CORROSION INDUCED FAILURE OF VERTICAL STRESSING BARS IN CONCRETE WATER RESERVOIRS

Paper Presented by:

Brad Dockrill

Author:

Brad Dockrill, Partner,

Vinsi Partners (Newcastle)

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CORROSION INDUCED FAILURE OF VERTICAL STRESSING BARS IN CONCRETE WATER RESERVOIRS

Brad Dockrill, Partner, Vinsi Partners (Newcastle)
Brett Eliasson, Partner, Vinsi Partners (Sydney)
Warren Green, Partner, Vinsi Partners (Sydney)

ABSTRACT

Two recent case studies are highlighted where the failure of vertical stressing bars in concrete reservoir walls was observed whilst undertaking structural risk assessments of water assets. Had these failures not been identified and rectified the consequences could have been catastrophic.

The two case studies show that, for many concrete reservoirs (of this type), it is more likely to be a case of when rather than if failure will occur. They also show that, using a co-operative approach, considered and proactive inspection and monitoring/repair regimes combined with sound engineering judgment, the risk of failure can be minimised to acceptable levels.

The case studies indicate reservoirs with vertical stressed bars without cementitious grout encapsulation are subject to failure due to stress corrosion cracking. Reservoirs designed with this feature and a sliding base (that is not freely sliding) required wall strengthening where bars failed. Remediation measures were developed including strengthening to allow the service life of the reservoirs to be extended by many decades whilst maintaining critical service delivery.

1.0 INTRODUCTION

During the past five years the authors have encountered a number of concerns in the design and construction of select concrete water reservoirs.

This paper highlights two recent case studies where the failure of vertical stressing bars in concrete reservoir walls (see Figures 1 and 2) was observed whilst undertaking structural risk assessments of water assets.

These case studies show that, for many concrete reservoirs, it is more likely to be a case of when rather than if failure will occur. They also show that, using a co-operative partnership with clients, considered and proactive inspection and monitoring/repair regimes combined with sound engineering judgement, the risk of failure can be minimised to acceptable levels.

Asset owners need to understand their risks and implement strategies to prevent failure. A small spend now can ultimately save a huge cost and unplanned losses in the future.
2.0 CASE STUDIES - OVERVIEW

2.1 Failure 1 – Tasmanian Reservoirs

The engineering commission was to undertake a study into observed defects and deterioration to over twenty water asset structures including reservoirs, pump stations, and wet wells in Tasmania.

During the visual inspection (a strategic part of a structural risk assessment) the failure of two vertical stressing bars were observed at one reservoir. When the failure occurred and how or why was unknown.

2.2 Failure 2 – Queensland Reservoirs

A structural risk assessment of 10 concrete reservoirs in Queensland was the basis of the second case study.

During the visual inspection the failure of two vertical stressing bars were observed at one reservoir. When the failure occurred and how or why was unknown.

The initial concern was that the 50Ml reservoir was located within and directly above a residential area. The consequences of failure were extreme.

During discussions with the client there was anecdotal evidence to suggest other bar failures and bars needed to be removed at two other reservoirs.

A preliminary structural adequacy check utilising Finite Element Analysis (FEA) was undertaken to allay immediate concerns. A monitoring regime was then instigated with contingency plans in place to lower water levels if required. This planning enabled a detailed site and materials investigation to be carried out to confirm design parameters, consider future remedial options and ultimately manage risk whilst maintaining normal operations.
3.0 INVESTIGATIONS

Microscopic examination and mechanical testing by two independent and nationally registered laboratories made the following general observations in relation to the inspection and testing of some vertical stressing bar samples from the Tasmanian and Queensland concrete reservoirs:

- Examination of the Tasmanian failure indicated corrosion causing existing cracks (3.5mm deep) in the bar (25mm dia) to increase.
- The mechanical testing of the Queensland failure indicated that the bar that failed had cracks appearing to have propagated through a corrosion mechanism. Crack depth was approx 3mm and several other cracks were seen adjacent to the point of failure subsequent to tensile testing.

Independent laboratory analysis confirmed the suspicions that the failure mechanism was stress-corrosion cracking (SCC) of the vertical stressing bars (see Figure 3). SCC is caused by the simultaneous presence of tensile stress and a specific corrosive medium.

