11.0 DAMS, LEVEES, AND MINE TAILINGS DAMS

11. 1 Water Storage Dams

The Hydraulic Works Directorate of the Government of Chile (Dirección de Obras Hidráulicas) reported that the vast majority of dams in Chile suffered no damage from the February 27, 2010 earthquake. Three water storage dams were identified with damage:

- Lliu Lliu (S33.096005°, W71.219220°);
- Huelehueico (S37.81667°, W72.51667°); and,
- Coihueco (S36.637166°, W71.797530°).

The earthquake occurred towards the end of the dry season in Chile when reservoir levels are normally low. No un-managed water releases were reported. Coihueco is the only one of these dams visited by GEER personnel during March 2010.

11.1.1 Coiheuco Dam (S36.637166°, W71.797530°)

The Coiheuco Dam was visited by two GEER teams. The first visit was on March 10, 2010 and the second visit was on March 14, 2010.

The dam was built during the period from 1964 to 1970 and has a maximum height of 31 m and a crest length of 1040 m. A Google Earth image of the dam taken before the earthquake with the reservoir full is shown in Figure 11.1a. The typical section used for the dam is shown in Figure 11.1b. It was not clear if soil liquefaction occurred at this site as potential evidence of liquefaction was destroyed by the time the GEER team arrived. Several slumps occurred in the upstream shell. A scarp is visible at the upstream crest and toe bulging occurs along the upstream toe. The left (west) abutment slump is most significant with clear toe bulging (Figure 11.2). A second slump occurs to the east with lesser amounts of toe bulging (Figure 11.3). There is another small area of crest movement further to the east (Figure 11.4). A small dam on the west side of the impoundment, to the south of the main dam, shows cracking along the crest (Figure 11.5).

