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REPAIR AND RETROFIT OF BRIDGES DAMAGED BY THE 2010 CHILE MAULE EARTHQUAKE

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ABSTRACT: The Chile Maule earthquake with magnitude 8.8 occurred off the coast of the Maule Region of Chile on February 27, 2010. Several bridges were heavily damaged by the strong shaking. Typical and important damage was the rotation and the unseating of superstructures found at skewed bridges supported by rubber pad bearings. Based on such damage experiences, the Chilean Seismic Standards for the Design of Bridges were revised in June 2010. This paper presents the repair and retrofit of bridges damaged by the 2010 Chile Maule earthquake with application of the New Seismic Standards.

Key Words: Chile Maule Earthquake, Bridge Damage, Skewed Bridge, Seismic Standard, Repair, Retrofit

INTRODUCTION

The Chile Maule earthquake with magnitude 8.8 occurred off the coast of the Maule Region of Chile on February 27, 2010. Several bridges were heavily damaged including complete collapse by the strong shaking. Japan Society of Civil Engineers (JSCE) dispatched the reconnaissance team to Chile and the damage investigation was made at 31 sites along Highway Route 5 as well as in cities of Santiago, Constitucion, Concepcion, and Arauco from March 28 to April 4, 2010, jointly with the Chilean Ministry of Public Works (MOP) (Kawashima et. al., 2010a, b).

Typical and important damage was the in-plane rotation and the unseating of superstructures found at skewed bridges supported by rubber pad bearings. Large rotation displacement was developed under the strong ground motion. Based on such damage experiences to the skewed bridges, the "Chilean Seismic Standard for the Design of Bridges" were revised in June 2010, and the unseating prevention concept was employed by reference to the Japanese Seismic Design Specifications for Bridges (JRA, 2002).

The author visited Santiago and Concepcion, Chile, in February, 2011, just 1 year after the earthquake, as a mission of the JICA short term expert program on "The Project on Capacity Building to Seismic Events and Tsunamis." During this occasion, the author visited the bridges which suffered damage during the 2010 Chile Maule earthquake and were repaired and/or retrofitted after the earthquake.

This paper presents the repair and retrofit of bridges damaged by the 2010 Chile Maule earthquake with application of the New Chilean Seismic Standards.

LESSONS LEARNED AND REVISION OF CHILEAN SEISMIC STANDARDS

Based on the damage investigation by the JSCE Reconnaissance team (Kawashima, et. al., 2010), the typical damage was caused by the in-plane rotation of a whole bridge system due to the strong ground motion. Prestressed concrete girder bridges have been commonly constructed in recent years in Chile. In particular, as for the bridges constructed in concessions after the mid-1990s, the diaphragms to increase the integrity of superstructures and the effective stopper mechanism have been eliminated for the structural simplicity. Therefore, there was no effective structure to resist large lateral displacement of superstructures and the resulting unseating from substructures against the strong shaking. It should be noted here that the girders have been supported by rubber pad bearings without any stiff connection including anchors between superstructures and substructures. The girders were relatively easy to move at bearing supports against the strong shaking.

Such damage caused by the in-plane rotation was particularly extensive in skewed bridges. The large rotation motion was developed due to the unbalanced restraint effect by the interaction between superstructure and abutment. The bridges suffered unseating of superstructures from substructures and/or the significant damage at the end of concrete girders. Photo 1 shows a typical collapse of superstructure and damage of concrete girder.

On the other hand, the bridges designed based on the original Chilean design practice including the placement of end diaphragms and lateral stoppers behaved very well even against the strong shaking as shown in Photo 2. It should be noted here that some bridges were damaged in coastal region where soil instability including soil liquefaction and lateral spreading was observed.

