# <u>Big Bay Dam Failure</u>

## System Response Event Tree & Failure Mode Development


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A number of the site conditions, design and construction details, and the distress indicators that developed between the initial reservoir filling and failure combine to suggest a complex internal erosion and piping potential failure mode development process. Based on the Author's evaluation of available information, and experience, a nine node system response event tree was developed to describe the failure development resulting from the "as constructed" outlet conduit/embankment dam at the location where the breach occurred. The figures referenced below are presented in Ferguson, et al, April 2014. This system response event tree described below has been slightly updated since the presentation in April 2014 as the author has continued to evaluate the failure mode development process at Big Bay Dam.

1. Reservoir is maintained at a relatively constant "full" level allowing steady state seepage conditions to develop relatively rapidly, and to be maintained over an extended period of operation.
2. Open defects exist in the outlet conduit and the openings are large enough to permit initiation and continuation of internal erosion and piping of either embankment and/or foundation soils through the defects.
3. Conditions along the continuous seepage pathway supported the development of a roof and/or maintenance of the erosion process. Embankment and foundation soils are fine enough so that erosion continues without any arresting mechanism such as self-filtering.
4. Over a period of 12 to 13 years, a continuous preferential seepage pathway developed from the upstream face of the dam to a location near the downstream toe (toe drain) of the embankment through a combination of continuous layers, stress reduction zone along the conduit, along the base of the conduit, through defects in the embankment cutoff wall, and in the upstream shell of the embankment.
5. Seepage daylights to an unfiltered exit along the downstream toe of the dam
6. A final cycle of backward erosion and piping initiates and connects to the continuous piping feature through the dam resulting in an open feature from the downstream toe to the reservoir.
7. The seepage erosion mechanism changes from detachment and transport (internal erosion) to contact erosion along the open pipe feature and the continuous open defect from the downstream toe to the reservoir rapidly experiences gross enlargement.
8. Intervention is unsuccessful
9. Breach develops through continued progression and gross enlargement resulting in uncontrolled release of the reservoir

It should be noted that the rapidity of the failure development (steps 5, 6, and 7) once a concentrated leak developed below the downstream toe of the embankment was observed occurred as a result of a relatively complex internal erosion process.  The 2014 root-cause evaluation felt that the best way to describe the process was a series of at least three to 4 internal erosion development cycles.  These four cycles are associated with four separate but likely points of internal erosion “initiation”:

1. First initiation: A relatively large open defect in the conduit near the upstream riser structure (see location 2 on Photo 3).
2. Second initiation: A relatively large open defect in the conduit under the downstream shell of the dam (see location 1 on Photo 3, and Photo 4).
3. Third initiation: A defect in the filter fabric lining of the downstream toe trench drain (see Photo 5 and failure mode description of discharge from toe drain prior to failure provided below).
4. Final initiation: A concentrated leak from the foundation downstream of the dam toe (see timeline item 6 under Cycle 4 below).

Due to it’s proximity to the reservoir, the failure process likely began at the location of the relatively large open defect in the conduit near the upstream riser structure (first initiation location, above).  These cycles likely developed sequentially but there could have been periods of overlap.  For example, Cycle 2 at the second initiating location at the major downstream conduit defect, may have begin prior to the completion of Cycle 1 with the two failure pathways eventually joining.   Additional descriptions of these internal erosion piping cycles are as follows:

**Cycle 1** - Gradients, flow quantities and the relatively short distance between the reservoir and the upstream location of the defect in the conduit (distress location 2 shown on photo 3) would have allowed an open erosion/piping feature to develop between the reservoir and the conduit defects through internal erosion within the upstream shell of the embankment or at the contact between the embankment and foundation along the side of the conduit.  Several such features may have developed over time and they may have become fairly large through progression mechanisms associated with the backward piping and erosion, or stopping processes leading to the formation of sink holes similar to that shown on Photos 7 and 8.

**Cycle 2** - Once the cycle 1 continuation process completed and an open pathway(s) developed in the upstream shell or foundation, water pressures in the embankment and foundation could have changed, locally altering the water pressures and gradients from that point to other defects in the conduit located further downstream such as distress location 1 shown on Photo 3.  This would have allowed (or accelerated) initiation and/or continuation mechanisms to occur between conduit defect locations 1 and 2 eventually leading to the development of an open defect (pipe) under the central portion of the embankment section.  The increase in water pressures and water flowing through the open defect between location 1 and the upstream face of the dam would have been suitable for a stopping mechanism to develop leading to
the sinkhole formation up through the downstream shell of the dam as shown as distress indicator 3 on Photo 3 and in Photos 9 and 10.

**Cycle 3** – Based on the information available, Ferguson believes that the most likely next (third) cycle of failure mode development would have been between distress location 1 (Photo 3) and a defect in the embankment toe drain system resulting in the discharge of water from the toe drain pipe with sediment late in the failure mode development timeline as described by Ferguson (2014):

