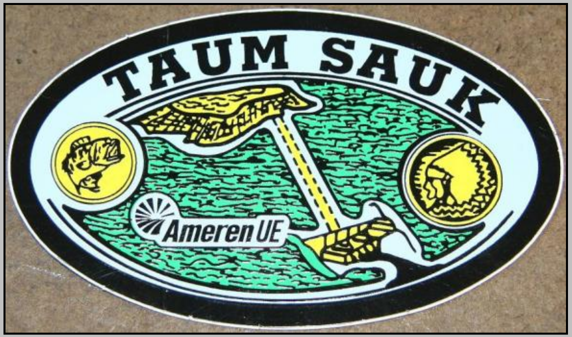
OVERVIEW OF THE TAUM SAUK UPPER RESERVOIR FAILURE

December 14, 2005
Reynolds County, Missouri



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The Upper Reservoir embankment was the last loose dumped (uncompacted) concrete-lined rockfill dike constructed in the U.S. The great majority of the dike was placed by end dumping (tipping) rock fill, and allowing it to stabilize at its angle of internal friction.
The upper 16 feet of the dike was placed as rolled fill, using four 4-foot thick lifts.
Note the three distinct zones, indicative of the different placement techniques.

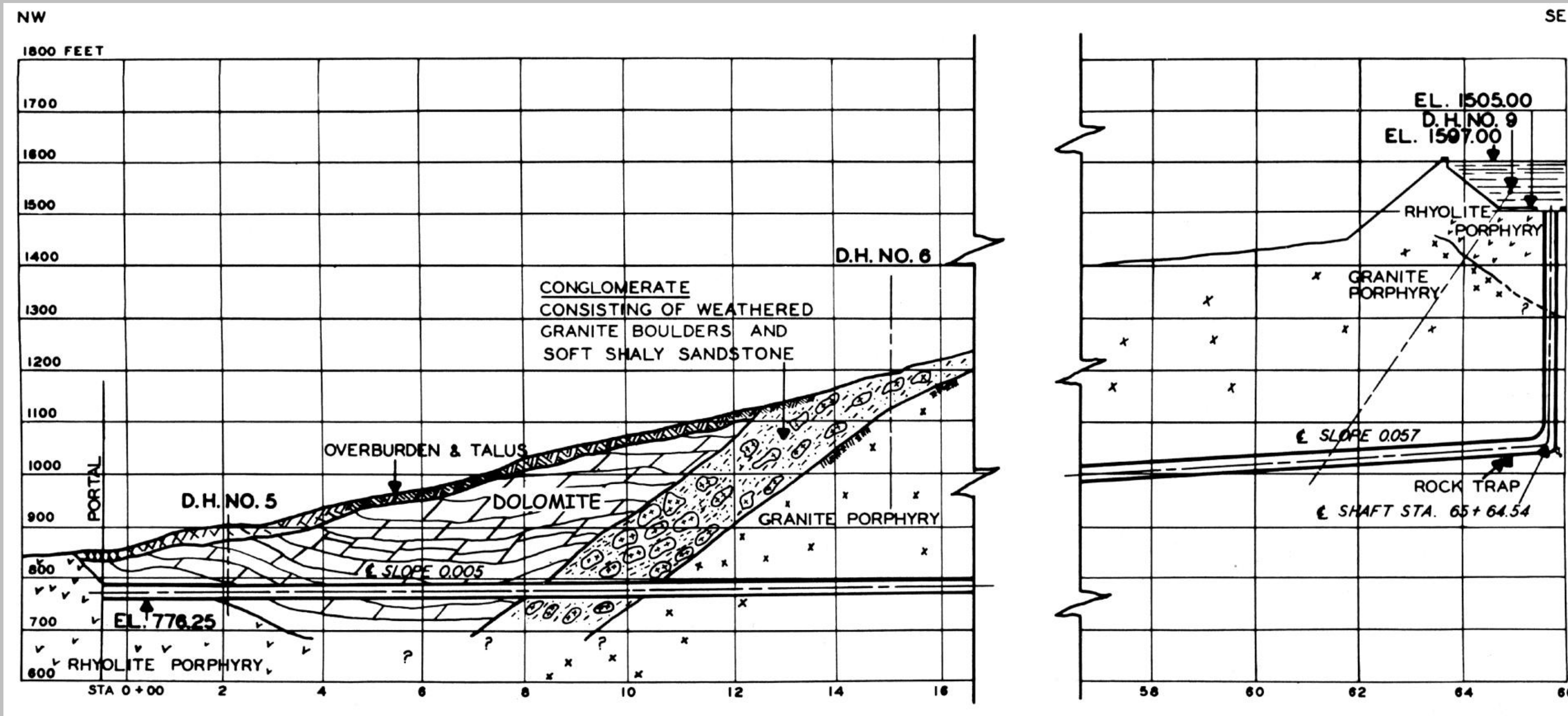
“DIRTY” ROCKFILL

- The cross section of the dam exposed by its failure exhibited a high fines content. The rockfill contained up to 28% fines while the project specifications limited the fines to 5% or less.
- This contributed to up to 2 feet of differential settlement, shifting of the concrete parapet walls, and cracking of the concrete liner, over the years. These same factors would have degraded the internal stability of the dike

Close up of “dirty” rockfill exposed at failure site. For scale, the large rocks are 10-12” in diameter.

