EERI/PEER/FHWA Bridge Team Report

Performance of Highway and Railway Structures during the February 27, 2010 Maule Chile Earthquake

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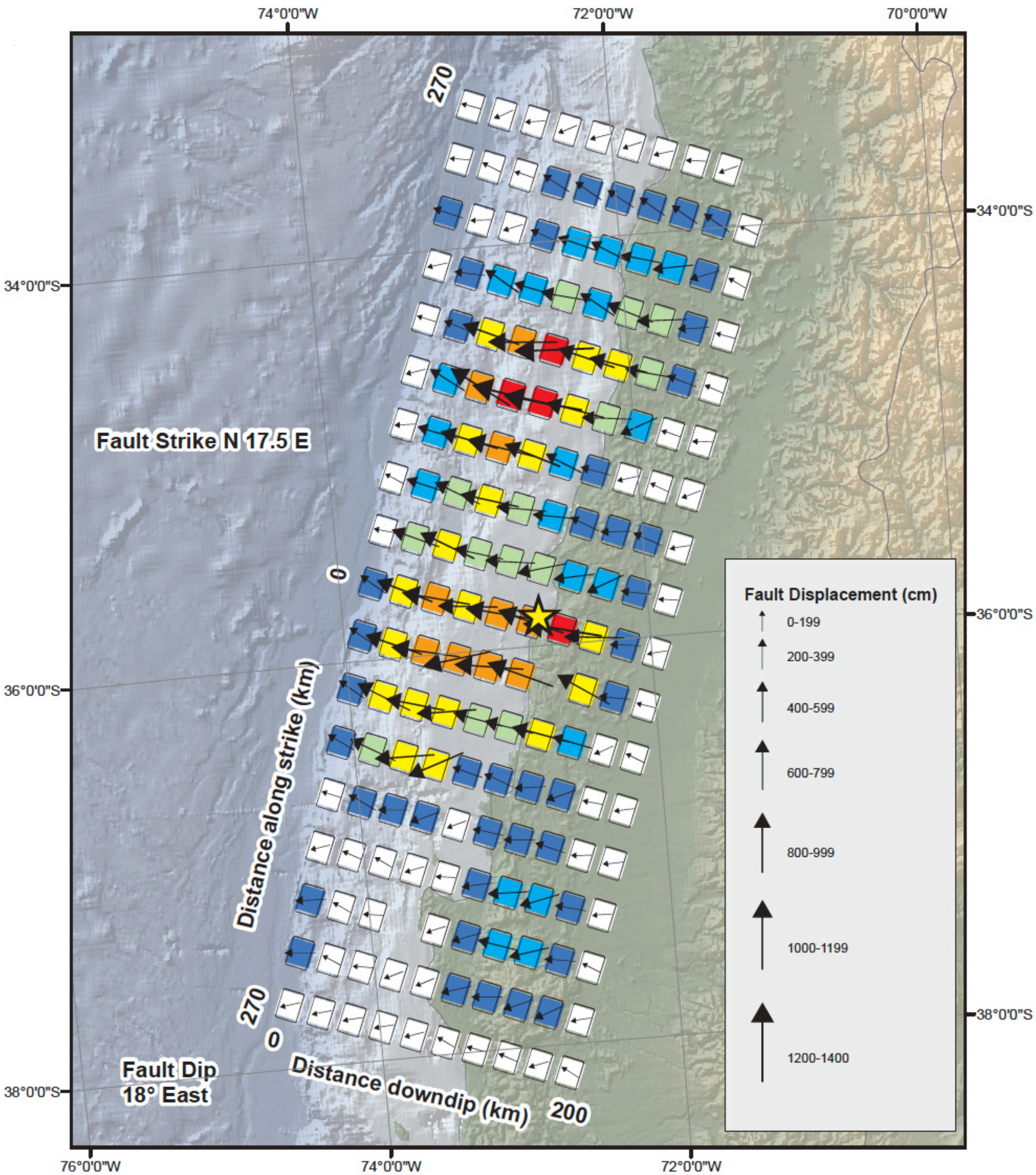
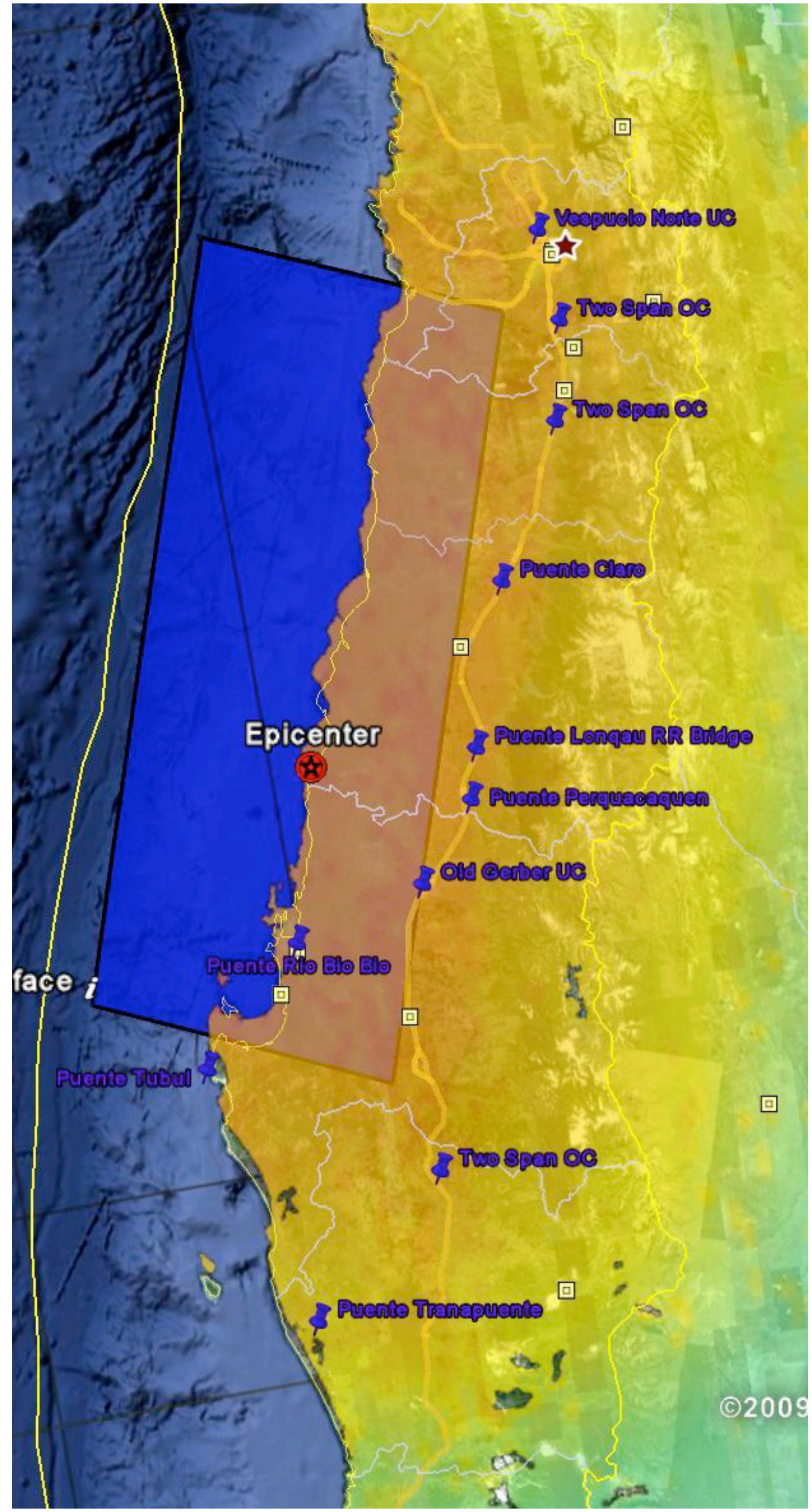
Fault Displacement Model
(Finite Fault Model)

