# 6. PERFORMANCE OF LEVEES (OR STOPBANKS) AND OXIDATION POND EMBANKMENTS

## History of Levee Construction

Shortly after their arrival in the Canterbury area in the mid-nineteenth century, the western settlers started constructing drainage systems and levees (or stopbanks) along rivers (Larned et al., 2008). Particularly, flooding of the Waimakariri River and tributaries posed a constant threat to the Christchurch and Kaiapoi areas. Early efforts to contain the rivers within their banks were piecemeal and only partially successful. To better coordinate the efforts, the Waimakariri River Trust was established in 1923 (Griffiths, 1979). In response to the 1926 floods (Figure 6.1), the Trust implemented a major river improvement scheme in 1930, known as the Hays No. 2 Scheme. Among other things, the scheme entailed an overall improvement of the levee system along the Waimakariri River. However, these improvements were unable to prevent the major floods in 1940, 1950, and 1957. These floods prompted a further river improvement scheme in 1960, which entailed benching existing levees and construction of new levees.

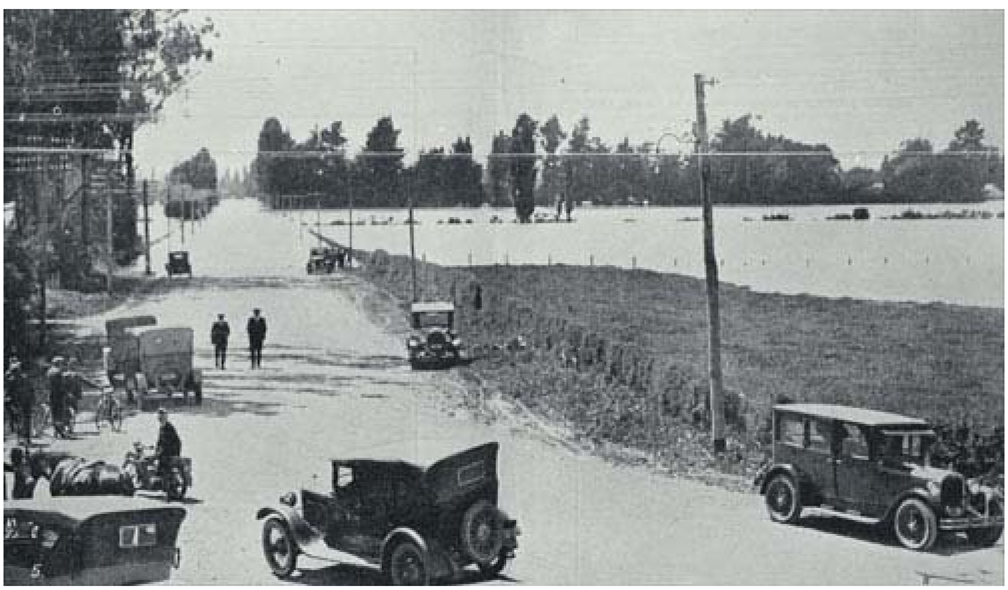

Figure 6.1 1926 photograph of the Waimakariri River overflowing its banks in Christchurch. (Te Ara Encyclopedia of New Zealand, 2010)

The mean annual flow of the Waimakariri River is 120 $m^3$/sec. However, in 1957 the largest flood on record occurred, which had an estimated peak discharge of 4248 $m^3$/sec (Griffiths, 1979). This flood was initially estimated to have a 100 year return period (Griffiths, 1979), which was later revised to a 500 year return period (Heslop, 2010), and was used as the design basis flood for the levee improvement scheme implemented in the 1960s.

A typical levee cross section in the Christchurch area has 3:1 horizontal to vertical slopes on both the river and land sides (Figure 6.2). They range in height from 3-5 m above the subgrade and have a 4-m wide top, which also serves as an access road. A flood event originating in the headwaters of the Waimakariri River takes approximately 1.5 days to travel downstream before it reaches the levee system that protects Christchurch and surrounding areas. At its crest, the 500 year event would leave 90 cm of freeboard, but may only last for four hours (Heslop, 2010).

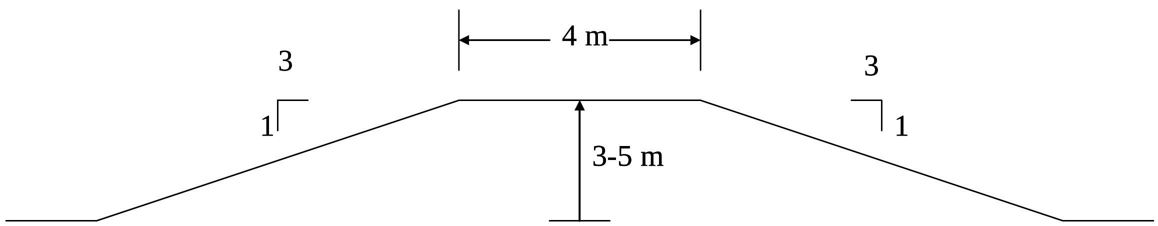


Figure 6.2 Typical geometry of levee cross section

The levees were often constructed by pushing up river gravels and silts. The typical cross section is made up of a gravel core with 1-m thick silt cap, which extends from the river side across the top (Figure 6.3). The levees typically sit on sandy soils at or near the ground water level. A toe filter was also constructed on the land side of the levee to prevent piping of sand during a high water event. During the 1960 river improvement scheme, the new stopbanks and the benches added to existing levees were compacted using vibrating rollers (Boyle, 2010). However, no compaction control or foundation analysis was conducted (Heslop, 2010).

