Forensic Investigation Concerning Inspection and Diagnosis of Condition of Water Storage Systems in the Gulf.

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Abstract. Sandberg were asked to visit and comment on a sizeable project in the Gulf involving water storage towers, ground reservoirs and ancillary buildings in contemplation of legal proceedings. The structures had been built by a contractor but some problems had occurred in construction due to the high temperatures and issues with the concrete placement. The main issue that needed to be resolved was whether the problems that occurred were within acceptable limits for that type of construction and what repair recommendations were appropriate.

The Client for the project had rejected the structures and was aiming for demolition and reconstruction which was a draconian step, given the level of problems – all of which were easily repairable. A significant amount of misdiagnosis had occurred with dark flecks on the surface of reservoirs being attributed to corrosion of reinforcement, for example, when in fact they were due to mould growth on the surface of the concrete and were literally surface deep only. There were also significant questions to be answered as to what constituted an acceptable level of leakage from water storage towers. An issue was also present with very severe corrosion to some reinforcing bars close to ground level in several ground reservoirs, despite the reinforcement being epoxy coated. It was considered highly likely that this damage was in fact due to stray current corrosion from current leakage from the cathodically protected water pipelines that delivered water to the facilities in question. This paper will discuss the inspection and diagnosis of the problems and the feasibility and need for appropriate repairs.

1 Introduction

Most of us are fortunate enough to enjoy drinking safe, potable water direct from the tap in our homes and businesses. Most of us give little thought to the challenges and difficulties faced by those operating the water supply system, whose job it is to design, install and operate infrastructure capable of handling, purifying, storing and delivering water safe enough for us to drink. We think little of the design and construction challenges that involves or how designers and contractors ensure that the durability of the installed plant and infrastructure will meet the required service lifetime. In temperate countries that is challenge enough, but when constructing storage towers, reservoirs and piping systems in hot, arid countries it is, perhaps, not surprising that difficulties can occur during construction and operation.

This is sometimes further compounded by the fact that designers are often based in Europe in more temperate conditions and may not fully appreciate the difficulties of constructing in a hot, arid climate. Furthermore, Engineers may try to apply the same acceptance standards that they would in more temperate countries, not fully appreciating the difficulties of construction in hot climates.

2 The Project

The project related to some water retaining and ancillary structures. The structures in question were elevated water tanks, some ground service reservoirs and other ancillary buildings built in the period 2006-2011 at a number of sites in the Gulf region.

The design, construction and maintenance of these structures became the subject of a dispute between the Contractor and Employer.

The issues in contention related primarily to cracking and leakage of some of the concrete water retaining towers and ground service reservoirs, together with some concerns regarding the possibility of reinforcement corrosion in both the water towers and ground reservoirs. The dispute resolution proceedings also included a number of other issues relating to the construction of ancillary buildings, compound walls and concrete roadways, plus some M&E (Mechanical – Electrical) issues. This paper focusses on the water retaining structures, however.

3 Standards and Publications Referred to.

The specification for the project called for the cast-in-place concrete for the water retaining structures to be a class 35A with a minimum cement content of 385 kg/m³ and a maximum of 400 kg/m³. The reservoirs were
specified as water retaining structures and the structural
reinforcement was specified as epoxy coated. The
cement was specified as ordinary Portland cement (i.e
CEM1). The specification required compliance with
BS8007:1987 (in 2006, that standard was replaced by BS
EN1992-3, but this project used the older standard). The
concrete finish was specified as class F3 (shall be
smooth and of uniform texture and appearance). In fact,
the authors of this paper made reference to the guidance
in BS EN1992-3 (4) since it gave good guidance on
industry expectations in relation to watertightness. All
structures were also coated externally and in the case of
plant rooms, internally too.

Other documents that were referred to in the
dispute included two from CIRIA and the UK Concrete
Society (1,2) and finally a publication by Anchor (3).

Considerable discussion also revolved around
technical reports prepared by three different Consultants,
plus the reports prepared by the representatives of the
Employer.

4 The Alleged Defects

The following describes some of the issues which were
in contention and shows the types of structure which
were the subject of the investigation.

4.1. Elevated Water Towers (EWTs)

![Fig. 1. Typical Elevated Water Tower](image1)

The towers were typically some 30m high and were
hollow internally with a metal access walkway internally
reaching as far as the bottom of the water retaining bowl.

![Fig. 2. Typical defects to a water tower bowl, showing
evidence of leakage and staining.](image2)

![Fig. 3. Photograph of one of the very few structures showing
live leakage of water internally. The dark staining may
indicate rust but this was never investigated or proved
in the initial reports](image3)

![Fig. 4. Efflorescence staining from leakage in an elevated
water tower. The leakage was claimed to be ongoing,
but the inset photo top right was taken from a report
generated 8 months previously. The stain looked
identical, suggesting that leakage had in fact stopped.](image4)
4.2. Ground Service Reservoirs (GSRs)

Fig. 5. Typical Ground Service Reservoir, with walls showing good condition.

