

9.0 EFFECTS OF GROUND FAILURE ON BRIDGES, ROADS, RAILROADS, AND LIFELINE SYSTEMS

9.1 Introduction

The February 27, 2010, the $M_w=8.8$ Chile earthquake caused significant damage to Chile's infrastructure. After the event, GEER personnel in cooperation with the University of Chile and Universidad Católica de Chile visited the affected area and evaluated the seismic performance of bridges, roads, railroads, and lifelines. Evaluation of this infrastructure required covering a large area (approximately 600km x 100km), including several regions and metropolitan areas of Chile. Figure 9.1 shows a Google map indicating the affected region and location of selected cases which are presented in this section.



Figure 9.1. Area covered by GEER reconnaissance team and location of select bridge, road, railroad, and lifeline cases described in this section.

Chile's two largest urban centers (Santiago and Concepción) are within the area impacted by this earthquake. These cities are connected by an important highway network, which runs primarily in the north-south direction (main highway Route 5). Moreover, due to its geographic characteristics, a large number of rivers that run predominantly in the east-west direction are in this region. Therefore many bridges, roads, railroads and water crossings are present in this area and were affected by earthquake strong shaking.

Most bridge structures performed well during the earthquake. From a geotechnical perspective, the most significant bridge damage appeared to be associated with lateral spreading or strong shaking. Certainly, the most sizable failures were near river crossings along the coast where several bridge spans became unseated (e.g., in Tupul and Concepción), which were subjected to both lateral spreading and strong shaking. However, strong shaking appeared to be the cause of most widespread damage, including a large number of overcrossings along Route 5 inland, as well as a number of underpasses and connectors in Santiago. The strong shaking in many of these cases appeared to be related to seismic site effects (e.g., local soil conditions or subsurface topography), as the damage appeared to be quite localized and nearby similar structures were undamaged (e.g., Quilicura area of Santiago or near Ercilla along Route 5 in the south). While damage was widespread to these smaller bridge structures, in general they performed well in that few totally collapsed onto the underlying roadway. Those that did completely collapse within the inland areas along Route 5 may be attributed to older construction and poor detailing.

Retaining walls, MSE walls, and tie-back walls associated with transportation structures, including bridge abutments, appeared to perform well throughout the affected region. Even in locations of significant lateral spreading, which caused considerable damage, bridge abutments performed well.

Widespread damage was observed in roads. Perhaps the most widespread geotechnical related issue was associated with settlement of compacted earth fills throughout the affected region. While there were isolated cases of embankment fill failures resulting in the closure of roadways (e.g., in and north of Lota), most noticeable were the patches of gravel quickly placed after the earthquake to compensate for settlement of bridge approach fills and culvert backfills. While generally not a life safety concern, these widespread settlements were a nuisance, leading to traffic problems.

Railroads were also damaged during the earthquake. The most common failure was associated with embankment loss of stability due to ground shaking, loss of rail alignment, and unseated railroad bridges. Nevertheless, in most cases the damage appeared to be limited and repairable, indicating good railroad performance despite the strong shaking that affected the region.

The following sub-sections of this section of the report include brief descriptions of selected bridge, roads, and railroad damage cases investigated by the GEER team during its visit in March 2010.

9.2 Llacolén Bridge (north approach), the Middle Bridge across the River Bio Bio in Concepción

The observed damage at the north approach of the Llacolén Bridge (S36.830108°; W73.067991°) suffered deck unseating and lateral spreading.

Lateral spreading ground was observed at the Llacolén Bridge in Concepción on the North approach shore (Figure 9.2). The Llacolén Bridge in Concepción was constructed in 2000 and spans 2,160 m across the Bio Bio river supporting four lanes of vehicular as well as pedestrian access to downtown Concepción (Figure 9.3). Ground damage at the north approach area was observed to extend inland into the southbound traffic lane of Calle Nueva road and south below the bridge's exit ramp continuing along a pedestrian walkway (Figure 9.4). Calle Nueva parallels the coastline and runs under the approach to the bridge. The lateral spreading ground resulted in unseating of the west and east bound traffic support deck (Figure 9.5). Flexural cracks on the river-side face of the 1.5 m diameter support columns were observed near the ground surface typically tightly spaced at approximately 0.10-0.20 m on center (Figure 9.6). The distribution of flexural cracking was more severe for those columns supporting the unseated deck, however, all columns at the north shoreline support observed flexural cracking at their construction joint (between 2-2.5m above ground surface). Ground settlement of 0.25-0.30 m was also noted to surround each of the exit ramp bents (Figure 9.7).



Figure 9.2. Plan view of the Bio Bio river region locating the damaged region of the Llacolén bridge in Concepción (S36.830108°, W73.067991°)



Figure 9.3 Elevation photograph of the Llacolén bridge in Concepción (S36.830108°, W73.067991°).

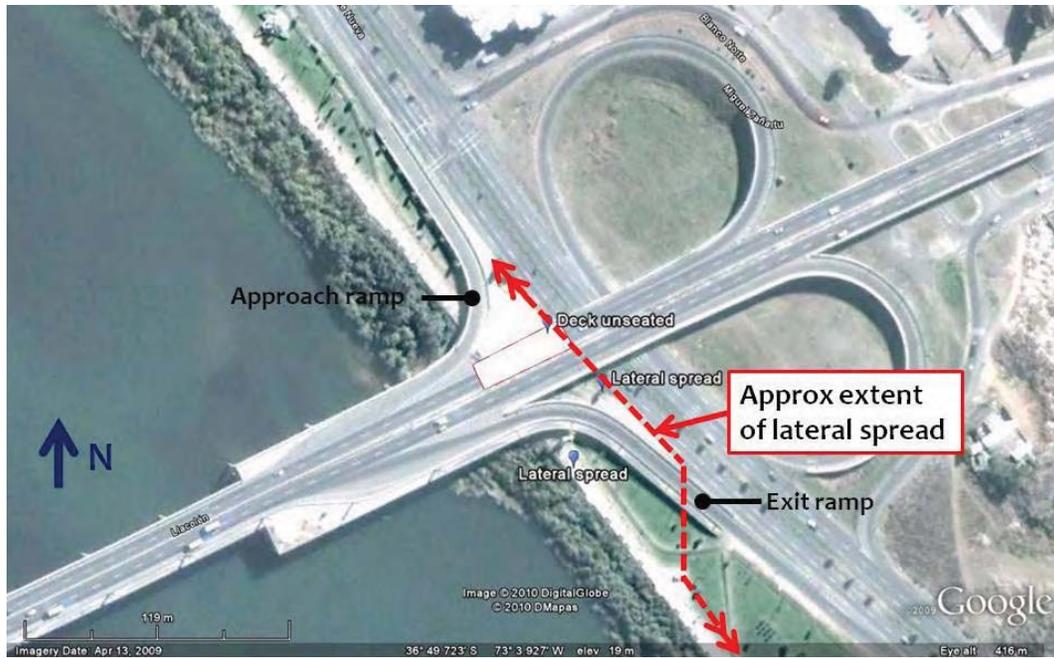


Figure 9.4. Plan view of the North approach to the damaged Llacolén bridge in Concepción ($S36.830108^\circ$, $W73.067991^\circ$).



(a)



(b)

Figure 9.5. Deck unseating at Llacolén bridge in Concepción. (note the temporary deck supporting approach traffic). View South ($S36.829707^\circ$, $W73.068220^\circ$, 1809 hrs on 3/14/2010) and (b) view north ($S36.830380^\circ$, $W73.067541^\circ$, 1911 hrs on 3/14/2010).



Figure 9.6. Substructure of the of the north approach to the damaged Llacolén bridge in Concepción showing the unseated deck in the foreground. Flexural cracking of the column supports was observed at ground level and extending to the construction joint (2-2.5m above ground) for all columns at this support (S36.830232°, W73.068379°, 1936 hrs. on 3/14/2010).



Figure 9.7. Ground settlement surrounding an exit ramp support bent at the Llacolén bridge in Concepción (S36.830380°, W73.067541°, 1901 hrs. on 3/14/2010).

9.3 Juan Pablo II Bridge, the North Bridge across the River Bio Bio, in Concepción

The Juan Pablo II Bridge (S36.815864°; W73.083674°), also known as Puente Nuevo (New Bridge), is the longest vehicular bridge in Chile with a length of 2310 m. The damage observed here was lateral spreading on the North East approach and liquefaction-induced settlements along the bridge (Figure 9.9a).