Unfortunately, the geotechnical reconnaissance team has not yet been able to obtain construction drawings and/or specifications used in either the 1930 or 1960 improvement schemes for the levees and are uncertain if such drawings/specifications still exist, if they ever did.

**Seismic Performance of Levees**

The geotechnical reconnaissance team performed damage surveys along stretches of the primary and secondary levees for the Waimakariri River and along the primary levees for the Kaiapoi River on the morning of the earthquake (4 September 2010) and then again a few days later (between 9-16 September 2010) . The surveys were performed on foot, in an automobile, and from a helicopter. Figure 6.4 shows the stretches of the levees that the GEER-NZ Team surveyed. The Team also corresponded with the Environment Canterbury (ECan) personnel (Ian Heslop and Tony Boyle) who are overseeing damage assessments and repairs of the levees damaged during the earthquake. Below is a summary of the observed performance of the levees along the Waimakariri and Kaiapoi Rivers.

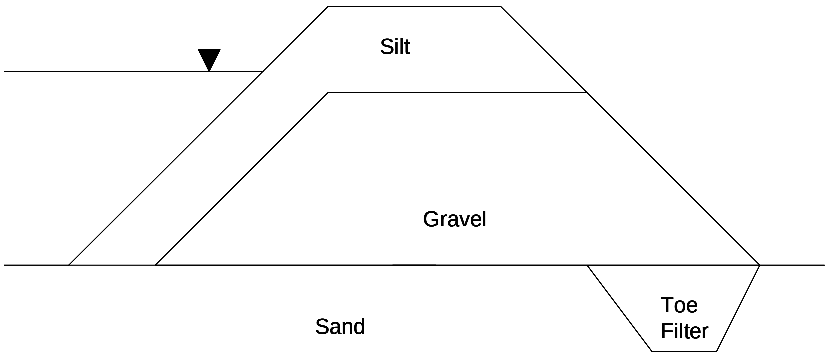


Figure 6.3 Typical soil composition of levee cross section


Figure 6.4 White lines denote the stretches of the levees along the Waimakariri and Kaiapoi Rivers that the geotechnical reconnaissance team performed damage surveys. Also denoted in the figure is State Highway 1 (SH1) and locations where the photographs were taken that are shown in Figures 6.6-6.11, 6.13, and 6.17-6.28. The distance from the left to the right edge of this image is ~10.25 km.

***Waimakariri River Levees***

Overall, the levees along the Waimakariri River performed well during the earthquake, with only ~4 km out of ~17 km of levees requiring repair (Boyle, 2010). The majority of the damage along the Waimakariri River was downstream of SH1 (Figure 6.5). On the day of the Darfield event, ECan estimated that flood protection had been reduced from the 500 year event (5000 $m^3$/sec) to the 15 year event (1500 $m^3$/sec) in the lower reaches of the river, east of SH1. The river rose to 1000 $m^3$/sec within days after the earthquake, raising concerns.

Repairs to the high priority sites were expected to be completed within a few weeks after the earthquake, with medium priority sites expected to be completed in a couple of months. The cost of the repairs to the high and medium priority sites is estimated to be ~$NZ 3million with total cost for all repair to be ~$NZ 4million (Boyle, 2010, Heslop, 2010). ECan annual budget for maintenance and construction is $NZ 4million.

