CHRISTCHURCH CITY COUNCIL LIFELINES – PERFORMANCE OF CONCRETE POTABLE WATER RESERVOIRS IN THE FEBRUARY 2011 CHRISTCHURCH EARTHQUAKE

Ian Billings[1] and Nicholas Charman[1]

SUMMARY

On 22 February 2011 an earthquake measuring 6.3 on the Richter Scale occurred in Christchurch City resulting in widespread damage to buildings and infrastructure.

Christchurch City Council (CCC) has an extensive potable water supply network including bulk storage and service reservoirs which provide water to approximately 320,000 residents. Inspections undertaken, following the 22 February earthquake, on 43 concrete reservoirs located on the Port Hills and Cashmere Hills areas noted varying extents of damage from nil through to major. Damaged roof to wall connections were observed in many reservoirs with damage to walls, base-slabs and internal columns limited to a few reservoirs only. Of the 43 reservoirs, complete functional failure occurred in only one, with reduced function and operation at other sites resulting from excessive leakage, necessity for emergency repairs, or associated pipe work damage. Those reservoirs currently out of operation for reinstatement, including Christchurch's largest, account for approximately 40% of the network's storage capacity.

Overall, given the magnitude of earthquake accelerations that occurred on 22 February 2011, the reservoirs are considered to have performed remarkably well. Those in the Port Hills area nearest the earthquake epicentre, have expectedly, incurred the most damage.

Reinstatement works, varying from minor crack injection and patch repair through to reconstruction and retrofit, have been developed appropriate to the extent of damage. CCC has prioritised reservoir repair to maximise available water supply for the 2011-2012 summer demand and this has required, in some instances, staging and deferring of reinstatement works.

A summary of structural and functional performance, results of physical investigations and detailed seismic assessments, and common damage areas observed are presented in this paper along with the reinstatement options developed.

INTRODUCTION

This paper describes the seismic performance of concrete potable water reservoirs located in the Port Hills and Cashmere Hills during the 22 February 2011 and 13 June 2011 earthquake events. It summarises; the overall performance of the reservoirs in these areas, results of detailed physical inspections, desktop seismic assessments and the reinstatement options that have been developed for the ten reservoirs most badly damaged.

WATER STORAGE NETWORK AND RESERVOIR DETAILS

Christchurch City Council has over 43 concrete potable water bulk storage and service reservoirs within its supply network, providing water to approximately 320,000 residents. The reservoirs are of varying age, geometry, construction type and volume capacity with the majority being located within the Port Hills and Cashmere Hills areas. The reservoirs are typically founded on platforms cut into the underlying tuff and basalt rock.

Older reservoirs are typically of in situ reinforced concrete construction with the more modern structures being precast, often post-tensioned circumferentially and occasionally vertically. A number of the more recent reservoirs are of design and construct delivery comprising singly reinforced, and in a couple of instances circumferentially post-tensioned, 150 thick precast walls.

The majority of the reservoirs are of circular plan geometry with the remainder being rectangular. Huntsbury No.1 is the largest rectangular reservoir with a storage capacity of approximately 35,000 m^3 (approximately 77 m x 63 m plan dimensions). The two largest circular reservoirs are located on Worsley's Road and have storage volumes of approximately 11,000 m^3 each (42.7 m internal diameter). The total potable water storage capacity of the concrete reservoirs in the Port and Cashmere Hills areas is in the order of 102,000 m^3.

[1] *Technical Directors – Beca Infrastructure Ltd.*

Figure 1: Huntsbury No.1 Reservoir. Christchurch's largest reservoir (capacity 35,000 m^3).

The reservoirs are a mix of Importance Level 3 and 4 structures to AS/NZS1170.0 with some being recognised as more critical for water storage and supply than others.

A number of reservoirs were provided with seismic actuated valves to close off the mains pipes.

