LAKE DELHI DAM BREACH – TWO PERSPECTIVES

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Abstract

On July 24th, 2010, after nearly 90 years of operation, the Lake Delhi Dam experienced what is believed to be a record inflow of water (based on recorded flows at a USGS gaging station on the Maquoketa River in Manchester, Iowa and estimated flows between the gaging station and Delhi Dam) that exposed long dormant design deficiencies and unrepaired maintenance problems. The record inflow coupled with design deficiencies and uncompleted repairs spelled disaster for the structure that had stood strong for so long. While Iowa's staff of one full time dam safety technician had regularly inspected the dam and requested that repairs be completed in a timely manner, the Iowa DNR was not in a position to begin a full scale failure investigation. However, the State was fortunate to receive the assistance of members of the national dam safety community to begin a dam failure investigation. Ultimately, the National Dam Safety Review Board agreed to convene an Independent Panel of Engineers (IPE) to review the operational characteristics of the project leading up to the breach; perform an evaluation of the breach of the dam to determine the specific failure mode; and submit a final report documenting the results of their findings on the cause of the breach of the upper reservoir and the important lessons learned. The IPE operated independently and access to individuals and to any requested information was freely granted. Areas of focus included: the design and construction of Delhi Dam; subsequent modifications to the dam; the operational and performance history of the dam; past examinations and reviews of the dam; the timeline of events involved in the breach of Delhi Dam; the post-breach condition of the dam; and the emergency response to the dam breach. The findings of the IPE are included in a detailed written report. This first part of this paper will discuss the steps Iowa's Dam Safety staff took prior to and immediately following the dam breach and the process used to request assistance through the National Dam Safety Review Board to convene an Independent Panel of Engineers. The second part of this paper will focus on the Independent Panel of Engineers (IPE) findings regarding Lake Delhi Dam Breach. Lessons learned from both the State and the IPE perspective will be presented.

Introduction

Delhi Dam was breached on July 24, 2010 after two days of heavy rain in the drainage basin above the dam (48 hr rainfall totals are shown on Figure 1). This article will discuss the dam's history, the Iowa Department of Natural Resources (IDNR)'s role in forming and assisting the Independent Panel of Engineers to investigate the breach, the dam breach investigation process, the likely cause of the dam breach and lessons learned.

The dam breach initiated about 1:00 pm on July 24, 2010 with an estimated peak breach outflow of 69,000 ft^3/s. The flood and the dam breach resulted in extensive property damage in the reservoir above the dam and in the communities downstream of the dam. No loss of life occurred as a result of the dam breach. There were a number of factors that were taken into consideration in the investigation of the breach of the dam. These included: the design of the embankment dam, which included a reinforced concrete core wall as the primary impervious element in the dam; the embankment materials, which appear to have consisted of a low plasticity sandy clay; the limited ability of the dam to pass a major flood (given the spillway capacity was initially designed to about 25,000 ft^3/s, at reservoir water surface elevation 900 ft); and, the binding of one of the spillway gates preventing its full opening during the flood event.

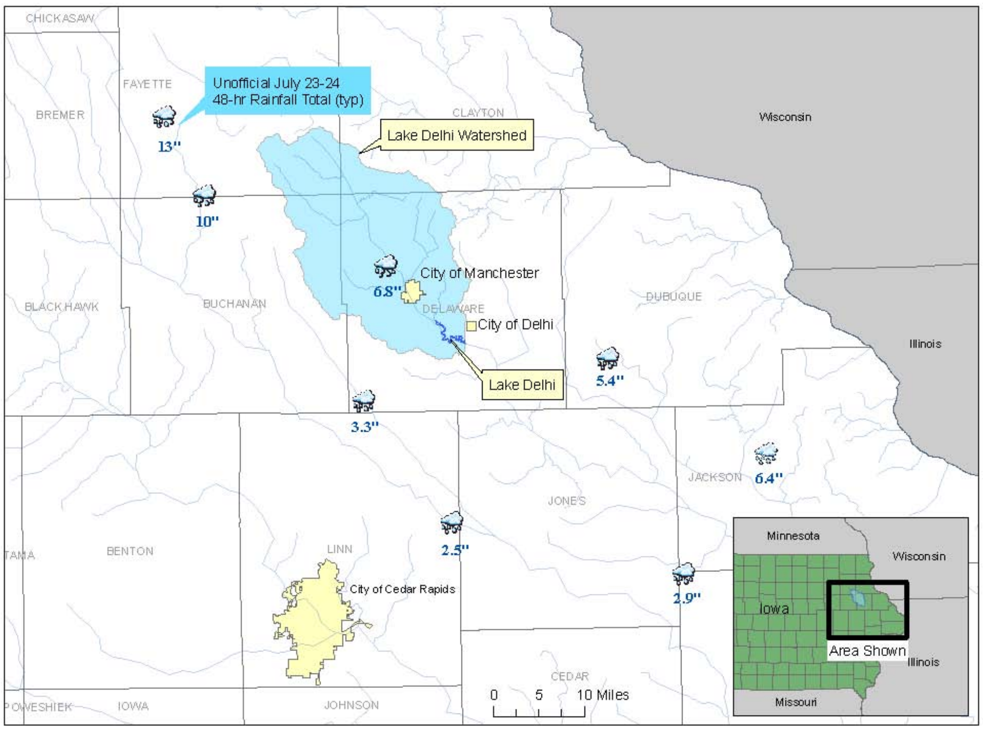

Figure 1. Location of Lake Delhi and Rainfall Information. Source: Iowa DNR

History and Background of the Dam

Location and History

Delhi Dam is located on the Maquoketa River about 1.4 miles south of the town of Delhi. The Maquoketa River, located in northeastern Iowa, is a tributary of the Mississippi River. Figure 1 shows the location of the dam. The dam was constructed between 1922 and 1929 (as shown in Figures 2 and 3) by the Interstate Power Company for hydroelectric power generation.

