Supplemental Report: Cracking and Leakage at Reinforced Concrete Pomona Water Reservoir 5C
Supplemental Report:      
Cracking and Leakage at       
Reinforced Concrete Pomona    
Water Reservoir 5C              

Prepared for                  
Rick R. Olivarez, Esq.       
Deputy City Attorney         
City of Pomona, California    
505 South Garey Avenue       
Pomona, CA 91769              

Prepared by                   
Piotr D Moncarz, Ph.D., P.E.  
Patxi Uriz, Ph.D., P.E.       
Exponent                      
149 Commonwealth Drive        
Menlo Park, CA 94025          

January 28, 2008               

© Exponent, Inc.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Inspection</td>
<td>2</td>
</tr>
<tr>
<td>November 8 and 9, 2007 – Tank Roof</td>
<td>2</td>
</tr>
<tr>
<td>Seepage</td>
<td>9</td>
</tr>
<tr>
<td>December 5, 2007 – Tank Interior</td>
<td>9</td>
</tr>
<tr>
<td>Petrography and Core Testing</td>
<td>16</td>
</tr>
<tr>
<td>Discussion</td>
<td>17</td>
</tr>
<tr>
<td>Concrete Cracking in Roof</td>
<td>17</td>
</tr>
<tr>
<td>Interior Conditions</td>
<td>20</td>
</tr>
<tr>
<td>Summary and Recommendations</td>
<td>21</td>
</tr>
</tbody>
</table>
Introduction

Exponent Failure Analysis was retained by the City of Pomona, California to investigate the condition of the reinforced concrete tank structure of Pomona’s Reservoir 5C. This report supplements the February 16, 2007 report by Exponent entitled, “Concrete Leakage at Reinforced Concrete Pomona Water Reservoir 5C” (the initial report). The initial report was based on engineering analysis and a site inspection carried out by Dr. Piotr Moncarz on November 17, 2006. The initial report focused on the causes of wall cracking of the tank and their consequences. The report also talks about the observed cracking of the reinforced concrete flat roof of the tank. The observations led to the need for an additional study to advise the owner on the long-term serviceability of the tank. The opportunity to inspect the tank from the inside, both when filled with water (inspection of the underside of the tank’s roof; November 8-9, 2007) and when emptied (slab-on-ground and the interior of the exterior walls, and the interior walls and columns; December 5, 2007), provided very valuable observations which are the principal basis for this report.

Exponent’s scope of work leading to the information presented in this report consisted of the following:

- Study reported in Exponent’s initial report.
- Site visits by Piotr D. Moncarz, Ph.D., P.E. and Patxi Uriz, Ph.D., P.E. on November 8-9, and December 5, 2007.
- Removal of concrete core samples from the concrete roof and slab-on-ground on November 9, 2007 and December 5, 2007, respectively.
- Petrographic analysis of a concrete core sample.
- Strength testing of concrete core samples extracted from the roof.
- Review of design documents.
- Review of applicable codes and standards.
- Engineering analysis.
- Provide recommendations for remedial actions if needed.

For information regarding the concrete tank location and its description, please refer to the initial report, dated February 16, 2007.
Inspection

On November 8 and 9, 2007, Dr. Piotr Moncarz and Dr. Patxi Uriz of Exponent inspected the reinforced concrete roof of the tank. The roof structure was inspected from both the outside and inside of the tank. In December 2007 Reservoir 5C had been evacuated and on December 5, 2007 the walls, columns, and the slab-on-ground of Reservoir 5C were inspected from inside of the tank. The following provides a summary of our observations.

November 8 and 9, 2007 – Tank Roof

The roof exterior was found to be in generally good condition with few large cracks (Figure 1) located approximately one-half of the distance between contraction (or construction) joints. Typical cracks were observed to be on the order of 1/32 of an inch. Figure 2 shows typical cracking patterns for large cracks, which extend from north to south, for the Northwest corner of the roof structure. The bold dark line in this figure represents the location of the 2 foot thick wall located underneath the slab, and the dotted circles represent locations of reinforced concrete columns and beams below.

Minor roof cracking was also observed which occurred parallel to the longitudinal walls and beams below.

