LESSONS LEARNT FROM DESIGN & CONSTRUCT SUCCESSES AND FAILURES OF LARGE CONCRETE WATER AND WASTEWATER STRUCTURES

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ABSTRACT

Concrete has been used as a construction material for water and wastewater treatment and storage structures for over 100 years in Australia. During this time, design and construction of these structures has remained a specialised practise and despite the vast majority of projects operating with no problems, design and construction issues continue to occur.

It appears that lessons from the past have been lost and that designers particularly, do not appreciate the sometimes subtle but always important key differences between normal concrete structures and structures for the Water Industry.

The widespread use of "Design and Construct" in water and wastewater projects has caused cost pressures to over-ride quality concerns and in some cases driven Contractors to find lowest-cost designers who do not have suitable expertise or experience with these structures. When Water Authorities do not have in-house structural engineering expertise to review D&C projects, this can lead to exposure to significant future risk of loss of service or even failures. This paper outlines examples of both successful and unsuccessful Australian water projects.

1.0 INTRODUCTION

The first systematic use of reinforced concrete for water storage structures was pioneered by John Monash and Joshua Noble in country Victoria and South Australia at the turn of last century. Between 1903 and 1912 concrete tank design and construction by Monash and Noble evolved rapidly to produce tanks up to 445kL capacity, some of which still stand today as a testament to concrete's inherent longevity.

Concrete is widely used for construction of water treatment and storage structures for a number of reasons:

- Inherent durability of concrete under a wide range of typical pH's and common chemical concentrations found in raw water and wastewater
- Concrete is a low cost and widely available building material
- Custom sizes and shapes can easily be formed in concrete to suit particular process requirements
- Autogenous healing is a property of concrete whereby initially leaking cracks will self-seal themselves over time and this property is used to improve the economy of concrete tank designs
- For additional reliability and water-tightness, concrete can be prestressed so that no cracking occurs and leakage is completely eliminated

From the earliest times, engineers have recognised the autogenous healing potential of concrete. During the water tank construction boom that followed the Second World War, a design method based on allowing tanks to crack and then self-heal was developed and codified by the Engineering and Water Supply Dept. (E&WS) in South Australia. This method was sponsored by the then Cement and Concrete Association, which published the design methodology and made it available for general use.

Current design theory and methods in Australia date back to 1988 when Australian Standard *AS3735 Concrete Structures for Retaining Liquids* was first published. Much of the information in the standard is based on research conducted by Nigel Priestly in New Zealand and for that reason there are close similarities between the Australian and New Zealand codes. This research work was in response to a number of "unexplained" concrete tank failures in the USA during the 1970's. Priestly and others showed that relatively mild thermal gradients in concrete walls and roofs could lead to excessive cracking and hence loss of function. His recommendations for limiting design stresses were incorporated into AS3735 and remain largely unchanged today.

2.0 DESIGN ISSUES

Based on the author's experience with both successful and unsuccessful water structure designs particularly over the past 10 years, four particular design issues commonly feature either at the start of a project and during concept design phase or during the investigation of structural distress or failure. In no particular order, these may be summarised as:

- Reinforced vs. Pre-stressed concrete
- Circular vs. Square or rectangular tanks
- Small vs. Large (more accurately scale effects)
- Code provisions vs. Design experience and common practice

2.1 Reinforced vs. Post-tensioned concrete

This is a question between two competing design philosophies. Reinforced concrete (RC) is currently an economical choice for tanks up to around 2ML capacity and is widely used for much smaller process tanks, flumes, clarifiers etc. Reinforced concrete tanks will crack when first filled with water and such cracks will typically take 1-6 weeks to self-heal depending on water quality and other factors. Pre-stressed concrete in water retaining structures is usually "post-tensioned" after the concrete has been cast and the term post-tensioned (or PT) is commonly used to refer to water structure construction. PT places the concrete into compression using high-tensile steel strands and the resulting compressed concrete cannot crack and hence cannot leak. The current New Zealand water structures code emphasises the difference between RC and PT construction by stating that the only way to guarantee a 100% water tight concrete structure is to either a. Prestress or, b. Line with a waterproof membrane.

All things being equal, RC structures typically have thicker walls, floors and roofs than PT structures and this can be a disadvantage when thermal stresses are considered.

2.2 Circular *vs.* non-circular tanks

A circle is the ideal structural shape for retaining water, because stresses are evenly distributed around the perimeter of the structure. The parameters of a tank, its diameter, height and wall thickness can be combined into a non-dimensional "shape factor" which can be used to generate easy-to-use design tables for entire families of different sized tanks.