The Juan Pablo II Bridge, shown in Figure 9.8, connects the cities of Concepción and San Pedro de la Paz across the Bio-Bio River. The bridge was designed by E.W.H Gifford & Partners and opened to the public in 1974. The bridge consists of 70 spans (L = 33 m, W = 21.9 m) each one composed of 7 reinforced concrete girders and a concrete slab. The segments sit on reinforced concrete bents with drilled pier supports. Figure 9.9(b) shows an example of a typical bridge bent configuration.



Figure 9.8. Juan Pablo II bridge connecting the cities of Concepción and San Pedro de la Paz across the Bio Bio River (S36.815122° W73.084369°; 1453 hrs on 3/15/2010)

During the 2010 Chile earthquake, the bridge suffered severe damage and was closed to the public. Evidence of liquefaction and lateral spreading was observed in the north-east approach with significant effects on the bridge. A Google Earth view of the northeast approach with schematics of the observed ground failure and structural effects is shown in Figure 9.9b. As shown in Figure 9.10, liquefaction of the soil and lateral spreading in the embankment contributed to settlements and lateral displacement of the bridge deck. Visual inspection of the surrounding soils indicated the presence of fine loose sands. Several sand ejecta features were observed near the structure on the south and north sides of the embankment as shown in Figure 9.12. Several samples of the ejected soil were taken at this site, and grain size analysis and Atterberg limit testing are being performed. The results of this testing will be included in later versions of this report.



Figure 9.9. Juan Pablo II Bridge (a) Google Earth view of northeast Approach with schematics of observed damage (S36.815864° W73.083674°) (b) Typical bridge bent configuration (S36.828181° W73.095850°; 1636 hrs on 3/15/2010)



Figure 9.10. Juan Pablo II northeast approach: (a) Settlement of bridge deck near bridge approach (S36.815900° W73.084064°; 1455 hrs on 3/15/2010), (b) Lateral spreading on northeast bridge abutment.

Column shear failure and significant displacements and rotation of the bridge bent were observed on the north-east approach. Figure 9.11(a) shows shear failure of the column facing the bent's south side. The north column, shown in Figure 9.11(b), shows evidence of tension cracks and rotation and also suffered shear failure. In contrast with the damage observed at the northeast approach to the bridge, the southwest approach suffered minor damage.

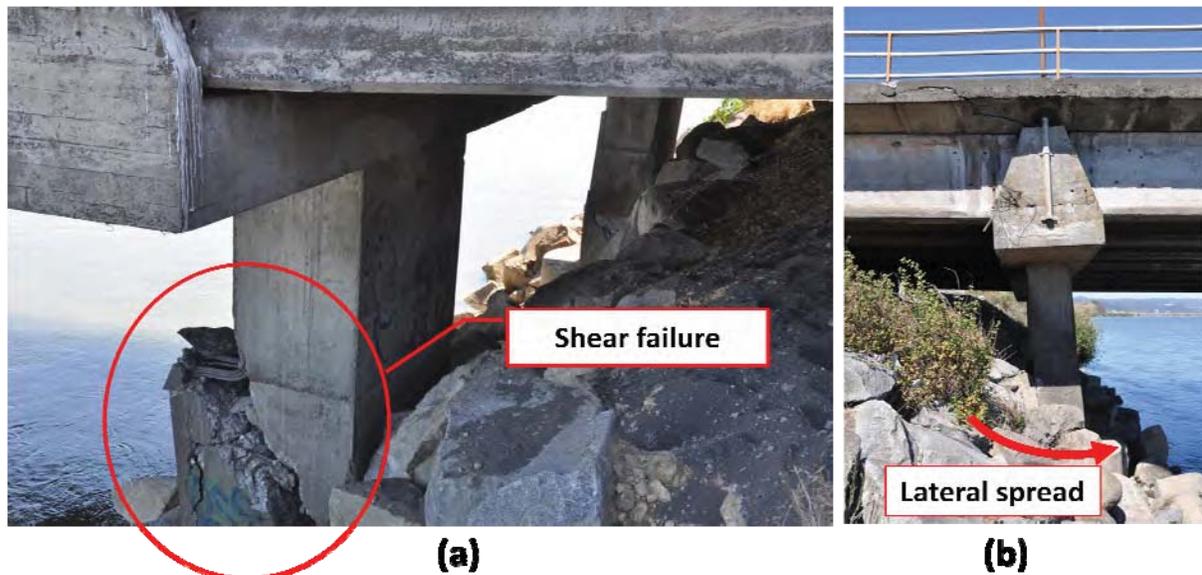


Figure 9.11. Juan Pablo II northeast approach: (a) Column shear failure (S36.816233° W73.084144°; 1528 hrs on 3/15/2010) (b) Rotation and lateral displacement of bridge bent (S36.816233° W73.084144°; 1530 hrs on 3/15/2010)

Noticeable pier settlements were observed at several locations along the length of the bridge. Vertical settlements appeared to be due to liquefaction of the soil near the pier foundations. Visual inspection of the surrounding soils indicated the presence of loose sands near the surface. Although the Bio Bio River was once navigable by ship up to the City of Nacimiento, over-logging during the twentieth century has led to heavy erosion that has choked the river with silt and rendered it impossible to ship traffic. Near Concepción the river behaves as a meandering river with fine-grained material deposited on the floodplains. The GEER team identified several sand boils near the approaches (e.g. Figure 9.12a) and along the bridge spans (in sections not covered by water). The presence of fine material is clearly shown in Figure 9.12(b).



(a)

(b)

Figure 9.12. Juan Pablo II bridge: (a) Sand ejecta near northeast approach and (S36.815619° W73.083311°; 1522 hrs on 3/15/2010) (b) Fine-grained material in the floodplains (S36.825592° 73.093264° on 3/15/2010).

Settlements on the order of 0.50 m to 0.70 m were observed in piers #73-76 and piers #113-116 as indicated in Figure 9.13 (odd numbers for piers on the north side and even numbers for piers on the south side). The bridge deck accommodated these settlements with large vertical deformations but with relatively minor damage of the asphaltic layer. This is observed in Figure 9.14(b). Settlements of piers # 73, 75, 113 and 115 on the south side were larger than those at piers #74, 76, 114, and 116 on the north side indicating rotation of the bridge bents.

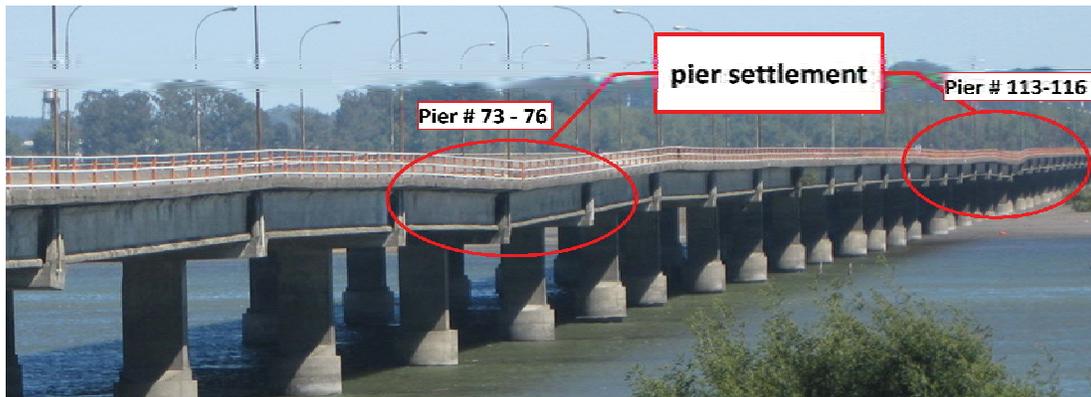
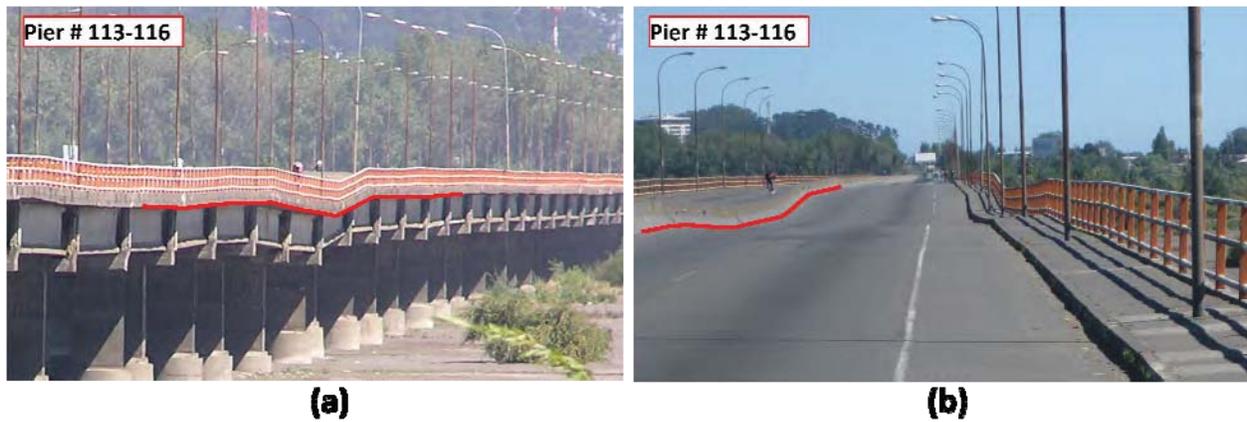