Figure 11.1a. Google Earth Image of Coihueco Dam taken in December 2007

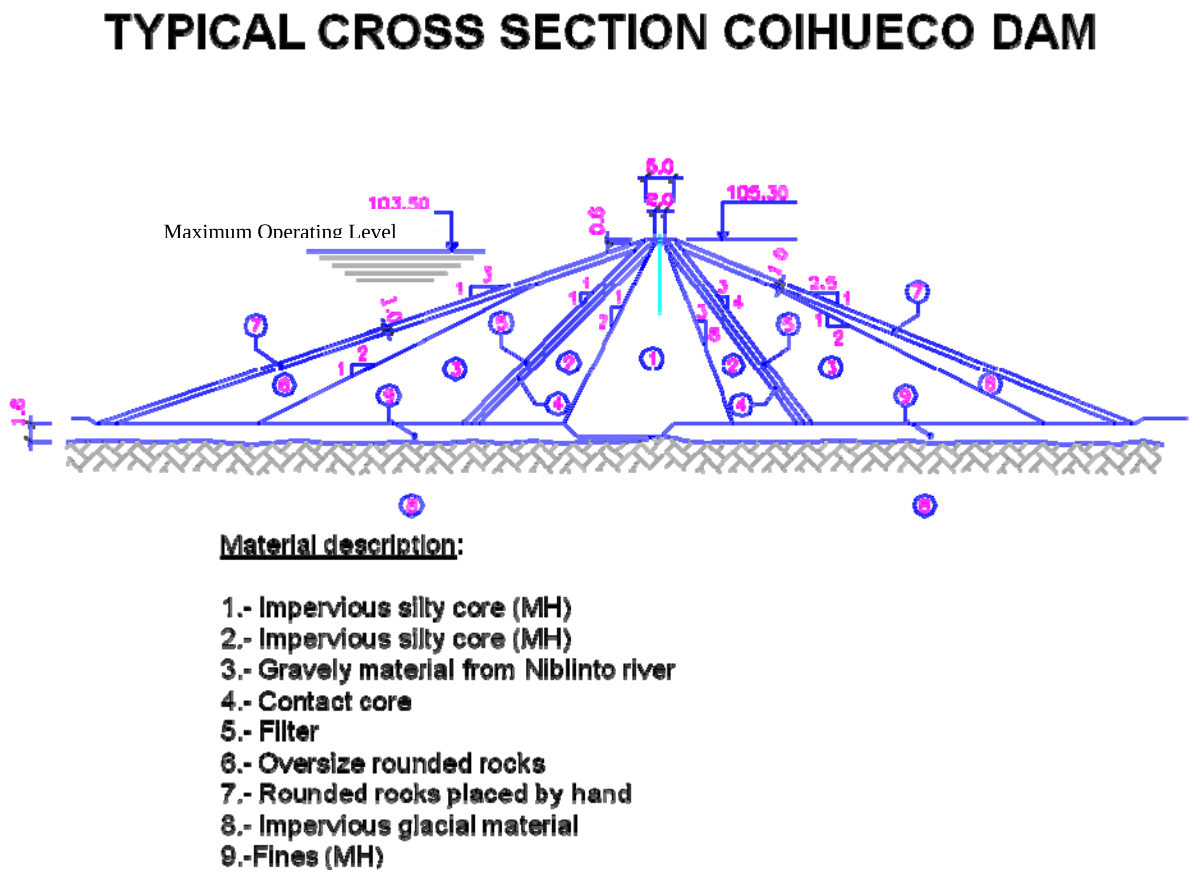

Figure 11.1b Typical Cross Section of Coihueco Dam

Figure 11.1c View of toe bulge area near left abutment of main dam, showing fine sand at the ground surface; due to the foot traffic it was not possible to see evidence that would allow one to classify these features as sand ejecta from soil liquefaction.