Generation of power was terminated at the dam in 1968. The dam is currently owned and operated by the Lake Delhi Recreation Association (LDRA). In 1991, the Lake Delhi Combined Recreation and Water Quality Tax District (District) was formed pursuant to Iowa Code Chapter 357E in order to allow lake residents to tax their property an additional $4 per

$1,000 of assessed value, to support the dam and lake. In 2005 the District issued tax-exempt bonds to finance dredging of the lake. The flood gates and wicket gates of the dam were damaged in 2008 and dangerous scouring of the underwater rock armor of the dam was discovered. At the invitation of Federal Emergency Management Agency (FEMA) representatives, the District applied for and was approved for repairs to the lake and dam. Several repair projects were completed and additional projects were underway at the time of the 2010 flood.

While the lake frontage was primarily privately owned, public access was allowed and the lake was patrolled by Iowa DNR enforcement officials. The dam was inspected every five years by the IDNR dam safety staff. The last full inspection was in 2009. At this inspection, the need for repairs to the spillway gates were noted, and IDNR required the repairs to be completed by the LDRA by the end of 2009. Follow-up contact made by the IDNR in January 2010 found that repairs were currently underway but were not completed. The repairs do not appear to have been completed prior to the July 2010 breach of the dam.

Figure 2. Construction of the dam. Core wall construction shown on the right end. Source: LDRA

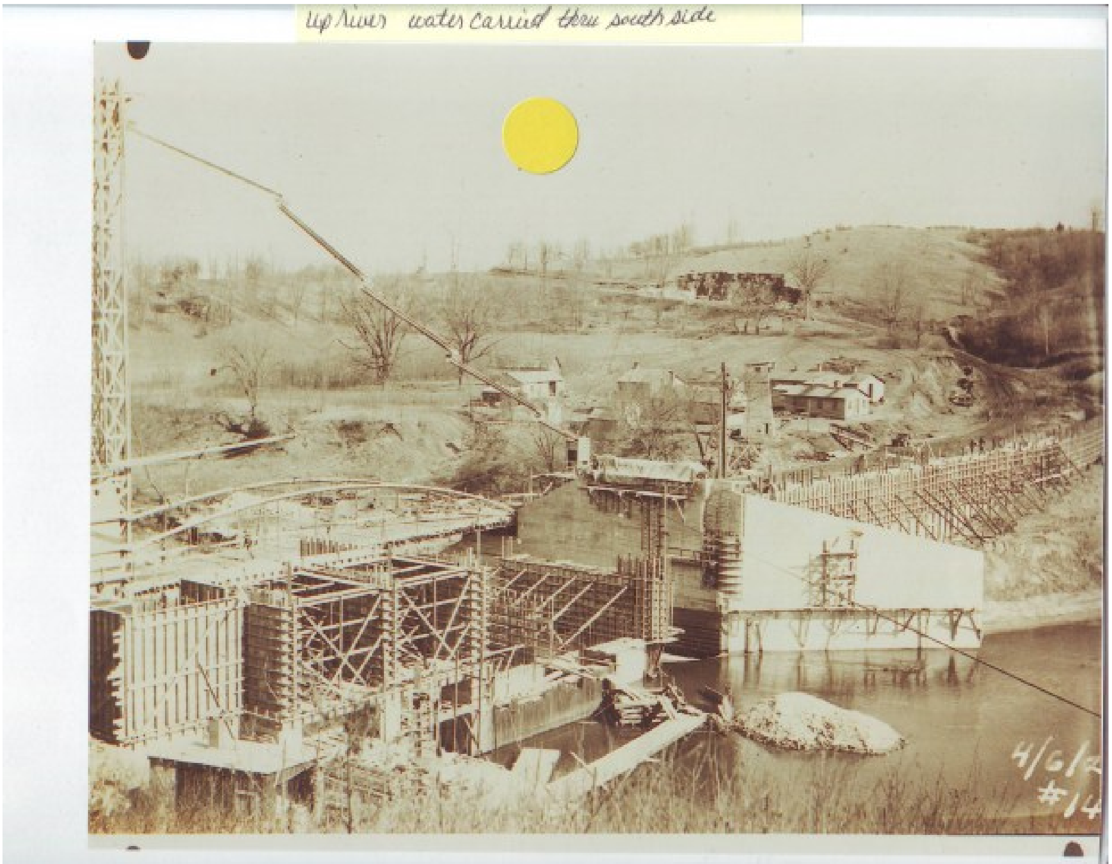

Figure 3. Historic construction. Borrow area and core wall construction shown. Source: LDRA

Dam Physical Description

Delhi Dam was designed as a concrete dam and earthen embankment. The 704-foot long structure consists of (from left to right looking downstream): a 60-foot long concrete reinforced earthfill section abutting the left limestone abutment; a 61-foot long conventional reinforced concrete powerhouse containing two S. Morgan Smith turbines with two Westinghouse generators (each rated at 750 kW); an 86-foot long gated concrete ogee spillway, with three 25-foot x 17-foot vertical lift gates; and, a 495- foot long embankment section with a concrete core wall. The embankment section was originally constructed with 1V:3H upstream slopes and 1V:2H downstream slopes, and extends to the south (right) abutment of the dam. The crest of the south embankment section of the dam is 25 ft wide and the dam crest is at elevation 904.8 ft NGVD29. A general plan of the site is shown on Figure 4 with a cross section of the embankment shown in Figure 5. Figure 6 provides a cross section through the spillway.