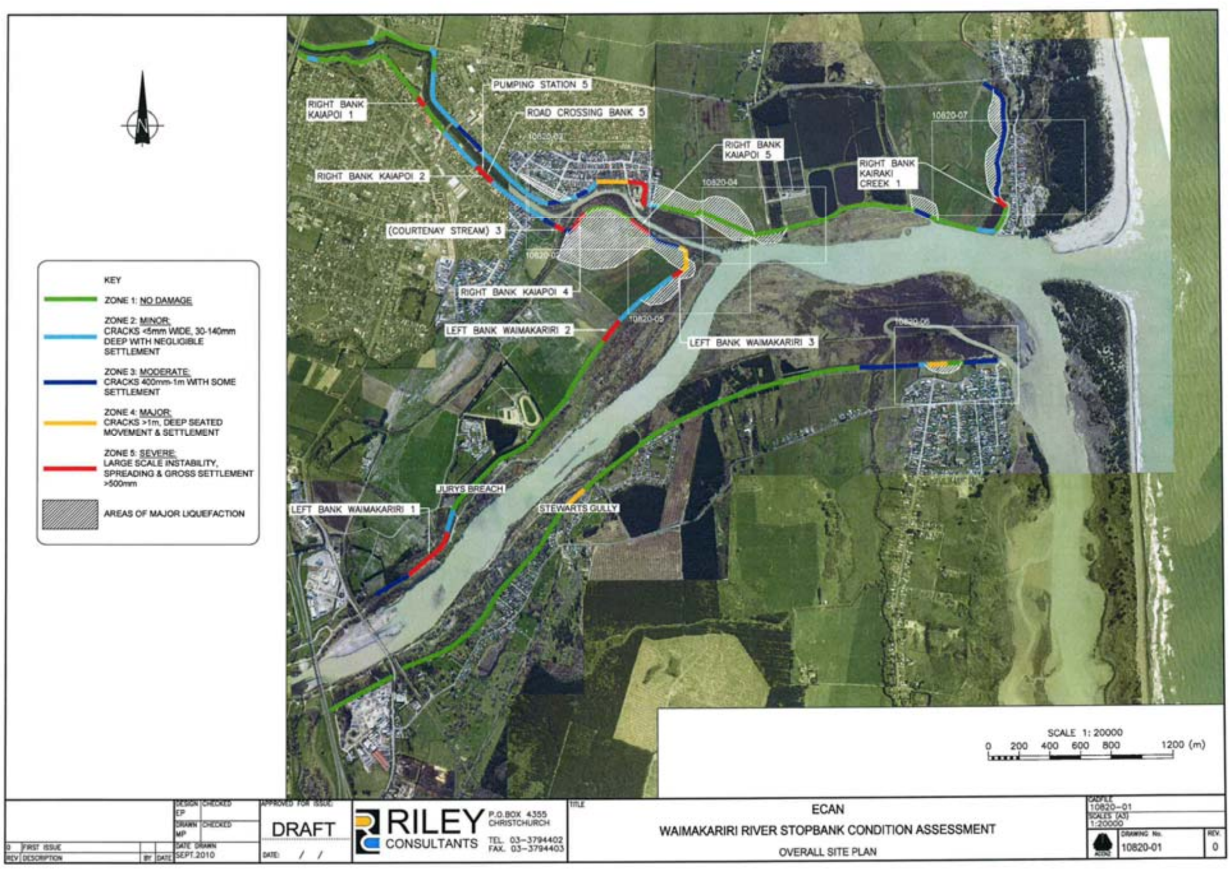


Figure 6.5 Post-earthquake damage survey of levees performed by Riley Consultants for Environment Canterbury along the Waimakariri River, downstream of SH1, and Kaipoi River. (Riley Consultants, 2010; courtesy of Ian Heslop and Tony Boyle, ECan)

Figures 6.6-6.11 are photographs of the levees for the Waimakariri River along Coutts Island Rd. Numerous sand boils were found along the base of the levee for an ~0.5 km stretch (Figures 6.6-6.8), on both the river and land sides. By the time of the team's damage survey on 11 September 2010, the top of levee along this stretch had already been regarded (Figure 6.9), likely to fill in longitudinal cracks that formed along the crest of the levee. Figure 6.10 is of a ~2-cm wide longitudinal crack in the crest of the levee, located just outside of the ~0.5 km stretch where the crest road had been regraded. It is assumed that the longitudinal cracks in the stretch of levee where the crest road had been regraded were more significant than that crack shown in Figure 6.10, thus warranting the regrading. The liquefaction along the base of the levee and longitudinal cracks in the crest abruptly stopped outside of the ~0.5 km stretch; this may be seen in Figure 6.11, where no damage to the levee could found.

Figure 6.6 Photo 1: Large sand boil at the base of the landside of the levee on Coutts Island Rd. The location of this photograph is denoted in Figure 6.4. (-43.425018˚, 172.628442˚)

Figure 6.7 Photo 2: Crack running along base of levee on Coutts Island Rd (landside) and liquefaction ejecta. The location of this photograph is denoted in Figure 6.4. (-43.424466˚, 172.629907˚)

Figure 6.8 Photo 3: Liquefaction ejecta (center of photo) along the base of the levee on Coutts Island Rd (riverside). The location of this photograph is denoted in Figure 6.4. (-43.424093˚, 172.630468˚)

Figure 6.9 Photo 4: Road on top of levee that had recently been regarded, presumably after the earthquake to fill in longitudinal cracks formed during the earthquake. Liquefaction was observed along the base of both sides of the levee along this stretch. The location of this photograph is denoted in Figure 6.4. (-43.423943˚, 172.631045˚)

Figure 6.10 Photo 5: ~2-cm wide crack running lengthwise along the top of the levee on Coutts Island Rd. This crack was at the edge of the ~0.5 km stretch of the levee where significant liquefaction was observed. Photo taken looking southwest. The location of this photograph is denoted in Figure 6.4. (-43.423440˚, 172.632349˚)

Figure 6.11 Photo 6: Stretch of levee without evidence of liquefaction. In the distance, a small rise can be seen in the road. This rise is the start of the ~0.5 km stretch where liquefaction was observed along the base of the levee. The location of this photograph is denoted in Figure 6.4. (-43.4225˚, 172.6350˚)

From interviews with local land owners, this section of the land that experienced widespread liquefaction was part of an old river channel. This was confirmed by review of old maps of the area. Figure 6.12 is an aerial image of the Coutts Island Rd area with the 1865 south branch of the Waimaikariri River channel highlighted in red. The ~0.5 km stretch of the levee where liquefaction was observed is denoted by the dashed yellow line (A) in this figure. As may be seen in this figure, the area that liquefied coincides with the location of the old river channel, while the stretches of levee with no observed liquefaction (dashed blue line) lie outside of the old river channel.