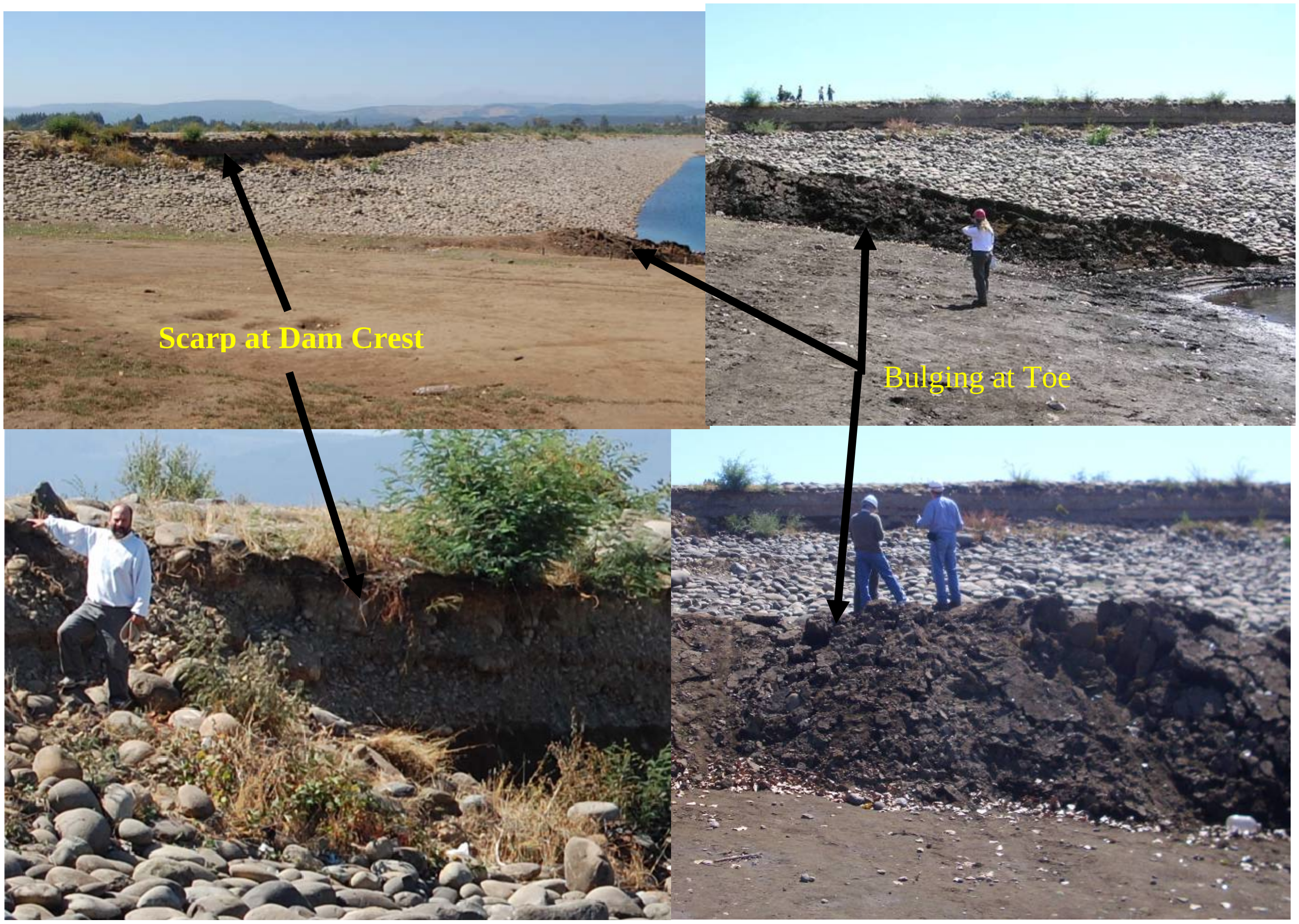

Figure 11.2. March 10, 2010. Slump of the upstream face of Coihueco Dam near the left abutment (S36.637166°, W71.797530°)

Figure 11.3. March 10, 2010. Slumping at Coiheuco Dam Crest and Bulging at Dam Toe. (S36.636508°, W71.792505°)

Figure 11.4. March 10, 2010. Small Area of Upstream Crest Slumping on Coiheuco Dam (S36.636902°, W71.788897°)

Figure 11.5. March 10, 2010. Cracking of Crest of Small Dam South of Main Coihueco Dam (S36.645411°, W71.800212°).

Rapel Concrete Dam (34.0413°S 71.5893°W)

Observations of the Rapel Concrete Dam were made from helicopter on March 10, 2010. The dam was functioning and no signs of damage were observed. A leak upstream of one of the gates is reported to pre-date the February 27, 2010 earthquake.

Figure 11.6. March 10, 2010. Rapel Concrete Dam Downstream Face (S34.038754°, W71.590223°)

Figure 11.7. March 10, 2010 – View of Upstream of Rapel Concrete Dam (S34.043786°, W71.592053°)

TAILINGS DAMS

There are no published reports of damage to operating tailings dams due to the February 27, 2010 earthquake. One tailings dam at a closed facility failed, creating a flow slide that travelled downhill several hundred meters.

Tailings Tranque Ovejeria (33.0527^{o} S, 70.8007^{o} W)

Tranque Ovejeria is a modern tailings sand dam. The dam is constructed using the downstream technique. Sand is produced from the tailings in hydro-cyclones and discharged onto the downstream face of the dam. The sand is spread by a bulldozer and compacted. An underdrain system is used to maintain a low phreatic surface in the dam. Tailings and the cyclone overflow are discharged into the impoundment. A geosynthetic liner is installed on the upstream face to reduce seepage into the dam from the tailings pond. The dam was visited by GEER personnel on March 9, 2010 and a follow-up reconnaisance was made by helicopter on March 10, 2010.

Both the on-ground inspection and the helicopter reconnaissance identified no problems with the tailings sand dam. There were many expressions of high pore pressure (sand boils) in the tailings upstream of the dam and the maximum settlement of the tailings near the dam was about 0.5 m, representing a strain of about 1%. The liner on the upstream showed no signs of dam. Several large valves rest directly on the liner, and there was not stretching or tearing of the liner at these valves. No cracks were observed on the crest or on the downstream face.