Fig. 6. GSR showing brown staining to walls. This was identified as rust staining in earlier reports although no proof was offered. Scraping the surface to remove the coating showed no evidence of corrosion or staining to the concrete underneath! This was considered to be mould growth by the author.

Fig. 7. Typical GSR showing brown staining to wall scraped away. There was no evidence of rust staining or indeed any staining underneath the coating.

Fig. 8. One of the very few GSR’s showing severe corrosion of reinforcing bars at the base of the wall, despite the epoxy coating. This was suspected to be due to stray current effects from the pipeline cathodic protection system.

5 The Dispute

5.1 A number of other structures were inspected during the course of the visual survey in February 2019 but the problems with those were minor and not contentious. In this paper we have focussed on the EWTs and the GSRs as the issues with these were the most contentious.

The paramount duty of Expert Witnesses is to be objective in their investigations, truthful, to employ their skills properly and above all to remember their duty is to the Court and not to the party employing them. Taking a partisan approach, or misusing data are viewed dimly by the Court, but in the experience of the authors that happens far too often.

For example, one report on this project stated “Severe leakage and calcite staining are occurring at the external conical wall.” The author of that report had made no attempt to determine whether in fact the leakage was ongoing, as the wording suggests and in fact in the majority of the cases there was strong evidence to suggest that the leaks had self healed. Elsewhere it is stated, “The ongoing and visible water leakage from many of the EWTs, including the dripping of water onto the ground, and the formation of rusty-brown stalactites (calcite straws) on the underside of the conical wall, gives rise to concern about loss of bar section due to corrosion at leaking construction joints.” During our inspection I saw only one example of actual drips coming from an EWT and only one significant example of ongoing leakage internally. The wording used – “rusty brown stalactites” implies reinforcement corrosion, but no testing or breakout was done to demonstrate whether this was the case. It might have been due to corrosion or it might equally have been leaching from iron rich aggregates.

Another report asserted that “the walls in many of the GSRs show corrosion driven rust stains from internal leakage. If the Technical Specification had been complied with, the GSR walls would not be
exhibiting external signs of reinforcing steel corrosion.” No investigation had been performed to show whether the stains were, in fact, due to rust and on subsequent investigation, no corrosion was found. (This relates to the brown flecks and staining and not to the very localised severe corrosion of the rebars that occurred in a very few GSRs).

In relation to the EWTs, the earlier report asserted that “the exterior wall exhibits a uniform pattern of extensive rust staining that clearly reflects internal corrosion of the reinforcing steel.” Again this was based on visual observation only and was never confirmed although ultimately it was agreed that the extent of actual corrosion should be investigated properly.

5.2 Compressive Strength

Further problems were encountered when it was claimed that the concrete strength failed to meet the specified requirements. The claim that the concrete failed to meet the specification was fundamentally flawed as the claim was based on concrete core test results. It is very well known that concrete cores do not give the same strength results as fully water cured concrete cubes and that typically, around 85% of the cube strength values might be realised by cores. In fact, the strength of concrete cores for the specified strength class C35 (fck,cube) should, according to European standards (EN 13791), achieve a minimum core strength of 0.85 x (fck,cube – 4) = 26.4MPa. One report concerning the results for strength cited just two of the EWTs, which were actually in the worst condition and not representative of all the towers in the contract. That report did not address a much larger number of test results from another report which painted a significantly different picture when considering the average strength of the concrete in the structures.

Furthermore, the standard assumes that concrete cores are tested in an “air dry” condition. The cores in this case were tested in a saturated condition, which gives a lower strength. The standard recommends that 10% should be added to the results for cores tested saturated, to compensate for this reduction in strength. This factor was not mentioned in one of the earlier reports. This is all illustrative of an approach that can sometimes be seen in legal work, where selective evidence is quoted in order to “prove” a particular point of view. It represents very poor practice.

Table 1 – table reproduced from expert report for the owner.

<table>
<thead>
<tr>
<th>Watertight Concrete Design Criteria vs Field Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria</td>
</tr>
<tr>
<td>Min. Cement Content</td>
</tr>
<tr>
<td>Max. Cement Content</td>
</tr>
<tr>
<td>Max Water/Cement Ratio</td>
</tr>
<tr>
<td>Min. Cube Strength</td>
</tr>
<tr>
<td>Concrete Grade</td>
</tr>
<tr>
<td>Max. Crack Width</td>
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<tr>
<td>Min. Concrete Cover</td>
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<tr>
<td>Reinforcing Steel</td>
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</table>

Table 1 shows the contract specification and advice drawn from BS8007 (5). It shows “Min” cube strength which is actually characteristic strength and not a minimum as suggested. The cement content test is typically accurate to around ±40 kg/m³, so the indicated cement content from the initial test results could in fact be higher. Table 2 shows the strength results for all the structures with values correctly uplifted by 10% for testing in a saturated condition. There are in fact just a few low test results, which should probably be classed as “outliers” in evaluating any average value. Whatever decision is made on the latter it can clearly be seen that in almost all cases the concrete complied with the specified requirements.