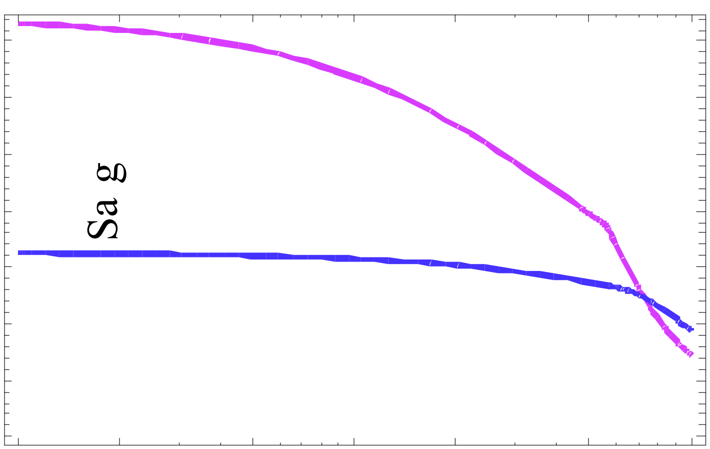


FINITE FAULT MODEL (Chen Ji, University of California at Santa Barbara and Gavin Hayes, USGS)



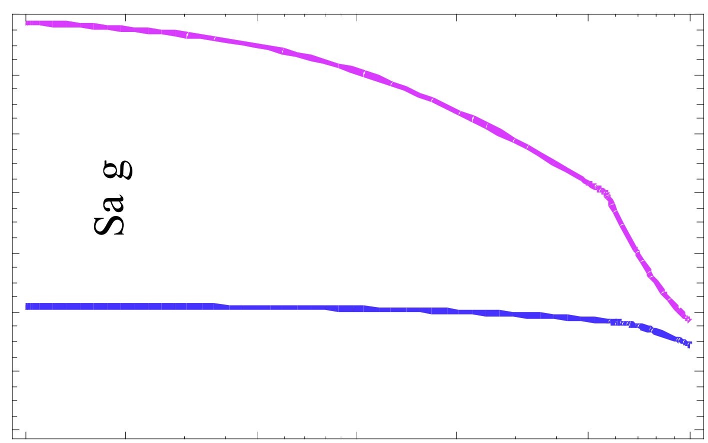
Comparison of Youngs et al. (1997) subduction model and Campbell-Bozorgnia (2008) shallow crustal model as applied to Cascadia subduction zone.

PGA on soft rock



Distance

Sa (1 s) on soil



Distance

Subduction is blue

Crustal (on a reverse fault with the geometry of Cascadia dip 15 deg east, top of rupture is 5 km, Mmax=8.3) is red

Caltrans Seismic Design Criteria and the **AASHTO Guide** Specifications For LRFD **Seismic** Bridge Design (used by the other states) are very similar and are based on designing the bridge for the displacement capacity of columns (or other fuse elements).