Archive records obtained for Huntsbury No.1 Reservoir, designed circa 1951, include calculations of hydrodynamic pressures and structure self-weight earthquake loading. These calculations were based on a horizontal acceleration of 0.1g, which appears to be consistent with requirements at the time of the design. NZS 3106 *Code of Practice for Concrete Structures for the Storage of Liquids* was first issued in 1986. This standard included detailed methodologies for the design of reservoirs under earthquake loading including; calculation of hydrodynamic pressures, connectivity and transfer of seismic shears from roof-to-wall and wall to base. It is likely that many reservoirs constructed before this standard was first issued are potentially deficient with respect to some of these specific design aspects. Also, the level of horizontal earthquake loading that the reservoirs were originally designed for is expected to vary considerably and relative to their respective age. It therefore appears likely that few, if any, reservoirs would fully meet current earthquake design requirements for water retaining structures.

It is apparent that seismic reviews have been undertaken previously on some of the older reservoirs and roof-to-wall connection retrofit works were observed on some sites. This connection / interface has been observed to have performed particularly poorly on many reservoirs and is discussed later.

SUMMARY PERFORMANCE OF CONCRETE RESERVOIRS

Inspections undertaken, following the 22 February earthquake, on 43 concrete reservoirs located on the Port Hills and Cashmere Hills areas noted varying extents of damage from nil through to major. The reservoirs were all evaluated, based on the damage observed, to Christchurch City Council's condition grading schedule. Overall the 43 concrete reservoirs are considered to have performed reasonably well structurally with approximately 75% of the reservoirs either not requiring any repair or only requiring minor repairs. The results of the grading are presented in Table 1 below.

Table 1: Reservoir condition grading following 22 February 2011 Earthquake.

CCC Condition Grade	Description	Number of Reservoirs
1	No repairs required – undamaged	23
2	Minor repairs required. Asset operable	10
3	Repairs required but asset still operable	5
4	Substantial repairs required. Asset barely operable	3
5	Asset inoperable. Major repairs or replacement required.	2

Commentary on those reservoirs graded 3, 4 and 5 is provided in later sections of this paper.

IMPACT OF 13 JUNE 2011 EARTHQUAKES

Two significant events, measuring 5.6 and 6.3 on the Richter Scale respectively, occurred in Christchurch on 13 June 2011 and further inspections of the reservoirs were subsequently carried out. Further structural damage and deterioration was noted in a number of reservoirs and additional geotechnical damage was also observed at some sites. In general the damage observed following the 13 June events has not impacted the grading results shown in Table 1.

As a result of damage occurring on 13 June to the repairs that had been completed on some of the reservoirs which had relatively minor damage, a review of the assessment and reinstatement philosophy was carried out. Seismic assessments were at that stage restricted to those reservoirs that were extensively damaged.

Following the damage to completed and partially completed repairs on 13 June it was agreed that detailed seismic assessments would be undertaken and engineered retrofit options developed for all reservoirs significantly damaged and those designated Importance Level 4. Engineered repair and retrofit would reduce the risk of further depletion of Christchurch's already heavily damaged potable water network / lifeline system should any significant events occur during the current period of increased seismicity.

SEISMIC DEMAND

Twenty of the concrete reservoirs within Christchurch City's potable water storage network (providing around 60% of its total capacity) are located in the Port Hills area and within a 5 km radius of the 22 February 2011 earthquake epicentre.

Earthquake forces due to the self-weight inertia of tank walls and roof combined with those from impulsive hydrodynamic components are generally calculated based on a very short period and peak spectral response. Comparison of the NZS1170.5 Design Spectra peak for Site Subsoil Class B (rock) against the horizontal acceleration response spectra at nearby strong motion recorders in the Port Hills area indicates that the reservoirs in this area are likely to have experienced accelerations greater than the relevant current code implied design values (based on hazard factor Z = 0.3*, return period factor R $\geq$ 1.3 or 1.8). Reservoirs located a greater distance from the earthquake epicentre have expectedly sustained less damage. *Note the 'Z' factor was increased from 0.22 to 0.3 in May 2011.

A comparison of peak accelerations recorded in the Port Hills area on 22 February against those from the same sites for the main 13 June earthquake indicates the June accelerations were in the order of two-thirds of the February values. However, seismographs installed in the Eastern area of the Port Hills after February recorded significant horizontal accelerations, possibly due to their closer proximity to the June earthquake epicentre.