Figure 9.13. Juan Pablo II bridge – Pier settlements (S36.815122° W73.084369°; 1453 hrs on 3/15/2010)



(a)

(b)

Figure 9.14. Juan Pablo II bridge (a) View of bridge bent settlement (S36.826596° W73.094345° on 3/15/2010)(b) View of bridge deck settlement (S36.826596° W73.094345° on 3/15/2010)

Although the GEER team had no direct access to the piers subjected to liquefaction and settlement it was possible to obtain some photos of the affected foundations. Figure 9.15(a) and (b) show the top view of a pier corresponding to pier group #113-116 and a close-up of the soil-pier interface. The figure shows the effects of liquefaction of the soil surrounding the pier with soil depressions and standing water covering an annular section around the pier. The soil in the vicinity of the pier shows evidence of water being brought to the surface and accumulation of sand probably ejected during the liquefaction event.

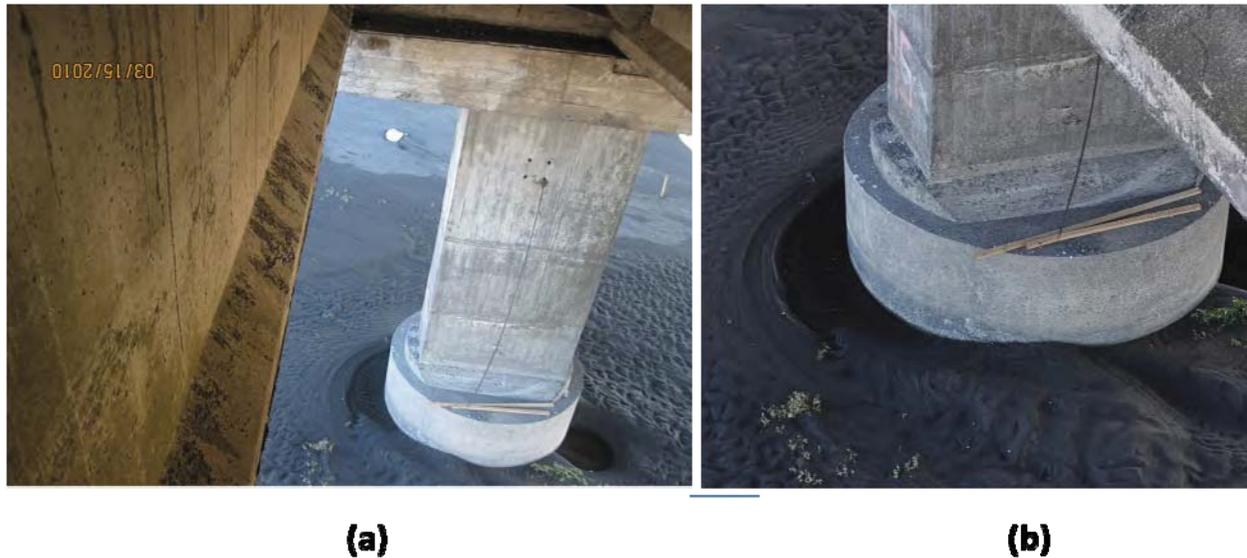


Figure 9.15. Juan Pablo II bridge—Evidence of liquefaction at piers subjected to settlements.(a)column and pier, (b) detail of pier and surrounding soil. (S36.826596° W73.094345° on 3/15/2010)

9.4 La Mochita Bridge, a Four-Span Bridge Parallel to the River Bio Bio in Concepción

La Mochita bridge, shown in Figure 9.16 (S36.846841°; W73.055496°), is a 4-span concrete bridge supported by seat-type abutments at each end and two-column bents at the interior locations. At this site, ground failure occurred which induced transverse movement of the bridge superstructure.

The bridge, which was constructed in 2005, spans north-south along the east bank of the Bio-Bio river, crossing a small inlet of water which fronts a water treatment facility in south Concepción. Bents are comprised of two 1.20 m diameter concrete columns (estimated) with pin connections at the deck, which are restrained vertically with a pair of tie bars integrated with a concrete block assembly (vertical restrainer blocks). The column bases are integrated with a concrete cap embedded below the ground. The bridge superstructure is composed of precast I-girders and a concrete slab. Bents 2 and 3 are founded on a soil mass that slopes towards the east water inlet. The high point of the soil mass is between 6-10 m east of the Bio-Bio river, with the low point at the water level of the east inlet, which at the time of the teams visit was below the base of the pile cap.

The bridge superstructure shifted transversely largely as a unit towards the east due to failure of the soil mass surrounding bents 2 and 3. Upon inspection of the ground at bents 2 and 3, significant spreading-like failure towards the water treatment plant inlet water was observed (Figure 9.17). This failure may have been attribute to either a deep seated slope instability or liquefaction-induced lateral spreading mechanism. It is noted that sand boils below the bridge were observed near bent #2 and 3 (Figure 9.18). Follow-up site investigation is being conducted by GEER to more fully understand the characteristics of

soils at the site and understand the underlying ground failure mechanism. Measurements taken by the team on March 15, 2010 indicated that the north end of the bridge deck shifted 0.5 m to the east relative to the approach fill, while the south end of the bridge shifted 0.9 m towards the east relative to the approach fill on that side. Bents 2 and 3 subassemblies (columns, bent cap and pile cap) were observed to rotate about the longitudinal axis of the bridge towards the east in consistent fashion with the deck movement. Rotations of bents 2 and 3 were measured as 2 and 4 degrees, respectively (Figure 9.19a). Bent 1 could not be accessed at the time of the teams visit, however, views from the land mass at bent 2 indicate that the deck moved independently of bent 1 (Figure 9.19b). In addition, ground failure was not immediately visible from this vantage point, or above the north shore of the bridge. Movement of the abutments was observed to be minimal, with the resulting damage to the superstructure largely attributed to the rotation of the bents (Figure 9.20 and Figure 9.21). It is noted that movement of the bridge resulted in damage on both east and west end transverse shear keys of the interior bents (Figure 9.22). In addition, the approach road from the north observed significant ground movement and distress leading to the bridge (Figure 9.23).