Chile's Bridge Seismic Code is similar to ATC-6 that Caltrans wrote after the 1971 San Fernando Earthquake.

Enough hinge seat width shall be available to accommodate the anticipated thermal movement, prestress shortening, creep, shrinkage, and the relative longitudinal earthquake displacement demand between the two frames calculated by equation 7.6. The seat width normal to the centerline of bearing shall be calculated by equation 7.5 but not less than 24 inches (600 mm).

$$N \geq \begin{cases} \left(\Delta_{p/s} + \Delta_{cr+sh} + \Delta_{temp} + \Delta_{eq} + 4\right) & \text{(in)} \\ \left(\Delta_{p/s} + \Delta_{cr+sh} + \Delta_{temp} + \Delta_{eq} + 100\right) & \text{(mm)} \end{cases} \quad (7.5)$$

N = Minimum seat width normal to the centerline of bearing

$\Delta_{p/s}$ = Displacement attributed to pre-stress shortening

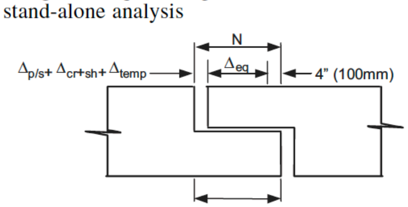
Δ_{cr+sh} = Displacement attributed to creep and shrinkage

Δ_{temp} = Displacement attributed to thermal expansion and contraction

Δ_{eq} = Relative earthquake displacement demand

$$\Delta_{eq} = \sqrt{\left(\Delta_D^1\right)^2 + \left(\Delta_D^2\right)^2} \quad (7.6)$$

$\Delta_D^{(i)}$ = The larger earthquake displacement demand for each frame calculated by the global or stand-alone analysis



3.1004.314 Largo de Apoyo Mínimo. Todos los puentes independientes de su categoría de comportamiento sísmico (CCS), deberán cumplir con los requerimientos de largo de apoyo mínimo de los extremos de todas las vigas. Los valores mínimos de los largos de apoyos son según la categoría de comportamiento sísmico las siguientes:

a. Para categorías de comportamiento sísmico a o b:

$$N = (203 + 1{,}67 \cdot L + 6{,}66 \cdot H) \cdot (1 + 0{,}000125 \cdot \alpha^2) \quad \text{mm}^*$$

b. Para categorías de comportamiento sísmico c o d:

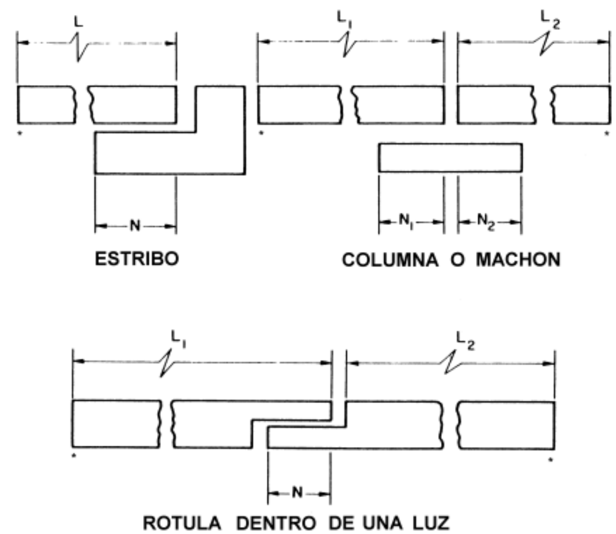
$$N = (305 + 2{,}5 \cdot L + 10 \cdot H) \cdot (1 + 0{,}000125 \cdot \alpha^2) \quad \text{mm}^*$$

donde:

L = longitud en metros del tablero del puente a la próxima junta de expansión o al extremo del tablero del puente. Para rótulas dentro de un tramo, L será la suma de L_1 y L_2, las longitudes de los tramos de tablero a cada lado de la rótula. Para puentes de un vano, L es igual al largo del tablero del puente. Estos largos se muestran esquemáticamente en la Fig. 3.1004.314A.

α = ángulo de esviaje de los apoyos medidos en grados a partir de una línea perpendicular a la luz, y

H = Para estribos: H = 0 para puentes de un vano.
H = altura promedio en metros, de las columnas soportantes del tramo de tablero hasta la próxima junta de expansión.
Para cepas: H = altura de la cepa en metros
Para rótulas: H = altura promedio en metros, de las dos cepas adyacentes.



* JUNTA DE EXPANSION O EXTREMO DEL TABLERO DEL PUENTE

Because most of the bridge damage during the Maule, Chile Earthquake was caused by unseating, we will compare this part of the two codes.