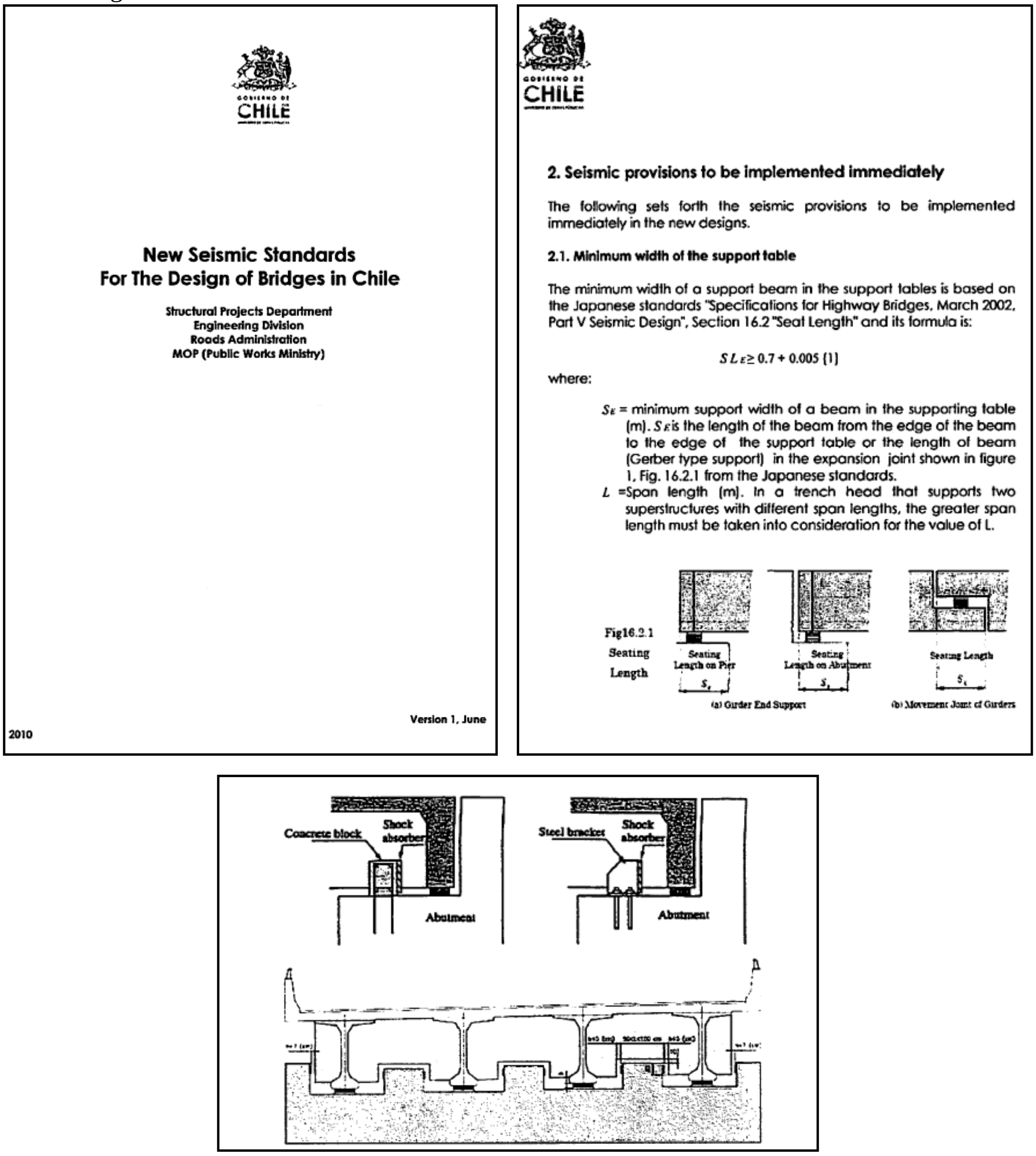
Photo 1 Typical Collapse and Damage of Concrete Girders during 2010 Chile Maule Earthquake
(Courtesy of Chilean Ministry of Public Works)
(Left: Collapse of Superstructures due to Rotation, Right: Damage at End of Concrete Girder)

Photo 2 Bridges designed by Original Chilean Practice with End Diaphragms
and Lateral Stopper Mechanism

Based on such critical damage experiences, the Road Administration of the Chilean Ministry of Public Works (MOP) revised “the Chilean Seismic Design Standards for the Design of Bridges” in June 2010, about 3 months after the earthquake. The new aspects learned from the damage have been incorporated into the revision as immediate and medium term measures to improve the seismic performance of bridges.

Fig. 1 shows the copies of the seismic provisions on the unseating prevention measures including minimum seat width and lateral stopper specified in the new seismic standards. The newly specified provisions were based on the “Japanese Specifications for Highway Bridges, Part V. Seismic Design, 2002.” The formula to calculate the minimum seat width and the stopper structures were from the Japanese Standard.

The repair and the reconstruction of the damaged bridges were made according to the new seismic design standard.