Figure 4. General Layout of the Dam and Spillway. Source: Iowa DNR

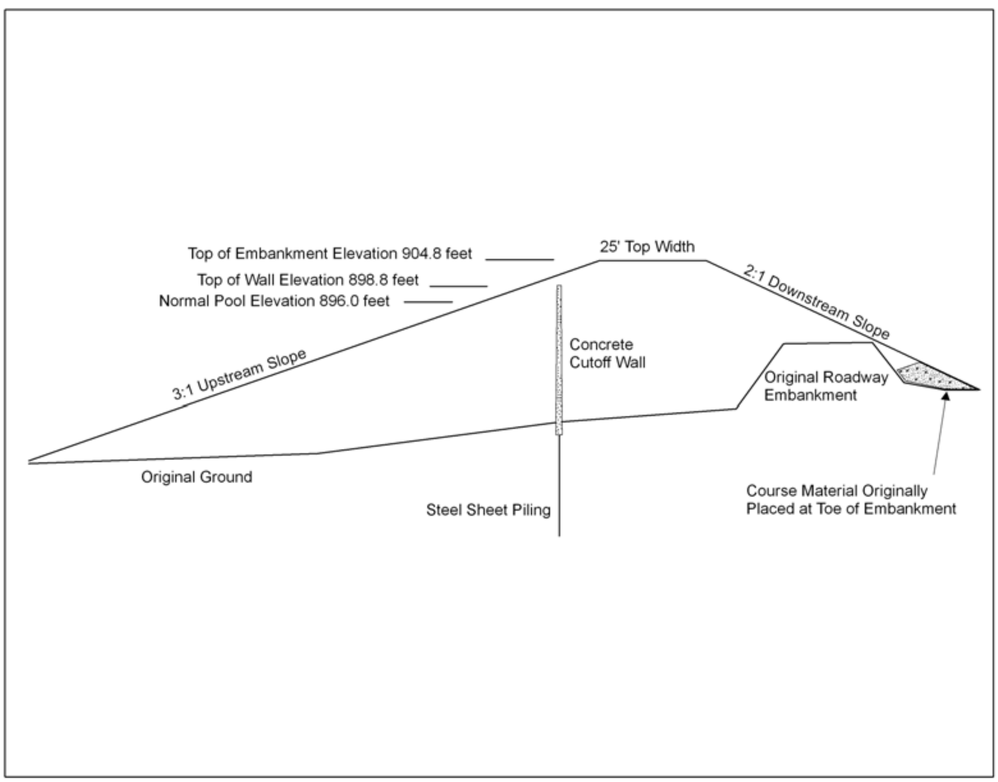

Figure 5. Typical Embankment Section. Source: Iowa DNR based on original design plans provided by LDRA.

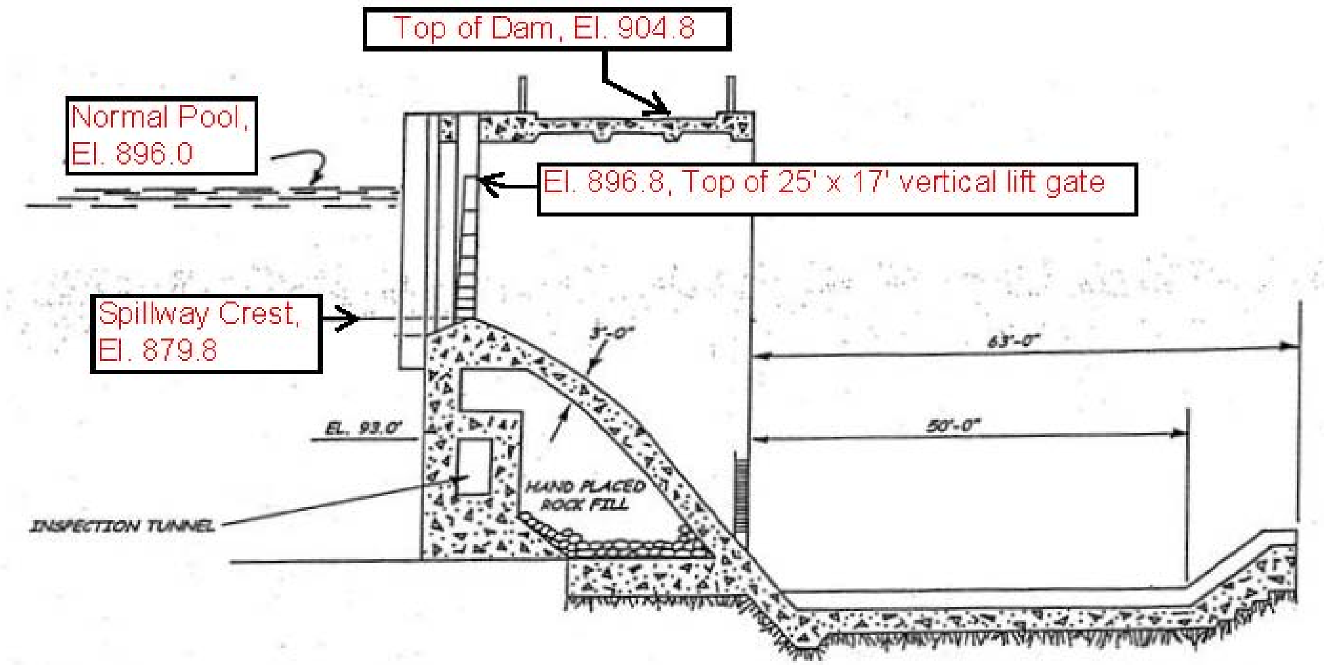

Figure 6. Cross Section of Spillway

The maximum section of the concrete portion of the dam has a height of about 59 ft and the embankment section has an estimated maximum height of 43 ft. Lake Delhi, the reservoir behind Delhi Dam has an area of approximately 440 acres and a storage volume of 3790 acre-ft at normal reservoir (elevation 896 ft) and a reservoir volume of about 9920 acre-ft at the crest of the dam (elevation 904.8 ft). The spillway crest is at elevation 879.8 ft and the hollow inside of the spillway crest structure is filled with rock.

