10.0 SLOPE STABILITY AND LANDSLIDES

While landslides of various types on natural and cut slopes occurred throughout the region affected by strong ground shaking, the overall landslide density was uncharacteristically low given the magnitude of the event and the topography of the region. The central region of Chile is forested and managed for timber resources. In addition to major highways, many forest roads traverse the hilly Coastal Range to access the timber and cuts along these roads experienced sporadic slope failures. The coastal zone is characterized by lengthy sections of steep bluffs in marine terrace and Tertiary sedimentary rocks. While there were a number of shallow slides along these bluffs, the failures were not pervasive except in a few highly localized areas. Deep seated slides were relatively rare. In most cases, the slides did not present a significant engineering issue. In most cases the debris was quickly plowed off the road and traffic could continue unimpeded. No damage of any significance was observed along any slopes stabilized by conventional slope stabilization techniques: rock bolts, wire mesh, shotcrete. Consequently, only illustrative examples of failures are presented without any specific regional grouping.

10.1. Rock Falls and Shallow Disaggregated Slides

Rock falls and shallow disaggregated slides in areas with steep rock slopes are a common occurrence in major seismic events. As already noted, while present, their density was quite low and their impact on engineered structures or human habitation was minimal.

Rapel Dam (34.041445°S, 71.588856°W) - Figure 10.1 shows a rock fall from a road cut in granitic jointed rock mass on the main road approaching the Rapel Dam. Fortuitously, there was no damage to the buildings, because the road acted as a buffer. Rock falls also occurred from steep unscaled slopes immediately below Rapel Dam on both abutments. While not causing any damage of consequence, the fallen rock did represent a removal nuisance (Figure 10.2). A shallow disaggregated slide in road cut in the weathered rock mass also covered a portion of the roadway along the immediate upstream section of the right abutment of the reservoir (Figure 10.3). This type of limited raveling failure is characteristic of failures observed sporadically throughout the region, as shown below.

Figure 10.1. Rock fall from a road cut at the approach to Rapel Dam (34.0365°S, 74.586983°W).

Figure 10.2. Rock fall from the downstream left abutment of Rapel Dam (34.04167°S, 71.59263°W).

Figure 10.3. Shallow raveling failure of a road cut in weathered and heavily jointed granitic rock at Rapel Dam (34.0407421°S, 71.587153°W).

Road Cut Failures – Sporadic failures in road cuts were noted throughout the region and their size and characteristics typically reflected the height of the cut and the competency of the source material. More competent rock types exhibited larger size boulders within the failed mass while less competent source materials exhibited more disaggregated masses of smaller boulders and particles. Figure 10.4 shows a relatively extensive failure in a cut in jointed welded tuff north of El Manzano along the western edge of Lago Rapel. Figure 10.5 is a shallow failure in an approximately 15 m (45 ft) high cut in highly weathered rock on the road from Nacimiento to Santa Juana. The volume of the material was just enough to overtop the barrier, but not enough to damage it or to impede traffic. Figure 10.6 is a cut in Holocene fluvial sand deposits just North of Pulen bridge (Bridge Case No. 9) that simply sloughed along most of its face. The failure was shallow and had no effect on traffic. Similar shallow slides were observed on numerous highway overpass fills which typically appeared to be densely compacted sand with very few fines. Finally, Figure 10.7 is a bench failure in a high, ~ 30 m, benched road cut in residual soil/heavily weathered rock. The failure appears to have occurred along a daylighting joint surface that was unrecognized when the uppermost bench was cut. An immediately adjacent, identically benched slope showed no signs of failure; hence, joint orientation most likely controlled the location and mode of failure.

Figure 10.4. Road cut failure in jointed welded tuff north of El Manzano. The height of the cut is about 6 m (20 feet). Picture looking NE (34.144076°S, 71.38000°W).

Figure 10.5. Shallow failure in a road cut in highly weathered bedrock (37.256493°S, 72.96018°W, looking SW).

Figure 10.6. Sloughing of unconsolidated fluvial sand in a road cut North of Santa Juana (37.1111°S, 72.9876°W).

Figure 10.7. Bench failure along a daylighting joint in a road cut in deeply weathered rock south of Lota (37.1213°S, 73.1550°W).