GOBIERNO DE CHILE

New Seismic Standards For The Design of Bridges in Chile

Structural Projects Department
Engineering Division
Roads Administration
MOP (Public Works Ministry)

Version 1, June 2010

GOBIERNO DE CHILE

2. Seismic provisions to be implemented immediately

The following sets forth the seismic provisions to be implemented immediately in the new designs.

2.1. Minimum width of the support table

The minimum width of a support beam in the support tables is based on the Japanese standards "Specifications for Highway Bridges, March 2002, Part V Seismic Design", Section 16.2 "Seat Length" and its formula is:

$$S L_E \geq 0.7 + 0.005 \quad (1)$$

where:

S_E = minimum support width of a beam in the supporting table (m). S_E is the length of the beam from the edge of the beam to the edge of the support table or the length of beam (Gerber type support) in the expansion joint shown in figure 1, Fig. 16.2.1 from the Japanese standards.

L =Span length (m). In a trench head that supports two superstructures with different span lengths, the greater span length must be taken into consideration for the value of L.

Fig. 1 Specified Unseating Prevention Mechanism
in the New Seismic Standards for the Design of Bridges in Chile which revised in June, 2010

BRIDGE DAMAGE AND THE REPAIR/RETROFIT

Fig. 2 shows the locations of bridges damaged during 2010 Chile Maule earthquake investigated by the JSCE reconnaissance team (Kawashima et. al., 2010a, b). The author investigated the repair and reconstruction works for some of the damaged bridges in February, 2011. The investigation was made for the bridges with red-colored underlines in cities of Santiago and Concepcion as shown in Fig. 2. In total, the repair and reconstruction of 12 bridges were investigated, in which 2 bridges were not investigated by the JSCE reconnaissance team in 2010.

In this paper, the typical damage and the employed repair methods are presented for some selected bridges.

