2003 Pacific Conference on Earthquake Engineering

Innovative seismic retrofit of concrete water supply tanks

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ABSTRACT: Many of the stock of concrete water supply tanks in New Zealand have distinct seismic defects while others provide for lower seismic force resistance than required by current standards applicable to new tanks. Against this background, water supply tanks form a critical part of infrastructure; integrity of post earthquake water supply is an important part of any asset management plan. This paper reports actual construction experience of the seismic retrofit of concrete city water supply tanks by the authors, 13 in the authors' specialist company and a previous seven while employed by a large consultant.

The tank seismic retrofit methods included external and hoop post-tensioning with greased and sheathed tendons at roof level outside pilasters on circular tanks, epoxy bonding angle shaped steel plates to transfer seismic shear forces at the base of precast circular tanks, use of epoxy impregnated carbon fibre to structurally connect components, and strengthening of 9,000 m^3 capacity rectangular concrete tank cells by post-tensioning with greased sheathed strand passing through the body of the tank cells.

The paper provides an overview of design philosophy methods, construction experience and the clear benefits for asset management of New Zealand infrastructure.

1 INTRODUCTION

A number of seismic design defects exist in the New Zealand stock of concrete water supply tanks, particularly the older precast concrete tanks built between 1964 and 1975. Many of these tanks, and some more recent ones as well, have a much lower level of seismic resistance than required for modern design. In a larger proportion of the seismically deficient tanks the walls themselves are often able to provide an adequate level of resistance yet the overall performance can be seriously diminished by various weak links in the load path transferring inertial forces to ground. In many cases it is the connections between components that are deficient and often it is possible to strengthen these weak links at a relatively small proportion of the tank replacement cost and so substantially boost both seismic performance and the integrity of the asset.

Such strengthening has been carried out on a significant number of concrete tanks using a variety of innovative methods specific to the circumstances. A selection of implementations of these strengthening designs is described in the following sections.

2 SEISMIC STRENGTHENING EXAMPLES AND CASE STUDIES

2.1 Wall to Base Connections for Circular Reservoirs

One of the most common seismic defects in New Zealand reservoirs is the lack of an adequate wall-to-base connection. In some circular precast reservoirs the base of the precast wall panels simply rest in a slot as illustrated in Figure 1, with no reinforcement connecting the components together.

In others the wall base is connected to a foundation ring beam but the foundation ring beam is not connected to the floor slab to fully transfer lateral seismic shears at the tank base/ground interface. This is illustrated in Figure 2. While the situation illustrated in Figure 2 is clearly better than that illustrated in Figure 1, a potential for seismic damage exists in both cases because the floor slab is not fully mobilised to transmit horizontal seismic shears.

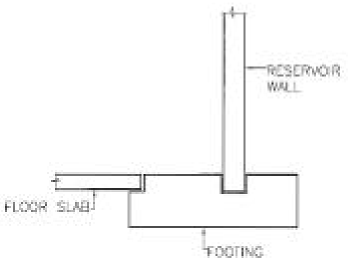

Figure 1: Wall in a slot and no slab connection

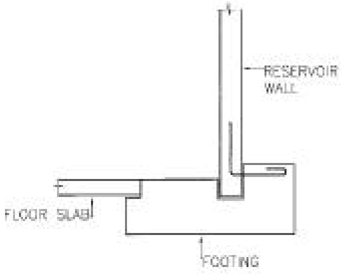

Figure 2: Wall connected in slot, no slab connection

Historically these details were developed for static loading where they are quite satisfactory because the forces are radial, but earthquake shaking produces asymmetric and circumferential forces.

When the authors' research on these deficiencies began about 14 years ago, the New Zealand Earthquake Commission funded a study to investigate the problem analytically using finite element techniques. A 10,000 m3 reservoir was modelled as shown in Figure 3 with the model allowing for friction at the base where the tank precast wall rested in the slot without connecting reinforcement, similar to Figure 1 above. An iterative approach was necessary at that time to model the non-linear effectively elasto-plastic behaviour resulting from allowance for friction at the wall bases.

Very high hoop tensile forces around the base as well as high vertical bending of the upstream and downstream walls were found to develop as a result of circumferential wall movement within the slot. The hoop tension results are presented at Figure 4 with acknowledgement to the Earthquake Commission who sponsored the study (Taylor 1991). The plotted results clearly show that tensile forces far exceed allowable code values and they arise due to the type of connection. It was concluded at this point that the tanks with weak base connections would benefit from seismic strengthening.