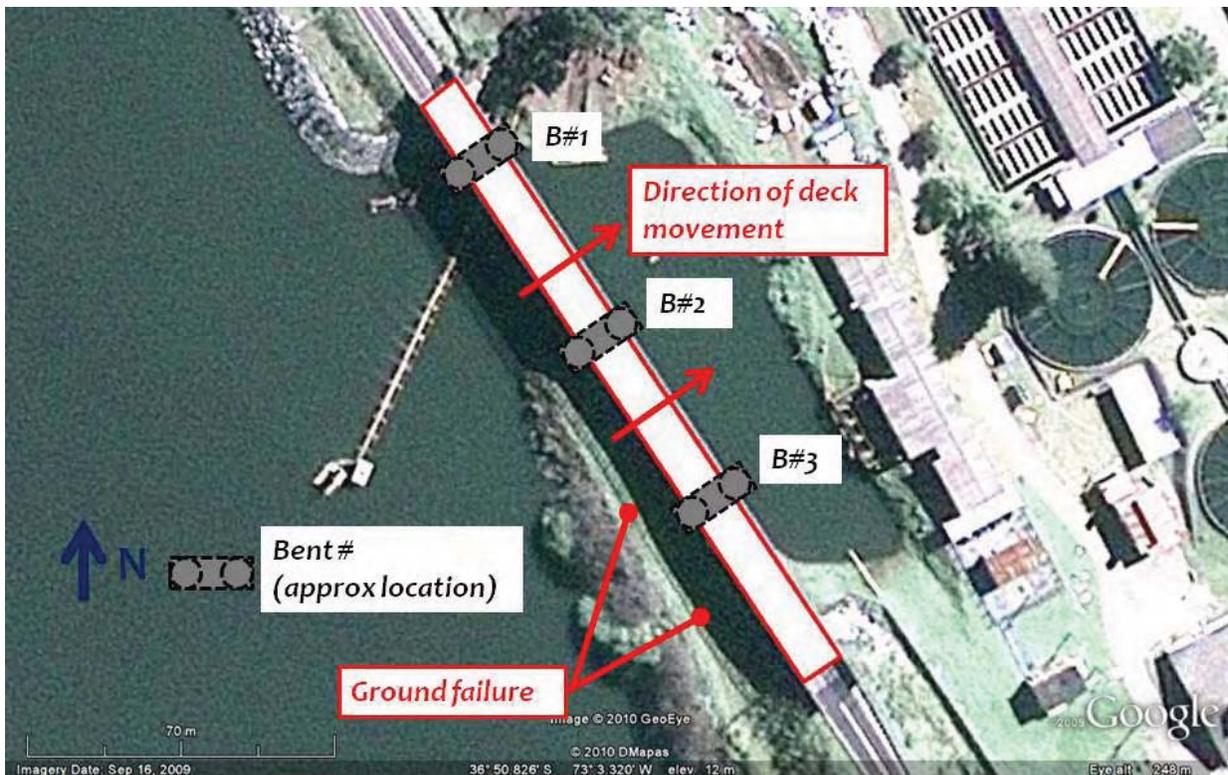


Figure 9.16. Plan view of the La Mochita bridge in south Concepción describing observed damage (S36.846841° W73.055496°).



(a)



(b)

Figure 9.17. Ground failure at the La Mochita bridge, (a) looking north at bent #3 (S36.847389°, W73.055219°; 1831 hrs on 3/15/2010) and (b) looking north at bent #2 (S36.847495°, W73.055027°; 1835 hrs on 3/15/2010)



(a)



(b)

Figure 9.18. La Mochita bridge: (a) Sand boils observed below the bridge (S36.847456°, W73.055129°; 1830 hrs on 3/15/2010), and (b) View looking north (S36.847453° W73.055225°; 1830 hrs on 3/15/2010)



(a)



(b)

Figure 9.19. La Mochita bridge: (a) Rotation of bent #3 and surrounding ground failure at La Mochita bridge. View looking south (S36.847302°, W73.055151°; 1835hrs on 3/15/2010), and (b) Transverse shift of deck relative to bent #1. (the tilt of bent #1 could not be measured at the time of site visit). Ground failure surrounding bent #1 was not observed from this vantage point. View looking north (S36.847049°, W73.055443°; 1835 hrs on 3/15/2010).



Figure 9.20. Transverse shift of deck relative to south abutment at the La Mochita bridge (S36.847547°, W73.054876°; 1834 hrs on 3/15/2010).



(a)



(b)

Figure 9.21. Mataquito bridge (a) Transverse gap developed between deck and south abutment. View looking north. (-36.847798°, -73.054797°; 1856 hrs on 3/15/2010), (b) Damage at the south abutment-road-deck interface due to transverse shift of the deck. View looking north. (S36.847761°, W73.054777°; 1856 hrs on 3/15/2010).



Figure 9.22. Damage to transverse shear keys at bent #3 due to movement of the La Mochita bridge (S36.847405°, W73.055084°; 1830 hrs on 3/15/2010).



Figure 9.23. Damage to the approach road north of the La Mochita Bridge (S36.846473°, W73.055881° on 3/15/2010). View looking north. The Bio Bio river is shown on the left (west) of the view.

9.5 Puente Bio Bio (Puente Viejo) in Concepción

The Bio-Bio bridge, also known as Puente Viejo (Old Bridge), was built in the 1930s and inaugurated in 1937. The bridge connected the cities of Concepción and San Pedro de la Paz and had a length of 1,419 m. For many years it was the only vehicular bridge connecting the two cities. Due to its precarious structural condition the bridge was closed in May 2002 and used only for pedestrian transit. During the 2010 Chile earthquake the bridge suffered severe damage with many slab sections collapsing (Figure 9.24a). Several bridge bents also collapsed during the seismic event (Figure 9.25). Evidence of liquefaction was observed at the East bridge abutment with visible lateral deformations and vertical settlements.



(a)



(b)

Figure 9.24. Puente Bio-Bio: (a) Collapsed slabs (S36.836789° W73.062203° on 3/15/2010), (b) Evidence of lateral spreading near East bridge approach (S36.837311° -73.061831°; 1753 hrs on 3/15/2010).



Figure 9.25. Puente Bi-Bio's collapsed slab sections and bridge bents (S36.837968° W73.062896° on 3/15/2010).

9.6 River Crossings in Talca

The City of Talca suffered significant damage to many buildings due to earthquake shaking. The damage was predominantly associated with low-rise adobe and unreinforced masonry construction (Figure 9.26). Taller, well-designed structures performed relatively well, with the exception of damage to exterior cladding and contents in the upper floors (RMS, 2010). The GEER team did not conduct an extensive survey of building damage within the city; rather the team focused on regions near the Rio Clara, which runs along the west edge of the city, extending north-south parallel with Route 5 (Figure 9.27). In addition, the team inspected areas along a branch of the river running east-west towards the southern edge of the city.

Bridges crossing the east-west branch of the river were primarily short span (less than 50 m long) slab bridges (Figure 9.28). Of the bridges inspected along the branch of the Rio Clara, no visible damage to the structure or surrounding ground was observed. Two long span bridges that cross the Rio Clara), one a vehicular bridge, the other a pedestrian bridge (Puente Rio Claro Nuevo and Puente Rio Claro Viejo) (Figure 9.29) were also of interest. Both structures are constructed of reinforced concrete, and of a girder-slab type configuration with the vehicular bridge bents supported on pier walls and the pedestrian bridge bents supported on angled multi-column subassemblies integral with a pier cap at both base and column head.

Local ground failure was observed approximately 50 m north of the Puente Rio Claro Nuevo (vehicular bridge) (Figure 9.30 and Figure 9.31). Two distinct regions were observed, a smaller lateral spread near shore (Figure 9.31), and a larger ground failure more characteristic of a soft clay failure confined within a park area (Figure 9.30). Soils near the shore area were predominantly gravely materials, likely with pockets of sand (one sand boil was observed at the near shore failure), whereas the park area was a soft clayey material. The ground failure extended approximately 90 m by 33 m north-south, however, it had no impact on the vehicular bridge, as it was open to traffic with no visible distress noted from the team's inspection on the east shore area. In contrast, the Puente Rio Claro Viejo (pedestrian bridge) suffered unseating of the longitudinally spanning girders and subsequent shear failure of the southern-most girder at a vista point near the mid-span of the bridge (Figure 9.32). From the team's limited access to the bridge it was not clear if the deck unseating was due to movement of the bent due to ground failure or excessive structural deformation at the bent.



Figure 9.26. Typical construction type and observed damage within the city of Talca (S36.832375,W73.055439; 2016 hrs on 3/17/2010).



Figure 9.27. Plan view of city of Talca locating the Rio Clara and Rio Clara branch inspected by GEER team (S35.440800° W71.647233°).



Figure 9.28. (a) Typical short span bridge construction on the branch of the Rio Clara, city of Talca (S35.428011° W71.670269°; 1302 hrs on 3/18/2010). (b) Bridges were observed to remain undamaged (S35.428086° W71.669894°; 1303 hrs on 3/18/2010).



Figure 9.29. Plan view of the Puente Rio Claro Nuevo and Puente Rio Claro Viejo, locating the observed ground failure area to the north ($S35.420772^{\circ}$ $W71.682932^{\circ}$).