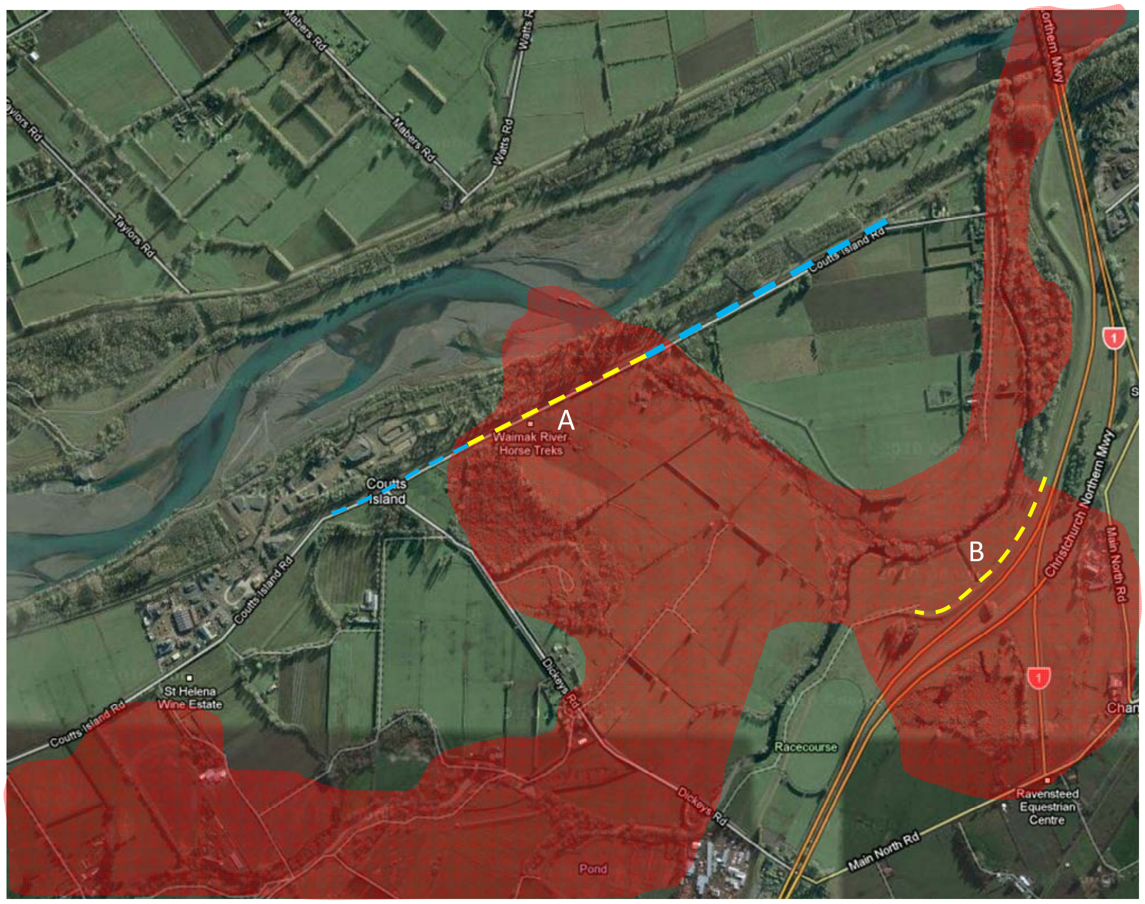


Figure 6.12 Overlay of 1865 stream channel on present day Coutts Island Rd. This image is ~3.5 km across (center -43.4266˚, 172.6302˚) (Google Inc. 2010)

Three Dynamic Cone Penetration Tests (DCPT) and four Spectral Analysis of Surface Waves (SASW) tests were performed along the base of the levees along Coutts Island Rd, both in the areas that did and did not liquefy (Figure 6.13). The results of these tests are presented in Figures 6.14-6.16. The DCPT were performed in holes hand augered down to the top of the respective liquefied layers, with the layers identified by comparing sand boil ejecta with soil extracted with the auger at various depths. The test were performed until there was a noticeable increase in the DCPT N-value or we ran out of rods (~4.6 m from the top of the ground surface). (See the Liquefaction and Lateral Spreading chapter for a more detailed description of the DCPT test).

Figure 6.13 Photos 7 and 8: DCPT (left: -43.425137˚, 172.628619˚) and SASW test (right: -43.424342˚, 172.630473˚) performed in areas that did and did not liquefy along the levee on Coutts Island Rd. The locations of these photographs are denoted in Figure 6.4.

