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The legacy of the 1987 Edgecumbe earthquake, New Zealand

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ABSTRACT: A series of six earthquakes of Mw 5.0 to 6.5 struck the Bay of Plenty, New Zealand, on 2nd March 1987 creating a surface rupture several kilometres long across the Rangitaiki plains, crossing the Rangitāiki River and causing up to two metres of ground subsidence. Fifty percent of the houses in Edgecumbe, a major earth dam and flood protection structures were severely damaged with the standard of flood protection reduced from 100-year to a 20-year return period level. Two concrete flood protection walls subsided 0.6m to 0.8m. These were subsequently replaced/heightened without rectifying foundation damage. One of these walls failed during a flood in April 2017, flooding Edgecumbe and causing severe damage. The failure has been attributed to the foundation damage from the earthquake 30 years earlier. Earthquake damage to Matahina Dam was mainly settlement of rock fill and downstream displacement of the structure, resulting in increased seepage, but internal damage was revealed during investigations and was subsequently repaired.

1 INTRODUCTION

1.1 *Background seismological setting*

New Zealand straddles the Asia-Pacific and Australasian tectonic plates, with the plate boundary crossing the country obliquely from north-east to south-west. The Pacific plate subducts beneath the north island, which sits on the Australian plate, while the reverse is true to the south-west of the islands with the Australian plate being thrust beneath the Pacific plate. The South Island of New Zealand sits in the fulcrum of a tectonic scissor-like action, where fault movement is largely strike-slip, with the two plates converging at the rate of about 40mm per year.

New Zealand suffers major earthquakes on a regular basis by virtue of this tectonic setting, on average about one shallow magnitude 7+ and ten magnitude 6+ shallow onshore events every decade since 1900 (Price & Stannard 2017). Over this period eight earthquakes stand out as particularly damaging, as indicated in Table 1.

The fact that some of these earthquakes with the most severe effects are not the events with the highest magnitudes, in particular the Christchurch event, shows that the location of an event is as important as its magnitude. It is also somewhat sobering to consider that this period does not include a rupture on the Alpine fault, which runs down the spine of the South Island, and which is capable of producing magnitude 8+ events. Such an event is likely to be followed by aftershocks as large as magnitude 7+. Major events on the Alpine fault are known to have occurred in approximately 1717, 1620, 1450 and 1100, but some remarkable research by GNS Science over recent years has extended this knowledge back 8000 years (Ref Berryman et al 2012), identifying the last 24 successive events and has shown that major events on the Alpine fault have a recurrence interval of 140 to 510 years.

Table 1. Most damaging earthquakes in New Zealand over the last 100 years

Year	Location	Magnitude Mw*	Depth km*	Effects
1929	Murchison (Buller)	7.3	20	17 deaths Damage (2017 value): NZ$348Million
1931	Hawkes Bay	7.4	20	256 deaths Damage (2017 value): NZ$754Million Cities of Napier and Hastings destroyed
1942	Wairarapa	6.9	12	1 death 5,000 houses and 10,000 chimneys damaged
1968	Inangahua	7.1	12	3 deaths Damage (2017 value): NZ$57Million to houses alone 100km railway line and 50 bridges destroyed
1987	Edgecumbe	6.5	10	No deaths Damage (2017 value**): NZ$393Million Heavy damage to industrial installations 50% of the houses in Edgecumbe damaged River flood defences and Matahina dam damaged
2010	Darfield	7.2	11	No deaths NZ$5Billion damage (NZGovt treasury 2012 estimate)*** Substantial liquefaction and damage to heritage buildings
2011	Christchurch	6.2	5	185 deaths. Damage: NZ$35Billion (NZ Govt treasury estimate)*** Christchurch CBD destroyed – closed for over two years Wholescale permanent abandonment of entire residential suburbs The most extensive liquefaction known to have occurred in an urban area globally.
2016	Kaikoura	7.8	15	2 deaths Damage: NZ$3.4Billion (ICNZ** and NZ Govt Treasury) Wellington and Kaikoura damaged The main east coast road and rail routes on the South Island cut for over a year.

