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Appendix EE
Potential Failure Mode Analysis

Chatfield Dam
Potential Failure Mode Analysis
April 2010

1. Overview of Potential Failure Mode Analysis (PFMA)

EC 1105-2-216 (Reallocation of Flood Control Storage to Municipal and Industrial Water Supply - Compensation Considerations) requires that a PFMA be performed prior to approval of a reallocation study at a project. A PFMA is normally performed in conjunction with Periodic Assessments (PA) or as a component of an Issue Evaluation Study (IES). Neither a PA or IES has been performed to date at Chatfield Dam. Therefore, HQ USACE directed Omaha District to perform an abbreviated PFMA to fulfill the requirement identified in the EC referenced above. The Chatfield Dam PFMA was conducted by a team of engineers, geologists and project personnel as listed below:

Person	Job Title
Fred Rios	Operations Manager
Steve Butler	Dam Safety Program Manager (Facilitator)
Lyle Peterson	Structural Engineer
Ron Beyer	Hydrologist
Jason Wagner	Geologist
Ben Letak	Geotechnical Engineer
Robert Worden	Geotechnical Engineer

2. Previous Investigations in Support of the Reallocation Study

The following geotechnical and structural studies have been conducted in support of the Chatfield Dam Reallocation Study. These studies were of great value in assessing the significance of failure modes evaluated during this PFMA.

Geotechnical/Structural Dam Safety Evaluation - This evaluation addressed potential dam safety concerns based on a permanent increase in the reservoir elevation due to reallocation. The evaluation was based strictly on static loading and specifically addressed instrumentation data, past visual inspections, slope protection, slope stability, and seepage. The study concluded that the new "normal" pool elevation proposed in the reallocation study will not adversely impact the integrity of the embankment or structures. The study recommended the development and implementation of a Reservoir Raise monitoring plan which would include additional inspections, instrumentation data acquisition and data analysis. The study also recommended updating, as appropriate, the Project Surveillance Plan and Emergency Action Plan. The study further recommended installation of additional instrumentation prior to the pool raise along with an increase in instrumentation readings and inspection frequencies during and following the pool raise. The evaluation emphasized that any dam safety concerns that develop during the pool raise could result in lowering the reservoir elevation and/or a pool restriction. The report has undergone an Agency Technical Review and review by Northwestern Division and all comments have been incorporated.

Seismic Studies

Liquefaction Assessment - The liquefaction assessment evaluated the liquefaction susceptibility of both the Chatfield Dam embankment and foundation for the existing conservation reservoir and a 12' raise proposed under the Reallocation Study. The assessment utilized information obtained from original design documents, studies and limited field work. Results of the assessment indicated probable zones of liquefaction both upstream and downstream for the valley and right abutment. The assessment recommended a follow-on Post-Liquefaction Stability Analysis (See details below) to determine if the embankment would remain stable if zones of the foundation were to liquefy after a Maximum Credible Earthquake. The report has undergone an Agency Technical Review and all comments have been incorporated.

Post-Liquefaction Stability Analysis – A Post-Liquefaction Stability Analysis was performed as a result of the recommendation from the Liquefaction Assessment. The study evaluated whether the embankment would remain stable if zones of the foundation were to liquefy after a Maximum Credible Earthquake. Results of the study indicated the embankment and foundation would remain stable after this event. No further seismic studies related to the embankment or foundation were recommended. The report has undergone an Agency Technical Review and all comments have been incorporated.

