"It is a New Dam, How Can it Fail? - FMEA for Design of New Tempe Town Lake Dam"

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Abstract--The current Tempe Town Lake Dam, consisting of four 15-foot high Bridgestone rubber bladders, will be replaced with eight hydraulically operated steel gates located approximately 100 feet downstream from the existing dam. As part of the design process a failure modes and effects analysis (FMEA) was performed by members of the design team, the contractor, the gate manufacturer and representatives from the City of Tempe, Flood Control District of Maricopa County, the State Dam Safety Group, and the 3rd Party Review Team.

Failure modes were grouped according to the major components of the project, which included structural, geotechnical/foundation, gate, mechanical, electrical, and controls. Within each category specific failure modes were analyzed by the team beginning with development of the failure mode from initiation through failure, listing the adverse and positive factors, and assigning a Failure Mode Category.

The process was aided by development of consequence levels before the workshop. Consequence levels were associated with downstream releases due to sudden failure of a gate as well as upstream flooding due to gates being damaged or stuck in the up position. It was noted early that upstream flooding was more critical to the City of Tempe than downstream releases; thus failure modes associated with gate(s) stuck in the up position were generally of higher consequence. The FMEA, which allowed examination of the design in the context of failure, was valuable because it challenged the designers to understand the inter-relationship between their respective parts of the system and in some cases resulted in minor changes to the design approach. More importantly the process highlighted operational and maintenance related issues that will be critical for a successful project.

This paper summarizes the application of FMEA process to design of the new dam and presents the benefits and lessons learned from the one-day FMEA workshop.

I. INTRODUCTION

Tempe Town Lake is a 220-acre urban lake located in the Salt River, in the City of Tempe, Arizona. Construction began on August 8, 1997 and Tempe Town Lake was officially opened to the public in November 1999. The lake is formed by two Bridgestone inflatable rubber dams constructed across the Salt River Channel at the upstream and downstream ends of the lake. The City constructed and maintains the dams. The lake created by the inflatable dams has become the focus of the community and the City has created a beach, outdoor walkways and concert facilities, a marina and a well-stocked fishery. The lake is the focal point of development in Tempe, including the recently constructed Tempe Center for the Performing Arts, new restaurants and business developments on the shores of the lake.

The original downstream dam consists of four 16-foot high air-inflated rubber bladders, each approximately 200 feet long, anchored to a concrete foundation slab. The foundation slab was constructed of roller-compacted concrete overlain by a reinforced concrete slab at the riverbed level to allow passage of water when the rubber dam is deflated.

In the past, dam inspection activities indicated that the rubber bladders used to construct the dam were deteriorating more quickly than anticipated as a result of exposure to the extreme heat in the Arizona desert. In 2007, Bridgestone evaluated the condition of the rubber dams and recommended replacing the bladders after 10 years of service (URS, 2008). The bladder replacement was scheduled to occur in early 2010, but because winter storms increased the flow of water over the downstream dam, installation was delayed until July 2010. On July 20, 2010, just hours before construction for the replacement of the deteriorated rubber bladders was to begin, bladder 2 failed, and the lake was completely drained. The sudden bladder failure did not result in any injuries or downstream damage, except for some scouring of the riverbed immediately downstream of the stilling basin. A photograph showing the failed rubber dam is presented in Figure 1.

Figure 1. Photo of Failed 16-foot-High Rubber Dam at Tempe Town Lake, July 21, 2010.

A forensic investigation performed by SEA, Ltd. (SEA, Ltd., 2010), determined that the failure was the result of the age of the dam and the high temperature to which the dam was subjected. These conditions caused delamination or separation of the layers of reinforced rubber that comprise the rubber bladder. This separation is characteristic of Intra Carcass Pressurization (ICP). The bladder carcass breach occurred at the bottom of the bladder where the bladder made contact with the concrete apron at the location where the bladder curvature deviates from its "cylindrical" profile and flattens on the foundation. The bladder flexes where the change in curvature occurs. This flexure was caused by a back and forth motion resulting from the movement of the bladder in response to the force of the water against the dam. The flexure within the bladder carcass is believed to have caused small internal tears which then became the accumulation location for air that penetrates the reinforced rubber carcass.