Failures in Coastal Bluffs – Tectonically uplifted Tertiary sediments and more recent beach terrace deposits form steep coastal bluffs along most of the affected coastline. The bluffs are particularly steep where they are directly at the beach level while in other locations they are less steep and slightly set back. In general, these types of slopes are susceptible to shallow raveling and sloughing, and such was the case in this event. However, as already noted, the failures tended to be concentrated in a few localities with only occasional failures along large sections of the coastline. This was quite surprising given the magnitude of the earthquake and duration of shaking.

Lebu and Arauco region **-** The active tectonic uplift along the section of the coast between just south of Lebu and extending northward toward Arauco has produced a series of prominent headlands in uplifted Tertiary sedimentary rocks capped by younger marine terrace deposits. These headlands reach heights of as much as 200 meters and drop abruptly and steeply to narrow rocky beaches. The steep seaward slopes would have been expected to have been subject to slope failure and indeed numerous slope failures were in evidence and they were locally pervasive. Figure 10.8 shows the headland just southwest of Lebu with the town of Lebu in the distance. As can be seen, whole sections of the slopes are denuded by shallow raveling and sloughing, however, deep seated rotational or block failures are not observed. Local evidence suggests that the coast was inundated by a tsunami and the toes of the slopes exhibit evidence of wave erosion. Hence, it is possible and likely that at least some of the landslide material has been removed by the tsunami wave action. Similar setting but less frequent failures are exhibited along the bluffs north of Pta Carneros just southwest of Arauco as shown in Figure 10.9.

Figure 10.8. Shallow slides along bluffs southwest of Lebu (37.6°S, 73.674°W).

Figure 10.9. Bluffs north of Pta Carneros, southwest of Arauco, showing frequent but not pervasive sliding and raveling (37.326°S, 732674°W).

The character of the coastline changes to the north of Arauco, with softer sediments exposed in the terrace and beach bluff slopes. The slopes tend to be more gentle and more densely vegetated. Similarly slope failures are less frequent although when they occurred they had greater impact as road alignments take advantage of the less rugged coastal zone. A series of slides occurred at the seaward ends of low ridges in soft sandstones west of Arauco, with two of the slides closing the coastal road. The aerial view of the general setting is shown in Figure 10.10 with the town of Tubul in the distance and Arauco off the picture to the distant left (SE). A view of a slide that closed the road just West of Arauco is shown in Figure 10.11.

Figure 10.10. Aerial view of the coastal bluffs West of Arauco (37.2205°S, 73.443°W).

Figure 10.11. Shallow failure along a truncated ridge forcing road closure West of Arauco (37.2437°S, 73.413°W) .

Concepcion Area – Very similar types of highly localized landslides occurred on bluffs in Tertiary sedimentary rocks in the region around Concepcion. Figure 10.12 shows steep bluffs on the eastern shore of Isla Quiriquina which experienced shallow raveling which mostly denuded the slopes. However, several larger failures occurred in this area as well. Figure 10.13 shows a large complex of shallow coalescing slides located on the western shore of Pta Tumbes just north of Talcahuano. While this landslide complex in Teritiary sedimentary rocks was one of the most extensive failures noted along the entire coastline, pre-existing photography suggests that this was a previously disturbed area used as a quarry with a history of prior sliding. This conclusion is supported by the fact that very few other slides are found in the vicinity. However, a well documented large failure of a road cut occurred across the bay just north of Tome (Figure 10.14). The road cut in interbedded sandstone and shale is about a year old and the estimated volume of the slide is 3200 cubic meters (Jose Miguel, personal communication).

