Figure 4.59 South Pier Container Crane with Impact Damage from Moored Vessel Impact (Vessel – Structure Interaction)

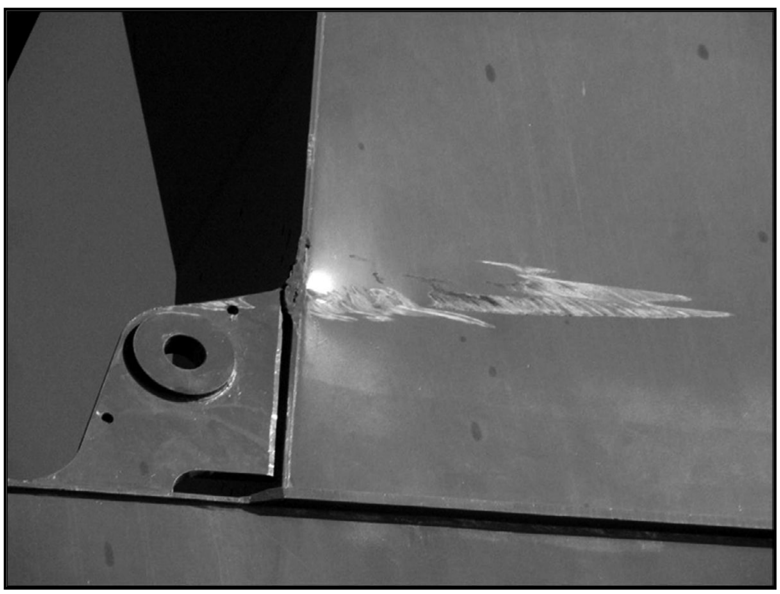

Figure 4.60 South Pier Close-up of Minor Dent / Scratch on Container Crane Due to Impact of Moored Vessel (Vessel-Structure Interaction)

<u>Backlands</u>

The yard between the north and south pier had lateral spreading adjacent to the sheet pile wall. Five stacked containers fell and ripped open. The lateral spreading and displaced direction of the north pier piles are believed to be an indication of kinematic soil motion having occurred. However, as shown in Figure 4.61 and Figure 4.62 the steel sheet piles along the beach at the shore side of the lateral spreading showed no tilt or displacement, possibly indicating that the entire soil layer moved as one unit.

Figure 4.61 Steel Sheet Piles Adjacent to Beach with Lateral Spreading in Backlands

Figure 4.62 Lateral Spreading in the Backlands, Adjacent to the Beach Sheet Pile Structure

<u>Tsunami Effects</u>

The tsunami was observed to be only one wave/run-up with a height of about 3m. The wave did not overtop either of the two piers or reach into the backlands. For this terminal, the tsunami effects were not significant and therefore no damage resulted. No tectonic plate uplift effects were noted, however the port is studying bathymetry and will be monitoring tidal variations in the near future to see if there are any differences.

Major Observations/Findings and Recommendations

This facility presents a range of structural behavior in response to the earthquake. The northern pier trestle may be partially usable for vertical loads but will require extensive rehabilitation to restore it to its original condition. Because of the kinematic loading, it is difficult to determine the below grade condition of the piles on the main portions of the pier. It is believed that the kinematic loading is a result of the 1-2m of lateral spreading observed near the abutment in the backlands. Some of the vertical piles were bent up to 30 degrees, with buckled stiffener plates and ruptured welds with failed connections at the pile/cap beam connection. Clearly this pier was not designed for kinematic loading but performed quite well with respect to inertial loading.

The new southern pier, with the base isolation configuration with square steel framing into the piles, and a waffle type concrete slab performed quite well. There was no evidence of permanent deformation and operations have resumed to full operational status. However, one container crane was slightly impacted by a moored vessel and experienced some repairable damage. This novel vessel-structure interaction due to earthquake loading should be studied in more depth and considered in future design of base-isolated marine structures.