Reconnaissance Observations

Each bridge type exhibited characteristic behavior

- Highway Overcrossings along Route 5
- Conception River Crossings
- Puente Tubul
- Route 5 Undercrossings and River Crossings
- Santiago Expressway Bridges
- Other Observations
- Concluding Remarks

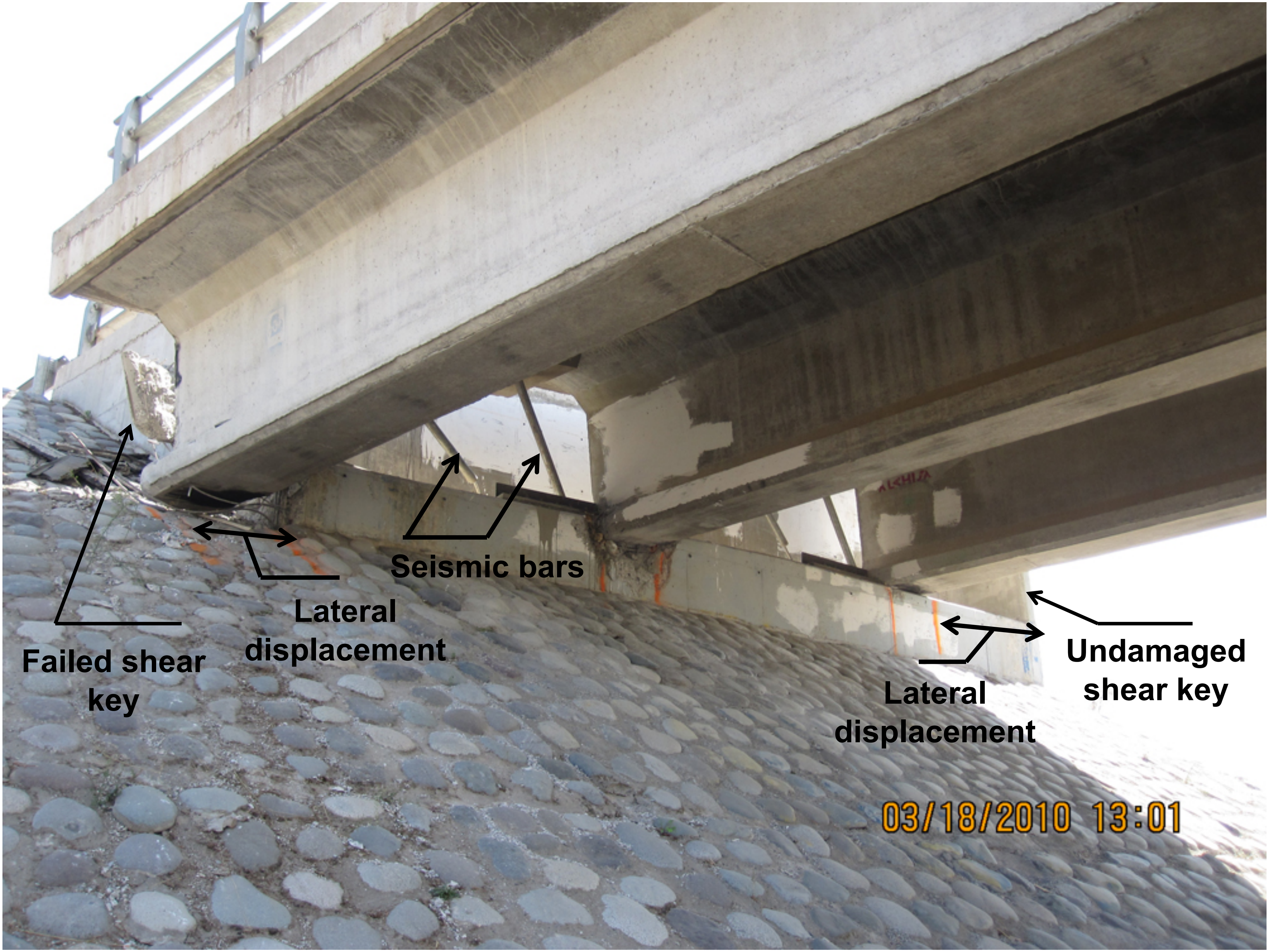
Overcrossings along Route 5

Typically two I-girder spans

- Most O/C's were completely undamaged, and damage appeared very localized and suggests influence on local site or directivity effects.
- In most of the damaged O/C's the entire deck twisted or rotated about a vertical axis representing center of stiffness. In these O/C's shear keys were few in number (exterior girders only), weak, flexible and heavily damaged
- The I-beams were heavily damaged in some of the damaged O/C's with stronger and stiffer shear keys and without end diagraphs.
- Structures with diaphragms and/or continuous decks, appeared to perform better.
- The use of "seismic bars" connecting the deck to the abutments or cap beam appears to have little impact on the performance of the OC's.
- No column damaged was observed
  - *Failure of the shear keys or stoppers at a possible early stage of shaking may suggests that little shear force was transmitted between the deck and the interior bent.*
- Collapse can be often associated with seat widths less than N, which is related to displacement of adjacent frames or girders.

In most of the damaged OC’s the entire deck twisted or rotated about a vertical axis representing center of stiffness (see next slide). In these OC’s shear keys were weak, flexible and heavily damaged. They were constructed at the exterior face of the exterior girders over the abutments and interior bent (6 shear keys n total).