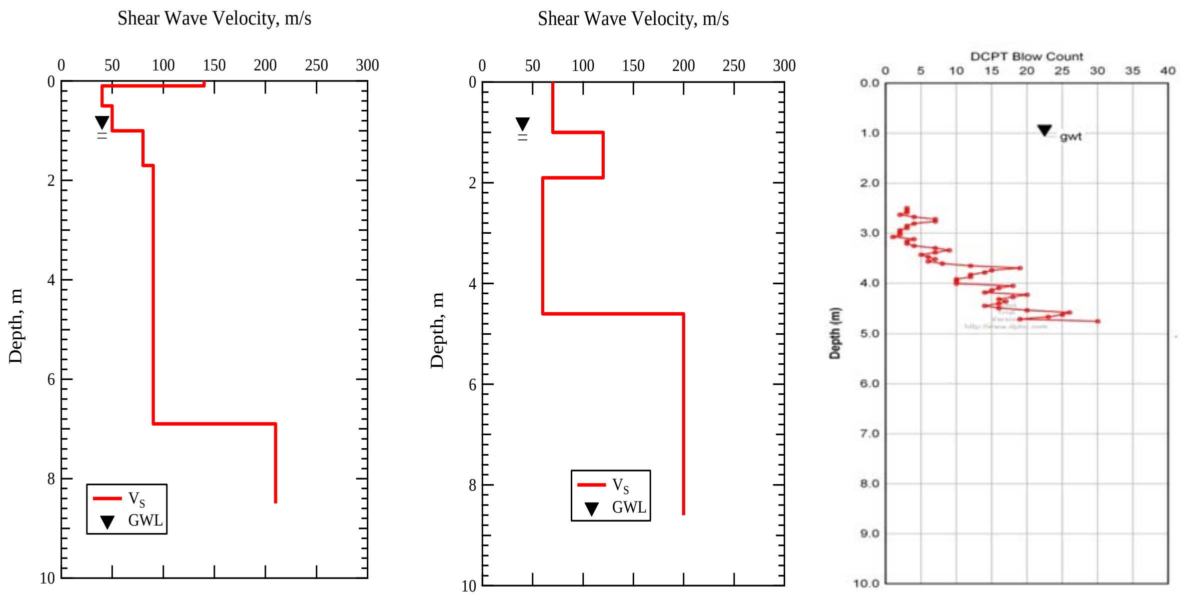


Figure 6.14 Results from SASW tests (left: SASW1 -43.425029˚, 172.628676˚; middle: SASW3 -43.424351˚, 172.630475˚) and DCPT (right: DCPT1 -43.425139˚, 172.628618˚) performed along the base of the levee on Coutts Island Rd in an area that liquefied.

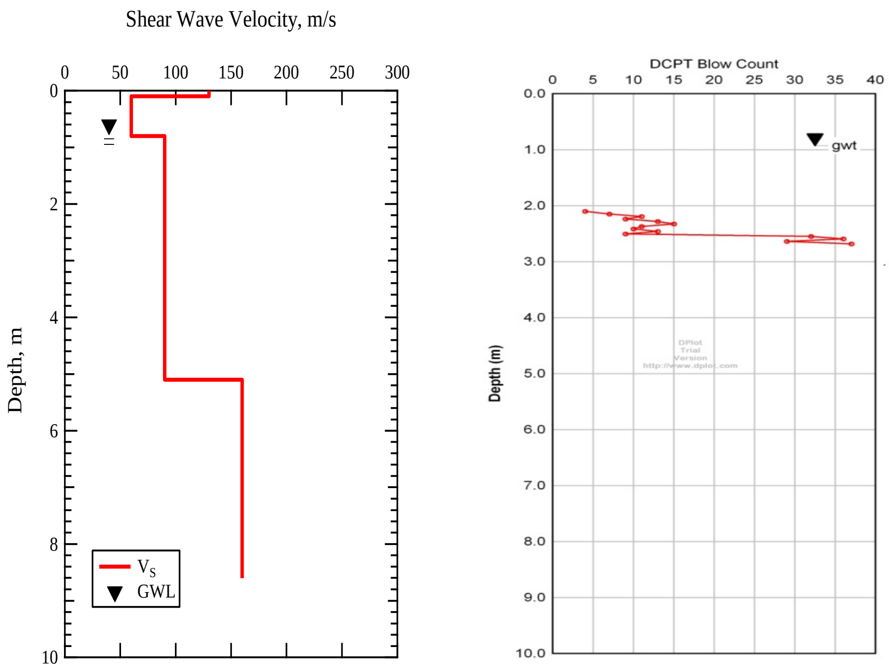


Figure 6.15 Results from SASW test (left: SASW2 -43.426294˚, 172.625439˚) and DCPT (right: DCPT1 -43.426186˚, 172.625673˚) performed along the base of the levee on Coutts Island Rd in an area that did not liquefy.