Figure 9.30. Ground failure in a park area near the shore of the Rio Claro in Talca ($S35.419919^{\circ}$, $W71.682289^{\circ}$; 1408 hrs on 3/18/2010), views looking north and south, for left and right images, respectively.



Figure 9.31. Near shore lateral spread on the western shore of the Rio Clara in Talca, view looking south. ($S35.419682^{\circ}$, $W71.682359^{\circ}$ on 3/18/2010). Both the pedestrian and vehicular crossing bridges are shown in the background.



Figure 9.32. Deck unseating and shear failure of longitudinal spanning girders of the Talca pedestrian bridge at the vista area (S35.421044, W71.683197; 1354 hrs on 3/18/2010)

9.7 Undercrossings and Connectors for Autopista Vespucio Norte Express in Quilicura

Several transportation structures along the Autopista Vespucio Norte Express (i.e., Vespucio Norte Expressway) were damaged in the Quilicura area of North West Santiago (Figure 9.33). There was at least one collapse and several spans were unseated requiring temporary support (Figure 9.34). Both older and newer structures were damaged, and the damage appeared to be the result of strong shaking. Since the damage appeared localized only as the Vespucio Norte Expressway came through the Quilicura area, it is suspected that local site effects, resulting from either soil conditions or subsurface topography contributed to the strong shaking. Retaining walls and mechanically stabilized embankment (MSE) walls appeared to perform well in the area (Figure 9.35). No other signs of geotechnical conditions influencing the performance, such as liquefaction or slope movements, were observed.



(a)



(b)

Figure 9.33. (a) Damaged shear key is an example of typical performance on bridges along this section of Vespucio Norte Expressway in Quilicura (S33.365585, W70.688657; 814 hrs on 3/19/2010), (b) Close up of damaged shear key along Vespucio Norte Expressway (S33.365893, W70.688584; 817 hrs on 3/19/2010).



(a)



(b)

Figure 9.34 (a). Example of one of the newer under crossings that suffered damage along the Vespucio Norte Expressway. The right span became unseated due to excessive transverse movement (S33.36245, W70.688865; 829 hrs on 3/19/2010) (b) Close-up of shear key area on bent cap, with metal shear key or keeper bar hanging on right side of bent cap. Note complete unseating of I-girder on right side of bent cap (S33.366638, W70.689301; 837 hrs on 3/19/2010).



Figure 9.35. Retaining walls and mechanically-stabilized-embankment (MSE) walls appeared to perform well in the Quilicura area of Santiago (S33.366137, W70.688913; 824 hrs on 3/19/2010)

9.8 Mataquito Bridge

Built in 2008, the Mataquito Bridge is a two-lane 280 m-long reinforced concrete bridge, which runs in the north-south direction over the Mataquito River. Despite evidence of liquefaction at both abutments of this bridge, its overall seismic performance was good. No signs of structural damage due to lateral spreading were observed. Vertical settlement of about 50 cm was observed at the north approach fill, probably induced by liquefaction.



Figure 9.36. Mataquito bridge-(a)Settlement of approach fill at North end (b) Ground cracks at the South abutment due to lateral spreading (S35.051961, W72.163217, 1419 hrs on 3/08/2010)

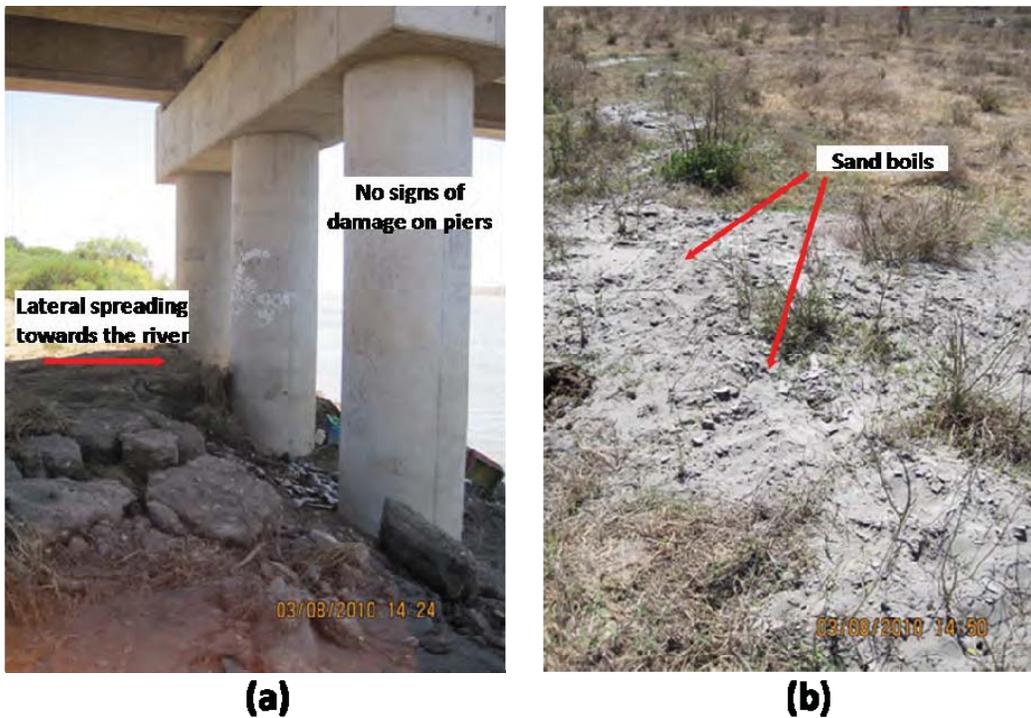


Figure 9.37. Mataquito bridge-(a) Blocks of soil crust against piers at the south end, (b) Sand boils at the north end of the bridge (S35.051961, W72.163217; 1450 hrs on 3/08/2010)

9.9 Pulen and Patagual bridges near Hualqui

There was moderate damage of these bridges due to liquefaction and lateral spreading. These two-lane single-span old reinforced concrete bridges were close to each other. In these bridges the longitudinal movement due to lateral spreading of both abutments seemed to have compressed the bridges causing geometric distortion and moderate damage. The originally horizontal decks of the bridges ended up with a concave-down shape. Some transverse cracks were observed on the bridge deck due to this effect. Information provided by local authorities indicates that most of these bridges, if not all, have been recently surveyed as a part of a broad bridge assessment and improvement program, so there may be accurate survey points that could be used for future detailed analysis of the deformations.

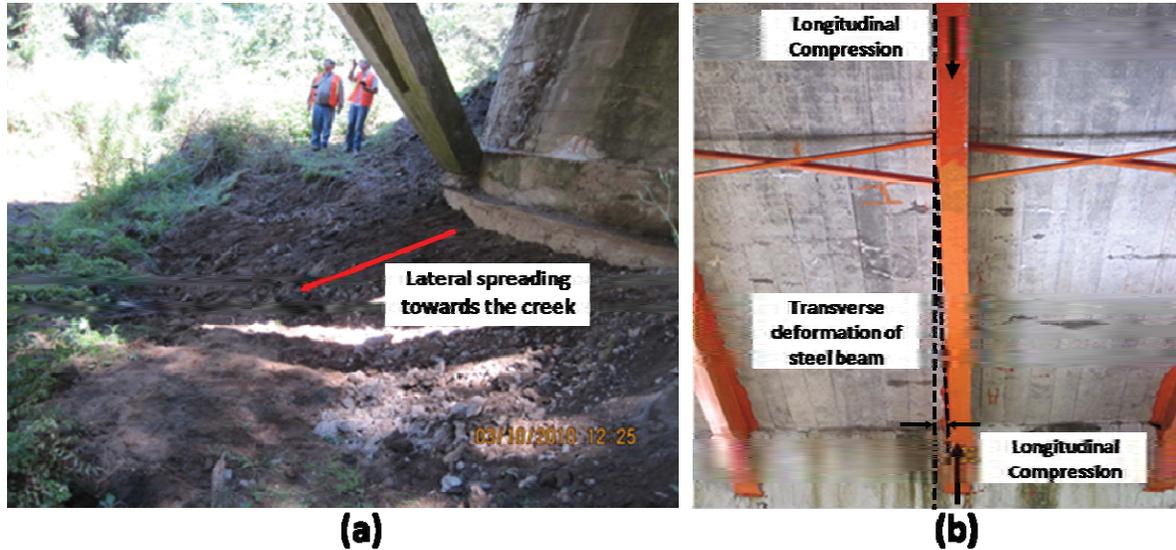


Figure 9.38. Pulen Bridge-(a)Evidence of lateral spreading at the north abutment (b) Loss of longitudinal alignment of steel I-beam (S37.112036, W72.986902, 1225 hrs on 3/10/2010)



Figure 9.39. Patagual Bridge-(a) Ground movement at the abutment (b) Sidewalk crack in the transverse direction on the top of the bridge deck(S37.111325, W72.987583, 1257 hrs on 3/10/2010).