The concrete reinforced earthfill section of the dam at the left abutment was originally constructed with two parallel concrete retaining walls, founded on rock and spaced 20 ft apart. Rock fill was placed between the walls. In 1967, a concrete crib wall and additional fill was placed upstream of the original walls. The area downstream of this section serves as a parking and staging area for performing maintenance in the powerhouse.

Previous Inspections and Evaluations of Delhi Dam

DNR Inspections

The State of Iowa Department of Natural Resources had regulatory oversight of Delhi Dam. The state inspects high-hazard dams on a 2-year frequency and "major" dams (defined in the states rules; "major" dams include most moderate hazard dams and some low hazard dams) on a 5-year frequency. Delhi Dam was inspected in 1999, 2004 and 2009 by the DNR inspector and by an engineering firm in 2002 and 1997. Delhi Dam has been classified as a moderate-hazard dam by the DNR and the inspections have been on at least a 5-year interval. The DNR Technical Bulletin No. 16, Design Criteria and Guidelines for Iowa Dams, identifies Moderate Hazard dams as: "Structures located in areas where failure may damage isolated homes or cabins, industrial or commercial buildings, moderately traveled roads or railroads, interrupt major utility services but without substantial risk of loss of human life." High Hazard dams are identified as: “Structures located in areas may create a serious threat of loss of human life or result in serious damage to residential, industrial or commercial areas, important public utilities, public buildings, or major transportation facilities.” Given the conditions downstream of Delhi Dam, a moderate hazard dam classification is judged to be appropriate. Chapter III of Technical Bulletin No. 16 indicates that the design flood for moderate hazard dams should be one half of the probable maximum flood (PMF) and that the dam should not overtop for this flood. Delhi Dam had the capacity to pass about the 100-year flood and would have overtopped for a flood representing one half of the PMF, even with the spillway gates fully functioning.

Ashton Engineering Reviews

Two detailed dam safety inspection reports were prepared for Delhi Dam by Ashton-Barnes Engineering in 1997 [Ashton 1998] and by Ashton Engineering in 2002 [Ashton 2002]. Both reports included documentation of an inspection of the dam, a discussion on stability of the dam, spillway adequacy and adequacy of maintenance and methods of operation. The reports also contained conclusions and recommendations. The 1998 report was more comprehensive and the scope was more clearly defined. The scope of the 1998 report included the following: perform analytical stability analysis of all pertinent dam features; perform stress analysis, as needed, to assess the condition of individual project elements; perform hydrological and hydraulic analysis required to assess spillway adequacy relative to current criteria; and evaluate the maintenance and current methods of operation. The 1998 inspection report stability and stress evaluation focused on the concrete portions of the dam and did not specifically address any stability or dam safety issues with the embankment dam. The 1998 report concluded that the spillway could just handle the 100-year flood event (estimated at that time). The dam was classified in the report as an intermediate size, low hazard potential dam, which would require that the dam handle between the 100 year flood and one-half the Probable Maximum Flood. Both the 1998 report and the 2002 report concluded that the spillway had adequate capacity. A recommendation was made to perform a study on ways to improve the spillway gate hoist system, which was inoperable. The 2002 inspection report had a similar focus and similar conclusions as that of the 1998 report. It was stated that “The equipment used to operate the control gates for the spillway has been completely reworked since the 1997 inspection. The current methodology of operation is satisfactory.”

Operation of Spillway Gates During Previous Floods

The Lake Delhi Recreation Association owned, operated and maintained Delhi Dam. Repairs of the gate hoisting mechanisms had been performed over the years and a complete replacement of the hoisting system was designed and was planned to be installed in 2010. The original hoist system consisted of motor operated hoists that included steel wire ropes attached to the bottom of the gates (2 cables per gate). The new hoists would have consisted of screw type actuators. The actuators would lift and lower the gates from the top instead of the bottom of the gates. It was also planned to strengthen the top of the gates. Repairs were made to the spillway gates and hoist equipment over the years, the most recent being in 2009. The DNR Inspection report dated 8/17/2009 reported that Gate 1 (the left most gate looking downstream) could only be opened 8 ft due to damage incurred during the 2008 floods. This gate was opened fully during the 2009 flood. There was another issue identified in the 8/17/2009 Inspection Report. It identified a hole in the left pier for the right spillway gate

(Gate 3). The hole was located about 15 ft below the top of the spillway gate. The hole extended completely through the pier behind the gate guide. In a follow-up note to the files from Dave Allen on 1/21/2010, it was noted that the concrete repairs had not been made. The inspection report had identified a completion date for the pier repairs of 12/31/2009.

The spillway gates at Delhi Dam were difficult to open and close. A small crane had been used previously to sometimes initiate opening of the gates. A jacking device was installed on the top of the gates to force the gates down to their fully closed position. A factor that can also affect the release capacity through the spillway gates is the potential for debris plugging the spillway gates. Debris, in the form of woody vegetation, had been reported to be a common occurrence at the spillway control structure. Boats on Lake Delhi had become unanchored during previous floods and were passed through the spillway gates.

Formation of the dam failure investigation team

In response to the dam failure, the Governor of the State of Iowa requested assistance from the National Dam Safety Review Board in providing an Independent Panel of Engineers to evaluate the cause of the overtopping and breach of Delhi Dam. This request was made to the Administrator of the Federal Emergency Management Agency (FEMA) dated August 6, 2010. The National Dam Safety Review Board includes representatives from federal and state agencies as well as a member from the private sector and operates under the direction of FEMA. The National Dam Safety Review Board is statutorily established under the Dam Safety Act of 2006 (Public Law 109-460) and provides the Director of FEMA with advice in setting national dam safety priorities and considers national policies affecting dam safety.

In the August 6, 2010 letter, the State of Iowa identified the scope of the Independent Panel of Engineers review as follows:

- Review the operational characteristics of the project leading up to the breach of the upper reservoir.
- Perform an evaluation of the breach of the dam to determine the specific failure mode.
- Submit a final report documenting the results of their findings on the cause of the breach of the upper reservoir and the important lessons learned from the failure.