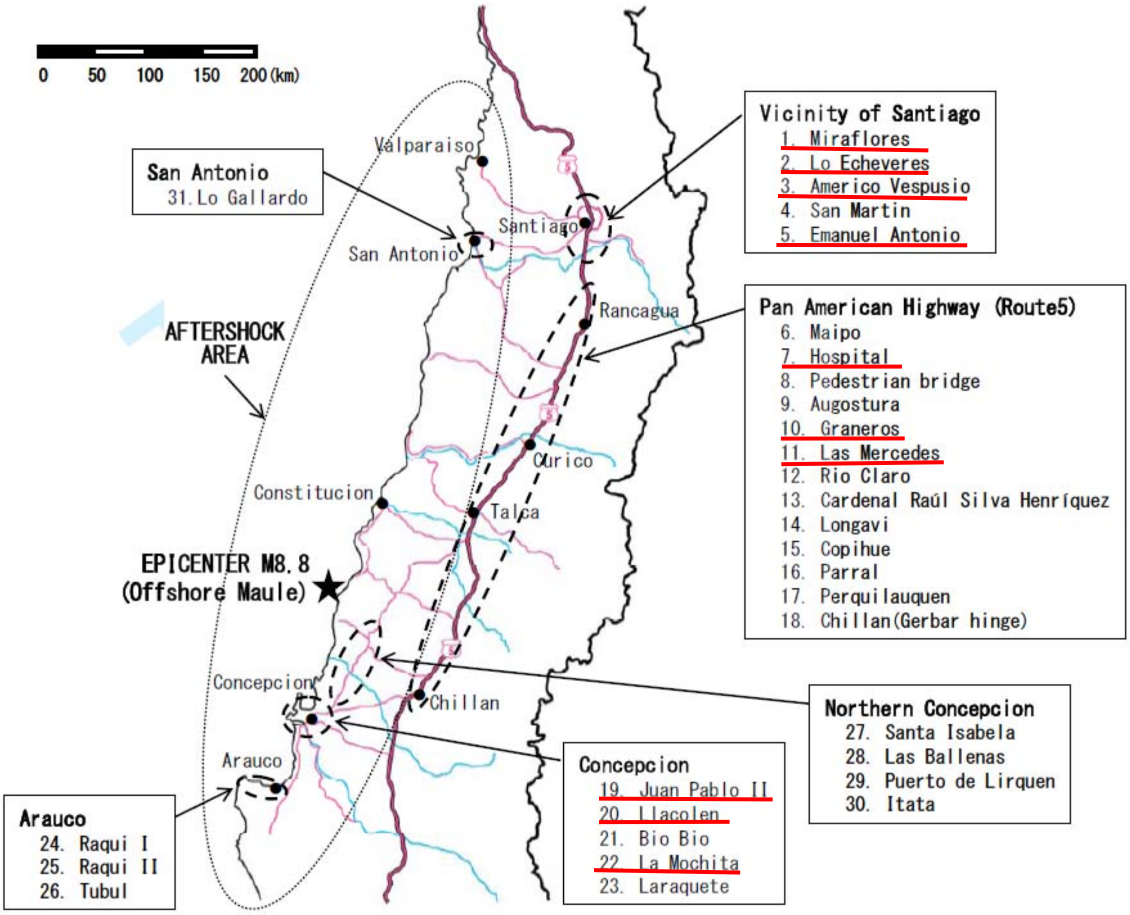


Fig. 2 Locations of Bridges damaged during 2010 Chile Maule Earthquake (Kawashima et. al., 2010a, b) (Repair/Retrofit was investigated for bridges with red-colored underlines in February, 2011)

Overpass in Santiago

Mira Flores and Lo Echeveres Overpasses

There is the Metropolitan freeway network in Santiago city. The network consists of a ring highway and trunk highways in a radial pattern. The critical damage including collapse of superstructures occurred on the network. The typical damage was found at Mira Flores and Lo Echeveres overpasses. The outer and inner ring bridges of Mira Flores overpass collapsed. They were 22.5m+28m+22.5m long 3-span simply-supported PC girder bridges with a skew angle of 68 degrees. Similarly, the inner ring bridge of Lo Echeveres overpass collapsed as well. It was a 92m long 3-span simply-supported

PC girder bridge with a skew angle of 60 degrees. Two overpasses had almost similar structural characteristics.

During the earthquake, the acute corner of the superstructures was offset nearly 1.5-2.0m in the transverse direction and unseated from the abutments. There was almost no significant damage to abutment walls and piers.

To repair the bridges, the collapsed superstructures were replaced by new PC girders. Based on the new seismic standards, the lateral beams to connect adjacent girders were placed at the girder ends and the concrete block type stoppers were installed between the girders at the cap beam. Photos 3 and 4 show the repaired abutments and piers of Mira Flores overpass and Lo Echeveres overpass, respectively. It should be noted hear that the widening of the seat width as well as the installation of the stoppers was also made at the abutment of Lo Echeveres overpass.

Photo 3 Repair and Retrofit for Mira Flores Overpass
(Left: Lateral Stopper at Abutment, Right: Lateral Beam and Lateral Stopper at Pier)

Photo 4 Repair and Retrofit for Lo Echeveres Overpass
(Left: Lateral Stopper at Abutment, Right: Lateral Beam and Lateral Stopper at Pier)

Antonio Matta Bridge

Photo 5 shows the collapse of Antonio Matta Bridge. The bridge is on the Manuel Antonio Matta Street which overpasses the Linea de Ferroccarril Railroad. Superstructure consisted of 3-span simply-supported steel girders and the continuous slab at joints. The skewed angle was about 50 degrees. The piers were reinforced concrete multi-column bent. The steel girders were supported by rubber pad bearings.

During the earthquake, a whole bridge was rotated and the large transverse displacement was developed at both ends, then the superstructures were unseated from their abutments. The displacement in the transverse direction at the abutment was about 90cm. In contrast, there was almost no damage to the reinforced concrete columns. The collapse mechanism is similar to that found at Mira Flores and Lo Echeveres overpasses.

Photo 6 shows the completion of repair for Antonio Matta Bridge. The existing steel girders were reused. At the abutments and piers, the stopper structures using concrete blocks were provided and the seat width was widened at the abutments as well.

Photo 5 Collapse of Antonio Matta Bridge
(Left: Side View, Right: Skewed Seat at Abutment)

Photo 6 Repair and Retrofit for Antonio Matta Bridge
(Left: Abutment with Lateral Stopper, Right: Pier Cap with Lateral Stopper)

Overpass on Highway Route 5

Las Mercedes Bridge

The rotation of a whole bridge occurred not only in skewed bridges but also in straight bridges. Las Mercedes bridge which crossed over Highway Route 5 was also heavily damaged due to the rotation. Las Mercedes Bridge was a 54m long 2-span simply-supported PC girder bridge with connecting deck slab at center pier joint. The length and the structural properties were typical for the overpasses on Highway Route 5. The skew angle was 79 degrees, it was an almost straight bridge. PC girders were supported by rubber pad bearings without any stiff connection between superstructures and substructures.