INSPECTIONS

External inspections were completed for all reservoirs and internal inspections for those most severely damaged and which were subject to detailed seismic assessments.

Depending on the extent of damage observed and correlation with seismic assessments, additional inspection and investigation were carried out. This included surveying, selected invasive testing (coring of concrete, exposing of roof-wall dowels) and materials testing.

The extent of geotechnical investigation was also tailored to suit specific sites depending on initial site observations, additional requirements from the structural assessments and for development of appropriate reinstatement concepts where applicable. This included digging of test pits, bore-holes and ground penetrating radar (GPR) surveys.

CCTV and leak detection inspections were also carried out, where considered necessary, on inlet and outlet mains pipes and stormwater lines.

DESKTOP SEISMIC ASSESSMENTS

The eight reservoirs that require the most significant structural repair have had detailed desktop seismic assessments completed based on current earthquake loading design requirements. These reservoirs are all typically located within a few kilometres of the 22 February earthquake epicentre and likely to have experienced horizontal and vertical accelerations in excess of code requirements, and considerably greater than originally designed.

Strength requirements, sliding, overturning and convective wave heights were all calculated and %NBS (percentage of the design requirement for a new build at the site) tabulated and included in assessment reports.

Analyses and assessments indicate reasonable correlation with damage mapping, and summary findings common to many of the reservoirs include; roof-to-wall and wall-to-base/foundation connection vulnerabilities, a potential deficiency in resistance to sliding and insufficient freeboard to roofs.

Where the seismic assessments indicated considerable deficiencies in some areas but this was not observed, additional inspection, including invasive investigation was completed.

DAMAGE OBSERVED AND FUNCTIONAL IMPACT

As indicated in Table 1, two reservoirs were assessed as being inoperable, three reservoirs barely operable and requiring substantial repair and a further five reservoirs that require relatively minor repair and currently remain essentially fully operable.

A summary commentary for each of those ten reservoirs follows. These summaries include damage observed, results of seismic assessments (where undertaken) and reinstatement details/concepts. The current operational status of each reservoir is also provided.

HUNTSBURY NO.1 RESERVOIR

- In situ reinforced concrete construction,
- Construction date circa 1953,
- Rectangular, storage capacity 35,000 m^3,
- Location: approximately 3 km from the 22 February 2011 earthquake epicentre,
- Status: out of service. Reconstruction of first smaller replacement reservoir currently proceeding. Second replacement reservoir size and capacity to be confirmed.
- Return to service date: First replacement reservoir December 2011. Second replacement reservoir around mid-2012.

This reservoir was significantly damaged during the earthquake resulting in functional failure and loss of contents.

The main structural damage was cracking of the individual base-slabs with cracks of up to 35 mm width measured and movement of slabs both horizontally and vertically by up to 50 mm. This cracking had a distinctive pattern extending diagonally across the reservoir. A similar pattern of cracking was also observed in the roof and movement/slippage of up to 20 mm along construction joints measured. Discrete localised cracking was observed in the walls and the central, low height, dividing wall was severely damaged at one location consistent with the base-slab diagonal cracking pattern. The adjoining pump station was also significantly damaged plus the main 600 diameter inlet / outlet pipe. Refer figures 2 and 3.

Figure 2: Huntsbury No.1 Reservoir – base-slab cracking.

***Figure 3:** Huntsbury No.1 Reservoir – dividing wall failure.*

Investigations in to where the water drained to have been inconclusive but it appears likely that a significant volume drained through the opened construction joints and cracks in the base-slab, and some drained through the mains pipes as the seismic actuated shut-off valves take time to close.

Extensive geotechnical investigation, including GPR surveying and inclined boreholes, indicated the likely presence of an underlying shear zone in the underlying rock extending diagonally across the reservoir footprint. This shear zone was considered the main reason for the observed pattern of structural damage. Following completion of a site viability report and detailed risk assessments of various concepts, the impact of the shear zone was assessed as being too high a risk for long term reliability of any structure constructed over it. Two significantly smaller reservoirs have therefore been proposed which will be constructed in the corners of the current reservoir footprint. The first replacement reservoir is currently under construction and due for completion in December 2011. The final configuration of the second replacement reservoir is still being assessed with construction completion anticipated around mid-2012. The estimated storage volume at the completion of reconstruction is about 12,000 m^3, providing only approximately one-third of the reservoir's original capacity.