Seismic Analysis of the Intake Structure - A modal analysis of the intake structure was conducted to evaluate performance of the intake structure during and immediately after a Maximum Design Earthquake. ER 1110-2-1806, titled "Earthquake Design and Evaluation for Civil Works Projects" requires that the level of ground motion used for the evaluation be based on whether the intake structure is deemed "critical" or "non-critical." The ER stipulates that for critical structures, the Maximum Design Earthquake is the same as the Maximum Credible Earthquake and for non-critical structures, a lesser magnitude Maximum Design Earthquake is used in the evaluation. The ER defines critical structures as the engineering structures, natural site conditions, or operating equipment and utilities at high hazard projects whose failure during or immediately after an earthquake could result in loss of life. The regulation stipulates that all other structures be considered non-critical. Omaha District determined that the intake structure was non-critical based on 2004 guidelines by Northwestern Division, titled, "Guidance for Determining Critical Structures Designation for Intake Towers." The analysis of the intake structure concluded that it meets or exceeds Corps of Engineers criteria for non-critical hydraulic structures during and immediately after a Maximum Design Earthquake, at either the current normal pool or the proposed reallocation pool elevation. No additional seismic studies for the intake structure were recommended. The report has undergone an Agency Technical Review and all comments have been incorporated.

3. PFMA Process

A description of the PFMA process that was used to identify and evaluate potential failure modes at Chatfield Dam is provided below.

3.1 Brain Storming Session. The facilitator led a brainstorming session to identify all potential failure modes for each project feature. All brainstorming ideas were recorded without comment on the validity of the idea. After the brainstorming session, the team designated each PFM as "not credible" or "credible" based on their understanding of the potential failure mode, the site conditions, and any supporting documentation.

Credible Failure Modes - Credible failure modes are defined as those potential failure modes that are physically possible under a specified loading condition.

3.2 Determining Significant Failure Modes. All "credible" failure modes were further evaluated to determine if they were considered to be significant. These determinations were based on engineering judgment, knowledge of past performance, loading conditions, and consequences. For the purposes of this PFMA, the following definition will apply to Significant Failure Modes:

Significant Failure Modes - Significant failure modes are defined as those potential failure modes which are credible and are judged or estimated to have a high relative probability of occurring under a specified loading and would result in relatively high consequences.

3.3 Identifying and Describing Credible Potential Failure Modes. Each credible potential failure mode (PFM) was then described fully by technical experts. The description identifies the initiator, and the failure progression. A definition of each is provided below.

The Initiator. The initiator defines the loading condition imposed on the dam system or triggering event. For example, this could include increases in reservoir due to flooding (perhaps exacerbated by a debris-plugged spillway), strong earthquake ground shaking, malfunction of a gate or equipment, deterioration of project components, an increase in uplift, or a decrease in strength.

Failure Progression. This includes the step-by-step process that leads to the breach or uncontrolled release of the reservoir and\or significant loss of operational control. The location where the failure is most likely to occur should also be highlighted. For example, this might include the path through which materials will be transported in a piping situation, the location of overtopping during a flood, or anticipated failure surfaces in a sliding situation.

3.4 Listing "More Likely" and "Less Likely Factors." After the detailed PFM descriptions were completed, the PFMs were further evaluated by listing the adverse factors that make the failure mode "more likely" and the favorable factors that make the failure mode "less likely."

3.5 Major Findings and Understandings.
The knowledge gained throughout the PFMA process was captured and documented in the form of "Major Findings and Understandings."

3.6 Action Items. Following development of a potential failure mode, the team identified what additional information or analyses would be useful in better understanding the potential failure mode.

4. Credible Potential Failure Modes Identified

The following table lists the credible failure modes identified during the Chatfield Dam brainstorming session.

Credible Potential Failure Modes Identified
Outlet Works
Seepage along conduit results in piping and failure.
Intake structure failure due to seismic event.
Gate failure from earthquake results in uncontrolled release of water.
Corrosion of gates leads to uncontrolled release of water.
Failure of 72 inch irrigation pipe results in piping failure.
Spillway
Failure of spillway due to PMF.
Embankment
Piping of embankment material into the foundation (cracks in the bedrock).
Embankment through seepage results in piping failure.
Liquefaction of embankment foundation due to an earthquake results in overtopping.

5. Evaluation of Credible Potential Failure Modes

The following table summarizes the evaluation of each credible potential failure mode identified.