During the earthquake, Las Mercedes bridge rotated around the center pier resulting in transverse displacement around 1.0-1.4m at both ends. Photo 7 shows the unseated PC girders at the abutment. There was evidence of the collision between the end of a deck slab and the abutment parapet wall at both ends.

Photos 8 and 9 show the repair and retrofit of Les Mercedes bridge. Both the end sections of concrete girders were repaired and strengthened by adding reinforced concrete to increase the lateral shear strength of the web and flange. Also, lateral beams to connect adjacent girders were placed at the girder ends. The seat width was widened by adding the reinforced concrete at the abutments, and the lateral stoppers made of concrete block were installed at both abutments and pier cap.

The similar repair and/or retrofit methods were employed for several overpasses on Highway Route 5. Photo 10 shows Los Pinos overpass. The lateral beams and lateral stopper were installed at the abutments and piers. It should be noted here that Chilean MOP also employed the strengthening method for the abutments which were constructed on soft soil ground condition. Photo 11 shows Azufradero bridges as an example of the strengthening method for the abutment. Removing the backfill soils, and vertical walls were added to increase the stiffness and stability of abutment walls and foundations.

Photo 7 Damage of Les Mercedes Bridge
(Left: Side View, Right: Lateral Offset at Abutment)

Photo 8 Repair and Retrofit for Les Mercedes Bridge (1)
(Left: Strengthening of PC Web, Right: Widening of Seat Width at Abutment)

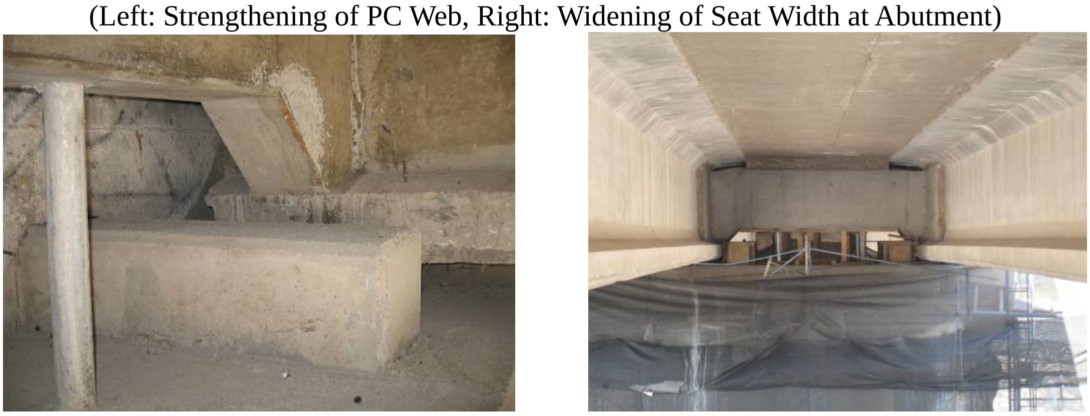


Photo 9 Repair and Retrofit for Les Mercedes Bridge (2)
(Left: Lateral Stopper at Abutment, Right: Lateral Beams and Lateral Stoppers at Pier)

Photo 10 Repair and Retrofit for Los Pinos Bridge
(Left: Side View, Right: Lateral Beams and Lateral Stoppers at Pier Cap)

Photo 11 Repair and Retrofit for Azufradero Bridge
(Left: Damage to Girders and Abutment, Right: Stiffening Wall at Backside of Abutment)

Hospital Overpass

One of the typical examples of collapse due to the rotation of skewed bridges was Hospital overpass on Highway Route 5 at the crossing over railways and a local road. It was a 2-span simply-supported PC girder bridge with deck slab which connected two spans. There were two overpasses to the north-bound and to the south-bound. The north-bound overpass collapsed as shown in Photo 12, whereas the south-bound overpass suffered almost no damage. The south-bound overpass was relatively old and designed based on the original Chilean design practice, in contrast, the north-bound overpass was recently designed bridge. It should be noted here the skewed angle of the collapsed north-bound overpass was 45 degrees, on the other hand, the south-bound overpass was a straight bridge. Both abutments did not suffer damage and pier suffered only minor flexural cracks at the columns.