The construction documents call for the roof to be coated with a crystalline water-proofing application. Field observations verified a coating, which in some instances was partially scaled.
Figure 1. Typical large cracking found at the Roof of Reservoir 5C.

Figure 2. Typical roof cracking observed at Reservoir 5C.
To facilitate the inspection of the roof from underneath, the City of Pomona lowered the water level in the tank such that an inspection could be performed from a small inflatable watercraft placed into the water tank; a professional diver maneuvered the boat around to allow for ease of inspection. Only a portion of the slab was able to be inspected in that manner, as the interior walls and baffles did not allow for access of the entire roof from below.

Inspection of the roof from the interior revealed the following conditions:

- The general condition of the roof was observed to be good with only minor cracking observed (Figure 4 through 6). The crack widths were observed to be on the order of 1/64 inch, with some locations showing signs of corrosion staining coming from the reinforcement (Figure 7).

- The minor cracking ran along the length of the roof from east-to-west. Two distinct cracks were found approximately 8 feet and 4 feet from the inside face of the exterior wall.

- Larger cracks were found running north-to-south, or perpendicular to the interior longitudinal wall, which corresponded closely with the large cracking discussed above and shown in Figure 1 and 2.
• A total of 6 cores were taken from the roof structure, three of these cores were through thickness of the suspended slab.

• Each of the thru-thickness-cores was drilled directly above cracks running from north-to-south (perpendicular to the longitudinal wall). Once the core was removed, the crack was observed to extend the entire length of the core; i.e. the entire thickness of the slab; the crack was wider at the top than at the bottom (Figures 8 and 9).

• Of the three cores drilled completely through the slab, two were found to be approximately 9 inches long, whereas one of the cores was found to be approximately 8 inches long, indicating the deck was approximately 8 inches thick in this location.

• Concrete patch material was observed on the interior and exterior walls. The patch material consisted of a thin crust-like, dark material, which was easily removed by hand in some locations (Figure 10).

Figure 4. Cracking at underside of roof is visible by observation of condensation.
Figure 5. Cracking at underside of roof is visible by observation of condensation.

Figure 6. Close-up of typical cracking running parallel to wall (moisture droplets had been wiped down).
Figure 7. Cracking and corrosion product under roof slab.

Figure 8. Typical core removed from roof (Core #4 shown) illustrating crack along entire depth of core; the crack width is larger at the top of the core.
Figure 9. Close-up of core #4.

Figure 10. Spalling concrete patch material.
Seepage

ACI 350.1 defines standard rates of seepage for hydrostatic tests of open or covered concrete tanks.\(^1\) Table 1 shows the designation and quantities for each of the different levels of loss. At the time of our inspection, a “snapshot” measurement of water drained through the tank seepage collection system was approximately 520 gallons per day (gpd). It is important to note that the total amount of water leaving the tank may be underestimated through use of this test. A more accurate level of water tightness would be to very carefully observe the water levels in the tank rather than monitoring only the water being collected by the underdrain. Water loss may occur through the walls and into the ground, or directly into the ground through the slab-on-ground. ACI 350.1 contains appropriate measures to gauge water-tightness.

For a 10,000,000 gallon tank, a seepage rate of 520 gpd represents 0.005% loss of water per day, i.e. five times less than the HST-025 designation. The construction drawings do not indicate water tightness requirements for this tank. The American Water Works Association recommends a maximum leakage allowance of 0.1 percent of the total volume over 24 hours, measured by a drop in the water surface not less than five days.\(^2\)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Maximum amount of water loss to meet designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST-NML</td>
<td>No measurable loss</td>
</tr>
<tr>
<td>HST-025</td>
<td>0.025% per day</td>
</tr>
<tr>
<td>HST-050</td>
<td>0.050% per day</td>
</tr>
<tr>
<td>HST-075</td>
<td>0.075% per day</td>
</tr>
<tr>
<td>HST-100</td>
<td>0.100% per day</td>
</tr>
<tr>
<td>HST-VIO</td>
<td>Visual inspection only</td>
</tr>
</tbody>
</table>

December 5, 2007 – Tank Interior

The City of Pomona had drained Reservoir 5C prior to the inspection by Dr. Piotr Moncarz, P.E. and Dr. Patxi Uriz, P.E. on December 5, 2007. A summary of findings is provided below:

- Cracks were found at the slab on ground. A majority of these cracks had been previously repaired by grinding and patching the crack with what appeared to be an elastomeric filler (Figure 11 and 12). A sketch of the crack pattern is shown in Figure 13.