After the failure, the scheduled bladder replacement was performed and all four downstream rubber bladders were replaced (Stantec, 2011). The replacement bladders were provided by Bridgestone under a five-year lease agreement to the City, although Bridgestone had, by that time, discontinued sales of their rubber dams. The replacement bladders are scheduled to be removed at the end of December 2015; the end of the lease period.

II. DESCRIPTION OF THE NEW DAM

Since 2011 Gannett Fleming, Inc. has assisted the City with evaluation, selection, and design of a “best-value” solution for replacement of the Town Lake downstream dam. The selected alternative is based on review of viable technologies for the Tempe location and environmental conditions; social considerations; and costs, including capital cost and life cycle costs. The replacement dam will be located approximately 100 feet downstream of the existing dam, and consists of eight hydraulically operated steel gates controlled by hydraulic cylinders which will be mounted on seven piers and the two abutment walls forming the eight spillway bays. Similar to the existing dam, the new dam will be anchored to a concrete foundation slab. The foundation slab will be constructed of roller-compacted concrete overlain by a reinforced concrete slab at the riverbed level to allow the passage of water when the gates are lowered.

The gates will be equally spaced between new abutments and seven new reinforced concrete piers. Each gate will be approximately 107 feet long and 17 feet high. The new piers will be about 9 feet wide on the upstream side and 4 feet wide on the downstream side, have vertical sides and extend 25 feet above the spillway slab to support the hydraulic gate operators. The dam will maintain a normal lake level of 1148.0 feet and will be able to pass 2 feet of water over the gates when they are in the fully upright position. A rendering of the new dam is shown in Figure 2.

Figure 2 – Rendering of New Tempe Town Lake Dam

The following are the major project elements which required data and analyses for the FMEA:

- Roller-Compacted Concrete (RCC) foundation – The RCC foundation will consist of an approximately 50 foot wide by 20 foot deep section across the entire width of the river channel. A reinforced concrete slab will be constructed on top of the RCC foundation and form the crest of the spillway.
- Upstream cutoff wall – A cutoff wall will be constructed beneath the upstream end of the foundation and extend to bedrock to control seepage beneath the foundation.
- Shoreline cutoff walls – Shoreline cutoff walls will be constructed to provide a continuation of the hydraulic barriers constructed as a part of the Town Lake infiltration management system. The shoreline cutoff walls will be constructed as a continuation of the cement bentonite upstream cutoff wall and will extend upstream to tie into the existing rubber bladder foundation. The shoreline cutoff walls will extend to the top of bedrock.
- Stilling basin and scour protection – A reinforced concrete stilling basin will extend approximately 50 feet downstream from the foundation slab; a scour wall will be constructed below the downstream end of the stilling basin. It is anticipated that the scour wall will be approximately 25 feet deep.
- Retaining walls – New retaining walls will be constructed along the north and south riverbanks in the areas immediately upstream and downstream of the dam and forming the abutments for the dam. It is anticipated that these walls will be constructed as cantilever T-type reinforced concrete walls.
- South Bank Interceptor (SBI) realignment – The SBI consists of a 108 inch reinforced concrete storm water line that runs north-south from the TCA building to the stilling basin downstream from the existing dam. This pipe will be routed into a 10 foot by 10 foot cast-in-place box culvert on the back side of the left abutment retaining wall and will discharge downstream of the new gate system into a separate energy dissipation structure.
- Dam Control System – A new control building will be constructed downstream of the dam on the north side of the river near the right abutment. Gates will be controlled from the control building utilizing hydraulic cylinders, mounted on the piers and abutment walls. Hydraulic cylinders will be pressurized through the hydraulic lines located within the spillway slab and connected to the individual hydraulic pressure units (HPU) also mounted on the piers and abutment wall.