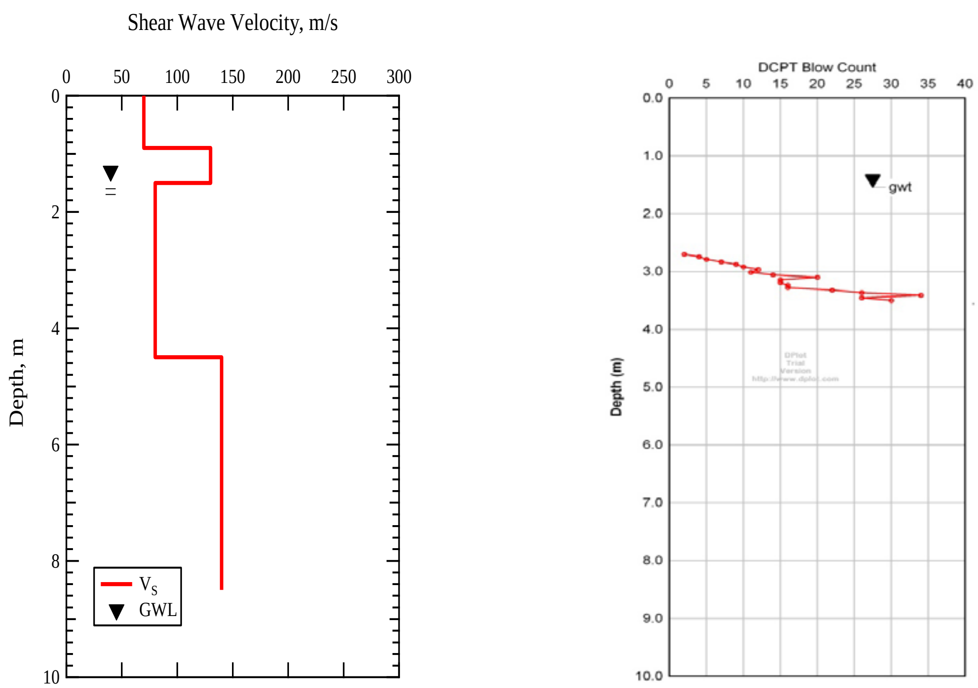


Figure 6.16 Results from SASW test (left: SASW4 -43.422635˚, 172.635038˚) and DCPT (right: DCPT3 -43.422685˚, 172.635081˚) performed along the base of the levee on Coutts Island Rd in an area that did not liquefy.

Other than SASW3 and DCPT1, performed about 175 m from each other in an area that liquefied, the agreement between the SASW and DCPT results is not very good in terms of depth to a stiff, presumably nonliquefiable layer. Further analyses are required to fully understand why. However, the sites that did not liquefy were along the banks of the old river channel. A liquefiable layer could not be found in these areas using the hand auger, and the soil profiles (DCPT2 and DCPT3) consisted of clayey sand and peat. Given the depositional environment of these profiles, it is likely that the strata varied significantly laterally, which could be the explanation for the poor agreement between the DCPT and SASW test results.

Figures 6.17 and 6.18 are photographs of a secondary levee for the Waimakariri River along State Highway 1. This stretch of levee is denoted by a dashed yellow line (B) in Figure 6.12. Liquefaction was observed on both sides of the levee and longitudinal cracks were observed running along the crest and sides of the levee (Figures 6.17 and 6.18). As may be seen from Figure 6.12, this stretch of the levee lies within the abandoned river channel of the old south branch of the Waimakariri River.

Figure 6.17 Photos 9 and 10: ~5-cm wide longitudinal cracks running along the crest (left) and base (right) of a secondary levee for the Waimakariri River. Photo taken looking southwest; SH1 on left of levee. The locations of these photographs are denoted in Figure 6.4. (-43.430108˚, 172.643434˚)

Figure 6.18 Photos 11 - 14: Liquefaction ejecta on both the river and landsides of the levee. The locations of these photographs are denoted in Figure 6.4. (-43.428968˚, 172.645435˚)

***Kaiapoi River Levees***

Kaiapoi is located at the northeastern end of the Canterbury Plains, about 20 km north of Christchurch. The Kaiapoi River used to be a part of the eastern reach of the old north branch of the Waimakariri River (Griffiths, 1979) and cuts through the center of Kaiapoi. The Kaiapoi River joins the Waimakariri River on the eastern edge of town and flows to the sea (Figure 6.4). Liquefaction was widespread along the northern and southern banks of the Kaiapoi River and adjacent neighborhoods.

The levees confining the flow of the Kaiapoi River suffered damage at various locations (Figure 6.5). These embankments, measuring about 2.5-m high (from the water line at the time of our observations) and 2.7-m wide, have slopes of approximately 2H:1V on the riverside and 3H:1V on the landside near the Willams St. bridge, which remained serviceable after the earthquake despite incipient liquefaction in the abutments and settlement and cracking of the approach on the eastern side of the bridge.

In downtown Kaiapoi adjacent to the river, the Visitors' Information Center on the north side of the river sank and tilted as a result of liquefaction and lateral spreading (Figure 6.19). Ground cracks, as wide as 30 cm and as deep as 100 cm, were observed running parallel to the river near this structure. The two-story Waimakariri-Ashley Coastguard building adjacent to the Visitor Center also suffered the same effects. Just east of this building (~100 m), ground cracks, on the order of 100-cm wide and 185-cm deep were also observed along the gentle inboard (land-side) slope of the levee (Figure 6.20). Lateral spread cracks with massive ejecta were observed at the toe of the embankment (Figure 6.21). Also, a skate park that was located about midway up the gently sloping inboard side of the levee was severely damaged by lateral spreading (Figure 6.22). Settlement/slumping of the foot path on the crest of the levee on the order of 10-30 cm were also noted. Detailed maps of the largest lateral spread cracks will be provided in subsequent versions of this report.

Two bore holes were made using a hand auger near the lateral spread cracks (-43.384767˚, 172.661133˚ and -43.384683˚, 172.661350˚). However, the profile largely consisted of random fill (gravels/cobbles and wood), making it difficult to advance the auger. One of the bore holes went down to a depth of ~5.5 m, yet a thick layer of soil matching the liquefaction ejecta material could not be found. However, thin (< 10 cm) alternating layers of loose saturated sand and very wet, very soft clay/plastic silt were encountered, particularly near the large lateral spread crack shown in Figure 6.20. This lateral spread crack had no trace of ejecta in and/or immediately near it. This crack was closer to the river than ones that were filled with ejecta at the toe of the levee ~30 m away (Figure 6.21).

