LOS CARAS ISOLATED BRIDGE IN THE 2016 MUISNE ECUADOR EARTHQUAKE
Behavior of Piers & Deep Pile Foundations

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OUTLINE

• OVERVIEW
• SUBSURFACE CONDITIONS
• GEOTECHNICAL DESIGN
• SEISMIC STRUCTURAL DESIGN
  Design Criteria
  Base Isolation
• OBSERVED PERFORMANCE
• NUMERICAL MODELS
• CONCLUSIONS
Base Isolation
Triple pendulum

Seismic Hazard
M$_w$ 7.1, 1998

M$_w$ 7.8 Muisne EQ
4/16/2016

DESIGN APPROACH TOWARDS
MINIMIZING THE RISK OF DAMAGE OR COLLAPSE
• **Los Caras** is the **longest Bridge in Ecuador** between Bahía de Caráquez & San Vicente.

• **48 piers, 2-km long.**

• Designed by the **Ecuadorian Army Corps of Engineers**, completed in 2010

• Following Muisne EQ, the bridge remained functional despite high accelerations, liquefaction, and largest-ever recorded triple pendulum bearing **displacement ≈ 65 cm** at Pier 12, with **average ≈ 35 cm**.
«LOS CARAS» BRIDGE DESCRIPTION

GPS: 0°36'33.6"S, 80°24'58.7"W

Ecuador Army Corps of Engineers
Typical Pier

- **FINISHES**
- **SUPER STRUCTURE**
- **SUB STRUCTURE**
- **FOUNDATION**

Diagram showing:
- Lamp
- Road of Bicycle
- Slab
- Base isolation
- Footing
- Column
- Pier
- Parapet
- Girder
- Tubular Pile

Dimensions and levels:
- N+11.95
- N+7.688
- N+2.330
- N+0.68
- N+0.00
- N+9.288

Basement isolation 13.20 m.
Main Studies & Findings

- **Top 10 m of subsurface conditions are poor**, typical of river estuaries, with top 4-m thick soft river mud layer, **followed by potentially liquefiable sands**.

- **Soil-Structure Interaction (SSI) models** to study the 2016 observations, especially for: 
  - *Pier 12* that suffered the highest displacements
  - *Piers 10, 44* which deformed according to the original design.

- Models replicated the observed foundation behavior: no **significant vertical settlements**, but large **horizontal movements** likely due to inadequate upper lateral support. This resulted in exceedance of design accelerations and deformations at *Pier 12*.

- Despite the distress, **the bridge remained in service immediately after the earthquake**, with minimal repair needs.

- This Bridge is a resilient example of a major project, confirming the value of using advanced seismic protective technologies in anticipation of major earthquakes.
Subsurface Conditions

- Characteristic estuarine environment formed by alluvial deposits.
- Good quality rock is found at depths > 100 m.
- Top 10 m of poor soils of river estuaries: top 4-m soft river mud, followed by liquefiable sands.
Foundation Design

- Site conditions required **use of deep foundations; open-end steel friction driven pipe piles** with diam. 1.22 m, wall thickness of 20-25 mm and length from 32 to 65 m.
- Pile foundation design was done per AASHTO LRFD (2007) [2].
- Skin Friction piles were selected for 38 piers (Pier 7 to 44) in the central segment.
- End-bearing piles were used only in Pier 6.
- Foundations were analyzed originally using p-y curves.

**8-Pile layout**

**9-Pile layout**
Geotechnical Design: P-y Curves

Pier 10

Pier 12
Geotechnical Design: P-y Curves

Pier 44
Isolation System

• The seismic hazard study for the bridge area revealed that the PGA at rock was around 0.40 g.

• Analysis was performed for the Design Basic Earthquake (DBE) and Maximum Considered Earthquake (MCE) levels for the bridge piers and seismic isolators.
Structural Design

• Soil influence on bridge behavior was established through the use of SSI models.
## Structural Design Displacements

<table>
<thead>
<tr>
<th>Pier ID</th>
<th>Longitudinal displacements</th>
<th>Transversal displacements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pier head disp. (cm)</td>
<td>Top isolator displ. (cm)</td>
</tr>
<tr>
<td>P10</td>
<td>17.72</td>
<td>44.60</td>
</tr>
<tr>
<td>P12</td>
<td>19.67</td>
<td>44.57</td>
</tr>
<tr>
<td>P44</td>
<td>12.57</td>
<td>48.67</td>
</tr>
</tbody>
</table>
Measured Displacements in Isolators

View No. 1

View No. 2

View No. 3

View No. 4

152 TFP

Pier

cm

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48

0 10 20 30 40 50 60 70

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48

Pier
The source of the problems in P12 could be structural, geotechnical, or a combination of the two.

The structure of the central section of the Bridge was revised in 3 instances, with 3 different objectives:

1) detect damage that can affect continuous operation of the bridge;
2) each seismic isolator was revised, and
3) each structural element was checked, in search of traces of plastic hinges, or cracking.

The entire detailed revision process allowed discarding any structural constructive defect that could have caused the greatest displacement, including the possibility that an inelastic behavior had occurred at the head of the piles, so the exhaustive examination included piers, isolators and superstructure.

The pier structure was more flexible than expected during design, due to a lack of lateral support of the soil layers. Sand liquefaction and soft clays in upper layers did not bring enough lateral support.
Numerical Models

• A few months after the earthquake, 16 compaction piles were driven around P12 in order to densify the soil around this pier.
• Two new models were built to increase the certainty of the global structural behavior and the observed displacements:
  1) A SAP2000 model, with global adjustment of the liquefaction criteria; and
  2) An OpenSees model.
• Compaction pile monitoring allowed having an additional tool to identify soft and dynamically liquefiable layers, and the extension of such layers.

![Image of compaction pile monitoring](image.png)
Conclusions

• During the seismic event of Muisne, Los Caras bridge had PGAs, very close to design accelerations, except for P12, which was higher.

• The characteristics of the foundation soil, forced the use of deep foundations supported by friction piles.

• Among all 38 piles of the central section, only P12 presents lateral transversal displacements superior to those foreseen in the digital interaction models, used for the analysis and design.

• SPT tests and the soil characterization tests conducted at the time of the design, were not enough to describe the soil behavior of the foundation on P12, under lateral seismic loads.

• In P12, the depth of the liquefiable strata and soft strata was greater than that detected during the geotechnical studies prior to the design of the bridge, and the traditional verification tests during construction.

• The density compaction piles provided a better description of the presence of wide horizontal layers, which allows to considerably improve the modeling of the foundation structure.
Conclusions

• The depth increase of inadequate soil layers, had no impact on the vertical bearing capacity of the piles, since the ability to support vertical loads depends on the resistance of deeper layers, but it had an impact on the lateral flexibility of the foundation structure due to horizontal seismic loads.

• The structure of the foundation did not suffer significant impact because it was designed with a seismic force reduction factor of only 1.1, which left capacity reserve in both the elastic and the inelastic range.

• The criteria and recommendations used to determine if certain granular strata levels are liquefiable or not, are probabilistic correlations, in which it is possible that a small percentage of such cases, are not met. In the case of Los Caras bridge the probabilistic correlation failure was 2.5% of all cases studied.

• Local soil amplification may be very important when dealing with soft or liquefiable soils, in river deposits.

• To improve bridge performance, under large seismic loads, there is a feedback need of test results made during construction, to make small adjustments to foundation design.
Thank you!