9.10 Laraquete Bridge

Two bridges were inspected in the Town of Laraquete, which is 50 km south of Concepción: A pedestrian two span bridge and an adjacent vehicular three span reinforced concrete bridge. The pedestrian bridge experienced damage due to foundation settlement of the middle bent with an estimated 0.50 m vertical deformation. Figure 9.41 shows the deformed bridge with noticeable inclination of the bridge deck. The adjacent reinforced concrete bridge, shown in Figure 9.40, suffered minor damage near the approaches due to pounding with the concrete structure and settlement due to poorly compacted fill. This bridge did not show evidence of foundation settlement.



Figure 9.40. Laraquete bridge (a) Aerial view (S37.166788° W73.184486°), (b) Bridge approach (S37.166804° W73.184760°; 1430 hrs on 3/10/2010)

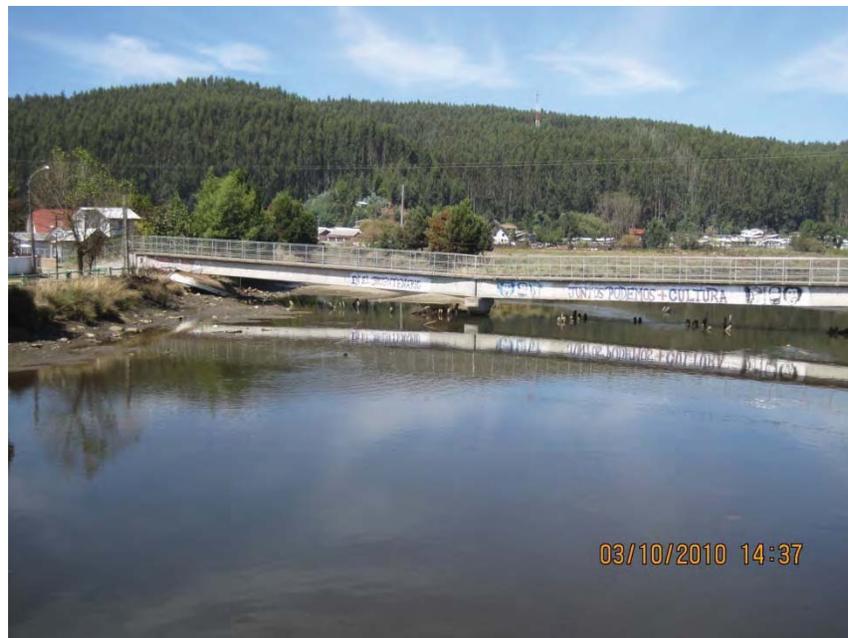


Figure 9.41. Pedestrian Laraquete Bridge showing large settlement of middle pier (S37.166742° W73.184384°; 1437 hrs on 3/10/2010).

9.11 Lebu Bridge (Puente Antiguo)

This bridge was operational by the time the GEER team got to Lebu. No major approach fill settlement could be observed. Good overall performance of the bridge in an area where evidence of ground uplift of 1.8 m to 2 m was found.



Figure 9.42. Lebu bridge: (a) Crossing Lebu bridge fully functional, and (b) Lebu bridge from the distance (S37.606344, W73.649496, 1818 hrs on 3/10/2010)

9.12 Nebuco Bridge along Route 5

The EERI LFE Bridge Team observed this pair of bridges crossing the Rio Nebuco just South of Chillan along Route 5. The northbound bridge had a single dropped span, which had already been removed. The newer southbound bridge suffered only minor damage and was still in service handling both northbound and southbound traffic. The collapse was apparently a result of strong shaking. No apparent signs of liquefaction or lateral spreading and slope movement were observed.



Figure 9.43. This pair of bridges crosses the Rio Nebuco along Route 5 (S36.641846° W72.211264°; 1843 hrs on 3/17/2010).

9.13 Damage to Bridge and Roadway near Tupul

A roadway and bridge near the small town of Tupul were damaged due to ground failure. The layout of the bridge and roadway is shown in Figure 9.44. The roadway is about 0.33 km long and single span bridges cross the river on the east and west ends. Damage to the roadway and the bridge on the east end closed the road to traffic following the earthquake. The two lane roadway, with an embankment height of about 2 m, traverses a swampy, low-lying area adjacent to a small river which flows northward into the Pacific Ocean. Therefore, soils in this area are likely to be soft and saturated. The eastern bridge, which is about 50 m long, is supported by steel beams which rest on a seat type abutment.



Figure 9.44. Damage to roadway and bridge due to ground failure near town of Tupul, Chile (S37.254345°, W73.437021°).

Lateral spreading toward the river produced ground displacement of about 0.6 m to 0.7 m at the west abutment. The bridge beams appear to have acted as a strut to limit displacement at the top of the abutment. This led to an offset of about 0.30 m to 0.35 m between the bridge abutment and a retaining wall adjacent to the abutment as shown in Figure 9.45(c). The displacement and rotation of abutment was still sufficient to deform the vertical restraining bars connecting the base of the abutment and the bridge beams by about 0.35 m as shown in the photo in Figure 9.45(b). Displacement of the abutment relative to the beams also led to shearing of the outer edge of the abutment wall as it impacted the bridge beam as shown in Figure 9.45(a).

On both sides of the roadway, slumps developed along nearly the entire length of the roadway leaving vertical scarps 1.0 to 2.0 m in height as shown in Figure 9.46. The slopes on both sides of the roadway appear to have rotated downward causing an upward heave and rotation of the outer edge of the failure surface similar to a bearing capacity failure surface. In addition to the slumping along the sides of the road, the middle section of the road experienced lateral displacement towards the north as evidenced by the bow in the centerline of the road evident in Figure 9.46(a).

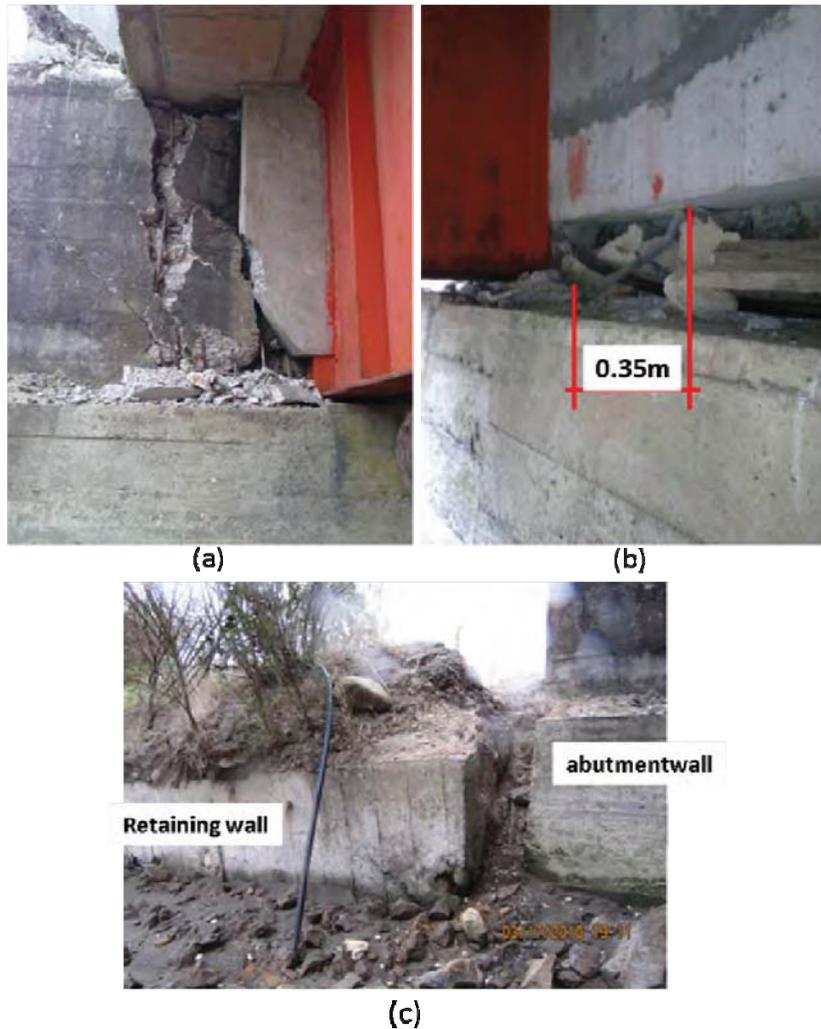


Figure 9.45. Damage to bridge abutment due to lateral spreading of soil around bridge abutment. (a) abutment wall movement relative to beams, (b) deformation of vertical restraining bar due to abutment movement relative to beams, (c) movement of retaining wall relative to abutment. (S37.254345°, W73.437021°; 1911 hrs on 3/17/2010)