POTENTIAL FAILURE MODES ANALYSIS SESSION – CHATFIELD DAM

No	Potential Failure Modes Description	Initiator/Sequence of Events Leading to Failure	Adverse Conditions/ Failure More Likely	Positive Conditions/ Failure Less Likely	Major Findings and Understandings	Action Items
1	Seepage along outside of conduit results in piping & failure of dam.	- High pool - Defect in conduit backfill creates preferential seepage path. - Seepage flow & gradient increase along conduit due to higher pool. - Piping of conduit backfill material begins at downstream slope in the stilling basin area. - Piping/backward erosion of conduit backfill, upper alluvial foundation, and/or lower embankment material continues from downstream to upstream. - Catastrophic failure of the embankment occurs above and/or adjacent to conduit.	- Dam has not experienced pools higher than 16' above normal (El. 5432). Record pool = El. 5448. Top of dam = El. 5527. - Possible poor compaction of backfill around 3' high x 3' thick seepage collars & 2' high x 3' thick alignment collars. - Small wet area documented 3 times (1979,2007,2010) behind manifold structure near the base of compacted fill slope at El. 5402. -Hand compaction equipment used to compact backfill immediately adjacent to conduit. -Pervious backfill placed adjacent to & above conduit may have up to 15% fines. Pervious backfill may not have flow capacity for drainage.	-Conduit construction is cast in-place concrete. -Seepage & alignment collars are well detailed. -Lower portion of conduit founded in Dawson Formation bedrock w/sloping sides. Dawson considered watertight. -Excavated trench above bedrock fairly wide (+5' each side) w/fairly flat slopes (1:1 to 2:1). -Impervious backfill 8"-12"lifts, >95% SMDD,-1%-+3% OWC -Pervious backfill 8" lifts, >80% RD, WC=saturated -Five seepage collars & 40 alignment collars create lengthened seepage path. -Seepage & alignment collars widely spaced @ 28' on centers. Compaction of backfill better between collars than around collars. -No evidence that intermittent wet area behind manifold structure is pool related. Wet area "not" documented during high pools in 1980,1983,1995. Some evidence wet area is related to surface runoff. Also, possibility exists that wet area may be result of surface runoff captured in utility trench between intake bridge & manifold structure. -Conduit above bedrock backfilled with compacted pervious fill from downstream side of impervious core & cutoff to the stilling basin. Pervious fill	-Historic wet area has low probability of being pool related. -No other physical evidence of seepage along conduit. -Continue with efforts to verify that wet area is caused by surface run-off. - Not considered to be a significant failure mode.	- Increased visual inspection & monitoring of area during high pools & significant local precipitation events. -Perform subsurface investigation in area to verify surface run-off is cause of wet area. -Investigate correlation between observation of wet area & local precipitation events. -Consider addition of PZ's in pervious backfill of conduit if wet area cannot be proven to be result of surface run-off.