McCORMACKS BAY RESERVOIRS

- Precast 200 thick wall panels, post-tensioned circumferentially, prestressed vertically,
- Construction dates 1984 (No.1), 1995 (No.2),
- Circular, storage capacity 5,000 m^3 each,
- Location: approximately 2.0 km from the 22 February 2011 earthquake epicentre,
- Status: No.2 currently empty for repairs, No.1 currently in service but leaking (see below),
- Return to service date: No.2 December 2011 (Stage 1 repairs), No.1 August 2012 (full repairs), No.2 October 2012 (Stage 2 repairs).

McCormacks No.2 was removed from service following the 22 February earthquake due to excessive leakage through the post-tensioned wall joints and cracks in the base-slab. McCormacks No.1 is currently operational but is leaking through wall joints, cracks in the base-slab and also through tendon anchorages. Both reservoirs are expected to be returned to full service but substantial repair is required.

Damage noted to Reservoir No.2 includes; cracking in base-slab, spalling and cracking around wall foundation ring-beams, vertical and horizontal movement of wall relative to foundation ring beam, cracking in wall construction joints, damage to roof-wall connections and minor internal column concrete spalling. The pump house between the two reservoirs also has structural damage.

Damage noted to Reservoir No.1 is very similar to No.2 but its roof is more severely damaged due to extensive failure of roof-wall connections, and water appears to be leaking through the circumferential post-tensioning tendons.

Refer figures 4 to 6 for indicative damage observed.

***Figure 4:** McCormacks Bay No.1 Reservoir – significant roof damage.*

***Figure 5:** McCormacks Bay No.1 Reservoir – leaking vertical construction joints.*

Figure 6: McCormacks Bay No.1 Reservoir – rock fall behind reservoir.

The detailed seismic assessment identified vulnerabilities with the roof-wall connection, the wall to base connection, the wall circumferentially and a potential deficiency in resistance to sliding. The damage observed is generally consistent with the seismic assessment.

Given the magnitude of horizontal accelerations experienced at the site on 22 February, the post-tensioning tendons may have been loaded slightly beyond their proof stress / limit of proportionality. The possible effect of this is that the residual wall compression under normal hydrostatic loading may have been reduced, and the reservoirs' residual lives compromised slightly.

Repair and retrofit requirements are extensive and costly including; construction of a full base-slab overlay and internal ring beam to tie the wall in to the base-slab and to provide a direct seismic shear transfer mechanism, a ring beam around the top of the wall tied to the roof (No.2 reservoir) and bandaging of all wall vertical construction joints full height. Reservoir No.1 repairs are still being developed at the time of writing but expected to be similar, with the impact of water leaking through the tendons still be assessed.

Reinstatement works for the two reservoirs has been staged to assist with achieving maximum network water availability for the 2011-2012 peak summer demand. Once water demand has reduced in the second quarter of 2012, Reservoir No.1 will be emptied to enable full repair to be undertaken. Geotechnical repairs at the site are also extensive and expected to continue till late 2012 - refer also to Geotechnical Observations and Issues.

CLIFTON 3 RESERVOIR

- In situ reinforced concrete construction,
- Construction date circa 1948,
- Circular, storage capacity 455 m^3,
- Location: approximately 3.7 km from the 22 February 2011 earthquake epicentre,
- Status: currently empty for repairs due to failure of the internal column supporting the roof but will be returned to service once repairs are completed.
- Return to service date: December 2011.

Damage noted includes failure of the internal column, sagging of the roof and shearing of the roof overhang at the roof-wall joint.

The roof has an overhanging nib with only a small overlap with the top of the reservoir wall. Under horizontal earthquake loading the roof has impacted the top of the wall and resulted in the overhanging nib shearing off. Excessive translation of the roof has subsequently occurred and resulted in the column failing due to only limited shear and flexural capacity. Refer to figures 7 and 8.