In a letter from the Deputy Administrator of FEMA to the Director of the Iowa Department of Natural Resources dated August 27, 2010, a commitment was made to convene a three member Independent Panel of Engineers (IPE) under the auspices of the National Dam Safety Review Board. The three members represent federal agencies with extensive experience in dam safety and include:

- William Fiedler, Bureau of Reclamation
- Wayne King, Federal Energy Regulatory Commission
- Neil Schwanz, U.S. Army Corps of Engineers

Each of the respective agencies absorbed the time and travel costs for this investigation. State funding was not used for this investigation.

IPE's investigation process

In order to fulfill its mission, the IPE initially collected and reviewed key information. The IPE operated independently and access to individuals and to any requested information was freely granted. Areas of focus included: the design and construction of Delhi Dam, subsequent modifications to the dam, the operational and performance history of the dam, past examinations and reviews of the dam, the timeline of events leading up to and including the breach of Delhi Dam and the emergency response to the dam breach. A key activity for the IPE was convening in Iowa during the week of September 6th, 2010. On September 7, 2010 the IPE reviewed records at the Iowa Department of Natural Resources (IDNR) Offices in Des Moines, Iowa and conducted interviews with personnel from the IDNR, as well as the dam operators, owner's representatives and local residents. On September 8 and 9, 2010, the team inspected the dam site and the upstream and downstream areas and conducted additional interviews with personnel from local government agencies and from the Lake Delhi Recreation Association. The team spent September 10, 2010 in Des Moines at the Iowa Department of Natural Resources Office and reviewed additional records and conducted additional interviews.

Figure 7. IPE investigation of former embankment foundation. Remnants of core wall on the right side of photo. Source: Iowa DNR

After the information gathering was complete, the IPE set out to draft their report. A thorough review of the geotechnical aspects of the original design and past modifications was completed. The original drawings and documentation were not very clear on the original foundation and geotechnical design, therefore, a soil sample of the remaining embankment was tested and two shallow hand augers of the foundation were obtained.

A hydrology and hydraulic analysis was undertaken by the IPE. The analysis utilized a HEC-RAS model developed by the IDNR shortly after the breach. There were many questions that arose after the failure in regards to one of the spillway gates that was not able to be fully opened. It was critical for the IPE to complete some "what-if" scenarios to begin to answer those questions. Flow data were available from a USGS gage located in the City of Manchester upstream of the lake. However, there were also significant local inflows to the lake that had to be estimated.

The IPE also provided a review of the emergency management response and a timeline of events based on testimonials and photos.

Iowa's role of information provider

In order for the investigation team to be completely impartial, the Iowa DNR facilitated the process to gather witnesses and provided records of the dam's history. Iowa DNR did not have an active role in developing the investigation report. This allowed the investigation team to not only review the failure itself, but to also review the State's dam safety program and regulation of the dam up to the time of failure.

Findings of the Panel

The key findings are described below. Complete findings and recommendations are available in the full IPE report.

Dam Design and Construction

There was limited information on the dam materials in terms of gradations of the materials and density of the in place embankment. It appears that the dam embankment consisted of a homogeneous material, with a reinforced concrete core wall placed upstream of the centerline of the dam. A sample from the remnant of the embankment was tested and it was determined that the material was a sandy clay with low plasticity (plasticity index of 9).

The concrete core wall (see Figure 8) was placed on top of steel sheet piling that extended to rock for some distance near the right abutment wall of the gated spillway. The core wall was founded directly on bedrock from the spillway wall to a distance of about 20 ft from the wall. South of that point the sheet piling is shown extending to bedrock for a short distance where the depth to bedrock was known. The top of the cutoff wall extended to within about 6 ft of the crest of the dam.

Figure 8. Remnants of sheet pile, core wall and spillway wingwalls. Source: Iowa DNR

The concrete cutoff wall on top of a sheet pile wall created a vertically rigid element in the dam that would not settle over time, as compared to the embankment on either side of the cutoff wall which could settle. This situation likely created differential settlement in the area of the cutoff wall that caused low stress that could have lead to cracks in the embankment fill emanating from the top of the cutoff wall. The potential seepage path created by the cracks from the cutoff wall and the low plasticity embankment material created a situation where internal erosion of the embankment could initiate and progress quickly.

The spillway was the primary waterway for passing flood flows at Delhi Dam. The wicket gates in the old power plant have a discharge capacity of about 500 ft^3/s but this flow is relatively small compared to the spillway capacity. The spillway is regulated by three 25-foot wide by 17-foot-high vertical lift gates. With all three gate fully opened and the reservoir at elevation 904.8 NGVD29 (130 ft local datum), the estimated spillway capacity is about 32,000 ft^3/s.

Dam Performance Prior to July 22-24, 2010 Flood

No adverse performance of the dam prior to July 2010 was reported to the IPE. No significant seepage had been reported at the downstream toe or on the downstream face of the dam.

Although the embankment performed well up to the recent event, it is very possible that prior loadings did not achieve a water surface elevation that exceeded the top of the core wall (EL 898.8 ft) or have a sufficient duration to develop internal erosion.

The spillway gates have been difficult to operate in the past. The gate guides are tapered at the bottom and sometimes the gates would stick in the closed or nearly closed position. A crane had been used in previous floods to operate the spillway gates.

The lack of maintenance of the embankment section immediately south of the spillway and the 2H:1V downstream slope made inspection of the dam for seepage flows difficult.

Dam Performance During July 22-24 Flood

During the July 22-24 flood, Gate 3 could not be opened more than 4.25 feet. This was a significant reduction in the spillway capacity.