---

\(^1\) “Tightness Testing of Environmental Engineering Concrete Structures and Commentary,” ACI 350.1-01, American Concrete Institute, 2001.

• Some locations indicated cracks had been ground down, but no elastomeric material was used as a fill (Figure 14)

• Some repairs did not continue to control joints, and in many of these cases the cracks continued to extend beyond the repaired area showing signs of corrosion product.

• Many un-repaired cracks were observed. Many of these cracks contained what appeared to be a corrosion product (Figure 15).

• Five cores were extracted from the ground slab (Core F1 thru F5). Cores F1 thru F4 were cored directly over existing cracks. All cores were approximately 8 inches in length, except for core F2 which was 11 inches long. Figure 16 shows the severity of cracking as found in Core F3.

• Cracks had been repaired also on the inside face of the exterior walls (Figure). Consistently with the exterior observations reported in the initial report, and with the calculations presented in that report, these cracks were more heavily concentrated at the ground level and diminished in quantity along the height of the wall.

• Concrete patch work was observed throughout the tank (Figure 19). The patch material was found to be placed on the walls vertically and around baffle openings. The patch material in most observed locations was delaminating from the concrete wall, and was easily removed by hand.

• The concrete patch material near one of the baffle openings was delaminated, revealing its thickness and appeared as if a portion of the spall was missing (Figure 20).

• A large spalled portion of concrete was found near one of the baffle walls which appeared to have been from a section of wall just below the roof. No reinforcement was found in this spalled portion of concrete however, the location from which it had spalled appeared to have exposed reinforcement.
Figure 11. Repaired concrete cracks.

Figure 12. Close-up of concrete crack repair.
Figure 13.  Typical crack pattern for portion of tank floor (not to scale).

Figure 14.  Previously ground cracks, with no filler present.
Figure 15. Core F1, illustrating length and severity of cracking in slab

Figure 16. Cracking and corrosion product near location of Core F3.
Figure 17. Repaired cracking on inside face of exterior wall.

Figure 18. Repaired cracking on inside face of exterior wall along with concrete patch material.
Figure 19. Close-up of delaminating concrete patch material.

Figure 20. Delaminating concrete patch on baffle opening.
Petrography and Core Testing

One of the cores (Core #6) from the roof was examined through petrographic examination,\(^3\) and two cores (Core #1 and #3) were crushed to determine compressive strength.\(^4\) Relevant findings from these tests are reported below:

- The concrete was properly consolidated and cured as determined by petrographic analysis.
- The Portland cement was sufficiently hydrated, and the water to cement ratio appeared to be low.
- The longitudinal crack through the length of the specimen contained secondary calcium carbonate deposits.
- The crack contained fractured aggregate particles, indicating the concrete had achieved sufficient strength prior to the formation of the crack.
- Compressive strength tests for Core #1 and Core #3 were 6,210psi and 6,590 psi, respectively.

---

\(^3\) Petrographic Examination of Concrete Core Specimen, Job Number C-4821 A-07, December 19, 2007, Micro-Chem Laboratories, Murphys, California.

\(^4\) Laboratory Test Results, DCI No. 6817-M04, December 3, 2007, Dynamic Consultants, Inc, Mountain View, California.
Discussion

Concrete Cracking in Roof

Shrinkage of concrete is a time-dependent decrease in volume compared to its original placement volume (see also the February 16, 2007 initial report). This well-known phenomenon is an integral part of any reinforced concrete design, as constrained concrete shrinkage can lead to tensile cracking of concrete. If the cracks are large enough, they prevent the high-alkalinity cement paste from protecting the embedded steel reinforcement (rebar) from corrosion.