Based on the authors' own research, and the Earthquake Commission study, strengthening against premature seismic failure by this mechanism has been recommended and a significant number of New Zealand tanks have been strengthened.

Different methods of achieving strengthening have been used including vertical or inclined diagonal dowel bars around the circumference and also a more innovative method of epoxy bonding L-shaped steel coupons on the exterior of tanks.

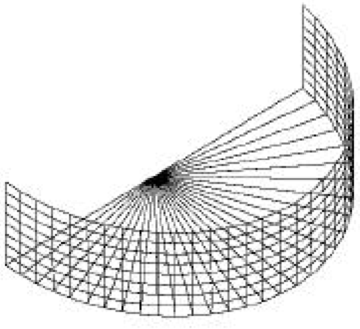

Figure 3: Indicative finite element model of 10,000 m^3 prestressed concrete tank.

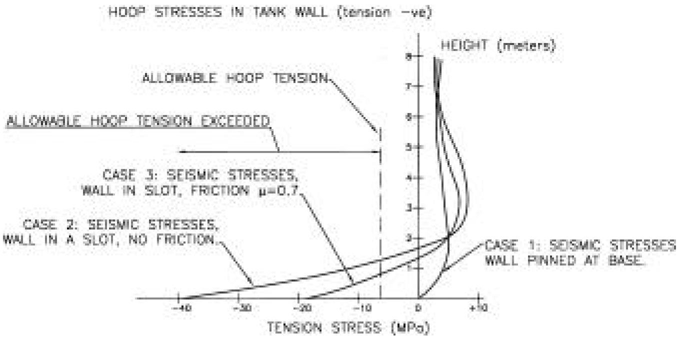

Figure 4: Hoop tension stresses on wall base due to movement of wall in foundation beam slot.

2.2 Strengthening Wall Base with Epoxy Bonded Steel Coupons

The method of bonding on steel plates or coupons to transfer large in-plane wall shears at the base is illustrated in Figure 5. Installation of angle shaped steel plates on a tank is shown in Figure 6. Bonding of steel reinforcement to concrete has been known for a long time and the method has been used, for example, to boost the flexural strength of reinforced concrete bridge beams, among other applications. Awareness of the need for stringent quality control and site practices has probably been one of the restricting factors on the growth of this type of technology.

More recently epoxy impregnated fibreglass and carbon fibre products such as TOWSHEET have popularised methods of surface applied reinforcement to existing concrete structures.

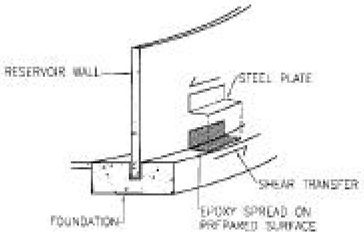

Figure 5: Horizontal shear transfer through L-shaped coupons

Figure 6: Installation of base L-shaped steel seismic shear coupons

Advantages of the steel coupon system described above include:

a) There is no interference with prestress or other closely spaced reinforcement at the base of a precast wall.

b) No risk of potential leaks resulting from drilling at the outside (on some occasions drilling of dowels inside the tank to connect the floor slab to the foundation ring beam is also required).

c) Relatively moderate cost.

d) No need to take the tank out of service in many cases.

e) High success rate provided correct design and construction procedures are followed.

In many applications of the angle coupon strengthening, contractors were invited to submit an epoxy to meet a stated performance criteria. Prior to installation on the job, slant shear testing of the epoxy to concrete and epoxy to steel bond was conducted with a number of specimens as illustrated in Figure 7. Rigorous preparation for both the slant shear test specimens and on site installation of the L-shaped steel coupons involved:

- Scabbling the concrete
- Shot blasting the steel contact surfaces to the Swedish Standard SA2 ½

- Flame drying surfaces immediately prior to installation of epoxy
- Taking slant shear specimens for all onsite bonding work on a given day or for a given number of coupons bonded
- Engineer on site for much of the critical bonding work
- Checking for voids in epoxy

A coupon receiving the epoxy coating is shown in Figure 8.