It was established that the failure was caused by corrosion causing existing micro-cracks in the bar to increase. The corrosive medium for SCC was pitting (localised) corrosion at the base of pre-existing cracks leading to crack propagation and growth or pitting corrosion causing crack initiation, propagation and growth.

![Figure 3: Typical Cross Section of Bars Examined](image)

The combination of pitting corrosion and tensile stress can result in brittle and catastrophic failure of a stressing bar. This failure can lead to a stressed bar being ejected vertically (to release energy) from the concrete wall panel.

The design and construction methods employed to the reservoirs in question did not afford long term corrosion protection to the bars creating a very real failure risk.

Armed with this knowledge focussed condition assessments of the reservoirs in Queensland and Tasmania were acrried out. A visual survey, combined with select diagnostic testing, ascertained deterioration mechanisms and appropriate service life cycles.
To complicate matters further the as-designed structural behaviour was found on many occasions to differ from that in-service. For example, while the original design intent was to have a “sliding wall base”, often the base joint had deteriorated to such an extent that a portion, and in a worst case instance the entire wall circumference, was essentially “pinned”. This variance in support conditions resulted in wall stresses vastly different to as-designed, with potentially harmful results.

This information combined with FEA enabled a scenario analysis to be developed linking service life, structural capability, reservoir capacity and options for remediation.

This enabled a risk profile to be formulated, with client involvement, based on prioritising likelihood and consequence. Residual risk and condition ratings were established utilising pre-defined and agreed criteria combining hard engineering data with client liabilities. The structure owners now had a prudent and informed decision making process regarding future reservoir usage.

4.0 ENGINEERING REMEDIATION

The first consulting engineering rule that should always be considered is “do nothing”. This can often be a perfectly manageable strategy when combined with appropriate operation & maintenance and engineering nous.

In these cases however, “do nothing” was not a viable solution.

A number of process controls incorporating reservoir level monitoring were designed and an inspection regime to observe bar failures to enable assets to remain on-line developed. This was critical in enabling the structure owners to continue to service their customers.

Remediation measures then developed included controlled induced failure of vertical bars, grout injection to existing bars and structural strengthening.

4.1 Controlled Induced Failure of Vertical Bars

Those bars that were considered in the “line of fire” to personnel when accessing the reservoir roof or equipment were designed to be failed in a documented controlled procedure (see Figure 4).

Figure 4: Typical Diagram of Vertical Bars to be Removed from “Line of Fire”
4.2 Grout Injection to Existing Bars

Existing vertical stressing bars were designed to be protected by cementitious based grout injection (see Figure 5). Use of cementitious based grouts introduces a passive film around the bar thereby limiting the rate of corrosion to the remaining sound bars and significantly reducing the risk of an unpredicted failure. These works were subject to a number of trials by the Contractor (in the workshop, laboratory and in the field) in the presence of the Superintendent and Principal to resolve constructability issues prior to site mobilisation.

![Figure 5: Typical Injection Ports for Grout Injection](image1)

4.3 Structural Strengthening

Areas where bars were failed as well as areas defined through the FEA as being structurally inadequate due to altered site restraints were typically designed to be strengthened through the use of carbon fibre laminates (see Figure 6). This process was relatively simple with quick turnaround times.

![Figure 6: Typical Arrangement of Carbon Fibre Laminates in Areas of Vertical Bar Failures](image2)

Figure 7 indicates the region of high bending (and tensile) stress in the wall once the base becomes restrained. This region of high tensile stress on the wall face was also designed to be strengthened by using vertical carbon fibre laminates.
5.0 CONCLUSION

Asset owners must understand their risks and implement strategies to prevent failure. The management of the vertical stressing bar failures as discussed shows how a strategic investigative and inspection regime coupled with comprehensive knowledge of structural and material behaviours is vital in managing the risk of concrete reservoir (of this type) failure.

The original design documentation (if available) may not reflect what has been constructed. In addition the as-designed structural behaviour may differ from that in-service. Critical criteria must be considered including:

- Vertical stressing bars; locations, protection?
- Have failures occurred; where, when, criticality of location?
- Reservoir structural behaviour, base restraint, thermal loading?
- Asset vulnerability, tolerable water levels, management of water delivery?
- Remediation specification, grouting/protection requirements, instigation of bar failures, bar removal, structural strengthening?

Evaluation of the above combined with sound engineering judgment ensures increasing ongoing service life is achieved whilst the risk of reservoir failure can be minimised to acceptable levels.

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