No	Potential Failure Modes Description	Initiator/Sequence of Events Leading to Failure	Adverse Conditions/ Failure More Likely	Positive Conditions/ Failure Less Likely	Major Findings and Understandings	Action Items
				placed adjacent to & above conduit - Upstream of the impervious core & cut-off trench conduit backfilled w/impervious backfill above bedrock. -Duration of higher pools are relatively short.		
2a	Intake structure failure by collapse and displacement of walls during seismic event.	-Large seismic event occurs -Concrete tower collapses. -Displacement of walls dislodges gates resulting in uncontrolled release of water through the conduits.	-Concrete reinforcement in tower is not detailed to provide ductility.	-Seismic analysis of the tower predicted that the magnitude of earthquake needed to initiate cracking of concrete is approximately the 7,000 year event. -The tower is not needed to lower pool after a major earthquake unless a very low probability earthquake is considered coincident with a very low probability flood.	-Determined not to be a significant failure mode based on results of seismic analyses described in Section 2 of this PFMA.	-No actions are believed to be necessary at this time.
2b	Intake structure failure by sliding during seismic event.	-Large seismic event occurs. -Concrete tower displaced horizontally by sliding on bedrock foundation. -Tower with gates are separated from conduits resulting in uncontrolled release of water through the conduits.	-Tower stability against sliding depends mostly on friction against bedrock below and embankment fill on the sides.	-Seismic analysis of the tower predicted a factor of safety against sliding of 4.3 for the 950 year earthquake and 1.2 for the Maximum Considered Earthquake. Corps of Engineers criteria requires a factor of safety greater than 1.1 for either of these cases.	-Determined not to be a significant failure mode based on results of seismic analyses described in Section 2 of this PFMA.	-No actions are believed to be necessary at this time.
2c	Intake structure failure due to embankment slide during seismic event.	-Large seismic event occurs -Local slide of embankment near tower moves tower horizontally. -Tower with gates are separated from conduits resulting in uncontrolled release of water through the conduits.	-Tower is incapable of resisting the large lateral soil pressures that a local slide would exert.	-Embankment not likely susceptible to instability after a large earthquake. -A slide in the area of the intake structure is not likely after a major earthquake.	-Determined not to be a significant failure mode due to results of previous studies outlined in Section 2 of this PFMA.	-No actions are believed to be necessary at this time.

No	Potential Failure Modes Description	Initiator/Sequence of Events Leading to Failure	Adverse Conditions/ Failure More Likely	Positive Conditions/ Failure Less Likely	Major Findings and Understandings	Action Items
3	Service gate failure from earthquake results in uncontrolled release of water.	-Large seismic event occurs. -Dynamic water pressures cause fracture of gates. - Fracture of steel gate results in uncontrolled release of water thru the conduits	-2007 inspection noted several weld defects. -Emergency gate and bulkhead cannot be placed during a significant flow.	-Project has one bulkhead and one emergency gate. If needed, bulkhead can be used to dewater one service gate and emergency gate can be used to dewater the other service gate. -Service gate is fabricated of a number of welded horizontal girders giving it redundancy in the event of fracture of one component. -Increase in water pressure caused by earthquake would not exceed the design pressure unless pool were near top of dam during the earthquake.	- Flood control project (designed training dike and channel downstream of dam) would handle any uncontrolled releases through the outlet works. Therefore, failure of gates results in extremely low likelihood for loss of life or significant economic damage. -Determined not to be a significant failure mode.	-No actions are believed to be necessary at this time.
4	Corrosion of service gates leads to uncontrolled release of water.	-Corrosion accelerates. -Corrosion is not repaired, and emergency gates are not placed. -Fracture of steel gate results in uncontrolled release of water thru the conduits.	-2007 inspection noted corrosion of steel plates and corrosion of welds. -Emergency gate and bulkhead cannot be placed during a significant flow.	-If corrosion advanced to degree that gates were deemed unsafe, emergency gates could be placed until service gates are repaired. -Project has one bulkhead and one emergency gate. If needed, bulkhead can be used to dewater one service gate and emergency gate can be used to dewater the other service gate. -The service gates are regularly inspected.	- Flood control project (designed training dike and channel downstream of dam) would handle any uncontrolled releases through the outlet works. Therefore, failure of gates results in extremely low likelihood for loss of life or significant economic damage. -Determined not to be a significant failure mode.	-A contract will be awarded in 2010 to remove corrosion and repaint service gates, transition areas, and water tight doors. -Continue inspection program.