Houses across from the levee on Charles St underwent significant earthquake-induced settlement. This damage is discussed in detail in the Impact on Structures chapter.

Further east along the Kaiapoi River (~400 m), the ground adjacent to a 6-m diameter structure (containing an underground tank and control equipment) settled by about 30 cm, resulting in damage to pipes attached to the tank (Figure 6.23). Additionally, aerial photographs of lateral spreading along the north bank of the Kaiapoi River going east from the town center are shown in Figure 6.24.

Figure 6.19 Photo 15: Visitors Information Center on the levee on the north side of the Kaiapoi River. The location of this photograph is denoted in Figure 6.4. (-43.387384˚, 172.659743˚)

Figure 6.20 Photos 16-18: Lateral spread cracks along landside of the levee on the north side of the Kaiapoi River. The locations of these photographs are denoted in Figure 6.4. (-43.384484˚, 172.660653˚)

Figure 6.21 Photo 19 and 20: Lateral spread cracks along landside of the levee on the north side of the Kaiapoi River. The locations of these photographs are denoted in Figure 6.4. (-43.384633˚, 172.661231˚)

Figure 6.22 Photo 21: Skate park on the levee on the north side of the Kaiapoi River. The location of this photograph is denoted in Figure 6.4. (-43.384094˚, 172.660370˚)

Figure 6.23 Photo 22: Tank that settled ~30 cm resulting in damage to attached pipes. The photograph numbers correspond to the locations denoted in Figure 6.4. (-43.386918˚, 172.664412˚)

Figure 6.24 Photos 23 and 24: Aerial photographs of lateral spreading of levees on the north bank of the Kaiapoi River. The locations of these photographs are denoted in Figure 6.4. (left: -43.387389˚, 172.666173˚; right: -43.386875˚, 172.672297˚)

The levee along the south bank of the Kaiapoi River also experienced extensive lateral cracking, and the adjacent homes on Raven Quay experienced significant post-earthquake settlement. Figures 6.25-6.28 are photographs of the levee on the south bank of the river.

Figure 6.25 Photo 25: Lateral spread cracks along riverside levee on the south side of the Kaiapoi River. The location of this photograph is denoted in Figure 6.4. (-43.385254˚, 172.660131˚)

Figure 6.26 Photo 26: Lateral spread cracks along riverside levee on the south side of the Kaiapoi River. The location of this photograph is denoted in Figure 6.4. (-43.385839˚, 172.660941˚)

Figure 6.27 Photo 27: Lateral spread cracks along the top of the levee on the south side of the Kaiapoi River. The location of this photograph is denoted in Figure 6.4. (-43.385693˚, 172.660688˚)

Figure 6.28 Photo 28: Failed drainage conduits running underneath the levee on the southside of the Kaiapoi River. The location of this photograph is denoted in Figure 6.4. (-43.388679˚, 172.666203˚)

**Seismic Performance of Oxidation Pond Embankments**

The geotechnical reconnaissance team also performed damage surveys on foot at the sewage treatment plant oxidation pond embankments in Bromley and Kaiapoi.

### *Kaiapoi Sewage Treatment Plant*

The Kaiapoi Sewage Treatment Plant, operated by the Waimakariri District Council, is located between Kaiapoi and Pines Beach and is bordered to the south by the Waimakariri River levee. From 2001 to 2003, the average and peak daily inflows were 3,235 and 10,695 $m^3$/day, respectively, and the average and peak daily outflows were 1,163 and 5,565 $m^3$/day, respectively (CH2M Beca Ltd., 2003). An aerial image of the plant is shown in Figure 6.29.


Figure 6.29 Aerial image of the Kaiapoi Sewage Treatment Plant. The southern perimeter (~0.6 km) of the oxidation ponds (bottom of image) forms the levees of the northside of the Waimakariri River. The distance from the left to the right edge of this image is ~1.5 km. (-43.384583˚, 172.688240˚)

The geotechnical reconnaissance team performed a damage survey on foot of the levees along the southern perimeter of the plant, denoted by the white line in Figure 6.29. No damage was observed along this stretch of the levees, although the team observed large lateral spread cracks (~30-cm wide) in the levees and shoreline about 100 m west of the southwest corner of the plant

(Figure 6.29). Photographs of the liquefaction and lateral spread features at this location are shown in Figure 6.30.

Figure 6.30 Liquefaction and lateral spread features on or near levees located about 100 to 200 m west of the Kaiapoi Sewage Treatment Plant. (upper left: -43.389175˚, 172.683235˚; upper right: -43.389701˚, 172.683390˚; bottom left: -43.389519˚, 172.682203˚; bottom right: -43.389432˚, 172.6682060˚)

### *Bromley Sewage Treatment Plant*

The wastewater treatment plant operated by the Christchurch City Council is situated at Bromley, approximately 6.5 km east of the Christchurch CBD and southwest of the Bexley subdivision. Here the domestic and industrial wastewater of Christchurch is treated before being discharged to the ocean via an outfall that discharges 3.2 km off the coastline. The treatment system comprises screening, sedimentation tanks, trickling filters, clarifiers and tertiary treatment within the oxidation pond system before discharge to the outfall. The capacity of the outfall is 5.5 $m^3/s$ and the treatment plant was operating at around 2 $m^3/s$ at the time of the earthquake. The oxidation ponds were constructed in the early 1960's and cover an area of around 230 ha (Figure 6.31).


