunami waves generated by the 2010 Maule Earthquake.
Chacao Bridge – design approach

Design Basis

1. Contract (ITB)
2. AASHTO 2012
3. Manual de Carreteras (Chilean code)
4. Other codes where necessary

=> Design Manual
Design challenges

- Project specific requirements unclear
- AASHTO deficiencies
- Manual de Carreteras limitations
- Eurocode
- Japanese code
- Common practice
- Robustness
- Collapse philosophy
Basic engineering

- Soil investigations
- Topography
- Bathymetry
- Wind measurements
- Seismic accelerometers
- Current
- Wave
- Ship traffic
- Risk analyses
- Seismic hazard analyses
- Wind tunnel testing
Sesimic analyses

- Sesimic hazard analyses
- Time series
- Response spectras
- All directions
- All foundation points
- Different return periods
- Soil structure interaction/impedance matrices

=> Input Global structural analyses
=> Slope stability during seismic events
Pseudo-static calculations $\text{FoS} \approx 1$
- Permanent displacement almost nil

Pseudo-static calculations $\text{FoS} < 1$
- Permanent displacement occurs
- Smaller the FoS greater permanent displacement
Time history analysis - Earthquake
Response spectra analysis - Earthquake

Response spectra for Central Pylon

Mode 82: T=1.3 s
Mode 107: T=0.98s
Mode 293: T=0.38s
Global model

- RM-Bridge V.10
- 2640 elements
- 9810 degrees of freedom
Features

- Large deformations
- Traffic analysis if all adequate traffic loading
- Composite sections
- All applicable static loading
- Dynamic wind analyses
- Dynamic seismic analyses in frequency domain
- Time series analyses
- Push-over analyses
Tsunami

- Hydrodynamic simulations gives a set of Tsunami parameters at the bridge site. (max. wave height, maximum current speed, wave period)

- These values are input to a local marine analysis model (solid elements) which again results in a set of marine loads to be applied in the global model (RM Bridge)
Soil Structure Interaction

- Total system split into two:
  1. A foundation system investigated in frequency domain or time domain in specialized software (SASSI/Dynaflow/Flaq)
  2. A structural system investigated in the modal domain or time domain by RMBridge

- Standard procedure used for numerous structures
  - Nuclear power plants
  - Bridges
  - Offshore structures
Earthquake Analysis

- Response spectra analyses as basis for design
- Time history analyses to verify results
- Time history analyses to check effects not easily and consistently modelled by the response spectrum method
- Push over analysis to investigate deformation capacity and establish where hinges will occur under an Earthquake exceeding the design earthquake
Earthquake Analysis

Comparison RS and TS
Chacao Bridge – foundations

Modal spectral analysis

- Due to slope instability under seismic conditions: permanent displacements
  - Structural model GA
    - Impedance matrix
    - Kinematic interaction forces
  - Geotechnical model

Chacao model

- Structural model GA
  - Imposed permanent displacements (H/V) to GA
  - Kinematic interaction forces
  - Forces induced by accumulation of permanent H/V displacements
  - Geotechnical model
2.50m Piles diameter with Structural Steel casing up to 79mm thickness

- Casing embedment in the pilecap
- Steel casing filled with reinforced concrete
- Bottom of steel casing
- Reinforced concrete pile
**Structural Steel Casing Design**
- 3D non linear model on Sofistik to show no bonding between steel casing and reinforced concrete part

- Steel casing and Reinforced concrete piles acts separately

- Each component can be designed separately by considering
  - Steel casing sustains Shear Force and Bending Moment
  - Reinforced concrete part sustains Axial Force, Shear Force and Bending Moment

- Main assumption:
  - Casing and Concrete have the same curvature
  - Moment and Shear are shared by Casing and Concrete with a proportion linked to their EI
  - EI is considered with cracked stiffness
Structural Steel Casing Connection to Pilecap

- Shear connectors are used to transfer the forces from the casing to the pilecap.
- Embedment length of the casing in the pilecap up to 3.65m.
• 4 units of pilecap with 9 piles each, linked with tie beams
• The pilecaps are prestressed to ensure pile to pilecap connection.
Two distinct mechanisms:

Transfer of the moment in the casing through the shear connectors

Transfer of the moment in the pile through Pressure/contra-Pressure mechanism

⇒ Two sets of Strut-and-Tie Models
3D Non-linear Model
3rd order Analysis with Code Astre
1/9th of the pilecap

Non-linear materials:
- Concrete
- Structural steel
- Prestressing steel
- Reinforcing steel
Stresses in reinforcement

Forces in shear studs

Stresses in steel casing

Stress flow in concrete
2D Strut-and-ties models to modelize 3D pilecap
Chacao Bridge – pylons (N+S)
Is it relevant to apply the same Code Requirements to Pylon A as Pier B?