Square or rectangular tanks on the other hand can fit close together to each other much more neatly and will take up less site area for any stored volume at a fixed depth. For that reason, they are widely preferred over circular shapes for process tanks and in some cases

for storage as well.
Rectangular tanks typically require thicker walls, due to structural inefficiency and this can lead to high thermal stresses as in the previous comparison between RC and PT construction. Rectangular tanks can be PT to reduce their thickness but this brings an entirely new level of design and construction complexity into play, which will be examined further later in this paper.

2.3 Scale Effects

Scale effects refers to the tendency over time of structures of all types (buildings, bridges, water structures) to be designed bigger and bigger. In the case of water structures this is driven by increasing population size requiring more water treatment and storage capacity and by the cost efficiencies of larger structures.

However, structures cannot be scaled up in size indefinitely and sometimes scaling up an otherwise successful design can lead to "unexpected" problems. Often the problems are caused when poorly understood structural effects, such as thermal effects on concrete walls or prestressing losses change from having minor effects to becoming significant design constraints.

2.4 Codes vs. Experience

Design Code AS3735 is really more of a set of guidelines than a comprehensive design manual. The Commentary to AS3735 states quite clearly that it is intended to be used by professionally qualified engineers experienced in the design of concrete structures for retaining liquids or equally qualified engineers working under the guidance of an engineer experienced in the design of such structures. The code and commentary are both quite slim documents and some of the omissions may seem to be surprising to engineers used to more detailed design codes such as AS3600 Concrete Structures or AS5100.5 Bridge Design – Concrete. Some of the "traps" in AS3735 include:

- Guidelines are provided for circular tank design including thermal effects but virtually nothing is provided for non-circular tanks.
- Earthquake forces are included in design load combinations but no information or guidance is provided on how earthquake forces should be calculated for water retaining structures
- Minimum reinforcement rates are provided with no warning that minimum rates will only be satisfactory in the simplest cases. In some cases, equations are given with no limitations at all, which could lead to dangerous extrapolation. An example of this that actually occurred will be given later in this paper.
- The critical difference between "ultimate limit state" design and "serviceability limit state" design as it applies to concrete water structures is not addressed at all. With limit state design being the predominant design methodology used by structural engineers in Australia for the past 25 years, many engineers do not understand how water structures can fail by cracking and leaking when they are otherwise strong enough to resist collapse.
- Many pages of detailed methodology and analysis are provided on how to check concrete walls for shear. In practise, for walls carrying water pressure, shear is never a design case consideration and much wasted effort can be expended on an essentially academic exercise.

3.0 CASE STUDIES

For the purposes of this paper, a total of 12 projects have been selected split into two main categories; successes and failures. Six of each category have been selected to provide balance, but in reality many more projects are successes than failures and in the examples provided most have been satisfactorily resolved in the end.

Due to requirements of confidentiality, the failure projects cannot be individually identified but never-the-less they provide much better opportunities to learn lessons and hence are over-represented in this sample.

The 12 examples come from Qld, NSW, Vic, SA and WA. Seven of the projects were D&C and the remaining five were alliance contracts of various types. Project values vary from $600,000 up to $900M but are mostly in the $1-10M range.

The number of each types of structure included are listed below and Table 1 shows the distribution of success/failure types in the sample:

Water Treatment Plants	4
Waste Water Treatment Plants	3
Water Storage Tanks	5

Table 1 Summary of Case Studies

Structural element	Successful	Problems	Total
Curved walls	5	2	7
Flat walls	1	2	3
Other	-	2	2
Total	6	6	12

Table 2 shows that the sample includes a representation of both reinforced concrete and prestressed concrete successes and failures:

Table 2 Summary of concrete types

Concrete type	Successful	Unsuccessful	Total
Prestressed concrete	4	3	7
Reinforced concrete	2	3	5
Total	6	6	12

Having selected this sample of projects, it is interesting to assess the reasons for success and failure in each case to try to find any patterns or common themes. Just as there is often more than one factor in a structural failure, investigation of the successes also shows that often more than one common reason applied. For that reason, the percentages in the following tables add up to more than 100%.

Table 3 Reasons for Successes

Independent engineering review	84%
Use of proven designs	67%
Specific extra care taken due to special circumstances	50%

Table 4 Reasons for Failures	
No independent engineering review	67%
Design inexperience	50%
D&C pressures	33%
Major consultant design	33%
Poor construction supervision	16%

Some of the above results appear to be obvious but sometimes the obvious is not easy to see or is easily forgotten. Both tables 3 and 4 show the importance of independent engineering review to achieving a successful water structure design outcome. Some of the failed projects did have reviews but these were not carried out by suitably experienced engineers. It is interesting to note that major consulting firms are not immune from design failures and this points to a failure in their internal review and QA processes as well as design failure.