III. FAILURE MODES AND EFFECTS ANALYSIS

Failure Modes and Effects Analysis (FMEA) was performed as part of the design process, at approximately the 60% design level. The FMEA consisted of a one-day workshop, performed by members of the design team, the contractor, the gate manufacturer and representatives from the City of Tempe, Flood Control District of Maricopa County, State Dam Safety, and the 3rd Party Review Team.

The purpose of the FMEA was to:

- Review the design and anticipated operation of the new dam and the current project criteria.
- Review the results of hydrology and hydraulic analyses, geotechnical and foundation analyses, structural analyses, and system mechanical and electrical analyses.
- Perform Failure Modes and Effects Analysis on the current design; this included:
    - Identification of potential failure modes.
    - Assigning a consequence level to each potential failure mode.
    - Listing the positive and adverse factors related to the potential failure modes.
    - Discussion of risk reduction measures and any other considerations.
    - Assigning Failure Mode Categories (I, II, III, or IV)
    - Determining what information, investigations or analyses, or design changes may be needed to resolve uncertainties related to potential failure modes.

Potential failure modes were developed from initiation through failure, initially through brainstorming before the FMEA workshop and then refined as appropriate during the workshop. Each potential failure mode was discussed and positive and adverse factors were then identified for each. Categories of identified potential failure modes based on the descriptions below were applied. The failure mode categories are based on guidelines for FERC's Risk-Informed Decision Making process, which are currently in development.

Category I **Highlighted Potential Failure Modes** - Those potential failure modes of greatest significance considering need for awareness, potential for occurrence, magnitude of consequence and likelihood of adverse response (physical possibility is evident, fundamental flaw or weakness is identified and/or conditions and events leading to failure seemed reasonable and credible) are highlighted.

Category II **Potential Failure Modes Considered but not Highlighted** - These are judged to be of lesser significance and likelihood. Note that even though these potential failure modes are considered less significant than Category I they are all considered credible and are also described and included with reasons for and against the occurrence of the potential failure mode. The reason for the lesser significance is noted and summarized in the documentation report or notes.

Category III **More Information or Analyses are Needed in order to Classify** - These potential failure modes to some degree lacked information to allow a confident judgment of significance and thus a dam safety investigative action or analyses can be recommended. Because action is required before resolution the need for this action may also be highlighted.

Category IV **Potential Failure Mode Is Considered to be Extremely Unlikely and the Consequences are Minor** - The candidate potential failure mode is found to clearly be extremely remote and the consequences are judged to be minor and thus the potential failure mode is judged to be of reduced importance based on the condition of the water retaining structures and the knowledge of the participants at the time of the FMEA.

Failure modes were divided into six major categories based on major components of the dam, structural (S-*); geotechnical/foundation (F-*); gate (G-*); mechanical (M-*); electrical (E-*); and instrumentation/control (IC-*).

In addition to the failure mode categories described above, consequence categories were developed and applied to each potential failure mode. The consequence levels were developed to provide common understanding and guidance for the workshop participants throughout the FMEA. A dam safety related incident at Tempe Town Lake could occur in a number of forms all of which will result either in an unplanned release impacting primarily the river channel downstream of the dam or the inability to provide sufficient release capacity (gate(s) stuck in up position) impacting primarily the City of Tempe upstream of the dam if the levees are overtopped. Consequence levels associated with these conditions are presented below.

Low (Natural or Anticipated Flows)
No significant impacts to the population other than temporary minor flooding of Rio Salado Pkwy (and Ash Avenue), Tempe Beach Park, the Marina and land adjacent to the river and temporary closure of gravel pit and other commercial operations within the riverbed during flooding. (210,000 cfs flow event, gates all open)

Moderate
Downstream: Due to sudden lowering of one or more gates: Unanticipated release results in flooding and minor property damage to gravel pit and other commercial operations within the riverbed due to lack of advance warning and temporary

shutdown of operations for repairs after flood passes. Direct loss of life is unlikely but possible, related primarily to difficulties in warning and evacuating people downstream of the dam. Scour downstream of the dam is significant. Costs of repairing scour and the negative publicity associated with a dam failure would also be incurred.