* Magnitude and depth from Geonet (GNS Science 2018).
** Damage values from ICNZ 2018. These values include only losses insured through the New Zealand insurance market, and should therefore be taken as lower limiting values.All pre 2000 values converted to 2017 values using the CPI.
*** Swiss Re Institute gives insured losses for the 2010 and 2011 events as NZ$40.8Billion, but attributes a higher proportion (31%) to the 2010 event Data taken from Te Ara, 2016.

1.2 *The 1987 Edgecumbe earthquake*

A sequence of seismic events occurred on a number of faults beneath the Rangitaiki River plains and offshore of the Bay of Plenty at the end of February and early March 1987, culminating in a Mw 6.5 earthquake at a depth of 10km on the Edgecumbe fault on March 2nd. No deaths occurred in the earthquake, which is likely to be the result of a strong foreshock putting power supplies out of action and being responsible for many people being outdoors when the main event occurred.

The ruptures occurred both on existing active faults and on faults which had not previously broken the (relatively young) surface alluvium (Beanland, Berryman & Blick 1989). The Edgecumbe fault lies at the junction of two tectonic provinces near the north coast of the North Island of New Zealand: the Taupo Volcanic Zone to the west, and the North Island Shear Belt to the east. The former is characterized by normal faulting striking north east to southwest, and the latter predominantly by oblique strike-slip faulting striking north to south. The two zones are quite distinctive and can be clearly identified by the fault strike directions displayed on Figure 1, which shows all known active faults in the region (Langridge et al 2016).

Edgecumbe town and Matahina dam sit at the eastern and western edges respectively of these tectonic provinces, approximately 15 km apart.

2 THE RANGITAIKI RIVER FLOOD PROTECTION SYSTEM

The Rangitāiki River is the largest river in the Bay of Plenty, passing through two artificial lakes, Lakes Aniwaniwa and Matahina, developed for hydroelectric power. The river is confined to its bed by steep sided terrain and gorges at Matahina Dam. Upstream of the dam it passes through both flood plains and gorge terrain, but below the dam the river floodplains widen out onto the Rangitaiki plains as the coast is approached. The river carried a high sediment load before the dam was constructed and built itself up above the surrounding floodplain, accentuating the effect of floods when stopbanks are breached. Since the construction of the dam most sediment now settles out in the reservoir preventing ongoing aggradation

2.1 *The development of the flood protection system*

The Rangitāiki River flood protection scheme has been developed over a long period of time, with floodbanks and associated works developing in a somewhat ad-hoc fashion until the early 1960s. An integrated scheme for the whole river was approved in 1970 in response to extensive flooding of the plains over the preceding 20 years. The largest single modification to the Rangitāiki's natural flow and behaviour was the development of the Matahina Dam, constructed for hydroelectricity generation and commissioned in 1967. There was considerable debate at that time concerning the role of the dam in flood control, and it was eventually agreed that the dam would be operated so as to attenuate flood peaks. Lake Matahina is therefore primarily a hydroelectric power installation, but is also used as storage for floodwaters.

The construction of the dam coincided roughly with a period from 1958 to 1972 that was marked by unusually frequent high river levels and floods. In those fifteen years, peak flows downstream of the dam exceeded 250 m^3/s on seven occasions, three of which exceeded 550

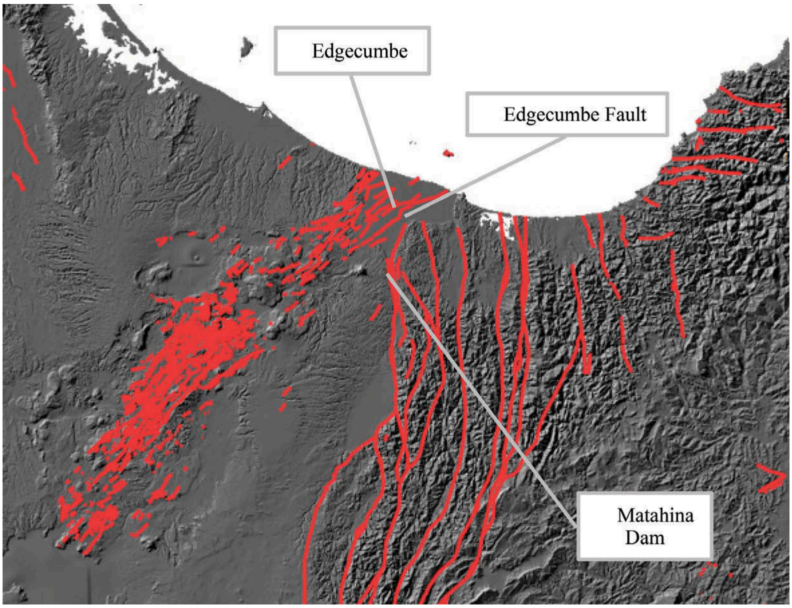

Figure 1. Active Faults in the Bay of Plenty as indicated in the New Zealand Active Faults Database held by GNS Science (Langridge et al 2016)