Tsunami effects were minimal, and the 3m height never reached the pier decks. No observations were made at the time of the earthquake and reportedly there was only one wave.

Acknowledgements

The ASCE/COPRI Team would like to thank Mr. Eduardo Faundez, Industrial Civil Engineer from the Port of Coronel for his assistance and guidance during our inspection.

4.7 Santa Maria Island

Observations of Santa Maria Island provided a clear example of the sheer power and energy released during the February 27, 2010 seismic event. Already a prime laboratory for the study of tectonic uplift, the island provided dramatic evidence of being tilted and thrust vertically upward at least 3m. The resulting impacts to coastal infrastructure were equally as dramatic. For example, an existing small craft harbor before the event was reduced to a shallow, non-navigable embayment.

Description

Santa Maria Island is located at latitude South 37 deg. 2.5 min. and longitude West 73 deg. 30 min. Santa Maria Island is located approximately 50 km southwest from Concepción, Chile, about 20 km west off the coast. The island is relatively small (approximately 11.5 km north-south and from 0.5 to 6.5 km east-west) and has three small communities that depend primarily on fishing with some agriculture for commerce. An aerial photo of the island is shown in Figure 4.63. The community at the north end of the island lives on a mesa that is approximately 70m above sea level, but the width is less than 200m and both sides of this mesa have steep cliffs and substantial cracks with massive slides resulting from earthquakes. Almost half of the 2,200 inhabitants of the island live in the southern community of South Port.

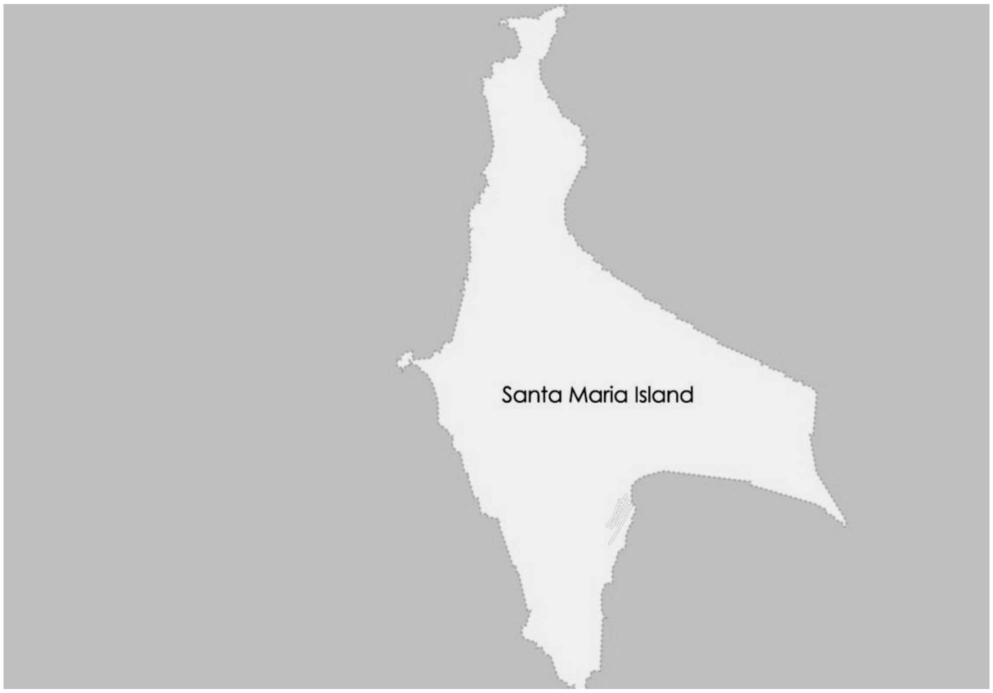

Figure 4.63 Aerial view of Santa Maria Island (Source: OpenStreetMap.org)