Upstream: Due to one or two gates failing to lower during a 210,000 cfs flood event (approximately equal to a 200-year event): Upstream flooding results in moderate property and environmental damage (no overtopping of levees). Damage to permanently occupied structures, Tempe Beach Park, the Marina and privately owned land east of the Marina, Rio Salado Pkwy and other low lying areas is possible. Some flow may break out and flow west along Rio Salado Pkwy, south into neighborhoods south of the Tempe Center for the Arts, and north under the 202 along Gilbert Drive and Mill Avenue. There is remote possibility for some direct loss of life, related primarily to difficulties in warning and evacuating recreationists around the lake. Costs associated with re-constructing the project features (levees) and negative publicity associated with flooding Tempe would also be incurred.

High

Due to three or more gates failing to lower during a 210,000 cfs flood event (approximately equal to a 200-year event): Upstream flooding results in extensive damage to permanently occupied structures, Tempe Beach Park, the Marina and Rio Salado Pkwy throughout the inundation zone. Levee overtopping occurs. Significant flow may break out north under the 202 along Rural Road. Direct loss of life is not likely but possible, related primarily to difficulties in warning and evacuating recreationists/ travelers and smaller population centers, or difficulties evacuating large population centers with significant warning time. Costs associated with re-constructing the project features and negative publicity associated with a dam failure would also be incurred.

IV. DISCUSSION OF RESULTS

The table below presents a summary of the failure modes identified and analyzed during the FMEA. Fourteen potential failure modes were analyzed and resulted in one Category I, four Category II, three Category III, and seven Category IV failure modes. For the purposes of this paper Category IV potential failure modes are not discussed further. Discussion of Category I, II, and III are presented below.

Failure Mode	Consequence Level	FM Category
S-01: Seepage through upstream facing into lift joint, uplift within RCC mass, leading to sliding/stability failure of the RCC foundation.	Moderate (Downstream)	IV
S-02: Significant flow event results in large scour hole that, progresses to a depth below the scour wall undermining the stilling basin resulting in stability failure.	Moderate (Downstream)	II
F-01: Seepage develops under or through the lower section of the cutoff wall leading to uplift conditions. The excessive seepage exceeds the capacity of the blanket drain beneath the dam and stilling basin and ultimately leads to a sliding stability failure.	Moderate (Downstream)	IV
F-02: Excessive loss of lake water from the reservoir. The shoreline cutoff wall will be extended from the downstream end of the existing stilling basin to the upstream edge of the new dam. This will result in a "window" for potential flow (reservoir seepage) out of the reservoir and higher than desired loss of lake water.	Moderate (Downstream)	III
F-03: Due to internal instability, fines fraction from within the sand gravel cobble (SGC) or basin fills is piped from downstream to upstream leading to internal erosion and enlargement of a pipe ultimately resulting in development of a large void(s) and settlement or sliding of the structure.	Moderate (Downstream)	II
G-01: Debris/Boulder gets trapped beneath the gate during flow. Gate is damaged or buckled or hinge damaged and can't be raised.	Low	II
G-02: Operational Malfunction or incorrect operation results in inability to operate or damage to the gate. Results in inability to lower the gate.	Moderate (u/s) to High	II→ I