m^3/s, compared with a median flow of around 62 m^3/s, prompting the development of a more formal Flood Protection Scheme for the lower reaches of the river. The scheme was implemented between 1965 and 1983, with significant subsequent upgrades usually following flooding or seismological events (Cullen, Christensen & Price 2017).

2.2 *Effects of the 1987 Edgecumbe Earthquake on the Rangitaiki flood protection system*

The 1987 Mw6.5 Edgecumbe earthquake caused settlement of up to 2 m across 200km^2 of the Rangitaiki plains, causing subsidence and damage to the flood protection system on the Rangitaiki River, and reducing its flood protection capability from a 100-year return period flood to an unacceptable standard of a 20-year return period flood (Dine et al 1988). Changes in the thalweg elevation of the river after the earthquake are shown in Figure 2 (Simon 2017).

Earthquake damage to the flood protection system consisted mainly of slumping and fracturing of river and drainage canal stopbanks caused by fault displacement, settlement and lateral spreading from liquefaction and shaking. Major failures of the stopbanks on the Rangitaiki River only occurred in areas where foundations were highly permeable or where the main fault trace crossed the river. 26,290 m of stopbanks were damaged on at least five rivers and canal systems in the region (5940 m on the Rangitaiki River) with an estimated cost of NZ$1.52M, and a further NZ$2.37M (both values at 1987) expended on raising flood defence stopbanks and walls back up to the 100-year return period flood protection standard on the Rangitāiki River. Included in those repairs were the costs of replacing one concrete floodwall and extending another one upwards, more than doubling the heights of both.

Although no allowance was made for a rise in sea level in the original design, allowance was made in the design of the stopbank repairs in 1988 for a 140 mm rise in sea level by 2020. As we are now almost at that point it is interesting to observe that the actual rise over that period will have been around 110 mm (NASA 2018).

Settlement continued for a long period after the earthquake, with 4mm per day being recorded eight days after the earthquake (Jones 1987), and fifteen years after the event a further 0.5m of settlement was reported. Immediately after the earthquake approximately 2500 ha of land became highly susceptible to flooding (10% of the entire area of the plains), with a further 850 ha having drainage restrictions (Dine et al 1988). This area is mostly farmland but includes a significant portion of Edgecumbe township, which is now lower lying than most of the surrounding areas, and some industrial areas. The earthquake caused many 'intermediate depth' water wells to flow in an artesian manner, and groundwater levels rose by up to 3 m in some places before dropping back within a week of the earthquake (Jones 1987).

A side-flow spillway designed to discharge floodwater into an overflow floodway suffered differential settlement. It was considered likely that if this spillway came into use in this condition that flows concentrated over certain sections of the grassed spillway could cause a failure leading to a major disaster (Dine et al 1988).

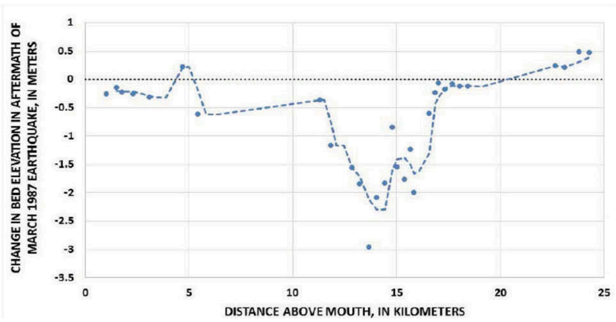

Figure 2. Changes in thalweg elevation of the Rangitaiki River after the 1987 earthquake (Simon 2017)

2.3 *The 2017 flood*

The Rangitāiki River breached a stopbank and floodwall at Edgecumbe on Thursday 6 April 2017 following an extreme rainfall event in the upper catchment of the river which produced a 200-year flood flow of 920 m^3/s upstream of the dam, the highest flow recorded in the river to date. Management of Matahina Dam reduced the flow to a 70-year flood event downstream of the dam, but the breach and flooding of the township resulted in some fifteen houses being rendered permanently uninhabitable, and in excess of 250 more requiring repairs necessitating their evacuation for a considerable period. This resulted in NZ$62.6M of insured damage (ICNZ 2018), making it the sixth largest insurance loss in New Zealand this century.