Nothing out of the ordinary was observed related to the dam performance during the July 22-24, 2010 flood, until the reservoir water surface exceeded the top of the core wall, at elevation 898.8 ft. A timeline of events for the July 22-24, 2010 event is provided in Table 1. Within about 8 hours of this occurring, vortices in the reservoir and sinkholes on the upper portion of the upstream face of the dam were observed. The first vortex was noticed about 40 to 50 ft south of the concrete structure at 3:30 am; the second, noticed later, was estimated to be about 100 ft south of the concrete structure. Figures 9 through 13 depict the failure of Delhi Dam as it progressed on July 24, 2010.

Table 1. Timeline of Events, July 22-24, 2010

Time	Event
July 22 – 24, 2010	Heavy rain in watershed
July 24, 2010	
3:30 AM	Dam operator observes sag in upstream fence, 4 ft whirlpool discovered, and county emergency manager was notified.
6:00 AM	Exit point of seepage confirmed in downstream toe, dam operator requests public alert for potential dam failure, and 6” sag in road over dam observed.
6:20 AM	National Weather Service issues dam failure flood watch.
9:00 AM	Dirty flow observed at toe of downstream slope.
9:40 AM	Observed 1-2 inches water flowing over the road.
10:00 AM	Significant erosion of the downstream roadway shoulder beginning, widening within 10 ft of concrete wall/structure.
11:30 AM	Water flowing through the roadbed, roadway washout likely.
12:00 PM	Heavy flow over top of dam and underneath the road.
12:15 PM	Roadbed collapses
12:22 PM	Headcut progressed 50% through roadway.
12:45 PM	Headcut progressed 75% through roadway.
1:00 PM	Headcut progressed completely through embankment.
1:02 PM	60 ft wide breach through roadway
2:40 PM	Breach was reported to be 200 feet wide, lake water level dropped by 25 feet.

Seepage from the downstream slope was first observed around 6:00 am July 24, 40 to 50 ft south of the spillway training wall. At 6:00 am, settlement of the dam crest was observed in the areas where the vortices and sinkholes were first observed. All of this evidence is consistent with internal erosion occurring in the portion of the embankment above the top of and downstream of the concrete core wall.

Figure 9. Discolored water (circled) exiting the dam, indicating piping. Source: SourceMedia Group News

The dam breach began to accelerate around 12:30 pm on Saturday, July 24th. The dam breach was caused by internal erosion of the embankment, flows over the embankment and structural failure of the thin concrete core wall. A full breach of the embankment dam occurred at about 1:00 pm on July 24th. The concrete core wall appeared to have failed due to differential loading caused by the flood and erosion of downstream embankment soils. As erosion of embankment soils continued, sections of the core wall also toppled, eventually ceasing at a maximum breach width of 235 ft. It is likely that the concrete core wall slowed down the rate at which the embankment dam breached.

Figure 10. Breach in progress, headcut completely through roadway. Source: Iowa DNR.

Figure 11. Breach in progress, headcut deepening through roadway. Source: Iowa DNR.

Figure 12. Breach in progress, core wall still in place. Source: Iowa DNR.

Figure 13. Full breach and uncontrolled release of water. Source: Iowa DNR.

The breach of Delhi Dam did not cause any loss of life. This is attributed to several factors: the concrete core wall likely slowed down the rate of the dam breach; warning of dam failure was issued several hours before the breach; the flood wave was dissipated in farm fields, which reduced the level of flooding in the downstream communities of Hopkinton and Monticello; and door to door warnings were issued in Hopkinton and Monticello resulting in evacuation of residents whose homes were subsequently inundated.

Alternative Scenarios for Reservoir Operations During July 22-24 Flood

A number of scenarios were evaluated to help determine if different spillway operations would have made a difference in reservoir levels and the breach of the dam.

One of the items explored was the effect of the partially closed spillway gate. A routing was performed in which all three gates were opened to 18 ft, which was the maximum opening achieved by Gate 1 during the July 22- 24, 2010 flood. The flood routing results indicated that Delhi Dam would not have overtopped if all three gates had been fully opened. However, the reservoir would have exceeded the top of the core wall by up to 2.4 ft for about a day, and it is likely that internal erosion would have initiated in the embankment. Figure 14 shows the results of this analysis. Based on the duration of seepage that likely would have occurred through the embankment, it is judged that the dam would have suffered damage and possibly a total breach, even with all three gates fully open.