G-03: Failure of a weld/bolted seam water gets inside the skin plates leading to corrosion and ultimate failure of the gate.	Low	IV
G-04: Failure of high stress points (cylinder to gate/pier or dogging pin) leads to catastrophic lowering of the gate or unbalanced load on the gate.	Moderate (Downstream)	IV
G-05: Structural failure of the d/s strut support. Dogging not engaged, hydraulic cylinder disconnected. Leads to catastrophic lowering of the gate.	Moderate (Downstream)	II
M-01: Loss of hydraulic pressure through failure of any system component leading to uncontrolled lowering of the gate.	Moderate (Downstream)	III
M-02: Loss of hydraulic pressure through failure of any system component leading to inability to lower the gate.	Moderate (u/s) to High	III
M-03: Partial rupture in hydraulic supply line, velocity fuse activates on one cylinder resulting in unbalanced load, racking of gate, and loss of the lake.	Moderate (Downstream)	IV
E-01: Loss of electrical supply results in inability to automatically or remotely lower the gates. Design storm event occurs and overtopping of the levee is possible.	Moderate (u/s) to High	IV
IC-01: Malfunction of instrumentation indicates the lake is at normal operating level when there is flow over the gates or that there is flow or high water when the lake is actually at normal pool.	Moderate to High	IV

Category I and II Potential Failure Modes

S-02 [Category II]: Significant flow event results in large scour hole that, progresses to a depth below the scour wall undermining the stilling basin resulting in stability failure. The immediate downstream area has seen the most intense failure event possible in the form of the sudden failure of bladder number 2. The scour associated with that event and previous flow events has not exceeded the depth of the existing scour wall, which is constructed to a depth of 25 feet. Recognizing that longer term flow conditions can be as critical if not more critical and result in more scour, design of the new dam includes a longer and more robust stilling basin. The team concluded that while this failure mode is credible, it should not be highlighted as Category 1 based on previously observed performance. In addition, were significant scour to occur, it would likely be associated with prolonged flow events, i.e. gates all lowered. Following these conditions the City would have the opportunity to inspect the area and repair excessive scour before filling the lake and establishing full load conditions on the structure.

F-03 [Category II]: Due to internal instability, fines fraction from within the SGC or basin fill is piped from downstream to upstream leading to internal erosion and enlargement of a pipe, progression upstream, ultimately resulting in development of a large void(s) and settlement or sliding of the structure. The dam is founded primarily on basin fill. Any SGC remaining beneath the excavation depth could be internally unstable but given the variability of the SGC the soil unit is not considered to be fully unstable from a self-filtering standpoint. In addition, the stilling basin is filtered and the filter was designed to be compatible with the SGC and provide filter protection. Considering the grain size characteristics of the SGC, the relatively long flow path from upstream to downstream, and the position of the scour wall at the downstream toe of the stilling basin it is unlikely that a piping failure could initiate at an exit point downstream of the dam and progress upstream to the extent that it would cause stability concerns to develop.

G-01 [Category II]: Debris/Boulder gets trapped beneath the gate during flow. Gate or bottom hinge is damaged or buckled and the gate can't be raised. It is recognized that boulders and debris will be present during large flow events. When a large flow passes, the City will begin to raise the gates to recapture the lake. In the event that debris or boulders have become lodged and adversely affect the ability to raise the gates normally, the gates can be stopped to determine how to address the problem. Considering the relatively low likelihood of occurrence, the low consequences were it to occur, and the opportunity for intervention, the team considered this a Category II failure mode.

G-02 [Category II→I] Operational Malfunction or incorrect operation results in the inability to operate the gate leading to inability to lower or raise the gate during a large flow event. If this results in the inability to raise gates the failure mode is considered as Category II because of the extreme circumstances that would need to occur to result in failure and the low consequences. However, the inability to operate the gates could result in gates being stuck in the up position. It is unlikely that this would occur during the design storm event and that it would affect more than one gate, but it is possible and intervention, would be difficult hence the classification was designated as Category II with possibility of Category I.

G-05 [Category II]: Structural failure of the downstream strut support. Dogging not engaged, hydraulic cylinder disconnected, leading to catastrophic lowering of the gate. Generally, any time the downstream strut supports are deployed the dogging pins should be engaged before placing the strut. The dogging pins should also remain engaged when the hydraulic cylinders are disconnected. All of these actions require human input/performance that should be clearly called out in the O&M manual. However, the team agreed that this potential failure mode should be a Category II to highlight the importance of procedures, particularly with regard to personnel safety.