Vertical axis
Rotation or twisting of the deck
Lateral displacement
Deck
Abutment



Failed shear key
Lateral displacement
Seismic bars
Lateral displacement
Undamaged shear key
03/18/2010 13:01

Exterior beams were heavily damaged in some O/C's with stronger and stiffer shear keys and without end diaphragms


Seismic bars (commonly observed in Chilean bridges)
(usually # 6 or 7 bars protected by a steel pipe)


03/18/2010 14:09

Concepcion River Crossings

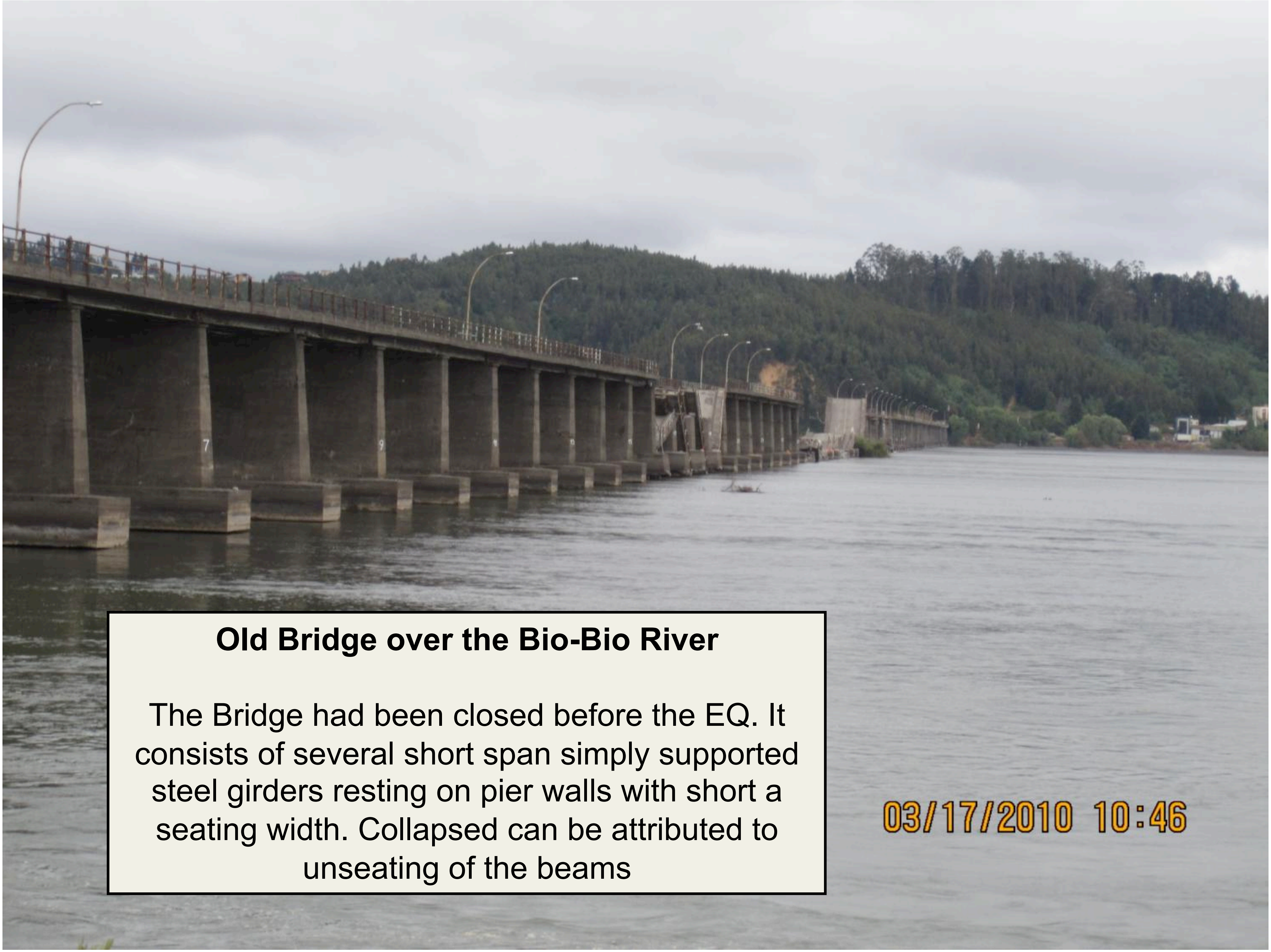
All Rio Biobio bridges closed after earthquake

Puente Viejo Bio Bio was already closed due to maintenance issues before the earthquake but couldn't be used as an alternate route because it had collapsed during the earthquake. It was a steel stringer bridge on big pierwalls.

Puente Llacolén carries traffic from adjacent streets and highways across the river and so it had stiff structures at both ends to accommodate ramps and connectors. It is likely that the more flexible ramps had large displacements and moved out of phase with the stiff, eastern end of the bridge. Also, there was some indication that lateral spreading may have moved the end structure towards the river. As a result of these problems several of the ramps became unseated during the earthquake.

Puente del Ferrocarril sobre el Bio Bio is a Warren truss supported on short, wide-legged towers going across the Rio Bio Bio had less damage. In general railroad bridges performed better than highway bridges perhaps due to the steel design and because railroad bridges are designed for a bigger live load. The eastern approach pier moved towards the river, however without dropping the truss superstructure which was shored up with stacks of railroad ties after the earthquake.

Puente Juan Pablo II is an older bridge and it is one of the few examples of bridge column damage that we saw during the earthquake. The eastern end of this long bridge moved towards the river, breaking a short stiff two-column bent at the water's edge from a combination of lateral spreading of the bank and ground shaking to fail the columns in shear. The deck was extremely uneven, suggesting that the precast I girder superstructure had moved off it's elastomeric bearings and the bridge was closed to vehicular traffic.