Photo 13 shows the reconstruction of Hospital overpass. The collapsed concrete girders were replaced by new steel girders. The end lateral beams were provided to connect adjacent girders and the lateral stoppers were provided at the abutments and piers.

Photo 12 Collapse of Spans at Hospital Overpass

Photo 13 Reconstruction and Retrofit of Hospital Overpass
(Left: Side View, Right: Lateral Stopper at Cap Beam of Pier)

Bridges in Concepcion

Juan Pablo II Bridge
Juan Pablo II bridge is a 2,310m long 70-span simply-supported bridge which crosses over Biobio river in Concepcion city. The concrete superstructures were supported by reinforced concrete piers. Extensive settlement as large as 0.5m occurred at pier foundations and 3 reinforced concrete columns and a lateral cap beam failed in shear as shown in Photo 14. The settlement of pier foundations was estimated to be developed due to the insufficient bearing capacity as well as the effect of soil liquefaction.

Photo 15 shows the repair and retrofit of Juan Pablo II bridge. Additional piles were placed at the both sides of settled piers to support the superstructures. The failed reinforced columns in shear were reconstructed. The lateral stoppers were also provided at the pier cap.

Llacolen Bridge
Similar to Juan Pablo II bridge, Llacolen bridge is a critically important bridge crossing Biobio river in Concepcion city. Main spans in the river section did not collapse, but an approach span consisting of PC girders collapsed as shown in Photo 16. Short seat support width resulted in unseating of the approaching span against large longitudinal displacement caused by the strong shaking. Photos 17 and 18 show the replaced span of Llacolen bridge and the retrofit. Collapsed concrete girders were replaced by the steel girders which were connected by lateral beams at both ends.

Photo 14 Damage of Juan Pablo II Bridge
(Left: Settlement of Pier Foundation, Right: Shear Failure of Pier Columns)

Photo 15 Repair and Retrofit of Juan Pablo II Bridge
(Left: Additional Piles at settled Piers, Right: Replaced Pier Columns and Lateral Stopper Structures)

The lateral stoppers were provided at the pier caps. The seat supports was also widened by adding reinforced concrete. Some of the reinforced concrete columns were jacketed by fiber sheets to repair the flexural cracks and to enhance the shear and ductility capacity. It should be noted that a new bridge was also under construction to cross Biobio river in Concepcion city as shown in Photo 19.

Photo 16 Collapse of Llacolen Bridge

Photo 17 Replaced Collapsed Span of Llacolen Bridge


Photo 18 Repair and Retrofit for Llacolen Bridge
(Left: Placement of Lateral Beams and Lateral Stoppers, Right: Widening of Pier Cap and Retrofitted Column by Fiber-Sheet Jacketing)

Photo 19 New Bridge Construction (Chacabuco Bridge) to cross BioBio River

La Mochita Bridge

La Mochita bridge is a 4-span simply-supported PC girder bridge which crosses a waterway along the BioBio river. The piers were two column bents. During the earthquake, the large lateral displacement of the superstructures as large as 85 cm was developed as shown in Photo 20. Several cracks were found on the ground surface around the foundations. The foundations were estimated to move laterally because of the lateral spreading of the surrounding soils. Since sand boiling was found at several locations on the surrounding ground, the lateral spreading was estimated to be caused by the effect of soil liquefaction.


Photo 20 Lateral Displacement of Superstructure and Foundations at La Mochita Bridge

Photo 21 shows the repair and retrofit for La Mochita bridge. The displaced deck was moved back to the original position and the lateral stoppers were installed at the top of abutments and piers. The two column bents were strengthened to wall type columns and new piles to increase stability were placed and connected the existing columns.

Photo 21 Repair and Retrofit for La Mochita Bridge
(Left: Pier Cap with Lateral Stopper, Right: Strengthening of Foundations by Placing New Piles)

CONCLUSIONS

This paper presented the repair and retrofit of bridges damaged by the 2010 Chile Maule earthquake with application of the New Chilean Seismic Standards for the Design of Bridges. Basic concept of the repair and retrofit measures were to increase the integrity of girders by adding the end lateral beams and to restrain the lateral displacement by providing with the unseating structures. Strengthening measures by constructing new piles and walls to the foundations were also employed for the bridges on the soft soil ground conditions to increase the stability of foundations against the effect of soil liquefaction.

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