<u>Category III Potential Failure Modes</u>

F-02: Excessive loss of lake water from the reservoir. The shoreline cutoff wall will be extended from the downstream end of the existing stilling basin to the upstream edge of the new dam/cutoff wall. This will result in a "window" for potential flow (reservoir seepage) out of the reservoir, beneath the riverbank and higher than desired loss of lake water. The team felt that this was not a credible failure mode but agreed that it could be quickly confirmed with a seepage analysis.

M-01 [Category III]: Loss of hydraulic pressure through failure of any system component leading to uncontrolled lowering of the gate. This potential failure mode was initially considered a Category IV, but is included in this discussion because it relates to potential failure mode M-02, below. It was considered a Category IV because the 60% design included velocity fuses which would activate in the event of loss of hydraulic pressure and prevent the gates from lowering unexpectedly. Sensors would indicate a slow leak has developed which is typically the case with this type of incident and the velocity fuse can activate for all of the gates at one time. However, since the design included a velocity fuse the discussion changed to potential failure modes associated with malfunction of a velocity fuse which could adversely contribute to potential failure mode M-02.

M-02: [Category III]: Loss of hydraulic pressure through failure of any system component leading to inability to lower the gate. Generally the team felt this was a Category IV potential failure mode because there would need to be more than two gates stuck in the up position and 210,000 cfs flow to overtop the levees (upstream consequences). There is sufficient lead time before major flow events allowing time for intervention. The likelihood of multiple gates stuck in the up position is very low. Vandalism is deterred by surveillance. However, if the velocity fuses were to malfunction multiple gates could be stuck in the up position. Therefore, this potential failure mode and potential failure mode M-01 were considered to be Category III pending further discussion between the City and the Design Team about the advantages and disadvantages of the velocity fuse.

V. CONCLUDING REMARKS

The FMEA, which allowed examination of the design in the context of failure, was valuable because it challenged the team (multidisciplinary designers, owner, operator, and contractor) to discuss and understand the inter-relationship between their respective parts of the system and in some cases resulted in minor changes to the design approach. More importantly the process highlighted operational and maintenance related issues that will be critical for a successful project. The City opted to include velocity fuses in the design, understanding that if a hydraulic failure were to occur there is sufficient monitoring included in the design to detect it before major problems occur and to intervene with appropriate inspection and repair. In a worst case scenario excessive hydraulic leakage could occur to the extent that intervention is unsafe and a gate or multiple gates would lower uncontrolled. Conversely if velocity fuses were included in the design and they malfunctioned, it could prevent lowering of the gate and/or result in an unbalanced loading and racking of the gate. Were this to occur on multiple gates during the design storm event it could lead to the highest consequence identified, overtopping of the upstream levees, flooding of Tempe, and a levee breach.

The FMEA process allowed for early consideration of potential failure modes on a new dam, while at approximately 60% design phase. This use of FMEA differs from the traditional use since the dam has not been constructed and potential failure modes were developed without the aid of observed deficiencies, as would be the case on an existing dam. The process was also considered quite valuable considering the multidisciplinary nature of this type of project, bringing designers from different disciplines as well as the owner, constructor, vendors and regulators together to develop better understanding of how their role interfaces with the overall project.

The development of consequence levels based on hydrologic analyses highlighted the unusual condition of upstream consequences as the highest level of concern. Having completed these analyses before the FMEA allowed the group to focus on potential failure modes and not get sidetracked with discussion of consequences in a broader sense.

Since the project was at the 60% design level, the analysis was somewhat simplified from the normal FMEA process with the use of generalized failure modes. The team was comfortable with this approach since the results from the FMEA will be incorporated into the design going forward and, where appropriate, into the O&M Plan. It is anticipated that the FMEA will be revisited by the owner at some point down the road, after commissioning of the dam to review the previously identified potential failure modes as well as discuss the possibility of others that arise after the dam has been in operation for a time.

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