Old Bridge over the Bio-Bio River

The Bridge had been closed before the EQ. It consists of several short span simply supported steel girders resting on pier walls with short a seating width. Collapsed can be attributed to unseating of the beams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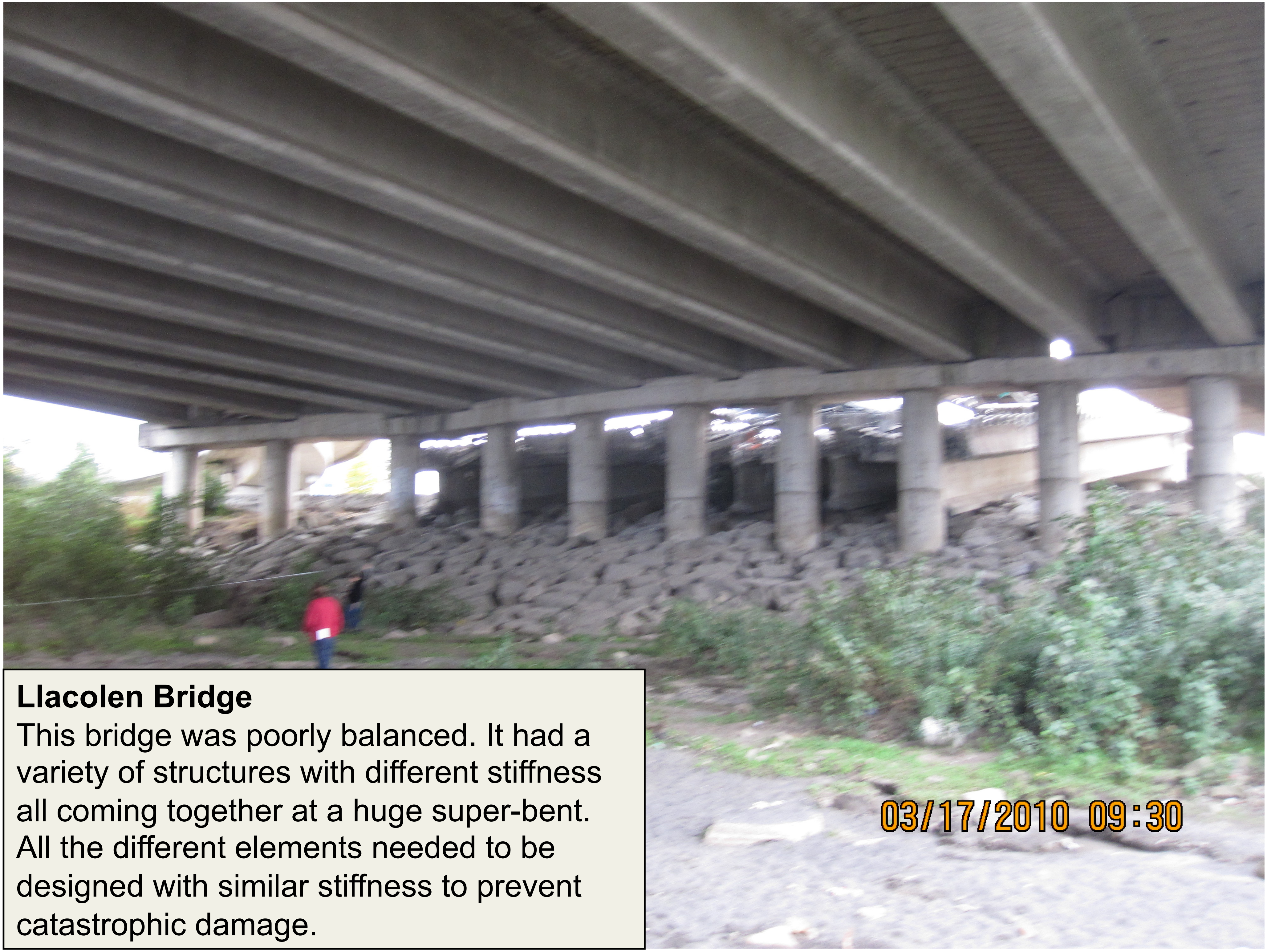