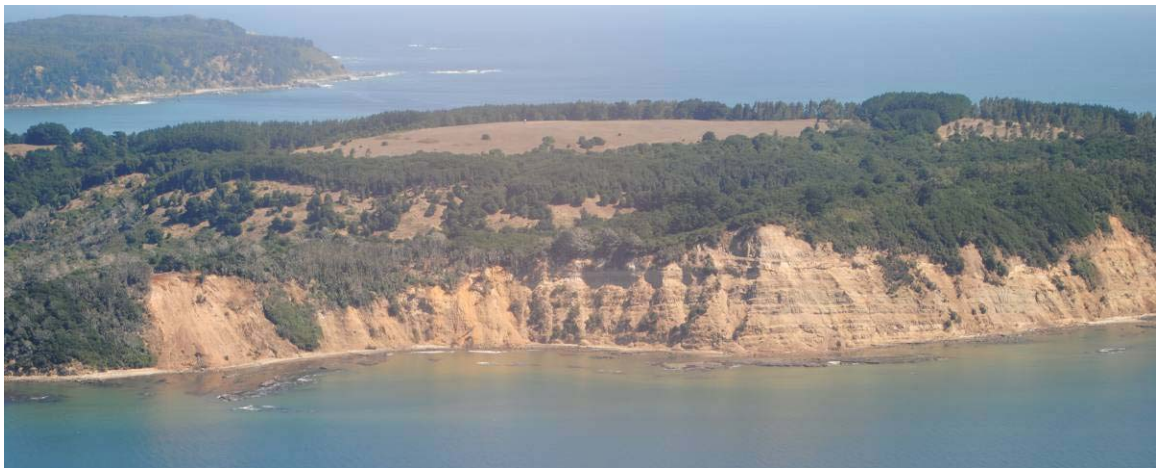

Figure 10.12. Shallow failures and raveling in Tertiary sedimentary rocks on Isla Quiriquina (36.627°S, 73.05°W).

Figure 10.13. Disagregated landslide complex, Punta Tumbes looking West (36.66°S, 73.098°W).

Figure 10.14. Landslide in a road cut in Cocholgue, north of Tome (36.595 S, 72.974 W). Photo and details courtesy of J.M. Lopez.

Navidad to San Antonio – Long stretches of the coastline north of Concepcion are fronted by bread beaches that are punctuated by occasional headlands with only occasional small slope failures. To the north of Navidad the coastline is defined by a relatively flat terrace capped by unconsolidated shallow marine and fluvial deposits. The terrace has an elevation of 80 to 100 m and drops abruptly to a narrow rocky beach. Numerous shallow failures by toppling and slumping of relatively thin slabs of bedrock and overlying sediments occurred in this region as illustrated in Figure 10.15.

Figure 10.15. Typical shallow failure of steep coastal bluffs, Reserva Nacional El Yali (33.841°S, 71.817°W) .

Interior Region – Widely scattered occasional disaggregated slides in natural slopes seemed to occur without any particular association with lithology or damage to nearby infrastructure as already shown at Rapel Dam. Figure 10.16 is an example of a typical small failure from a steep slope which occurred just below the Colbun Dam which suffered no damage.

Figure 10.16. Typical shallow disaggregated slide, Colbun Dam (35.668°S, 71.351°W) .

Given the paucity of sliding and rock falls in the main event, or at least lack of any significant damage due to them, it is interesting that rock falls and shallow raveling type failure was captured on camera in the foothills of the Andes during the M 6.9 event on March 11 (Figure 10.17). The site is east of San Fernando, in the direction of the Tiguiririca volcano, roughly 160 km east south east from the epicenter of the event, in steep terrain in highly fractured volcanic rock of the Coya-Machali Formation. Hence, rock falls presumably occurred in the main event but were not observed due to darkness and were apparently not considered significant enough to be reported as they did not cause damage of any consequence.

Figure 10.17. Rock falls and shallow debris slides following the M 6.9 event on March 11, 2010 (approx. 34.8°S, 70.5°W). Note, the time in the picture is 20 minutes off. Picture courtesy of Cristian Avila.

10.2 Deep-Seated Slides

In general, deep-seated block or rotational slides were notable by their general absence. The one observed large failure, a deep-seated block slump, occurred in the coastal terrace in the El Yali National Park (Figure 10.18). The failure is clearly joint controlled, however, the exact reason for the size of this slump in an area otherwise characterized by relatively minor toppling or slumping (see Figure 10.15) is not readily apparent without further investigation.

Figure 10.18. Deep-seated bedrock slump in Tertiary sedimentary bedrock capped by marine terrace sediments (33.846°S, 71.821°W).

10.3 Summary

he general paucity of landsliding is best illustrated by the fact that even clearly identifiable areas of prior extensive landslide activity had little or no evidence of seismically triggered slides. For example, Figure 10.19 shows an old landslide complex along the coastal ridge just north of Lebu. The only evidence of sliding is seen at the lowermost portions of the slopes which form the back of the beach.

Overall the most likely explanation is that the earthquake occurred during the dry season and groundwater levels were low and the slopes were quite dry, as evidence of past debris flows and other rainfall triggered slides was abundant throughout the region. In addition, apparently the intensity of shaking was focused in relatively small zones within the whole region and in those locations the landslide activity was greater as well.

Figure 10.19. Old landslide complex north of Lebu showing no evidence of seismically-induced slope movement (37.561°S, 71.64°W).