No	Potential Failure Modes Description	Initiator/Sequence of Events Leading to Failure	Adverse Conditions/ Failure More Likely	Positive Conditions/ Failure Less Likely	Major Findings and Understandings	Action Items
5	Failure of 72 inch irrigation pipe results in erosion of stilling basin.	-Any reservoir level. -Unknown flaw in pipe results in uncontrolled release of water which floods the manifold structure. -Water escapes from the manifold structure through opening in doors and vents. -Erosion of the area around the stilling basin occurs and results in potential loss of the stilling basin and creation of a preferential seepage path.	-The pipe is fracture critical. -Pipe is under full head at all times. -Pipe flows are controlled by valves at downstream end. -Pipe break would not immediately be detected because the gallery is not regularly inspected. -Bulkhead cannot be used to shut off pipe during a flowing condition.	-A means to shut off the pipe exists at the upstream end if there is a pipe failure. The valve is a 72-inch butterfly valve located in the intake structure. Access to the valve can be maintained even if the 72-pipe fails because the valve is housed in a water-tight structure completely isolated from the pipe tunnel. -Pipe appears to be in good condition. -Outside surface of pipe is easily inspected. -Inside of pipe is periodically inspected. -Inspection results indicate the pipe is in good condition. -A new trash rack was placed in 2010.	-Pipe is in good condition and is regularly inspected in accordance with applicable regulations. -Determined not to be a significant failure mode.	-NDT will be performed in FY2010.
6	Failure of spillway due to PMF.	- High pool. - Flow through the spillway. - Joint off-sets result in pressure beneath spillway slab. - Pressure beneath spillway slab causes slab to fail. - Subgrade soils are exposed and quickly erode to the crest - Uncontrolled release of reservoir occurs.	- Significant spalling and joint off-sets are present in downstream spillway slab. - Flow velocity over spillway estimated to be as high as 80 fps.	- Duration of spillway flow is short (approximately 2 days). - Slab is 1.5 feet thick at upper end and 4 feet thick at the lower end. - There is a drainage layer/pressure relief system beneath the spillway slab. - Portion of drainage system inspected 15-20 years ago and was found to be open. - Ogee weir is keyed into bedrock making loss of the spillway crest due to progressive upstream erosion extremely unlikely.	- There does appear to be some potential for damage to the spillway. However, the chance of uncontrolled pool releases due to breaching of the spillway crest is extremely remote. - Determined not to be a significant failure mode.	- Continue repairs to the spillway slab joint off-sets. - Periodically check the condition of the pressure relief system beneath the slab.
7	Piping of embankment material into the foundation	-High pool. -Defects (cracks/fractures) are present in Dawson Formation bedrock foundation that	- Dam has not experienced pools higher than 16’ above normal (El. 5432). Record pool = El. 5448. Top of dam = El. 5527.	-Pervious fill zone constructed on downstream side of impervious cutoff trench. - Piezometers at stations 81+20	-No documentation of gradation of pervious backfill is currently available.	- Increase visual inspection & monitoring during high pools. -Response test piezometers