Pylon A

Pier B
- Shear Force and Moment is interrelated
- Strength of Hinges and Ductility is interrelated
- Behave inelastically without significant strength loss

Plastic hinge methodology vs. elastic design approach.
Example push over analysis – South and North pylon

Observations

- Hinges will first develop in bottom of pylon, and secondly at elevation in approx. 2/3 of the pylon height.
- Hinges will first develop well beyond the MPE design level earthquake (2-2.5 times 1000 year event).
Summary, north and south pylon:

- Heavily reinforced
- Wind on freestanding tower in general governing for design
- Elastic behavior for MPE (1000 year seismic event) and 1.4 x MPE
- BFF 1.4 taken into account to ensure ductile behaviour
- Permanent deflection in seismic events taken into account in the design
Chacao Bridge – central pylon
• PROBLEM OF SUSPENSION BRIDGES WITH MULTIPLE SPANS
• If one span only is loaded, there is a large longitudinal bending moment in the central pylon and in the loaded span, and large deck deflection
→ So, the central pylon must be stiff enough
• But if the central pylon is too stiff, there is a large difference in main cable forces on both sides of this pylon, so the cable could slide on its saddle
CENTRAL PYLON PUSH-OVER ANALYSIS: PROCESS

- Identify potential 1st plastic hinge.
- Identify 2nd plastic hinge and diffusion of plastic deformation.
- Resize reinforcement for critical locations.
- Check brittle failure
- Check actual strains for each and every step
- Check pylon actual capacity/strains: main client’s concern. What is happening actually for a seismic level higher than the design one (MPE)?
Chacao Bridge – SAB
Spans 41m+53m+43m.
Detailed Design of the Chacao steel box according to AASHTO, using beam or FE methods
Buckling analysis of a stiffened panel and plot of the resistance interaction curve (s; t), according to the Eurocode FE method.
Fatigue analysis of specific details (Orthotropic slab, truss connection ...)

each detail is studied with a refined model in order to determine the stress range accurately
Local design of the hanger anchorage plate
3D Non-Linear FE Analysis with solid elements in ANSYS
Local FE model at the end of the bridge girder which describes the boundary conditions (Link shoes, buffers, wind bearings ...) with MIDAS.
- FEA Models Crossbeams
- Crossbeam spacing: 4m
Chacao Bridge – main cable

Main cable

<table>
<thead>
<tr>
<th>Parameter</th>
<th>General spans</th>
<th>North side span</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter steel wire (excl. zinc)</td>
<td>5.32 mm</td>
<td>5.32 mm</td>
</tr>
<tr>
<td>Nominal wire diameter (for capacity)</td>
<td>5.40 mm</td>
<td>5.40 mm</td>
</tr>
<tr>
<td>Number of wires per strand</td>
<td>127</td>
<td>127</td>
</tr>
<tr>
<td>Number of strands per cable</td>
<td>60</td>
<td>62</td>
</tr>
<tr>
<td>Steel area</td>
<td>0.169 m²</td>
<td>0.175 m²</td>
</tr>
<tr>
<td>Nominal cable area (for capacity)</td>
<td>0.174 m²</td>
<td>0.180 m²</td>
</tr>
<tr>
<td>Cable diameter outside clamps (ex. wrapping wire, void ratio 0.19)</td>
<td>524 mm</td>
<td>532 mm</td>
</tr>
<tr>
<td>Cable diameter inside clamps (void ratio 0.17)</td>
<td>517 mm</td>
<td>526 mm</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength wire</td>
<td>1860 MPa</td>
<td>1860 MPa</td>
</tr>
</tbody>
</table>

Shape in spans

Shape at saddles

CAMPECHE, MÉXICO
• Central Pylon Saddle:
  • Eurocode used for slippage control:
    \[
    \max \left[ \frac{F_{Ed_1}}{F_{Ed_2}} \right] \leq e \left[ \frac{\mu \alpha}{\gamma_{M,fr}} \right]
    \]
    \[
    \left[ \frac{F_{Ed_1} - k F_r \mu}{F_{Ed_2}} \right] \leq e \left[ \frac{\mu \alpha}{\gamma_{M,fr}} \right] \text{ (with clamping)}
    \]
  • Traffic in one span only governing.
  • Optimization of pylon stiffness, saddle slippage capacity and deck deflection.
  • Clamped system with vertical shear plates for utilizing friction from transverse pressure from strands

• North and South Pylon Saddles:
  • Seismic reaction forces between pylons and cable governing
Main Structural Parts
- Massive Concrete Block
- Bent Block
- Shed
- 3D Finite Element Model for North and South Anchorage Blocks
  - Half model considering symmetric boundary condition
  - Solid Element for concrete and bar element for tendons
  - Consideration of soil stiffness for each layer
  - Consideration of main construction sequences
Chacao Bridge – misc.

- Outfitting and equipment
  - FMU
  - Access
  - Inspection wagons
  - Roadway outfitting
  - SHMS
  - Dehumidification systems
  - HVAC
  - Electric

- Operation and maintenance
- Approach roads
- Landscaping
Chacao Bridge – construction

[CABJ] Central Pylon Test Pile

Casing Driving and Pre-boring
Drilling uncased level below casing
[CABJ] Central Pylon Test Pile (1/21)

Connecting Rebar cage No.4
MOP anuncia que construcción de Puente Chacao finalizaría en 2023

Autor: P. Barría y C. Mardones

El puente colgante de 2.750 metros busca unir en tres minutos la isla Grande de Chiloé con el continente.
El 01 de Marzo de 2018

Comienza construcción definitiva del Puente Chacao en el sur de Chile

La obra será ejecutada en 60 meses con un presupuesto superior a US$700 millones

A bordo de un transbordador que recorrió la zona de faenas que realiza la plataforma Jack Up Pionner III en el Canal de Chacao, Región de Los Lagos, el ministro de Obras Públicas anunció la construcción definitiva del puente que conectará a la isla de Chiloé con el continente. Durante el recorrido, el equipo técnico de la empresa coreana Hyundai, a cargo de la construcción del puente, recibió los planos de construcción.
Chacao Bridge – conclusions

• Technical challenges due to site conditions
• Technical challenges due to seismic demands
• Complete designs delivered DD, CDD, FDD
• Partial early approval of design 2017
• Approval of design expected May 2018
Chacao Bridge – conclusion