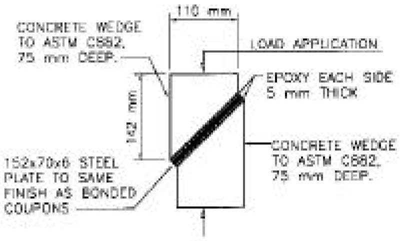

Figure 7: Quasi ASTM slant shear test specimen

Figure 8: Steel L-shaped coupon under epoxy application

A particularly successful New Zealand manufactured epoxy used in this type of work is EPAR-HPM and in almost all cases epoxy bond to the steel was superior to bond to the concrete. Some bonding problems have occurred with other epoxies, particularly at the initial test stage.

A key aspect of the coupon design is to provide adequately for movement under load as the tank is emptied and filled. Such movements can be quite significant and the design detail used is shown in Figure 9.

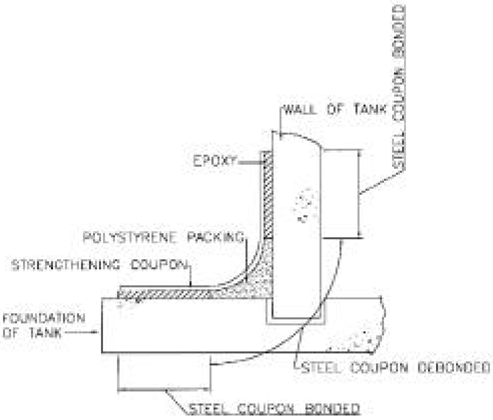

Figure 9: Design detail of L-shaped steel coupon shear

This provision for movement under serviceability load is a key and fundamental aspect of the steel coupon design.

There has been relatively little uptake by other consultants of this system which has proved to be very cost effective in a number of installations.

The seismic strengthening of the base of circular reservoirs with steel coupons typically costs approximately 4% – 5% of the replacement cost of the reservoir.

2.3 Seismic Roof Strengthening

A series of five 4,500 m^3 capacity precast post-tensioned concrete reservoirs have conical concrete roofs supported entirely on the perimeter wall as shown schematically in Figure 10. The outward thrust generated by the roof is resisted by additional prestressing at the top of the walls. This, however, has proved insufficient and cracks have developed at the top of the walls producing a potential serviceability problem.

There was also a significant seismic design issue resulting from the inability of the walls to resist an increment of outwards thrust generated by vertical acceleration of the roof.

Detailed exploratory work to check the condition of post-tensioning strands was seen as having serious disadvantages in a salt laden coastal marine environment and opening up the strand for even short periods was considered to pose a longer term corrosion risk. Construction of an internal column as an alternative means of support to the roof was impractical as the reservoirs could not be taken out of service for the necessary length of time.

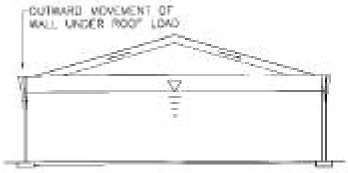

Figure 10: Schematic illustration of roof support.

Figure 11: Close up of spacer block for roof strengthening and stressing cable make up

A system of supplementary external prestressing to the top of the walls was finally adopted and is shown in Figure 11 with discrete saddles a cost effective way to position strands to clear pilasters. Forming a continuous band of concrete at the top of the tank wall was not cost effective because of obstruction of the pilasters.

Two cables are draped over concrete saddles and tensioned to provide an inward force at each saddle. The post-tensioning strand comprised greased and HDPE factory sheathed 15 mm diameter superstrands in sets of four in each of two ducts. The two ducts were filled with grout contained by a 50 mm – 60 mm diameter HDPE tube. Provision was made for a future third cable with an unused central saddle on the spacer blocks (see Figure 11) in the event that non-seismic forces such as creep and thermal expansion had been under assessed.

Although conceptually simple, much engineering supervision and design work was required to achieve the required tolerance compliance. Many critical tolerances must come together to make the concept work in practice, including height of spacer blocks, amount of epoxy under spacer blocks, tilt of spacer blocks and correctly formed cable channels in the blocks. All of these were resolved and the project completed successfully.

The cost of the work was about 8% of the replacement cost of each reservoir.

2.4 Tying in the Base of Rectangular Tank

A 9,000 m^3 rectangular twin cell reservoir, as illustrated in plan in Figure 12, had adequate flexural capacity in the reinforced concrete cantilever walls to resist static loads, illustrated in Figure 13. However, the footings were not connected to the floor slab and had insufficient sliding resistance under earthquake loading. While the cantilever walls and footings were tied in at the corners and did have some ability to span between return walls, the longitudinal reinforcement in the footings was very light, and consequently insufficient to develop an adequate horizontal spanning capacity.