Eye witness evidence of the breach enabled the mode of failure of the floodwall to be clearly identified and explained. Floodwater rose up above the base of the wall for only the second time in its history, remaining against the wall for a period of 5 hours. This would of course have been longer if the breach had not occurred; in the previous flood, in 2004, water lay against the floodwall for 9 hours and 12 minutes.

The authors were members of an independent review panel commissioned by the Bay of Plenty Regional Council to report on the circumstances that led to the breach of the stopbank and floodwall, and the resulting flooding of Edgecumbe on 6 April 2017.

2.3.1 *Failure of the Edgecumbe floodwall*

Following the subsidence at Edgecumbe from the 1987 earthquake the 0.61 m high concrete floodwall constructed in 1973 was replaced by a 1.40m high wall in 1993. A report on the earthquake damage compiled immediately after the earthquake indicated that this floodwall had suffered foundation failure in the earthquake, and the initial estimates of damage rated this section of repairs as the most costly of all left bank works on the Rangitāiki River, at $46,350 (value at 1987). The damage was described as "river bank slumping" and "foundation failure of concrete walls", requiring "stabilisation of the toe above and below the plane of failure is required by placement of rock" and "re-establishment of the original structure", and was illustrated in the damage summary report immediately after the earthquake as shown in Figure 3 (Jones 1987).

Investigations after the 2017 failure indicated that the wall was founded on imported fill consisting of a weathered Greywacke rock material known locally as "rotten rock", supplied as "quarry floor scrapings" and comprising a well graded mixture of clay to coarse gravel sized particles. This would have been placed prior to the first wall construction in 1973, and possibly much earlier than that, most likely without a specification or any earthworks control. The same material was also used to rebuild the river berm adjacent to the floodwall following erosion during a flood in July 2004. This material is commonly used for stopbank construction in New Zealand, and is an acceptable material to use for this purpose.

A number of causes could have contributed to the failure of the floodwall, and as most physical direct evidence was destroyed in the flood it is not possible to be conclusive as to its cause, but what is clear is that the wall collapse was a progressive failure consisting of two sliding failures, firstly that of a cribwall forming the toe of the stopbank, followed by the floodwall itself, which slid out onto the adjacent road. Further, these occurred as a result of a build-up of pore water pressure in the shallow ground on the landward side of the wall, which was accentuated by the confining effect of a concrete slab covering the ground surface and restricting seepage dissipation. The upright wall, still standing after the failure, can be seen in photographs taken 5 minutes and 2.5 hours after the breach first occurred, Figures 4 and 5.

Seepage analysis indicated that the duration of the flood was inadequate for sufficient pore pressure to have developed via porous flow, and therefore must have emanated through a preferential flowpath(s), and other evidence suggested that this must have been through shallow ground. Two factors most likely to provide such a flow path were identified as either a permeable layer arising from variable quality fill in the foundation, or ground fissuring from the 1987 earthquake which was recorded immediately after the earthquake but which was not rectified before the new wall was constructed in 1993. This failure is therefore likely to be a legacy of the 1987 earthquake 30 years earlier.

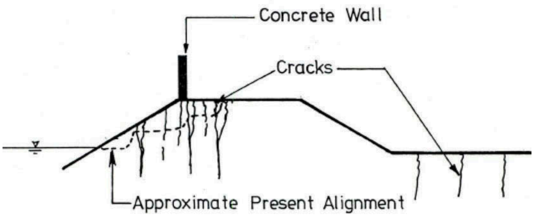

Figure 3. The illustration of damage to the floodwall foundations in the damage records for the earthquake, captioned in the report as "Damage Type: slumping of foundations with structures on top" (Jones 1987)

Figures 4 & 5. The breach, showing the failed wall 5 minutes and 2.5 hours respectively after the breach (Sources: Bay of Plenty Regional Council Contractor, and Bay of Plenty Regional Council respectively)

3 MATAHINA DAM

Matahina Dam is an 80 m high 400 m long earth and rockfill dam lying 15 km upstream of Edgecumbe town on the Rangitaiki River, Figure 6.