Another common factor that appears in both tables is “extra care” in the success table and the corresponding “design inexperience” in the failure table. Although PB’s successful designs in this study largely used tried and proven techniques, there can often be new challenges. These included working with a new D&C Contractor in WA to deliver a first concrete tank into a market dominated by steel tanks. In another case, knowing the limitations of AS3735, PB’s designers took extra care with the design to ensure that shrinkage stresses in thick flat wall sections were kept well inside Code requirements.

Design inexperience is the opposite of taking extra care. When you “don’t know what you don’t know” it is a very dangerous situation for a structural designer to be in. Examples of this from the failure examples include:

- A 45m diameter reinforced concrete tank base slab designed with no joints and largely minimum reinforcement. The letter of AS3735 was complied with but shrinkage stresses cracked the slab into 3m x 3m trapezoidal shapes and resulted in such high leakage that it was not possible to fill the tank for leak testing. Eventually a rubber membrane liner was installed after all the larger cracks were individually sealed using epoxy injection.
- Major retrofitting of corner strengthening was required to a 40m x 50m reinforced concrete main bioreactor tank that was partly buried. The designer had ignored thermal effects on the exposed sections of concrete and had overlooked the short-term design case when half the tank was emptied for maintenance. The fact that non-circular tanks have high vertical and horizontal stresses at the corners was not fully understood, leading to significant under-design.

D&C pressures require further explanation. Some water structures, in particular water storage tanks, are extremely competitive in the marketplace with a large variety of contractors vying for limited work. Most of the specialist tank contractors have high ethical standards and use reputable design consultants but unfortunately there are “cowboys” in this part of the construction industry as there are in others. The pressure to reduce a design to the bare minimum means that sometimes designs are taken beyond AS3735 requirements by a significant margin. Where PB has reviewed such designs and investigated the reasons for, it the results have been concerning.

It appears that there is a perception that AS3735 is excessively conservative and that because a particular design has been used for the last 10 years without a problem, it must be OK.

In fact, AS3735 is intended to provide a higher standard of concrete construction than AS3600 and a design life of 40-60 years. In the case of prestressed concrete design, losses in prestress due to creep, shrinkage and relaxation continue for over 30 years and extreme events such as earthquakes or high temperatures are based on 1 in 50 or 1 in 100 year return periods. So a design that has been "problem-free" for 10 years most likely has not yet seen its design loads.

One way to reduce the cost of a circular tank is to reduce the quantity of prestressing and reinforcing steel. PB has reviewed two such tanks, from different D&C contractors, where reinforcement across critical wall joints was 75% less than required for one tank and in the other was omitted altogether. The tanks were 3.2ML and 20ML prestressed tanks, one was already constructed while the other was able to be rectified prior to construction.

A particular type of problem occurs when lack of design experience meets the scale effect. PB reviewed a previously successful prestressed rectangular tank design that had been scaled up by a factor of 4 to overall dimensions of 100m x 200m with the completed tank extensively cracked. Prestressing losses in very large structures require careful consideration due to much higher than usual friction effects. In this particular case, the D&C contractor decided to save cost by adopting standard design details more usually adopted for multi-storey car park slabs. PB has found that poor detailing of PT slabs 25-30m long has virtually no effect in practice on design suitability but in slabs 50m or longer "good design practice" is essential if problems like cracking and leaking are to be avoided.

3.0 CONCLUSION

There are a number of factors that will increase the risk for a Water Authority that the design and/or construction of new water infrastructure will run into problems. To mitigate against these, Water Authorities can take active measures to protect themselves against the possibilities of time and cost over-runs, loss of reputation, poor customer perception and potentially claims from third parties such as EPA and end users. Based on the case studies examined above, these measures should include:

- Selection of an appropriate delivery method based on the nature of the project and degree of risk
- Critical assessment of all D&C bids for both technical as well as financial aspects. Engage specialist technical advisors if in-house expertise is unavailable
- Ensuring that Alliance-type projects have a sufficiently robust independent technical review mechanism. The peer reviewers must actually have expertise in the fields being reviewed.
- Maintaining a visible level of oversight during construction and to the completion of commissioning. This will serve to remind designers and contractors that any design changes, modifications or rectifications carried out during construction need to be reviewed to the same standards and with the same degree of rigour as the original project.

4.0 REFERENCES

Salu, MS & Turner, DT (2006) *History, Current Practice and Future Developments in Australian Concrete Water Storage Structures.* New Zealand Concrete Conference, Christchurch, NZ