Santa Maria Island is an extension of the Arauco Peninsula and has been uplifted and tilted slightly eastward, with at least 3m of coastal uplift. Previous work by paleoecologists shows that people practicing agriculture were present on the island at least 1,200 years ago according to Dr. Simon Haberle of Australian National University. Immediately prior to the earthquake, he and his team were working on Santa Maria Island collecting paleo cores to determine the nature and timing of past environmental changes. According to Melnick et al. (2006), a blind reverse fault has been documented at this location and it creates a fault-cored anticline, which is responsible for uplift and tilt of Santa Maria Island at about 2 mm/year. Melnick studied the tilted abrasion surfaces and proposed that this splay fault may have been triggered by the 1835 event (Melnick et al., 2006). Their field work at the island in early March 2010, after the M_w 8.8 event, suggested further uplift and tilting of the island. Uplifting here has been observed previously and reported by Darwin (1851); he reported that he observed 3m of uplift at Santa Maria Island due to the 1835 earthquake. According to Darwin (1851) "… the southern end of the island of St. Mary was uplifted eight feet, the central part nine, and the northern end ten feet."

Ruegg, et al. (2009) have had three campaigns of global positioning measurements since 1996 during which they have determined that the vertical movement of this area is about 10 mm/year and the eastward movement is about 68 mm/year. In their work they predicted an earthquake similar to the 2010 quake near Maule.

> In the worst case scenario, that strains have not been relieved at all since 1835, at a convergence rate of 68mm/year, more than 10m of slip deficit will have accumulated since 1835. It is possible that the northern part of the plate interface between Constitución and Concepción was affected by the earthquakes of 1851, 1928 and 1939, but it is unlikely that this was the case near the city of Concepción. We would then conclude that the southern part of the Concepción–Constitución gap has accumulated a slip deficit that is large enough to produce a very large earthquake of about Mw=8.0–8.5. This is of course a worst case scenario that needs to be refined by additional work (Ruegg, et al., 2009).

At the time of the Team's visit, the Regional Planning Department was meeting with the local group at the north to convince them to move to a safer part of the island. It has been reported by the Department of Public Works that the island rose approximately 3m during the February 27, 2010 earthquake with a large lateral movement to the west. The tsunami height is believed to be approximately 6m at this location.

Observations

The general landform of the island varies from high bluffs on the western side of the island and falls to a wide coastal plain on the eastern side. Both the southern and southeastern points are growing from the material eroded from bluffs on the western side and the northern point of this island. Figure 4.64 shows a slump created by the earthquake at the northern point of the island within about 100m of the island's end. Similar slumping occurred on most of the western side of the island, shown in Figure 4.65.

Figure 4.64 Earth Slope Failure on the Island North Point, Looking North

Figure 4.65 Failure on Western Side of Santa Maria Island

Figure 4.66 was taken before the earthquake of January 1, 2002 at 8:00 AM while Figure 4.67 was taken near high tide on April 13, 2010 at approximately 11:00 AM. Figure 4.67 shows the effect of the uplift is visible at the north end of the island. Notice that there are no exposed rocks in the surf in the earlier photo although it does appear that a wave is breaking over a shallow object. There is also a small jetty at the upper end of the beach. In Figure 4.67 there is no beach of sand as it has been washed away by the tsunami. In the surf zone there are many rocks now exposed and above the water. The evidence of the South American Tectonic Plate uplift and tsunami is obvious and the effect of this on the fishing community is apparent by the absence of the buildings and the boats.

Figure 4.66 North Point of Santa Maria Island Before the Earthquake
(Photo by Simón Alvaro Muñoz U.)