5.3 Water to Cement Ratio

It was initially suggested that tests performed by Sandberg showed that the concrete failed to comply with regard to water to cement ratio. The specification called for a maximum 0.45 and the test results suggested 0.6. However, it was never mentioned that the test in question is considered accurate to plus or minus 0.05 and can be significantly affected by the presence of plasticising admixtures in the concrete, as were used in this case.
5.4 Epoxy Coated Rebar

The project used a blue, fusion bonded epoxy coating on the reinforcing bars. In just a few locations on the GSRs, heavy corrosion of the rebars close to ground level was present. On the basis of that limited evidence, it was postulated that there were widespread problems with rebar coatings. In fact, that corrosion was very probably the result of corrosion due to stray current, which is discussed in the next section. One report advanced alarmist conclusions about rebar corrosion and consequent concrete problems on a project-wide basis. It was inaccurately suggested that “The immediate consequence is the risk that, wherever the epoxy-coated bar has been used in heavily loaded structures, such as the base of water-retaining GSRs or the elevated water tanks of the EWTs, this may result in structural inadequacy.

<table>
<thead>
<tr>
<th>Site</th>
<th>Structure</th>
<th>Element</th>
<th>Sample ID</th>
<th>Density</th>
<th>Core strength MPa</th>
<th>Corrected insitu Cube Strength Mpa (10% uplift for wet testing)</th>
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<td>51.0</td>
<td>56.1</td>
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<td>38.9</td>
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</tbody>
</table>
5.5 Stray current corrosion

Stray current is well known for causing corrosion of buried metal structures such as pipelines that can lead to severe local attack. Simplified, the current from a direct current (DC) source, which can be rail traction or cathodic protection (CP) anodes in the soil, is received (picked-up) by parts of a non-connected metal structure and emitted from other parts, returning to the system ground. Where current enters the rebars, cathodic reactions are accelerated, which is generally harmless. However, where the current exits, anodic reactions are accelerated, passivation is lost and local corrosion may occur. In concrete, the reinforcement can act as the receiving/emitting metal [6]. Due to the relatively high resistance of concrete, connecting the reinforcement to the system ground usually solves the issue. Nevertheless, stray current induced reinforcement corrosion can be severe, in particular due to its localized nature.

As mentioned above, the corrosion apparently occurring in some of the lower walls of the GSRs may be related to stray current effects. An obvious source of DC is CP of water pipelines. Some protective measures are present, either intentional or not. The rebar epoxy coating will limit current pick-up, and ideally even will isolate rebars from each other. However, in practice such coating is never perfect and will contain defects (holidays), which will allow current entering the steel; and rebars may be electrically connected when bonded to form the rebar cages, unless handled very carefully. The total amount of current picked-up will depend on the number and size of holidays and contact points. As the total steel surface area in the outside surfaces of a GSR of about 50 m x 30 m is large, significant current may
flow into the rebar cage. Current exit also occurs at holidays in the coating, but this can be more concentrated depending on the location and proximity to a nearby section of the pipeline (low resistance path). Another protective measure is the use of a polythene membrane between the soil and the concrete. Here some current leakage may occur, e.g. along imperfect overlaps. As with the epoxy coating, few or small defects in a large surface may still allow current penetration. The current exit path may be influenced by the polythene sheeting, but even smaller defects will not stop it.

Considering the above, the occurrence of stray current induced corrosion of reinforcement in the GSRs cannot be excluded. The local nature of the observed corrosion and the relatively early visibility are evidence to support this mechanism. Dedicated investigation is needed to either confirm or deny this possibility; if confirmed, the spatial extent should be determined, in particular below ground level.

6 Summary and Conclusions

In the previous sections, we have shown that, in common with most civil engineering structures, defects occur in practice. The key point is whether the defects will impact on the service life of the structure and whether they can be easily remediated. It is critical to assess the condition of potentially affected structures dispassionately and objectively and to recommend solutions based on best practice and experience.

Most important of all, if a dispute proceeds to Arbitration or to Court Proceedings, it is essential to report findings accurately and truthfully and to be objective in the assessment. In the author’s experience as an expert witness this is unfortunately frequently not the case. Evidence is misrepresented, distorted and even omitted to support a particular viewpoint. Fortunately, the barristers, legal representatives, judges and arbitrators are experienced and shrewd people and can form their own judgement when they see such distortions in play.

References

5. BS 8007, 87th Edition, March 1, 2008 - Design of Concrete Structures for Retaining Aqueous Liquids