Repair and retrofit includes break-out and reconstruction of the damaged top and bottom of the column, jacking of the roof vertically and fitting of a reinforced concrete ring beam at the top of the wall to restrain the roof against lateral movement. A kerb is also being constructed at the base of the column to provide additional restraint. Minor repairs to floor sealants and wall cracking are also required.

Figure 7: Clifton 3 – internal column failure.

Figure 8: Clifton 3 – failure of roof overhanging nib (repaired nib shown).

UPPER BALMORAL RESERVOIR

- Precast 150 thick wall panels, post-tensioned circumferentially, conventionally reinforced vertically,
- Construction date 1986,
- Circular, storage capacity 1,000 m^3,
- Location: approximately 2.0 km from the 22 February 2011 earthquake epicentre,
- Status: currently empty for repairs to significant damage that occurred to the internal column and around the top of the wall at roof beam supports,
- Return to service date: December 2011.

The roof comprises precast roof beams that are slotted into the reservoir wall and pilasters. Under horizontal earthquake loading the roof beams have impacted the wall and resulted in major cracking and damage to the top of the wall. At pilaster locations, the beams have punched off the wall concrete at the ends of the beams. The excessive roof movement has also resulted in damage to the top of the internal column. Refer figures 9 and 10.

Figure 9: ***Upper Balmoral Reservoir –concrete shear failure at pilaster locations due to roof beam (concealed) impact.***

Figure 10: ***Upper Balmoral Reservoir – concrete damage at roof beam wall support.***

The detailed seismic assessment identified vulnerabilities in the roof-wall connections, the internal column and the wall to base connection.

Repair and retrofit includes break-out and reconstruction of the damaged top of the column, and fitting of a reinforced concrete ring beam at the top of the wall (tied to the roof beams). An internal ring beam is to be constructed to tie the wall into the base-slab and to provide a direct seismic shear transfer mechanism.

Note that Huntsbury No.1, McCormacks No.2, Clifton 3 and Upper Balmoral reservoirs account for approximately 40% of Christchurch's network potable water storage capacity.

MURRAY AYNSLEY RESERVOIR

Murray Aynsley Reservoir (rectangular, 350 m^3 storage, construction 2000) was removed from service after the 22 February earthquake, primarily due to geotechnical issues at the site, and is scheduled to be re-commissioned in November. Minor structural repairs have been carried out along with relocation of services / water mains.

MT PLEASANT NO.2 – 2 RESERVOIR

Mt Pleasant No.2 – 2 Reservoir (circular, 1,000 m^3 capacity, constructed 1957) was emptied after the 22 February 2011 earthquake as it was leaking through vertical cracks at construction joints in the wall. These repairs have been completed and the reservoir returned to full service.

MONCKS SPUR 3, CLIFTON 4, MT PLEASANT 4 RESERVOIRS

Repairs are required to Monks Spur No.3 (370 m^3 capacity, construction 1987), Clifton No.4 (1,000 m^3 capacity, construction 2000), Mt Pleasant 4 (1,000 m^3 capacity, construction 1964). These circular reservoirs all currently remain operational, though Clifton No.4 is leaking through joints in the wall and at the base of the wall.

Structural damage is generally minor but they are all expected to be removed temporarily from service for repair. Common to all three reservoirs is damage of the roof-to-wall connection. Spalled wall concrete at dowel locations was observed on all three reservoirs and roof-wall connection dowels cored from the Moncks Spur and Mt Pleasant sites indicate the dowels themselves are severely damaged.

Seismic assessments of these three reservoirs are currently in progress. Current findings are that roof-to-wall connection capacity, based on current code new build standards, is deficient at Moncks Spur 3 and Mt Pleasant 4 and marginal at Clifton 4.

Repairs and retrofit being developed for Moncks Spur 3 and Mt Pleasant 4 reservoirs include patching of spalled areas of concrete, crack injection and construction of a ring beam at the top of the wall to restrain the roof.