1. The Owner's Maintenance Man had been notified by one of the residents in the area that the 6-inch diameter drainpipe discharging from the west side of the outlet works discharge culvert wing wall into the dissipation pool area was flowing "mud". The date and time of this notification is not clear in the available information but was likely sometime on the morning or early afternoon of March 11th, the day prior to the failure.  This pipe normally did not flow water other than during periods immediately following significant rain.  The amount of time that this condition (drain pipe flowing "mud") had existed was not established during deposition.  It may have been a few hours or perhaps several days to a week or more.
2. On Thursday afternoon, March 11th, the Maintenance Man went to the site and observed about 1-inch of water flowing from this pipe and described it as "muddy water". The Maintenance Man notified the Owner who in turn notified the Engineer about 3:30 pm of the problem.  The Maintenance Man left the site for the evening at about 5:00 pm.  Depositions indicate that the Owner or Engineer did not visit the site prior to the Maintenance Man's departure.
3. The Engineer confirmed he had received a phone call from the Owner and was informed of the observations of the Maintenance Man about the drain pipe discharge with a "slightly muddy tint". The Owner was informed by the Engineer that it would not be unusual for some of the drains to have increased discharge due to the heavy and extended rainfall ending just a week or two prior to the incident.  It was further reported that the Maintenance Man did not feel any soil or fines particles in the pipe discharge.  The Engineer indicated he would visit the site the following morning.
4. The Engineer was on the way to the site on Friday when he received a call from the Owner about 8:30 am and was informed that the Maintenance Man reported that the drain discharge appeared to have a little soil material in it and had more of a muddy tint. The Engineer arrived at the site sometime between 9:00 and 9:30 am.
5. Upon arriving at the site, the Engineer noted that the reservoir pool was about 6 to 8 inches above normal and observed that the dissipation pool below the outlet discharge did have some muddy discoloration and that the discharge from the drain pipe had increased.

During Cycle 3, the amount of seepage, water pressures and gradients occurring around the filter drain system that had been installed around the downstream end of the conduit, and in the toe trench drain would have been relatively complex.  Because of the method of construction of these systems at the dam, as previously noted there would have been a high likelihood of clogging, creating a localized "confining" layer and/or seepage barrier that would have forced seepage through the foundation materials into any defect of the toe drain, and perhaps exiting other areas of the foundation just downstream of the toe of the dam.  Any unfiltered and localized defect such as a tear in the toe trench drain filter fabric would likely been a candidate location for initiation, and backward erosion/piping to develop. Once the continuation phase of that erosion cycle reached the open erosion pipe at downstream conduit defect (distress location 1), an open channel (erosion defect) from a location along the upstream side of the toe trench drain near the downstream toe of the embankment to the reservoir would have existed.

**Cycle 4** - Once the third cycle completed, and a relatively open defect existed between the reservoir and the downstream toe drain system, large pressures and gradients could have locally developed in the embankment and foundation area around and immediately downstream of the embankment toe trench drain leading to the 4th cycle of initiation and continuation of an unfiltered piping defect. This last cycle occurred over the relatively short distance between the concentrated leak described under item 5 of the failure mode event summary, and the open defect immediately upstream of the clogged toe drain trench. Once the continuation phase of that erosion cycle was complete, a relatively open pathway from the reservoir to the downstream defect toe could have existed resulting in the conditions described in the later stages of the failure mode events, and very rapid progression (gross enlargement) of the pipe, and breach formation described as follows:

1. Upon further inspection, the Engineer noted that there was a single point of seepage exiting the foundation at the ground surface immediately downstream of the dam toe, west of the wing wall, above the level of the dissipation pool, and away the location of the 6-inch drain pipe discharge. The discharge exiting the ground surface was described as about a ½-inch diameter flow bubbling about ½-inch above the ground surface. The Engineer estimated rate of flow to be ½ to 1 gallon per minute. There was minor evidence of soil particles (10 grains in one minute flowing over a fine screen) being transported in the discharge but there was no accumulation of sand material around the discharge area. The Engineer indicated that the flow from this discharge was traveling along the ground surface to the dissipation pool and that some of the water was infiltrating down through the relief drain materials and into the discharge pipe and causing the flow from the pipe.
2. The Engineer then proceeded to complete an inspection of the outlet discharge conduit that was flowing, the toe of the dam both east and west of the location of the outlet discharge structure, the dam crest, and the reservoir pool along the upstream dam slope looking for any seepage, signs of distress, or whirlpools. None were noted. He went back to the seep and noting no change, left the site at 11:00 am.
3. The Maintenance Man called the Engineer at about 11:30 to 11:45 and noted that the flow from the 6-inch discharge pipe had increased. He then left the site to get lunch and returned to the seep area and noted a significant change in the seepage.
4. Although the timeline could not be established exactly, sometime around 12:00 to 12:15, the Maintenance Man described seepage from an area about 20 to 30 feet southwest of the drain pipe discharge location, muddy in color and spraying 30 to 40 feet into the air. He immediately contacted the Engineer who was just minutes from returning to the site.
5. Upon arriving back at the site, the Engineer described the seep as spouting approximately 2 to 3 feet in height and with a diameter of about 18 inches. He further

noted that “Quite suddenly, the area around the boil appeared to liquefy and/or settle downward and rapid erosion set in to the north (*backslope of the dam*) and to the south (*downstream direction*)” (italics are the authors). The erosion into the downstream slope of the dam progressed quickly. During deposition, the Engineer noted that the location of this seepage was 10 to 15 feet off the backtoe of the dam, and about 60 to 70 feet off the “distilling” basin and west side of the box structure. We (the authors) interpret this location to be 10 to 15 feet downstream of the downstream toe of the dam. Seepage at a location like this would typically be associated with foundation seepage. However, as will be noted further below, the location of the toe drains and the 1999 remedial construction in the area around the outlet works discharge structure and box culvert, along with the potential for clogging of these drain systems could have substantially altered seepage patterns.

6. The Engineer noted that the crest of the dam had breached and uncontrolled release of the lake pool began at approximately 12:25 pm.

Recent modeling of 3D seepage conditions around piping features (Anderson and Ferguson, 2015) strongly support the possibility that the relatively rapid transmission of high water pressures to the downstream toe area could have resulted in the localized “liquefaction” described by the Engineer as water literally exploded out of the continuous open piping feature between the reservoir and the downstream toe. The combination of a fully open defect, high water pressures along the defect and potential for localized liquefaction instability, large seepage flows, and highly erodible nature of the foundation and embankment soils combined to result in the dramatic and very rapid failure development sequence.

## References:


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