To accommodate shrinkage and temperature dimensional changes of the large roof area, contraction joints in the roof are called out on structural drawings to be approximately 30 feet on center. The joints are designed to alleviate stress buildup in concrete and control the location of cracking by purposely creating a weak plane in the cross-section of the slab. At the tank’s roof, the weak plane was created by a saw cut soon after placement, or a tooled line in the concrete where a crack would be expected to form. The American Concrete Institute (ACI) defines two common types of contraction joints, full and partial. In full contraction joints, all of the reinforcement perpendicular to the joint is terminated at the joint (see Figure 21), additional smooth dowels are added (if needed) to help transfer shear loads across the crack. In partial contraction joints, at least 50% of the reinforcement is terminated at the joint, which may also utilize smooth dowels to transfer shear (if needed). Continuous reinforcement is helpful for regions of high seismic hazard (such as Pomona) to transfer tensile loads across the joint. In both cases, waterstops are typically placed across the joint to protect against rain water leakage.

The structural drawings for the tank indicate all reinforcement to be continuous through the contraction joint (see Figure 22); in essence this creates a partial contraction joint. A waterstop is called out to be located at the mid-depth of the slab in between the top and bottom layers of reinforcement. A crystalline membrane has been specified on the roof structure to provide additional sealing surface against rain water penetration. As the crystalline membrane is likely to have crack over the contraction joints, water intrusion may result in reinforcement corrosion for all reinforcement located above the waterstop.

Table 2 gives recommended minimum values for temperature and shrinkage reinforcement for varying distances between contraction joints. For contraction joints located 20 feet to 30 feet ACI 350-06 recommends a reinforcement ratio (ratio of area of concrete to the area of steel in a given cross-section, \( \rho \)) of 0.003 for strength of reinforcement specified (60 ksi). For partial

---

5 “Design Considerations for Environmental Engineering Concrete Structures,” ACI 350.4R-04, American Concrete Institute, 2004.

6 “Code requirements for Environmental Engineering Concrete Structures and Commentary,” ACI 350-06, American Concrete Institute, 2006.
contraction joints, it is recommended that this number be multiplied by 1.5, which would elevate the recommended reinforcement ratio to 0.0045. The reinforcement ratio for shrinkage provided in the structural drawings is 0.0036 (#4 at 12 inches on center – each face).

Furthermore, ACI 350-06 section 7.12.1.2 also stipulates that for regions of high constraint (where concrete is restricted from free shrinking), special considerations need to be given for the increased amount of temperature and shrinkage reinforcement required. The roof slab at Reservoir 5C is cast monolithically with the interior walls and large beams in each of the four roof quadrants. This results in a restraint to the slab when trying to shorten in the longitudinal direction.

Reinforcing steel is placed inside the concrete elements to provide additional strength in carrying tensile stresses. Once the concrete cracks perpendicularly to the rebar, the rebar plays a principal role in keeping the crack width under the control. If insufficient reinforcement is provided, it becomes ineffective in controlling the distribution and the width of cracks, resulting in fewer, wider cracks. As shown in our previous report ACI 224\textsuperscript{7} reports reasonable crack widths for the roof would be about 1/64 inch (0.016 inch) (Table 3). The larger, more widely spaced cracks observed were more than twice that size. Repetitive loading (such as temperature cycles) of narrow cracking has been observed to over the time double the widths of cracks. The Pomona tank can be considered a relatively new structure thus, in the long term, it is to be expected that the observed cracking will continue to expand.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{contraction_joint_details.png}
\caption{ACI 350.4 recommended contraction joint details.}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Joint Sealant w/ Bond Breaker & Reinforcing Bar & Waterstop & Smooth Dowels (If Needed) \\
\hline
Prevent Bond Between Surfaces & \\
\hline
\end{tabular}
\caption{Contraction Joint Details}
\end{table}

\textsuperscript{7} “Control of Cracking in Concrete Structures,” ACI 224R-01, American Concrete Institute, 2001.
Figure 22. Contraction (construction) joint from structural drawings. Note: reinforcement is continuous through contraction joint. (Source: Sheet DS-2 of the construction drawings)

Table 2. Minimum shrinkage and temperature reinforcement. (Source: ACI 350-06)

<table>
<thead>
<tr>
<th>Length between movement joints, ft</th>
<th>Minimum shrinkage and temperature reinforcement ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grade 40</td>
</tr>
<tr>
<td>Less than 20</td>
<td>0.0030</td>
</tr>
<tr>
<td>20 to less than 30</td>
<td>0.0040</td>
</tr>
<tr>
<td>30 to less than 40</td>
<td>0.0050</td>
</tr>
<tr>
<td>40 and greater</td>
<td>0.0060*</td>
</tr>
</tbody>
</table>

*Maximum shrinkage and temperature reinforcement where movement joints are not provided.