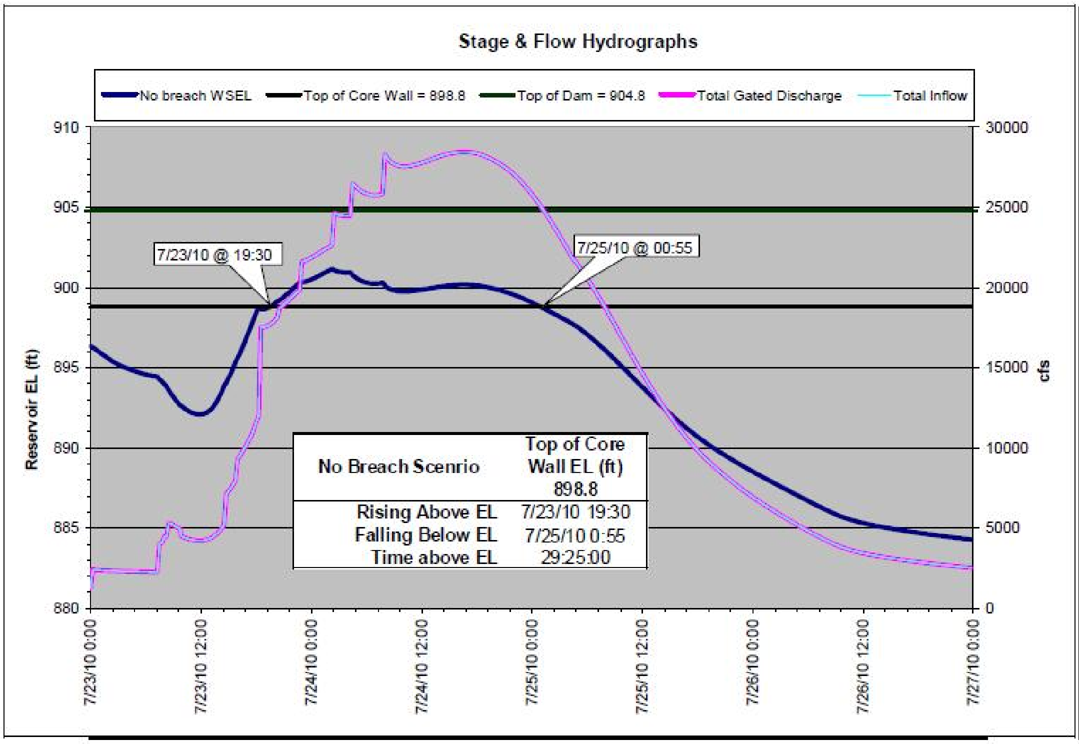

Figure 14. Hypothetical Scenario using Logbook Controlled Gates with all 3 Gates Fully Operational to 18 feet Maximum Opening. Source: Lake Delhi IPE Report.

One of the criticisms from downstream residents is that the dam operators should have lowered the reservoir in anticipation of the peak flood inflows. Routings were performed that evaluated the effect of lowering the reservoir by 2-, 4-, 8- and 10-ft at the beginning of the flood. The results of these flood routings indicated that the dam would likely have still have been overtopped and the reservoir would have exceeded the top of the core wall elevation for an extended period, even with the hypothetical drawdown levels. This reflects the fact that the reservoir volume is relatively small in comparison to the flood volume and any space that was created would have been filled prior to experiencing the peak flood flows.

Cause of Dam Breach

From the eyewitness descriptions, photographic and video evidence and limited excavation investigation, the cause of the dam breach was internal erosion in the embankment coupled with overtopping flow. The internal erosion was most likely caused by a seepage path initiated along differential settlement of the embankment material adjacent to the core wall. The failure mode was triggered by reservoir levels that exceeded the top elevation of the concrete core wall, which was exacerbated by the inability to open the third gate beyond the 4.25 ft measured in the post breach investigation.

Figure 15. Aerial view of breach. Source: Iowa Wing Civil Air Patrol.

The location and design of the concrete core wall and the fact that it did not extend to the crest of the dam created more favorable conditions for internal erosion of embankment materials once the reservoir reached the elevation corresponding to the top of the core wall. The IPE believes that any flood of sufficient magnitude to raise the reservoir above the top of the concrete core wall for a more than several hours would have resulted in the embankment experiencing piping/internal erosion.

If internal erosion did not occur, the duration of 16 hours and maximum depth of 1.4 ft of overtopping predicted by the flood model (with one gate malfunctioning) would have likely caused a breach via overtopping and headcutting erosion. The results of this analysis are shown in Figure 16. Overtopping erosion to the point of breach was predicted with WINDAM, a NRCS erosion program. A summary of the WINDAM analysis is included in the full IPE Report referenced at the end of this article. Several other factors that would add to the likelihood of overtopping erosion are the downstream slope of 1V:2H, erosion features located at the toe as described in recent inspection reports, the rock toe and inclusion of the 1920's roadbed, unknown (but likely low) insitu soil densities and the trees and vegetation on the downstream slope. Conversely, if the dam had not experienced overtopping flows above the original dam crest elevation (this would have required that Gate 3 was fully functional July 22-24, 2010 flood event), it is possible that the internal erosion mechanism by itself would have lead to the breach of the dam.

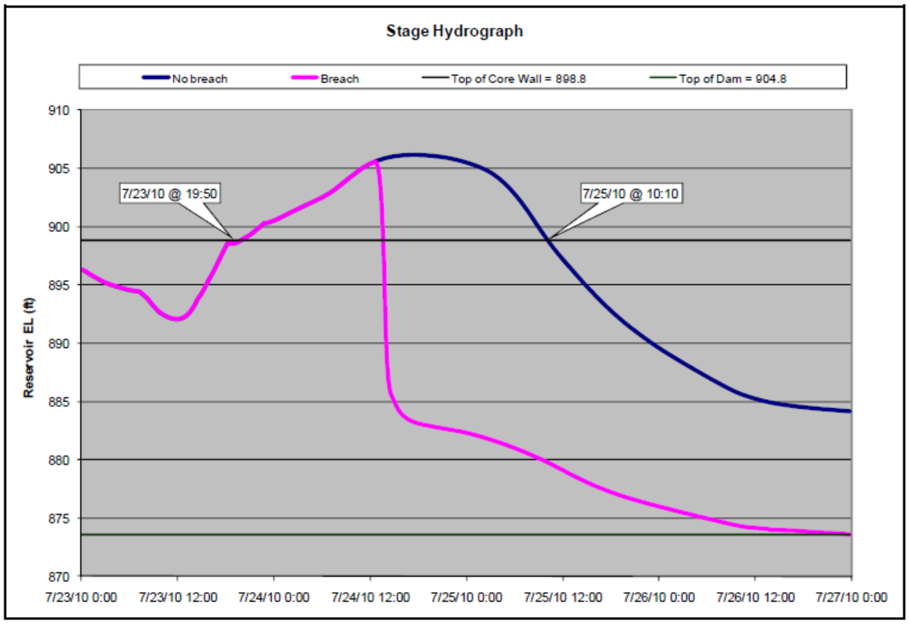

Figure 16. Estimated time of reservoir levels higher than the top of core wall (shown at EL 898.8ft NGVD) Source: Lake Delhi IPE Report.

Recommendations and Lessons Learned

The scope of the IPE investigation was limited. Several recommendations were made that will add to a better understanding of the breach at Delhi Dam:

- Investigate the remaining sinkhole and the flow path from the sinkhole to its terminus.
- Conduct a complete investigation of the remnant of the embankment, 1967 berm and foundation soils including but not limited to classification of soil and critical material properties.