No	Potential Failure Modes Description	Initiator/Sequence of Events Leading to Failure	Adverse Conditions/ Failure More Likely	Positive Conditions/ Failure Less Likely	Major Findings and Understandings	Action Items
	(cracks in the bedrock).	creates preferential seepage path through the impervious cutoff trench fill into bedrock. - Seepage flow & gradient increase through impervious core in bedrock downstream of inspection trench due to higher pool - Piping of impervious core material into bedrock begins. - Piping/backward erosion of embankment material continues from downstream to upstream. -Sinkhole develops on upstream face of embankment. - Catastrophic failure of the embankment occurs.	-Extent of cracks/fractures in Dawson Formation bedrock impossible to determine. - No impervious cutoff trench in higher areas on abutments -Pervious backfill placed adjacent to impervious cutoff trench may have up to 15% fines. Pervious backfill may not have flow capacity for drainage. - Despite significant head loss across cutoff, piezometers at stations 81+20 and 93+00 appear to fluctuate with the pool somewhat.	and 93+00 in the alluvium immediately upstream and downstream of the cutoff trench exhibit significant head loss across cutoff. - Toe drain system monitored monthly & no flow ever reported. - Cutoff trench impervious backfill constructed with 8”-12”lifts, >95% SMDD,-1%-+3% OWC - Impervious trench backfill compacted by rollers. - Duration of higher pools are relatively short. Photographic evidence shows typical cracks in the foundation rock are very small. No large void spaces in the rock are believed to be present. The foundation rock does not outcrop downstream and the overlying alluvial soil does not have any open work features.	- Photographic evidence shows typical cracks in the foundation rock are very small. -No large void spaces in the rock are believed to be present. -The foundation rock does not outcrop downstream and the overlying alluvial soil does not have any open work features. -Determined not to be a significant failure mode.	downstream of cut-off. -Search for documentation of pervious backfill gradation.
8	Embankment through seepage results in piping failure.	- High pool - Defective layer in impervious core creates preferential seepage path through the core to the downstream embankment zones. - Seepage flow & gradient increase through impervious core and downstream embankment zones due to higher pool - Piping of downstream embankment material at downstream slope/toe begins. - Piping/backward erosion of embankment material	- Dam has not experienced pools higher than 16’ above normal (El. 5432). Record pool = El. 5448. Top of dam = El. 5527. - Several piezometers at stations 81+20 and 102+00 in the impervious core exhibit water levels higher than expected & show some correlation w/reservoir fluctuations. - No pervious drain & horizontal blanket in higher areas on abutments	- 10’-20’ thick inclined pervious drain & horizontal blanket constructed on downstream side of impervious core to control seepage through core in main valley section. - Piezometers in core in areas other than stations 81+20 and 102+00 do not exhibit higher water levels or correlations with reservoir fluctuation. - Toe drain system monitored monthly & no flow ever reported. - Impervious backfill 8”-12”lifts, >95% SMDD,-1%-+3% OWC - Gradation of pervious fill for inclined drain & horizontal	- A 10’-20’ thick inclined pervious drain & horizontal blanket exists on downstream side of impervious core to control seepage through the core in main valley section. -There is high confidence that the blanket and inclined drain material has an adequate gradation to prevent migration of fines and piping. -Determined not to be a significant failure mode.	-Continue with efforts to determine if piezometer data is reliable. - Increase visual inspection & monitoring during high pools & significant local precipitation events. - Perform response tests on piezometers indicating higher than expected water levels in impervious core to determine if reliable. -Install additional PZs in the impervious core of the embankment.

No	Potential Failure Modes Description	Initiator/Sequence of Events Leading to Failure	Adverse Conditions/ Failure More Likely	Positive Conditions/ Failure Less Likely	Major Findings and Understandings	Action Items
		continues from downstream to upstream. - Catastrophic failure of the embankment occurs.		blanket limited to < 5% fines. - Duration of higher pools are relatively short.		
9	Liquefaction of embankment foundation due to an earthquake results in overtopping.	- Large seismic event occurs - Liquefaction of the susceptible foundation soils occurs. - Embankment deforms due to foundation liquefaction. - Loss of freeboard occurs - Uncontrolled release of pool due to loss of freeboard.	- Geotechnical investigations not 100% effective in locating all areas of liquefiable material. - Not practical to remove all liquefiable materials from the embankment's foundation.	- Area of low density material susceptible to liquefaction is small. - Reservoir has very large flood storage. Probability of large seismic event at the same time as a high pool is extremely remote. -Previous studies indicate significant loss in embankment crest elevation is extremely unlikely. -Previous studies outlined in Section 2 of this PFMA indicate this is not a significant potential failure mode.	- Previous studies have determined this is not a significant failure mode.	- No actions are believed to be necessary at this time.

6. Summary.

None of the failure modes identified during the PFMA were determined to be significant. Rational for this determination is included in the table above under the Major Findings and Understandings column. Regardless of whether a particular failure mode was deemed significant or not, action items were identified to further investigate many of the failure modes identified. These investigations will be incorporated into the on-going dam safety program.

Omaha District has a comprehensive dam safety monitoring program in place at all its dams to ensure public safety. Project personnel routinely inspect Chatfield Dam and collect instrument readings throughout the year to evaluate dam performance. On an annual basis, dam safety engineers inspect the dam to ensure it is safe. Chatfield Dam is scheduled for a Periodic Inspection in 2013.