Figure 4.67 North Point of Santa Maria Island After the Earthquake

The area near the shoreline also indicates the significant rise of the island above the former sea level. The retaining wall shown in Figure 4.68 indicates the line or top of algae growing on the structure. At the south end of the island, the fishing community had approximately 200 fishing boats. After the tsunami, there were no more than 40 boats remaining. Figure 4.69 and Figure 4.70 show the effects of the earthquake and tsunami on the ramp used to launch the fishing boats. Figure 4.69 was taken before the earthquake on January 24, 2008 at 5:25 PM. The dark sand indicates the high tide condition. Figure 4.70 was taken April 13, 2010 at about 11:40 AM. It can be seen in this photograph that the wetted line of the sand on the right of the picture marks the location of high tide that occurred about 30 minutes before the photograph was taken. The difference in the high water lines from the two photos is estimated at approximately 2m.

Figure 4.68 Retaining Wall Showing the Former Line of Marine Algae

Figure 4.69 Fishing Boat Launching Ramp Before the Earthquake (Photo by Simón Alvaro Muñoz U.)

Figure 4.70 Fishing Boat Launching Ramp After the Earthquake

The destruction of the ramp is probably a combination of the earthquake and the scouring action of the tsunami. The fishing pier in the distance was destroyed by the tsunami, although many of the pilings remained. There are many species of sessile organisms and sea grass that are now dehydrated on the shoreline as shown in Figure 4.71 and Figure 4.72. The latter figure was taken from about 70m and it is not as clear as the former that was taken close by the rocks. Nevertheless, it is clear that the sea bed has risen and the exposed organisms are now dead and decaying.

Figure 4.71 Area Formerly Underwater, Which is Now Nearly 2m Above Mean Sea Level

Figure 4.72 Exposed Marine Grass and Organisms on the Northwestern Side of the Island

Findings

It is clear from the observations made by the Team that the tectonic uplift of the island has created a significant change in the local environment. The earthquake was also responsible for the soil failures along the bluffs of the island on both the east and west sides. The effect of the tsunami on the infrastructure was only apparent at the southern community. There, several hundred fishing boats were lost and the launch ramp was undermined from scour. The large spit on the southeast side was overwashed in a number of places with the dunes being breached and flooding of the interior occurred.

Currently there is no launch facility since it no longer extends below sea level. Therefore all boats are launched through the surf. The fishing pier is not operational as it was destroyed by the tsunami. With a decrease in water depth at the pier, it will need to be extended to deep water before it can be restored to functionality.

Lastly, the inhabitants at the northern end of the island live in a high hazard zone. It appears that the sloughing of the high bluffs will continue to threaten their lives and homes and agrarian fields.

Acknowledgements

The ASCE/COPRI Team would like to thank Police Chief Luis Ramirez for his assistance and guidance during our inspection.

4.8 Caleta Tumbes

Caleta Tumbes suffered significant damage from both the February 27, 2010 earthquake and resulting tsunami, though it was difficult to discern the primary cause of so much damage. This location was particularly hard hit, with the majority of the landside structures and coastal infrastructure being significantly damaged or destroyed. Tsunami impacts may have been exacerbated by a focusing of wave energy in the channel between the point of land where the village is located and a moderate-size island located directly off the point.

Description

Caleta Tumbes is located at latitude South 36 deg. 38 min. and longitude West 73 deg. 5 min. Observations were made at the small fishing village of Caleta Tumbes located on the northeastern tip of the Peninsula Tumbes, which forms the western boundary of Bahia Talcahuano (see Figure 4.73). The M_w 8.8 earthquake that occurred at 3:34 AM local time on February 27, 2010 was centered off the coast of the Maule region, approximately 70km north of Caleta Tumbes. This megathrust earthquake generated a devastating tsunami that propagated radially from the epicenter. Similar to Dichato, though at a larger scale, the north-facing opening to Concepción Bay was particularly susceptible to the impacts of the south-traveling tsunami waves (see Figure 4.73).

The impact of the tsunami may also have been exacerbated by a focusing of the tsunami wave energy in the channel between the eastern edge of the peninsula and the adjacent Quiriquina Island to the east, creating an amplified impact of high tsunami inundation and flow velocities. The vast majority of the fishing fleet was completely destroyed.