Note: This table applies to spacing between expansion joints and full contraction joints. When used with partial contraction joints, the minimum reinforcement ratio shall be determined by multiplying the actual length between partial contraction joints by 1.5.
Table 3. Guide to reasonable* crack widths, reinforced concrete under service loads. (Source: ACI 224)

<table>
<thead>
<tr>
<th>Exposure condition</th>
<th>Crack width</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in.</td>
<td>mm</td>
</tr>
<tr>
<td>Dry air or protective membrane</td>
<td>0.016</td>
<td>0.41</td>
</tr>
<tr>
<td>Humidity, moist air, soil</td>
<td>0.012</td>
<td>0.30</td>
</tr>
<tr>
<td>Deicing chemicals</td>
<td>0.007</td>
<td>0.18</td>
</tr>
<tr>
<td>Seawater and seawater spray, wetting and drying</td>
<td>0.006</td>
<td>0.15</td>
</tr>
<tr>
<td>Water-retaining structures*</td>
<td>0.004</td>
<td>0.10</td>
</tr>
</tbody>
</table>

* It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement.

Interior Conditions

The general conditions of the interior concrete in the tank were good. No indications of visible deterioration or construction defects which would lead to immediate serviceability concerns were identified. The repaired cracks in the slab-on-ground were found to be generally in good condition. In locations where new (possibly existing prior to previous repair) cracks were observed, corrosion product was observed at the surface, and extraction of cores illustrated fairly wide cracking. Some of those cracks previously not existing or not repaired are candidates for repair in one of the soonest tank emptying cycles.

The corrosion product observed is a potential problem for long-term serviceability. The loss of reinforcement steel can potentially weaken the concrete slab leading to reduced water-tightness during the intended life of the tank. For this reason, the observed cracking with corrosion deposits should be repaired to maintain serviceability.

Similar to the cracking in the slab-on-ground, the observed repairs on the wall did not show signs of deterioration. The repaired wall cracks appeared to be fairly stable, and while leaking to the exterior notwithstanding (see the initial Exponent report), these walls were in good condition.

Cementitious patching repairs to the concrete walls were delaminated in many cases. In the delimitation observed near the baffle opening, the very thick patch material was no longer adhered to the wall, rendering it ineffective. It is important to maintain the repairs to the level which was intended during its original design or in the post-construction problem elimination.
Summary and Recommendations

Based on the inspections and analysis the concrete tank structure is in a good condition. Although the roof structure has some large cracks, they do not seem to constitute any important change in the operability nor in the structural capacity of the structure. The general concrete quality was very good, as verified by petrographic examination and visual inspection. Repairs made previously to the slab-on-ground are in good condition and appear to be working properly. The amount of seepage observed through the underdrain did not raise a serious concern for safety or large amounts of water loss – although a more rigorous test would be recommended to benchmark, and accurately gauge, the total amount of water leakage from the tank over the future life of the tank.

In order to maintain the structure in good working condition for the rest of its intended operating life, Exponent recommends the following:

- Monitor external wall seepage and for clear water flow on the surface carry out interior inspection of the area and repair the corresponding interior cracks(s) at the next maintenance inspection of the emptied tank. Should the seepage become visible significant and the next scheduled maintenance more than a few months away, consider the condition as requiring exception attention.

- Repair the large cracks on the roof greater than 0.012 inch wide by grinding and filling cracks with an elastomeric material suitable for exposed exterior conditions.

- Continue inspection and maintenance on existing crack repair to the slab-on-ground and walls on the tank interior.

- Grind and repair other cracks observed at the slab-on-ground, especially those with corrosion deposits visible.

- The concrete patch material on the inside of the tank needs to be repaired.

- A more rigorous test of the seepage rate is recommended to determine if water seepage is excessive, and determine the location of leakage if the amount is determined to be excessive.