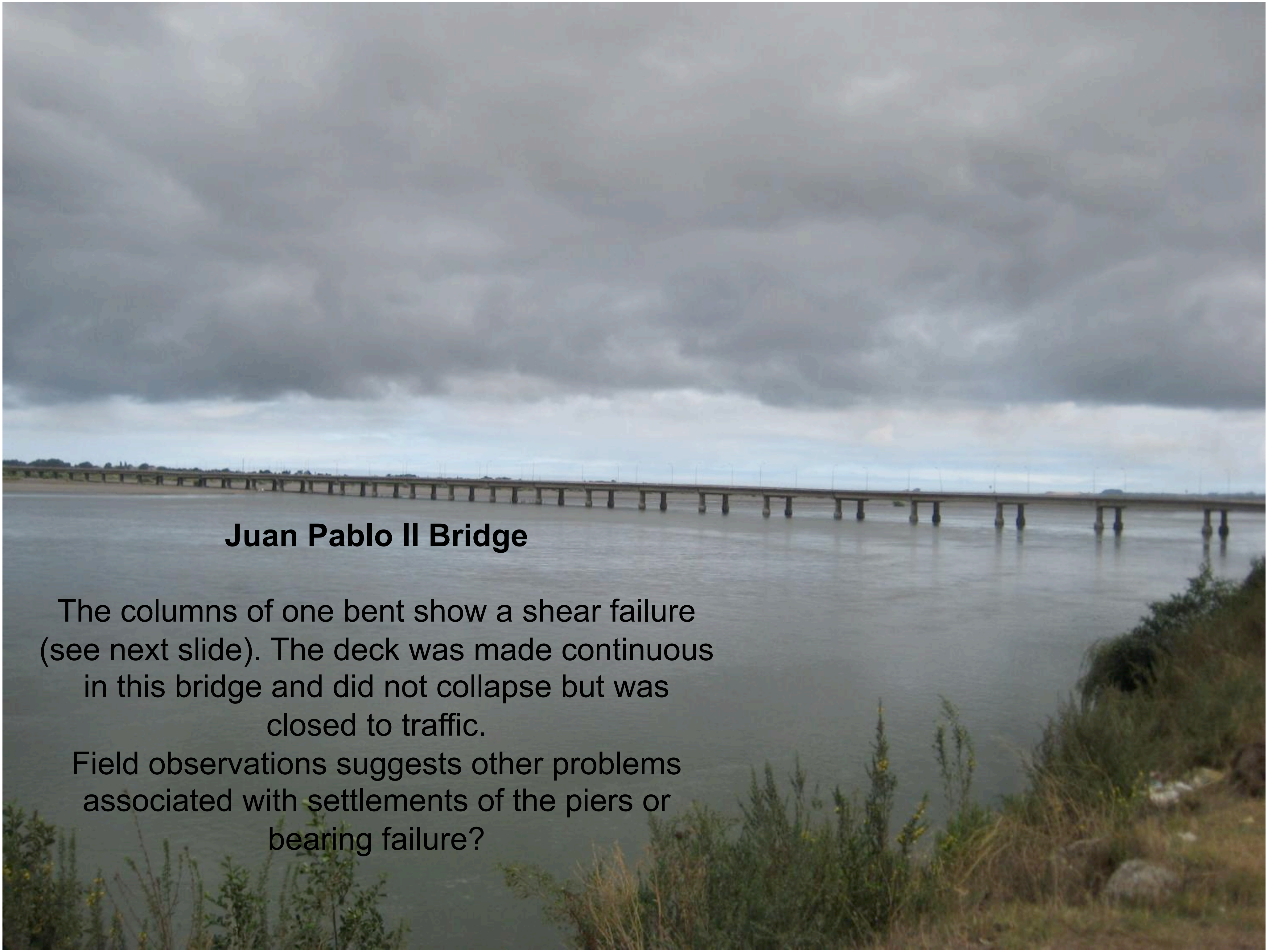
Llacolen Bridge

This bridge was poorly balanced. It had a variety of structures with different stiffness all coming together at a huge super-bent. All the different elements needed to be designed with similar stiffness to prevent catastrophic damage.


03/17/2010 08:58


2010/03/17 09:19
2010/03/17 09:57


EDISON
03/17/2010 11:14


Juan Pablo II Bridge
The columns of one bent show a shear failure (see next slide). The deck was made continuous in this bridge and did not collapse but was closed to traffic.
Field observations suggests other problems associated with settlements of the piers or bearing failure?

Juan Pablo II Bridge
Shear failure of columns.
Note the lack of transverse reinforcement.


03/17/2010 11:54

Route 5 Undercrossings

From minor damage to collapse

- Observed large approach fill settlements, some side slope failures
- Collapse of bridges can be attributed to unseating of girders.
- Much of the damage related to transverse movement with lack of restraint (no diaphragms and inadequate shear keys)
- Occasional failure of older structures (Rio Claro, Rio Nebuco)
- Often found new and parallel older structure due to highway widening.
  - One often damaged. The other generally had larger shear keys and diaphragms and experienced less damage or no damaged.
  - Having two different era structures side by side seemed to improve chances of one structure surviving.


Gravel fill
Approach settlement


2010/03/17 18:47
Puente Nebuco


03/17/2010 19:39
Puente Perquacaquen


03/18/2010 09:51
Puente Claro

Puente Tubul

This was the southernmost location of a complete bridge collapse. A landslide made for a long detour over a dirt road to reach this bridge. When we first came to the site, we weren't sure if the damage was due to tsunami, lateral spreading, or strong shaking. However, the residents (mostly living in tents and still awaiting the government's assistance after the earthquake) said the damage was definitely the result of ground shaking (Scott, our geotechnical engineer said he later heard that the relatively small tsunami wave had erased the evidence of lateral spreading). However, it is apparent that the bridge experienced a strong longitudinal jolt that caused the pier walls to move (and for one pier wall to break) and causing all eight steel girder superstructures to become unseated.