The dam straddles a number of strands of the Waiohau fault, which is about 2km wide and is the most westerly fault in the North Island Shear Belt tectonic zone. A number of fault traces were identified in the foundation of the dam during its construction, but no offset was recorded passing upwards through the alluvium, leading the designers to conclude that these faults had not moved during the last 20,000 years (McMorran 2001). They were therefore treated as inactive in the dam design.

The dam was completed in 1967 and soon afterwards, on first filling, it suffered serious internal erosion issues in the right abutment; these were non-seismic related, but of interest here as they were relevant to damage found following the Edgecumbe Earthquake. The reservoir was drawn down and substantial repairs carried out. It was subsequently found that internal cracking of the core had occurred near the right abutment which was associated with differential settlements of 0.3 m at the core-abutment contact (Mejia 2013).

3.1 *Earthquake damage*

In March 1987 the dam suffered strong shaking from the Edgecumbe earthquake, recording a peak ground acceleration of 0.33g at the base of the dam. This caused the rockfill at the dam crest to settle about 100 mm and the dam to move 250 mm downstream, generating deformation of the dam shoulders. Minor cracking on road surfaces were noted at both abutments. The rockfill in the upstream and downstream shoulders settled 0.8 m and 0.1 m respectively, and settlement continued for several weeks after the earthquake. Settlement was not

Figure 6. Matahina Dam in 1987 (GNS Science VML No 15554, photographer Lloyd Homer)

considered to be excessive, but nevertheless regarded by the dam's engineers with some disquiet due to the dam's history. Seepage increased into the drainage galleries, but no major leakage occurred (Gillon 1988, 2007).

The reservoir level was drawn down by 2.5 m as a precaution immediately after the earthquake and inspections of the dam carried out. These indicated little damage, but further investigations were proposed due to the dam's history of leakage and susceptibility to internal erosion.

3.2 *Subsequent discoveries*

During these investigations, nine months after the earthquake, an erosion cavity formed on the crest of the dam. An emergency drawdown of the reservoir was made and excavations into the left abutment identified serious erosion issues. These investigations showed that remedial measures following the 1967 internal erosion issue had performed well, but they unexpectedly revealed an erosion cavity in the right abutment considered to be unrelated to the earthquake shaking, in addition to a cavity in the left abutment (Gillon 2007). The reservoir level was then completely drawn down for further investigation and repairs.

It was concluded from the investigations that meta-stable filling within pre-existing settlement induced cracks in the left abutment had been disturbed by the strong ground motions, allowing internal erosion to re-commence. This eventually resulted in a cavity developing within the core just above water level, and should internal erosion have continued it was likely to have resulted in a sudden large outflow (Gillon 2007).

In the 1980s there was a move to improve the seismic safety of dams in New Zealand, and the poor performance of Matahina dam in the Edgecumbe earthquake indicated its need for such a re-evaluation. Studies then established that some of the known faults in the dam foundations previously thought to be inactive were in fact active, and it became clear that the seismic safety of the dam was inadequate. The dam was then dewatered and substantial remedial works were carried out in the 1990s.

The experience of the Edgecumbe earthquake emphasised the importance of seismic resilience of dams to the engineering profession and regulators in New Zealand, and as a result Matahina has become one of two dams pivotal in the advancement of modern earthquake engineering for dams in New Zealand.

4 CONCLUSIONS

The Edgecumbe earthquake of 1987 was responsible for severe damage to the flood protection system along the Rangitaiki River and to Matahina dam. Thirty years later the collapse of a floodwall in Edgecumbe town is considered most likely to be attributable either to damage from the earthquake, or to poor quality of fill in the wall foundations.

Matahina dam suffered two drawdowns as a result of the earthquake, one immediately after the event, and the second nine months later following some subsidence on the dam crest. Investigations and repairs for earthquake damage exposed earlier defects which may not have been detected otherwise.

Lessons learnt from earthquake damage to the dam, and from the extensive investigations and repairs, resulted in this dam becoming an important contributor to the development of modern earthquake engineering of dams in New Zealand.

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