A number of design options were considered including tying the footing to the slab with custom made steel coupons, or using epoxy impregnated carbon fibre strips (TOWSHEET). Eventually reducing the horizontal span of the footing was decided on using internal post-tensioning as a cost effective and fundamentally reliable system to seismically strengthen the reservoir.

The internal post-tensioning system is illustrated in plan in Figure 12 where the arrangement of post-tensioning strand is such to permit one cell being emptied at a time, whilst allowing the work to proceed. A cross section of the post-tensioning is shown in Figure 13 and a cross section showing the greased and sheathed ducts is similar to that shown in Figure 11.

The seismic strengthening using post-tensioning cost approximately 8% of the replacement cost of the tank. Epoxy impregnated carbon fibre such as TOWSHEET could have been installed at a lesser cost but the reliability of bonding to damp internal surfaces, where surface deterioration of concrete had occurred, was not considered proven.

2.5 **Strengthening Single T-Beam Reservoir Base**

A reservoir of approximately 2,500 m^3 capacity had been constructed using vertical prestressed concrete double tee-beams. These building floor type beams were flange supported at the base and spanned as flexural elements to a ring beam and roof slab at the top. Under load the vertically spanning tee- beam wall elements had flexed significantly allowing the vertical joints to open and leak at approximately one third of the height. A study of the design calculations showed that whilst the calculations showed a certain amount of shear reinforcement in the flanged seating for the double tee-wall elements, approximately half of this quantity was shown on the drawings and is believed to have been installed.

The remedial design involved pouring a concrete base beam.

The purpose of the strengthening as shown in Figure 14 was two-fold:

1. To assist with improving the flexural performance of the panels by providing a small degree of base fixity and to ease the movement demands on the sealing work carried out separately.
2. To boost the seismic strength of the reservoir base and prevent a sudden and premature failure under seismic load.

The cost of the seismic strengthening part of the work was less than 6% of the replacement cost of the reservoir.

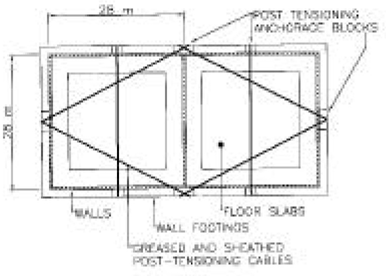

Figure 12: Plan of 9000 m^3 reservoir showing layout of post-tensioning in two cells.

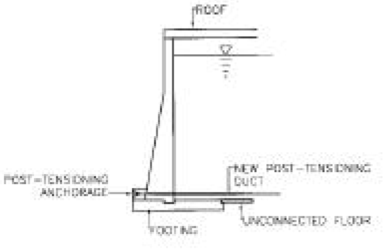

Figure 13: Section through wall showing post-tensioning through body of tank cell.

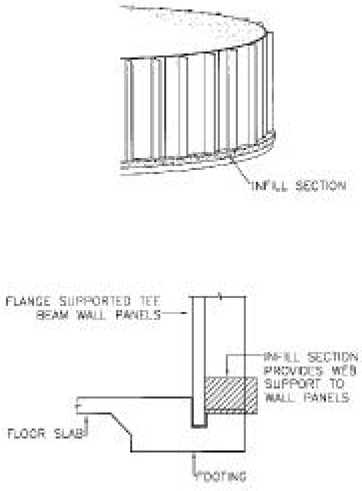

Figure 14: New Ashhurst seismic base strengthening showing base shear strengthening.

3 CONCLUSIONS

Design studies, practical construction costs and project economics have clearly shown that it is possible to substantially upgrade the seismic strength and performance of existing concrete tanks often at a small fraction of the replacement cost. The New Zealand Standard NZS3106 has been generally taken as setting an acceptable level of seismic performance, and maximum probable damage studies and site specific earthquake spectra preparation have been commissioned in only a small number of cases. It is clear that hazard mitigation benefits to each reservoir strengthened are considerable.

4 ACKNOWLEDGEMENTS

We would like to acknowledge the Palmerston North City Council, Taupo District Council, New Plymouth District Council, Tauranga District Council as well as a number of other councils, and their personnel involved for their contributions, reviews and comments.

The authors commissioned Mr Howard Chapman, formerly of Opus International Consultants Limited, to review the 4,500 m^3 capacity tank seismic roof strengthening part way through the process (described in Section 2.3 above) and they would like to acknowledge his thorough critique of concept and detail.

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