Figure 9.46. Photos showing scarps along both sides of the roadway due to bearing capacity failure in soil underlying the fill. Note lateral spreading in upper photo (S37.254161°, W73.437577° on 3/17/2010)

9.14 Road and Railroad Embankment Failures North of Lota

Several large ground failure areas were observed north of Lota along Route 160. Two failures resulted in damage to a roadway embankment section (denoted herein as the “south bound failure” and “north bound failure”; Figure 9.49), while a third failure resulted in damage to an elevated railroad section (denoted as “railroad failure”; Figure 9.47 and Figure 9.50). Minor side road spreading-like failures were also noted near the approach abutments to two short span overpass bridges, north of the embankment failures, as well as just north of the short span bridges. The area east of Route 160 is largely marshy with low lying organic material (Figure 9.47). South of the north bound failure and east of the south bound failure of the elevated roadway sections is a small housing development.

The north bound ground failure appeared to be deeply seated, perhaps due to softening of the foundation materials. It was not clear whether the south bound failure was due to a deep seated foundation failure or due to poorly compacted earth fill in the embankment section. A gray sandy fill overlaid by compacted clay fill was used in the elevated road embankment. The roadway elevation was approximately 10–15m above the valley area (10 m nearest to the overcrossing bridges, with high point above the housing development area). The bridge overcrossings, and therefore the road embankments, each of the north and south bound sections may have been constructed at different times, as evident in the differences in construction type of the bridges (Figure 9.50(a)). The neighboring elevated railroad failure is characterized by a slumping and spreading of the elevated section, which is likely due to movement of the compacted fill (Figure 9.50(b)). The railroad was approximately 5-7 m above the low lying marshy area along its failure zone.

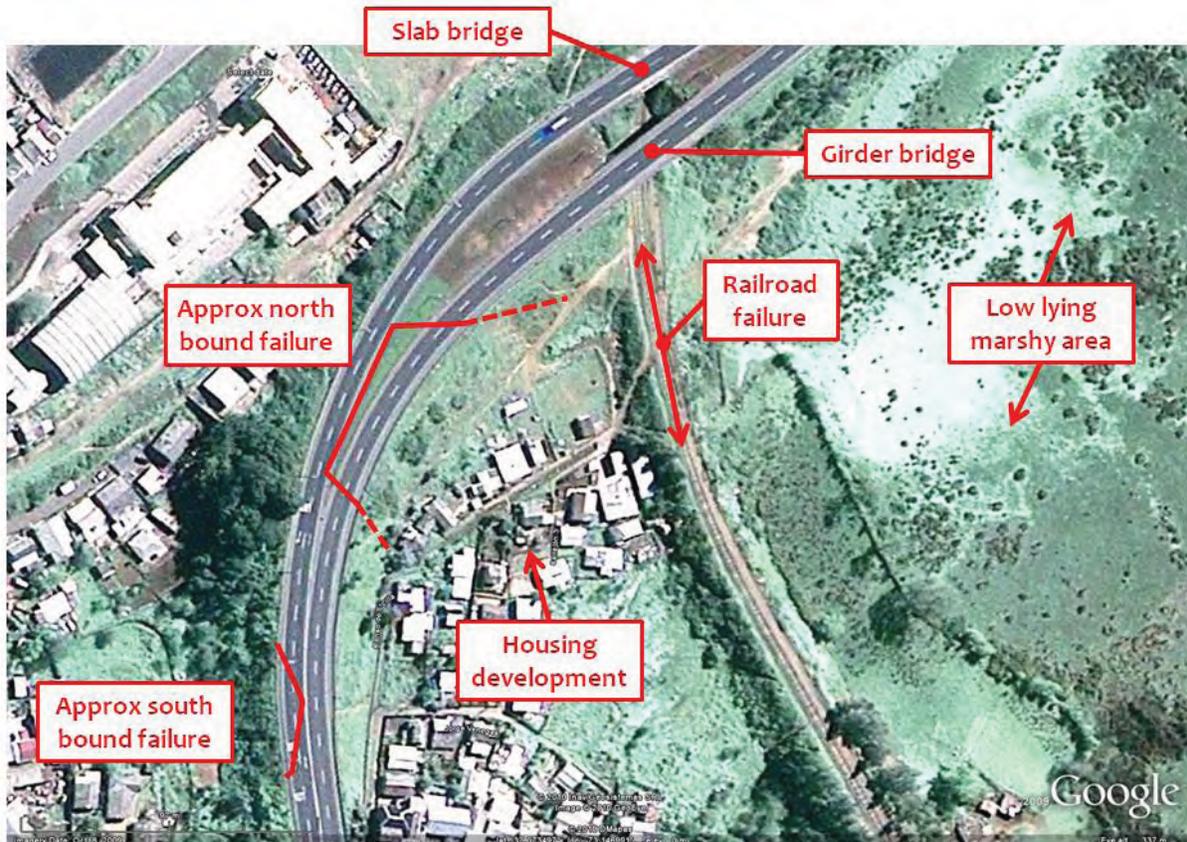


Figure 9.47. Plan view of approximate affected area (Google Earth image at S37.0734°, W73.1469°).



Figure 9.48. View looking north on route 160 showing south bound and north bound failure areas (S37.0744°, W73.1480°; 1220 hrs on 3/16/2010).



Figure 9.49. Lota (a)View looking south on route 160 showing north bound failure area (S37.0730°,W73.1475°; 1145 hrs on 3/16/2010) (b)View looking north on route 160 showing south bound failure area (S37.0746°, W73.1479°; 1215 hrs on 3/16/2010).



Figure 9.50. Lota (a)Slab and girder-type overpasses at northern end of road embankment failure area, showing railroad and supporting ground settlement. View looking west. (S37.0729°, W73.1469°; 1150 hrs on 3/16/2010), (b) Ground failure below elevated railroad east of road embankment failure. (image looking east; S37.0727°, W73.1471°; 1150 hrs on 3/16/2010)

9.15 Collapsed of Embankment Fills near Copihue and Parral

Two collapsed embankment fills were identified near Copihue and Parral. The first, shown in Figure 9.51, occurred on a straight section of Ruta 5 located ~ 8 km North of Parral (S36.0796 W71.7881). The Southbound lanes collapsed to the West and appeared to involve a shallow translational slide in near surface foundation soils as evidenced by the location of the failed soil mass including a mound of soil pushed up at West toe of the embankment (Figure 9.51a). The embankment failed along a length of approximately 150 m at a location where a low lying softer soil area was located at the toe.



Figure 9.51. This embankment fill collapsed together with an overhead near Copihue, north of Parral, closing the South bound of Route 5 (a) View from the South, (b) View from the North (S36.087891, W71.791513, 1325 hrs on 3/11/2010)

The second failure, shown in Figure 9.52, occurred on an overpass of Ruta 5 located ~ 13 km North of Parral. (S36.0347 , W71.7558). The overpass embankment was curved and the embankment failed over a length of about 80 m towards the outside of the curved section. Again, the failure appeared to involve a shallow translational slide in the near surface foundation soils as evidenced by the intact failed soil mass and the mound of soil pushed up at the toe (Figure 9.52a). Foundation soils in the region appeared to be relatively competent (unlike the above case) suggesting possible elevated pore pressures in the foundation soils played a role in the observed failure with 3-D effects leading to failure to the outside of the curved embankment section as opposed to the inside of the embankment. The outside section of the slide mass remained completely intact as evidenced in Figure 9.52b.