Figure 11.8. March 10, 2010 View of Ovejeria Tailings Dam from Helicopter
(S33.054182^{o}, W70.768953^{o})

Figure 11.9. March 9, 2010 View from the Left Abutment Along the Ovejeria Tailings Dam (S33.049364^{o}, W70.785354^{o})

Figure 11.10. March 9, 2010 View along the Upstream Face of the Ovejeria Tailings Dam. There is no damage to the liner and no signs of slumping of the sand beneath the liner (S33.052911^{o}, W70.807067^{o})

Figure 11.11. March 9, 2010 Sand Boils in Tailings about 10 m Upstream of Ovejeria Tailings Dam (S33.052016°, W70.798687°)

Figure 11.12. March 10, 2010. Upstream face of the Ovejeria Tailings Dam showing approximately 0.5 m of the tailings adjacent to the dam. (S33.052081, W70.792067)

Tailings Tranque Tortolas (33.1228° S, 70.7413° W)

Tranque Tortolas uses modern tailings sand dam construction techniques. The dams are constructed using the downstream technique. Sand is produced from the tailings in hydro-cyclones and discharged onto the downstream face of the dam. The sand is spread by a bulldozer and compacted. An underdrain system is used to maintain a low phreatic surface in the dam. Tailings and the cyclone overflow are discharged into the impoundment. A geosynthetic liner is installed on the upstream face to reduce seepage into the dam from the tailings pond.

An overflight by helicopter was made of this tailings impoundment. The impoundment was operating and dam construction was ongoing. No damage was observed.

Figure 11.13. March 10, 2010 View of Tortolas Tailings Dam from Helicopter (S33.115406°, W70.733297°)

Figure 11.14. March 10, 2010 View of Tortolas Tailings Impoundment from Helicopter (S33.144658°, W70.710449°)

Tranque Cabildo (32.4238^{o}S 71.0796^{o}W)

The Calbildo tailings dam was visited by helicopter on March 10, 2010. The helicopter landed and a ground based inspection was made of the dam. No issues were observed with this dam due to the February 27, 2010 earthquake. The tailings facility was not being operated. There was a minimal amount of water in the pond against the natural topography and long dry beaches adjacent to the dam. The downstream face of the dam is being rehabilitated by planting trees and an irrigation system has been installed.

Figure 11.15. March 10, 2010 View of Cabildo Tailings Dam from Helicopter (S32.427724^o, W71.077282^o)

Figure 11.16. March 10, 2010 View of Cabildo Tailings Dam from Helicopter Showing Sprinkler System on Downstream Face (S32.422414^o, W71.077165^o)

Tailings Tranque Caren (34.0961^{o}S, 71.1771^{o}W)

The Caren Tailings Dam is a zoned earthfill embankment using a sloping upstream core. The dam is raised using the downstream method. Dam raise construction was in progress at the time of the February 27, 2010 earthquake. Foundation preparation was complete for the downstream raise and compacted rockfill had been placed to about original ground level. The dam was visited on March 10, 2010. The March 11, 2010 M6.9 aftershock also affected this dam, but the site was not visited by GEER personnel following this second event. Minor (mm width) transverse cracking observed near each abutment, Figure 11.19. Evidence of settlement or movement of the downstream face not observed. Tailings upstream of the dam liquefied. Sand boils were observed in many areas of the tailings beach, Figure 11.17.

Figure 11.17. March 10, 2010 Sand Boils in Tailings Upstream of Caren Dam
(S34.111476^o, W71.141992^o)

Figure 11.18. March 10, 2010 View from Helicopter Towards the Left Abutment of the Caren Tailings Dam (S34.093959°, W71.175046°)

Figure 11.19. March 10, 2010 Millimeter Width Transverse Crack Near the Left Abutment of Caren Tailings Dam (S34.096050°, W71.180748°)

Figure 11.20. March 10, 2010 View of the Downstream Face of the Caren Tailings Dam Showing Progress of Dam Raise Construction (S34.092422^{o}, W71.173250^{o})

