

8. Conclusions

The Upper Reservoir Embankment has had a long history of settlement and high leakage increasing to about 60-100 cfs between 1999 and 2003. Although there were many periods of concern and repair was required to keep the water within the reservoir, the embankment and parapet wall did function for 42 years as the containment structure for the Upper Reservoir. The steep rockfill embankment, as discussed in Section 3.1, was possibly marginally stable for the actual “dirty” dumped rockfill and the seepage conditions previously experienced. After installing the geomembrane liner in 2004, it is most likely that the Upper Reservoir Dam was more stable than it has ever been under normal loading because the total leakage was only 5-10 cfs. Nevertheless there was no margin for accepting the additional pore pressures and erosive effects of overtopping, as was the case with the failure on December 14, 2005.

It is the Panel's opinion that the cause of the December 14, 2005 failure was overtopping of the parapet wall and embankment. The possible modes of failure for the breach event of this dam and the factors which made this dam especially vulnerable and sensitive to overtopping have been discussed in Section 7.

Although this dam and parapet wall combined to give an embankment more vulnerable and sensitive to overtopping than most embankment dams it is the opinion of this Panel that the primary root causes of failure on this particular date were those factors which caused the overtopping to occur. The secondary root causes or contributing factors are those factors which combined to make this embankment more vulnerable to failure by overtopping.

A summary of primary root causes is given below. These factors contributed to the fact that overtopping occurred.

- The pressure transducers that monitored reservoir water levels became unattached from their supports causing erroneous water level readings.
After these transducers became loose from their supports, their position heads changed and the reservoir levels indicated in the PLC system gave reservoir levels lower than the actual reservoir levels. The fact that the new system installed in 2004 did not consist of a structural support system anchored to the face slab enabled this mode of instrument failure to occur. As constructed it was inferior to all of the water level measuring systems used on the Project between 1963 and 2004.
- The emergency backup level probes were set at an elevation above the lowest points along the parapet wall; thus, they failed their protection role because this enabled overtopping to occur before the probes could trigger shutdown.
These probes were a good conceptual second line of defense. However, the Hi-Hi Warrick Probe had to be in contact with the reservoir water for 60 seconds in order to trip off the last pumping unit. The Hi-Hi Warrick Probe unfortunately was set at Elev. 1597.7 at Panel 58 where the top of the parapet wall was at 1598.0 It did not apparently occur to those setting this probe that there were 33 wall panels with their tops lower than the Hi-Hi probe with the lowest one (Panel 72) having a top at Elev. 1597.0 Thus the emergency backup system was effectively eliminated by this error of setting the Warrick Probe at an elevation which would allow considerable overtopping, if the main system would fail.
- The normal operating high water levels of 1 ft. below the top of the parapet wall was too near the top of the wall to allow for any mistakes of mis-operation.

This low free board was not realistic for the system adopted for monitoring water levels in 2004. A more rigorous study of the potential errors in the measurements should have been made before adopting this low free board which required such a high accuracy from this system. The adoption of this 1 ft. free board was totally inconsistent with having personnel making key design and installation decisions who were not even aware of the lowest elevation of the parapet wall within the nearest 1 ft.

- Visual monitoring of the Upper Reservoir water levels was almost non-existent and there was no systematic “ground–proofing” recorded of the relationship of the top of the wall and associated water levels actually being achieved.
- There was no overflow spillway to safely carry accidental over-pumped water downstream and below the dam.

The omission of a spillway from the design was a most important root cause of this failure. If a spillway had been constructed with a capacity of the two pumping units, an overtopping failure would not have occurred.

A bullet point for a secondary root cause of the December 14, 2005 breach is given below with detailed explanation.

- The marginally stable dumped “dirty” rockfill embankment and associated parapet wall atop the dam, constituted an unforgiving containment structure. It could not tolerate the additional pore pressures and erosive effects of the overtopping water plunging over the top of the parapet wall onto the narrow dam crest and cascading down the steep 1.3:1 slope.

The steep dumped rockfill slopes composed of rockfill with as much as 20% fines and 45% sand sizes and smaller, make this dam especially sensitive to erosion due to overtopping and also conducive to increases in pore pressures during overtopping because it is not free draining. Storing water against a 10 ft. high parapet wall founded on the dam crest is also a feature which makes this dam vulnerable to overtopping because the overflowing water impinges on the dam crest at a velocity of 25 ft./sec. which enhances erosion and makes a large release of erosive energy possible, should the erosion at the downstream footing of the wall allow tipping or sliding of the wall. As indicated in previous sections of this report there were plenty of indications, earlier in the history of this dam, that there was “dirty” rockfill in portions of this dam and much of the repairs as well as comments in writing were directed to the area of the dam that breached between Panels 88 and 99.