GEOTECHNICAL OBSERVATIONS AND ISSUES

Significant geotechnical issues were identified at Huntsbury, McCormacks Bay and Murray Aynsley reservoir locations.

At Huntsbury extensive geotechnical investigation indicated that an underlying shear zone, extending diagonally across the reservoir footprint, likely exists and which is considered the main reason for the observed structural damage. This shear zone may remain active for some time and the effects of movement along it were assessed as being too high a risk for long term reliability of any structure constructed over it.

The McCormacks Bay site requires extensive, and costly, stabilisation. The access road to the reservoirs has significant cracking, settlement (up to 500 mm) and slumping towards the slope below the reservoirs. The stacked basalt block gravity wall supporting this road partially collapsed resulting in rockfall hazards to the road and residents below. Emergency temporary rockfall fences were installed to mitigate short term rockfall risks. A permanent piled replacement retaining wall is currently proposed along the edge of the road. The construction platform for the reservoirs was cut into rock and there is a near vertical face (up to around 21 m high) behind the reservoirs. The large ground accelerations that were experienced at the site on 22 February and 13 June led to significant loosening and dislodgement of material from the rock face. Rock and material has piled up behind the reservoirs and some rocks may have impacted the reservoir wall. It is currently proposed that reinforced steel mesh and a grid of rock anchors and soil nails be installed over the full extent of the cut face.

Murrray Aynsley Reservoir is located approximately 4m from the edge of a 15-25 m high old quarry cliff. Sections of the cliff face collapsed on 22 February and the ground up to the reservoir has severe tension cracking. Continued regression of the slope would likely lead to undermining of the reservoir and relocation of the reservoir appears likely to be necessary in the future.

CONCLUSIONS

Inspections undertaken, following the 22 February earthquake, on Christchurch City Councils concrete potable water reservoirs located on the Port Hills and Cashmere Hills areas noted varying extents of damage from nil through to major. Approximately 75% of the reservoirs either do not require any repair or only require minor repairs. Moderate repair through to full re-construction are required at other sites. Five reservoirs are currently out of service for repairs and these account for around 40% of the network storage capacity.

Damaged roof to wall connections were observed in many reservoirs with damage to walls, base-slabs and internal columns limited to a few reservoirs only.

A few reservoir sites in the Port Hills area have significant geotechnical issues.

Horizontal acceleration response spectra from strong motion recorders in the Port Hills area indicate that the reservoirs in this area are likely to have experienced accelerations greater than current relevant code implied design values, and significantly greater than original designed to resist.

Detailed seismic assessments have currently been completed on ten reservoirs and typical findings include; roof-to-wall and wall-to-base/foundation connection vulnerabilities, a potential deficiency in resistance to sliding and insufficient freeboard to roofs. It is likely that there are a number of reservoirs throughout New Zealand that have similar vulnerabilities.

Repair and reinstatement of the most badly damaged reservoirs are being staged to maximise available network storage capacity for the 2011-2012 peak summer demand. Some of the repairs are necessarily being deferred until 2012 and will be completed during a period of reduced water demand.

LESSONS LEARNED

Key summary learnings consistent between physical investigation observations and desktop seismic assessment conclusions include:

- Robustness in design is an important design parameter,
- Connectivity between roof to wall, and wall to base is critical,
- Avoidance of joints in floor slabs provides increased reliability,
- Thin walls with a single reinforcing layer have limited robustness,
- Foundation competency is important.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the following individuals, institutions and consulting engineering companies for their assistance and data supply:

Bryan Hickling (Christchurch City Council), Rodger Vickers (CPG New Zealand Ltd), Christchurch City Council, Fulton Hogan, Opus International Consultants Ltd, CPG New Zealand Ltd, Geonet (Earthquake Commission and GNS Science).

REFERENCES

1. NZS 3106: 2009 Design of concrete structures for the storage of liquids, *Standards New Zealand*.

2. NZSEE (2009), Seismic Design of Storage Tanks.

3. NZS 1170.5: 2004 Structural Design Actions Part 5: Earthquake Actions – New Zealand, *Standards New Zealand*.