Figure 11.21. March 10, 2010 Crest and Downstream Face of Caren Dam from Left Abutment (S34.095570^{o}, W71.179076^{o})

Las Palmas Tailings Pond Failure (35.184679^{o} S, 71.759410^{o} W)

Las Palmas mine was operated from the early 1980's until 1997. The mine was closed and the tailings area partially covered with a thin (+/- 6") layer of gravelly material. Drilling of the tailings is reported to have been carried out in January and February 2010 to assess reprocessing of tailings for additional gold recovery. The profile seen at the upper failure scarp shows the gravelly cover layer and unsaturated tailings. Variable oxidation of the tailings has occurred with colours varying from tan to rusty in oxidized tailings to grey in unoxidized tailings. Clear evidence of liquefaction of the tailings with sand boils and ejecta along cracks indicating some portion of the tailings was saturated . Tailings flowed almost 0.5 kilometers.

The site was visited by GEER personnel on March 11, 2010 and then a follow-up visit was made on March 28, 2010 to collect data with LIDAR and DCPT.

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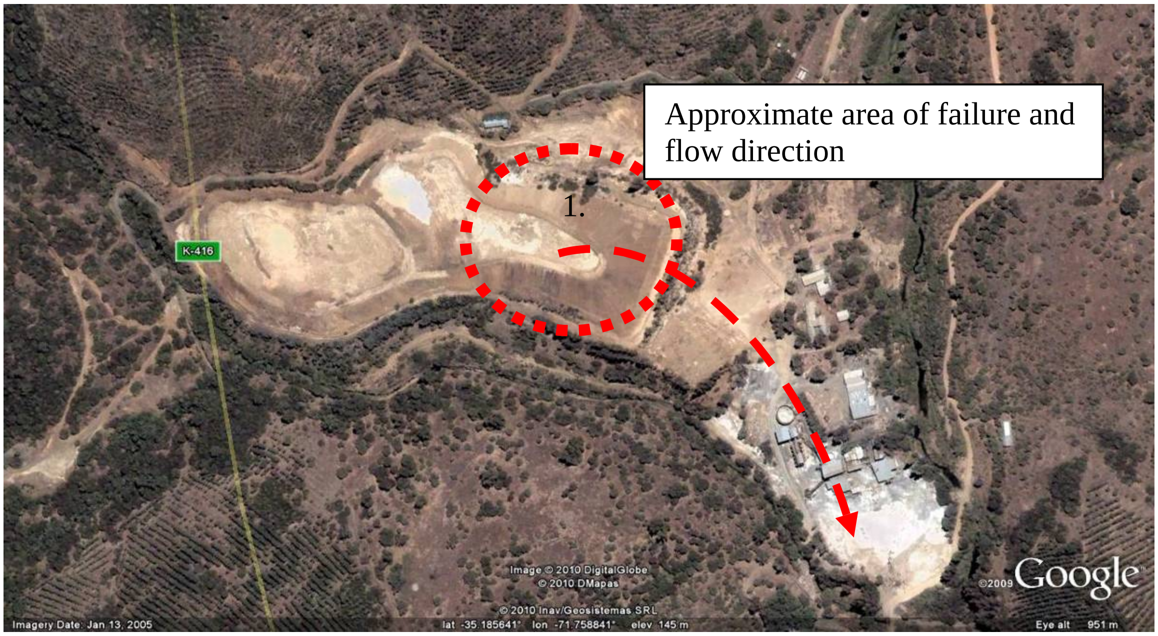

Figure 11.22. Google Earth Image Tailings Impoundment Pre-Failure
(35.184679^{o} S, 71.759410^{o} W)

Figure 11.23. March 11, 2010. Upper Scarp of Failed Tailings Impoundment Looking Southwest (35.184679° S, 71.759410° W)

Figure 11.24. Upper Scarp of Failed Tailings Impoundment Looking Northeast (35.184679° S, 71.759410° W)