Figure 9.52. Curved overpass embankment failure 13 km North of Parral (a) Translational 3-D slide failure, (S36.0343 W71.7568; 1405 hrs on 3/11/2010) and (b) Failed outside of the curved embankment (S36.0347 W71.7558; 1409 hrs on 3/11/2010)

9.16 Ground Failure along Highway 5 near Paine

Abutment and embankment failures were common along Route 5. Figure 9.53 and Figure 9.54 show typical highway failures due to poor compaction of the embankment fill and abutments near Paine 62 km South of Santiago. The same scenario repeated at multiple sites. In contrast, mechanically stabilized retaining structures performed exceptionally well. Figure 9.53 shows the failure of an overpass bridge. The figure shows cracks on the sloping ground that propagated away from the abutment, and reduced in size away from the bridge. It seems cracks succeeded the abutment failure. The structural damage of the overpass was caused by differential settlement of the supports. Figure 9.54 shows the failure of the highway shoulder and pavement due to poor compaction of the fill material.



Figure 9.53. Highway 5 crossing near Paine; (a)View of bridge approach from East ($S33.854592^{\circ}$ $W70.747687^{\circ}$; 1118 hrs on 3/16/2010); (b) View of damaged bridge abutment ($S33.854211^{\circ}$ $W70.747784^{\circ}$; 1120 hrs on 3/16/2010)



Figure 9.54. Highway 5 failure near Paine; (a)shoulder settlement due to poorly compacted soil ($S33.864897^{\circ}$ $W70.742222^{\circ}$ 1203 hrs on 3/16/2010), and (b) road failure due to poorly compacted soil ($S33.864897^{\circ}$ $W70.742222^{\circ}$; 1204 hrs on 03/16/2010)

9.17 Railroad Bridge over the Bio-Bio River

The Bio Bio river railroad bridge is one of the oldest crossings of the Bio Bio river. Originally built in 1889 m, it was completely retrofitted in 2005. This railroad structure is composed of parallel top and bottom chords separated by diagonal and vertical members in a Warren truss arrangement. Three hundred and seventy pillars support the structure covering a length of 1889 m. The bridge was damaged during the 2010 Chile earthquake due to strong shaking and possibly lateral spreading of the river banks. Of the 370 pillars of the bridge, 19 were damaged during the earthquake and several portions of the rail were bended or miss-aligned (Figure 9.56). Visual inspection of pillars near the West abutment seems to indicate several piles moved in the lateral direction and rotated (Figure 9.55). The rail lines were moved out of alignment as shown in Figure 9.53.



Figure 9.55. Bio Bio Railroad crossing (a) Pillars move and rotated during earthquake (b) Detail of broken crossbar, (S36.836075° W73.086969°; 1717 hrs on 3/17/2010)

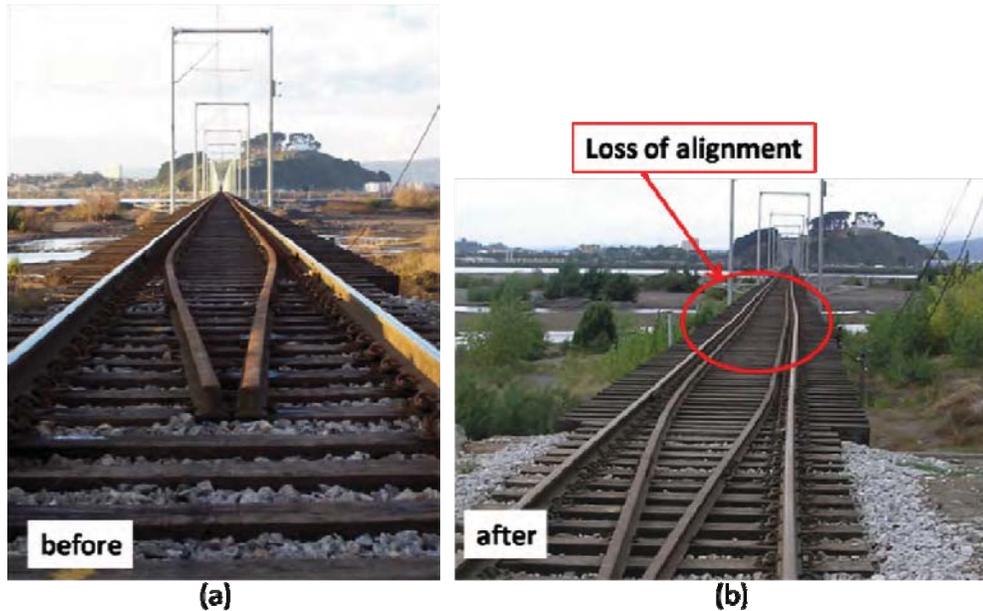


Figure 9.56. Bio Bio Railroad crossing (a) rails aligned before earthquake, (b) rails bended after earthquake (S36.836097° W73.087094° on 3/17/2010)

9.18 Railroad Bridge near Longavi

The EERI Bridge team observed the unseated railroad bridge span shown in Figure 9.57 approximately 330 km south of Santiago. This appeared to be the result of strong shaking, as no signs of liquefaction were observed. The Route 5 highway bridge was undamaged. An adjacent highway bridge was out, but demolished prior to the earthquake (S36.004136, W71.726193). Approximately 217 km south of Santiago, a railroad bridge crossing the Rio Claro was apparently undamaged, though the approach fills settled over 0.5 m, resulting in separation of the tracks from the support.



Figure 9.57. Unseated railway bridge span near Longavi from excessive transverse movement (S36.004136, W71.726193, 0801 hrs on 3/18/2010)

9.19 Culvert near Mataquito River

In this area, the tsunami caused most of the damage, washing off the road and uncovering a concrete pipe (Figure 9.55). Considering the extent of the damage in this zone, the pipe did not distort very much. This part of the road, however, was totally destroyed.

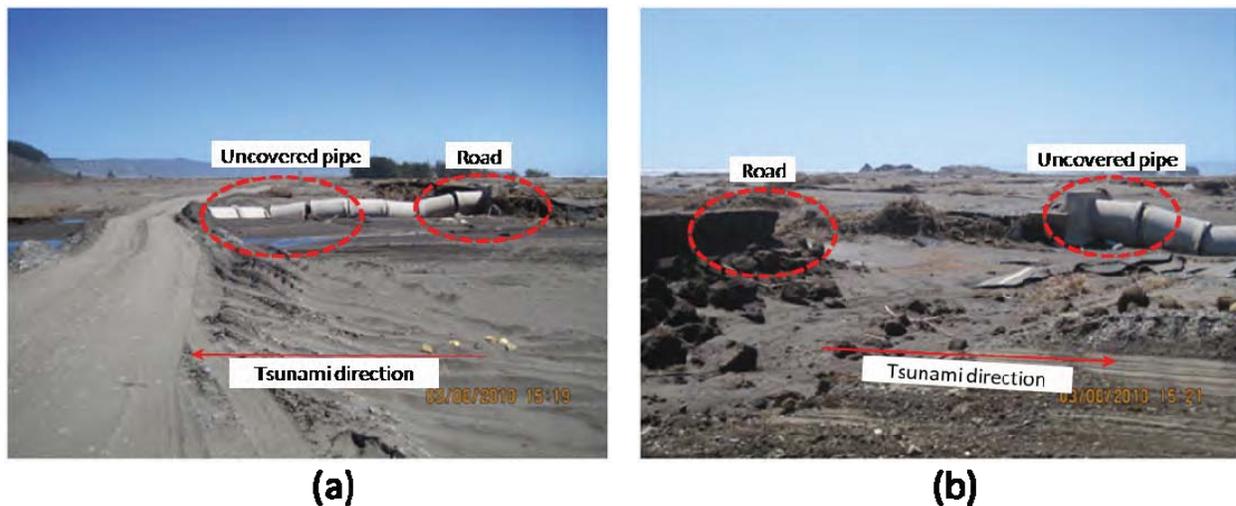


Figure 9.58. Failed culvert pipe: (a) View from the north, and (b) View from the south (S35.115611, W72.203245, 1519 hrs on 3/8/2010)