Figure 6.31 Aerial image of the Bromley Sewage Treatment Plant. The distance from the left to the right edge of this image is ~4.4 km. (-43.535029˚, 172.714052˚)

Dyers Road along State Highway 74 cuts through the oxidation ponds and connects the northern approaches to Christchurch with the port of Lyttelton to the south. Road pavements were cracked at the side of the oxidation ponds (between Ponds 2A and 3) and the road was impassable following the earthquake. According to the engineer interviewed at the site, a 50-cm wide crack had opened near the centerline of the road, although it was already filled with compacted dense graded aggregate during the site visit (Figure 6.32). Nevertheless, longitudinal cracks were still evident on the side of the road (Figure 6.33).


Figure 6.32 Repaired Dyers road that runs between Ponds 2A and 3. (-43.529933˚, 172.715200˚)

Figure 6.33 Lateral spread cracks running parallel to Dyers Road adjacent to Pond 2A. (-43.531393˚, 172.712473˚)

The middle third of the Pond 1/2A embankment sustained the most severe failure throughout the pond system over a length of around 45 cm. At this location there are multiple deep longitudinal cracks along the embankment. The cracks were 150-cm deep and up to 70-cm wide at the top. Many of the cracks were interconnected and some were transverse to the embankment, running from Pond 1 to Pond 2A. There is a 122-cm diameter concrete pipeline beneath Pond 1 that can take flow from the treatment plant and bypass it directly to Pond 4. This pipeline "floated" over several hundreds of meters by up to 1.2 m in elevation, but typically less than 30 cm (Figure 6.34). During site inspections on Monday 6th and Tuesday 7th September 2010 there were no observations that the pipeline had "floated". Also examination of the Google GeoEye image taken hours after the earthquake showed no trace of this pipe. The pipe was firstly observed to have "floated" on the 9 September 2010 as the pond water level was being lowered as part of the emergency mitigation measures.

The discharge weir structure at the outlet of Pond 2B has three pipes that transfers flow to Pond 3. The pipelines consist of two original pipelines of 90-cm diameter and a larger more recent pipeline of 180-cm diameter. The weir structure is located out into the pond and allows flow over individual weirs on all four sides. Each of the three pipelines became dislocated in the gap between the structure and the embankment allowing water to flow directly in to the pipelines at the gaps formed in the pipe separations. Furthermore, sinkholes were formed on the embankment berms and in the middle of Dyers Road, indicating that the pipes had separated beneath the embankment fill (Figure 6.35). The eastern end of Pond 2B was cracked and the internal side of the embankment had slumped into Pond 2B by up to 40 cm at its eastern end. The slumping was also evident along most of the length of the Pond 2A/2B internal baffle, which was recently constructed in 2004. Sand boils were also evident along the toe drain that runs along the northern side of Ponds 2B, 3 and 6 (sand boils were rare on top of the embankments).

Extensive cracking was experienced along the majority of the embankment that separates Ponds 3 and 6. The total length of this embankment is around 600 m in length and severe to moderate cracking was experienced over a length of about 450 m. Several sets of cracks were noted to exist across the width of the embankment at the worst affected locations. The larger of the cracks were around 40 cm to 50 cm in width and around 150-cm deep. The base of the crack was not visible due to either pond water or collapse debris blocking its lower extent. A small sinkhole had formed over the outlet pipeline from the northernmost weir structure in Pond 3. As with the pipelines beneath Dyers Road, it would appear that the pipeline was either broken and/or the spigot had been pulled from its collar allowing soils to fall down in to the pipeline.

Numerous small sand boils were encountered across the floor of the estuary adjacent to Pond 6. One of these sand boils was observed to be flowing water 80 hours after the main earthquake. While not directly inspected, when viewed at low tide it appeared that there has been considerable liquefaction along the alignment of the outfall pipeline (commissioned in 2010), which traverses across the estuary to the New Brighton spit. A large volume of ejecta appears to be located near to the main channel in the estuary (location of thinnest cover over the pipeline).

The distortion of the embankments noted above is indicative of bearing failure of the embankment as it has settled and spread in to the liquefied sub-soils, with large tension cracks forming through the fill used to form the embankments and pulling apart of concrete pipelines as the fill has spread. Site investigations undertaken indicate that the soils beneath the pond embankments are potentially liquefiable to depths of 10 m to 15 m.

Because of the slumping of the pond banks, engineers decided to drop the pond water levels and reduce the hydraulic pressures on the embankments. At the time of the reconnaissance team visit, sheet piles were being driven into the Pond 3/6 embankment to stabilize it and arrest further movement (Figure 6.36). Furthermore, the pipelines beneath Dyers Road were being replaced.

Figure 6.34 Buckled pipe protruding from Pond 1 during pond dewatering, and after pond level was lowered. Pipeline crown was at the pond invert prior to the earthquake. (-43.530867˚, 172.705190˚)


Figure 6.35 Lateral spread cracks at the eastern end of Pond 2B. The sinkhole in the foreground of the photo on the right formed over the top of two outlet pipelines. (-43.52895˚, 172.717300˚)

Figure 6.36 Sheet piles being driven to stabilize the pond embankment to arrest further movement. (-43.530563˚, 172.718349˚)

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