Figure 11.25. March 11, 2010. View Along Flowpath of Tailings
(35.18468^o S, 71.759410^o W)

Figure 11.26. March 11, 2010. View Along Flowpath of Tailings (35.18468^o
S, 71.759410^o W)

Figure 11.27. March 11, 2010. Side View of Tailings Flow
(35.186864^{o} , 71.757873^{o}W)

Figure 11.28. March 11, 2010. Side View of Tailings Flow
(35.187204^{o} S, 71.757997^{o} W)

Figure 11.29. March 11, 2010. Gravelly Cover Layer Over Oxidized and Unsaturated Tailings (35.184679^o S, 71.759410^o W)

Figure 11.30. March 11, 2010. Variably Oxidized Tailings – Unsaturated Conditions in Upper Portion of Tailings Impoundment (S35.18728^o, W71.75781^o)

Figure 11.31. March 11, 2010. Sand Boil in Tailings (S35.18872^{o}, W71.75764^{o})

Figure 11.32. March 11, 2010. Sand Boil In Tailings along Flow Path
(S35.18872^{o}, W71.75777^{o})

Figure 11.33. March 11, 2010. Tailings Sand Boil Due to March 11, 2010 M6.9 Earthquake near Rancagua (S35.184146°, W71.761118°)

Figure 11.34. March 11, 2010. Ejecta of Tailings from Cracks Indicating Liquefaction of Tailings (S35.183986°, W71.761844°)

Levees

Earth levees generally performed well. The GEER team surveyed several lengths of levees and only observed two cases of poor levee performance. These two cases are described below.

Levee Breach West of Colbun

An earth levee that is located west of Colbun failed at 6:50 pm on March 13, 2010 (Figure 11.35), two days after the M_w=6.9 aftershock (epicenter at S34.259°, W71.929°) that occurred on March 11, 2010 at 11:40 am. The levee was inspected after the M_w=8.8 main shock of February 27, 2010, and no evidence of distress was noted. Additionally, a rapid inspection of the levee after the significant aftershocks on March 13, 2010 did not identify evidence of distress. The levee breach reportedly released a discharge of 80 cm, which is reported to have flooded a few neighboring homes in this agricultural area of Chile, but none of the homes were significantly damaged.

Figure 11.35. Earthen levee breach west of Colbun (S35.698672°, W71.487294°; photograph taken by Mr. Juan Carlos Romo of the El Mercurio on March 12, 2010; http://diario.elmercurio.cl).

The levee breach site was visited by GEER team members on March 18, 2010. At that time the levee was being reconstructed as shown in Figure. 11.36. A sample of the levee fill material was taken and is in the process of being classified. The levee fill material appears to be a silty sandy gravel material with a significant amount of cobbles. The levee is approximately 7 m high with a crest width of 6 m. Its side are sloped at about 1.5H:1V with cobble facing on its water side. The width of the zone being rebuilt was 15 m. The levee was reported to have been built 25 years ago. Whereas at other locations the existing material was excavated to build the levee, it is reported that no or little excavation occurred at this location because the natural ground surface elevation was already low at this location.

Figure 11.36. Site of earthen levee breach during reconstruction on March 18, 2010 (S35.698672°, W71.487294°).

Levee Slumping North of Juan Pablo II Bridge

A liquefaction-induced levee slump occurred along the River Bio Bio north of the Juan Pablo II bridge's NE abutment (Figure 11.37). The water level was well below the top elevation of the slumped crest of the levee so there was no breach at this location. Details of the levee construction are not known.

Figure 11.37. View obliquely down on the slumped levee from the NE approach of the Juan Pablo II bridge with evidence of sand ejecta in the foreground, and ground level view looking back at slumped level crest (S36.814555°, W73.084624°); 1700 hrs on 3/15/10).

Mine Rock Dumps

Soldado (32.65556°S 71.1145°W)

Overflight by helicopter made. No evidence of movement of these high rock dumps.

Figure 11.38. March 10, 2010. Soldado Waste Dump
(S32.654695°, W71.121352°)