The IPE also made recommendations that address issues related to managing dam safety issues and a dam safety program:

- More consistent approaches should be developed for classifying dams according to hazard and achieving compliance with the associated design standards. The DNR classified Delhi Dam as moderate hazard, but Ashton Engineering classified the dam as low hazard. This has an impact on the design flood standard that is applied to dams.
- Dam inspectors performing inspections for the DNR and consulting engineering firms performing dam safety evaluations should have strong backgrounds in dam engineering and potential failure modes analysis. There were design weaknesses at Delhi Dam that an experienced dam engineer should have recognized, which likely would have led to additional investigations.
- The failure of Gate 3 to fully operate during the flood appears to have been caused by the failure to complete concrete repairs behind the left gate guide. Education and enforcement mechanisms are needed to clearly identify critical dam safety issues and their impacts and to ensure these issues are resolved quickly.
- Review/ update the estimated return period for the July 2010 flood event based on historical inflows at Delhi Dam.

Some additional lessons learned from the failure of Delhi Dam are presented below. These are areas that were outside of the scope of the IPE report on Delhi Dam, but are valuable considerations.

Lessons Learned for the Evaluation of Other Dams

The failure of Delhi Dam was attributed to a combination of events – a spillway gate that could not be fully opened which resulted in the embankment portion of the dam being overtopped and internal erosion of the embankment section of the dam which initiated in the upper portion of the embankment, above the concrete core wall. The failure occurred during historic reservoir levels, which resulted in a first filling situation for the untested portion of the embankment dam above the core wall. While the dam could have failed during the July 2010 flood due to any single mechanism (gate No. 3 not fully operational, dam overtops or internal erosion initiates within the embankment), it is not clear that the dam would have failed if all three mechanisms had not been in play. The failure and the contributing factors that caused it provide the following lessons to be considered when evaluating other dams:

1. As reflected in statistics of dam failures, first filling is a critical condition for dams. It applies to not only dams filling initially after construction is complete, but to any dam where the historical maximum reservoir water surface is exceeded and untested portions of the dam and foundation are loaded for the first time. Undetected flaws can become apparent during first filling conditions.
2. Dam failures are sometimes caused by a combination of events. While single events are easier to predict, it becomes difficult to predict the combination of events that might lead to failure. In the case of Delhi Dam, the combination of a large flood event, a malfunctioning gate and the loading of the embankment dam above the top of the core wall all contributed to dam failure.
3. Some potential failure modes considered under normal or static loading conditions are also considered under flood and seismic loading conditions. This is typically the case for internal erosion potential failure modes related to embankment dams. It is often concluded that while the conditional failure probability (the probability of failure given that the loading occurs) will increase for higher loadings, the increase in conditional failure probability will be more than offset by a decrease in the load probability (i.e. it may be judged that the increase in failure probability for a static condition to the condition during a 100-year flood will be a factor of less than 100). This does not account for specific features that may come into play at higher reservoir water surface elevations. For Delhi Dam, the concrete core wall was a significant feature that created vulnerabilities in the embankment dam once the top of the wall was exceeded by the reservoir water surface. In the case of Delhi, the probability of dam failure as a result of internal erosion through the embankment section of the dam increased dramatically under flood loading that caused the reservoir water surface elevations to exceed the top of the core wall.

Lessons Learned for Future Dam Failure Investigations

The investigation of the failure of Delhi Dam by an independent panel provided a valuable opportunity for the dam safety community. Most things went well but there are things that should be considered for future dam failure investigations:

1. The panel for Delhi Dam functioned independently and was able to determine what information was needed for the review and which individuals should be interviewed. None of the team members had any prior involvement or connection to Delhi Dam. This was important to ensure that the panel was not biased and also was helpful from a public perception standpoint.
2. Constructing a timeline of the July 2010 flood and the events leading up to and during the failure of Delhi Dam was the critical activity for the panel. Interviews with observers and involved personnel were important to constructing the timeline. This was an intensive effort but was necessary. The panel tried not to influence the interviewees by asking leading questions or sharing observations relayed by others. Detailed notes were taken and the interviews were recorded. Reviewing the interview information was time consuming. If methods could be developed to record and organize information consistently it would streamline the process of consolidating the various accounts.
3. The IPE did not begin its work until about almost two months after the failure. While this did not appear to significantly compromise the process, convening a tem and initiating the investigation sooner would have improved the process. People that were interviewed would have likely remembered more details if interviews had been conducted closer to the event.
4. The panel had the luxury of performing some limited investigations (sampling remnant embankment materials and classifying the soil type) and performing some flood routing studies. These studies were invaluable in shaping the findings from the panel. It helped confirm some initial opinions of the panel and allowed the team to weight the contribution of key factors in the dam failure.
5. The panel members worked for different federal agencies and were geographically separated which made coordination of the final report challenging. A face to face meeting was conducted just prior to finalizing the report and this was critical to the effort. An earlier meeting would have improved the overall process.

What's next

The Lake Delhi Recreation Association is currently planning to reconstruct the dam and potentially restore hydroelectric power generation. The funding source for this rebuilding effort is still unknown. The LDRA is beginning the process of a full engineering study to determine alternatives for dam reconstruction.

The Iowa DNR dam safety program continues to improve its program with dam owner outreach and additional staff for breach evaluation and mapping.

ASDSO has recently formed a committee to evaluate failure investigations of Delhi Dam and other dams which have failed with the goal of improving the current practice of investigating dam failures.

References

1. Fiedler, W., King, W., Schwanz, N., 2010, Independent Panel of Engineers: Report on Breach of Delhi Dam, December 2010.
2. State of Iowa, *Lake Delhi Recover and Rebuild Taskforce Report,* December 2010.