03/16/2010 17:00


SOL DEL PACIFICO
372
03/16/2010 17:06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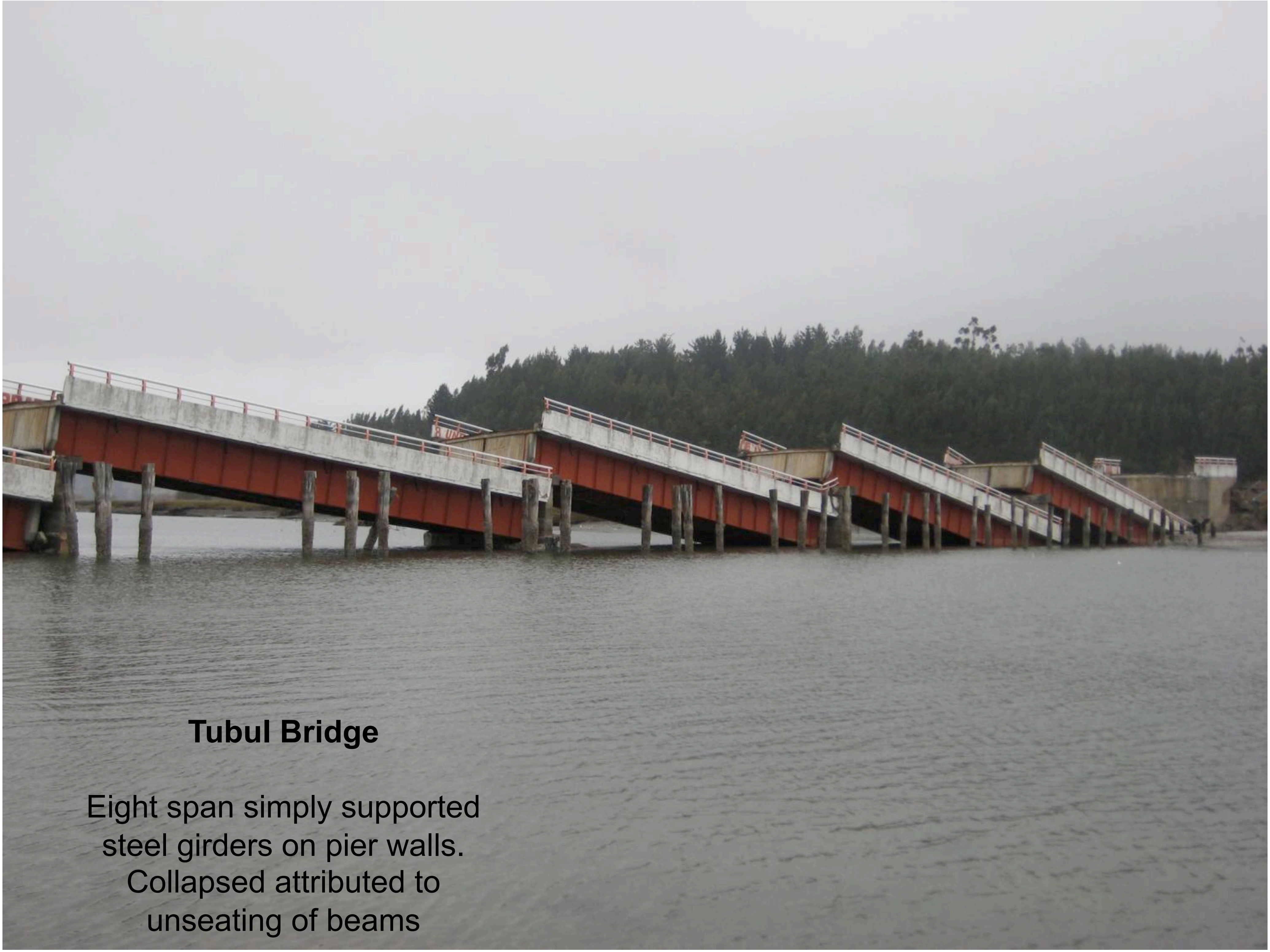
03/16/2010 17:15



Tubul Bridge

Eight span simply supported steel girders on pier walls. Collapsed attributed to unseating of beams

Santiago Expressway Bridges

Vespucio Norte in Santiago

- Damage appears localized and suggests local site effects from soil column or topography
- Several damaged along Vespucio Norte, a tollway in NW Santiago
- Similar to other cases, traffic was often diverted to better performing older structures
- Almost no column damage was observed, but girder damage and unseating were common


03/19/2010 10:11


OjO
PRONTO
03/19/2010 08:12


INDEPENDENCIA
03/19/2010 08:30


Salida 78
Los Andes
Colina
FRANCO
OjO
PRONTO
03/19/2010 08:58


03/19/2010 11:42


03/19/2010 12:05

Other Observations

- Saw many undamaged POC's
- POC's are not designed for seismic loading , but did okay for the most part. Most of them were constructed using precast elements.
- The girders were attached to the bent cap with a couple of embedded bars as observed in some POC's in Santiago that collapsed.

- Railroad bridges generally less vulnerable to damage than highway structures
  - Loss of ballast was common from fill settlement
- Culverts appeared more vulnerable
  - Several collapsed, causing settlement of roadway
- Tunnels were generally unaffected by earthquake
- Retaining walls, MSE walls, tie-back walls associated with transportation performed well. No collapse or damage was observed in these structures.
- Steep-sided fills often results in slumping or slope failures, causing traffic delays

Pedestrian OC.

Railroad bridge with unseated span, parallel to Route 5 near Longavi.


2010/03/16 19:56

Concluding Remarks

- Structures with less continuity generally suffered more damage or collapse
  - Diaphragms, larger shear keys, continuous spans, wide seats seemed to improve the seismic performance of the observed structures.
- Localized damage suggests the importance of local site effects (soil/ topography or directivity).
- Significant liquefaction and lateral spreading was observed in Concepcion and along coast which could had adversely impacted the performance of bridges.
- Widespread fill settlement was easily repairs, but adversely affected traffic.
- Most bridges suffered because they didn't have a consistent displacement design philosophy. US bridges are designed so the seats are longer than the adjacent piers displacement capacity. The seats we saw seemed to be poorly designed and many failed.