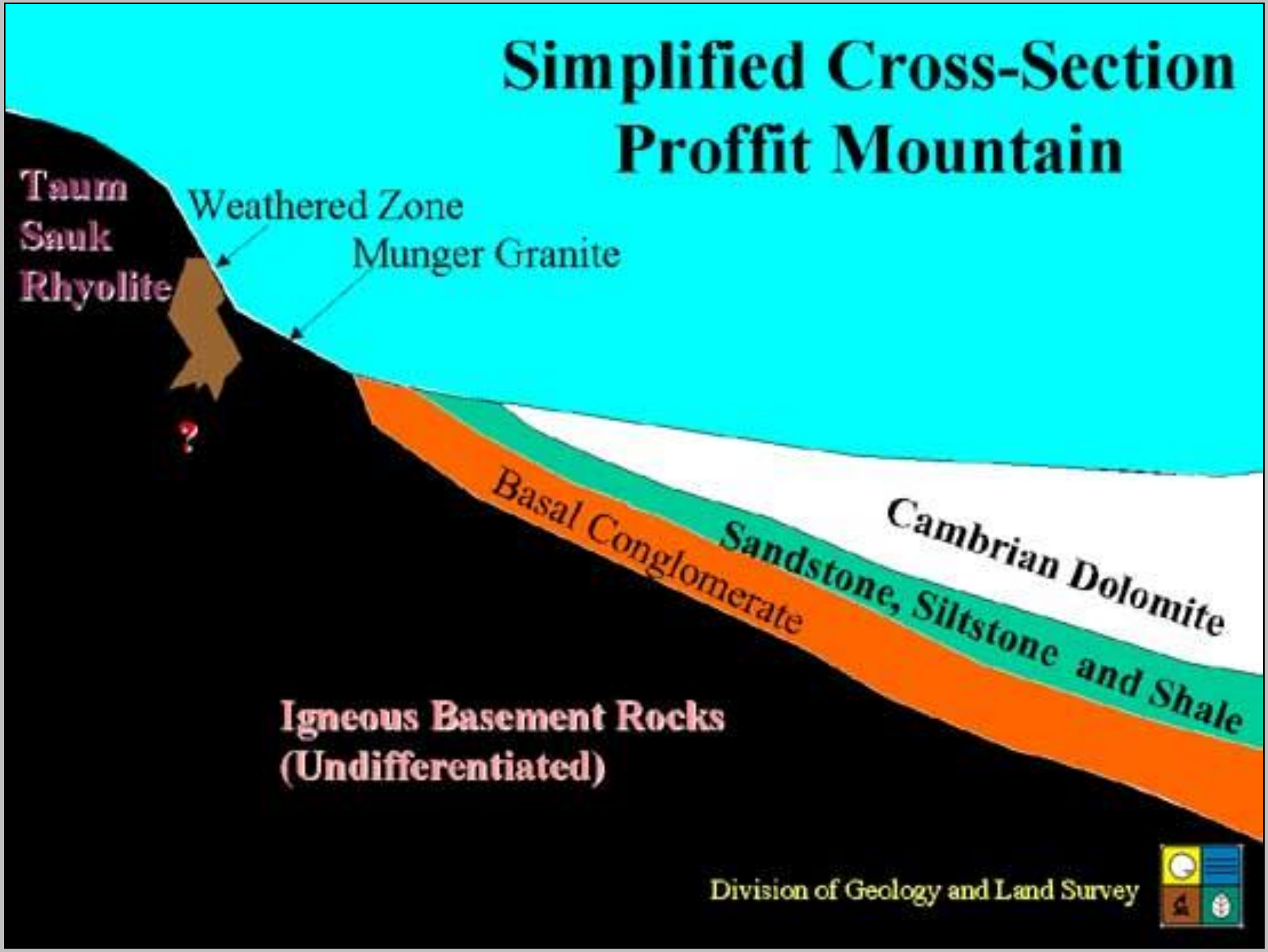
INCLUSION OF WEATHERED SAPROLITE IN EMBANKMENT

- The slopes of Proffit Mountain contain zones of deeply weathered igneous rock (saprolite), some of which appear to be decomposed diabase sills/dikes, causing hydrothermal alteration of adjacent granite and rhyolite.
- A letter by Cooke (1967) states that settlement rates of the embankment were unprecedented, but acceptable for the performance of the project. Up to 0.8 feet of settlement occurred during the first 5 years of operation, leading him to conclude that the rockfill was contaminated.
- Cooke stated that it would have been impractical, if not impossible, to remove the contaminated fill material during construction and that this weak material was likely responsible for the unusually high settlements measuered at Taum Sauk.



- **Partial geologic profiles along the lower and upper portions of the Taum Sauk feed tunnel, excavated in 1960-62.**
- **The project originally envisioned an inclined shaft, which was explored using a test boring inclined at 55 degrees, shown at right. The unit overlying the granite porphyry is a Precambrian fanglomerate**

Geologic units exposed by scouring of the outbreak flood. Note the reddish saprolite. **Photo from the Associated Press**



- **Stratigraphic relationships between units exposed along path of outbreak flood, just below the reservoir. Note the weathered zone at the break in slope.**

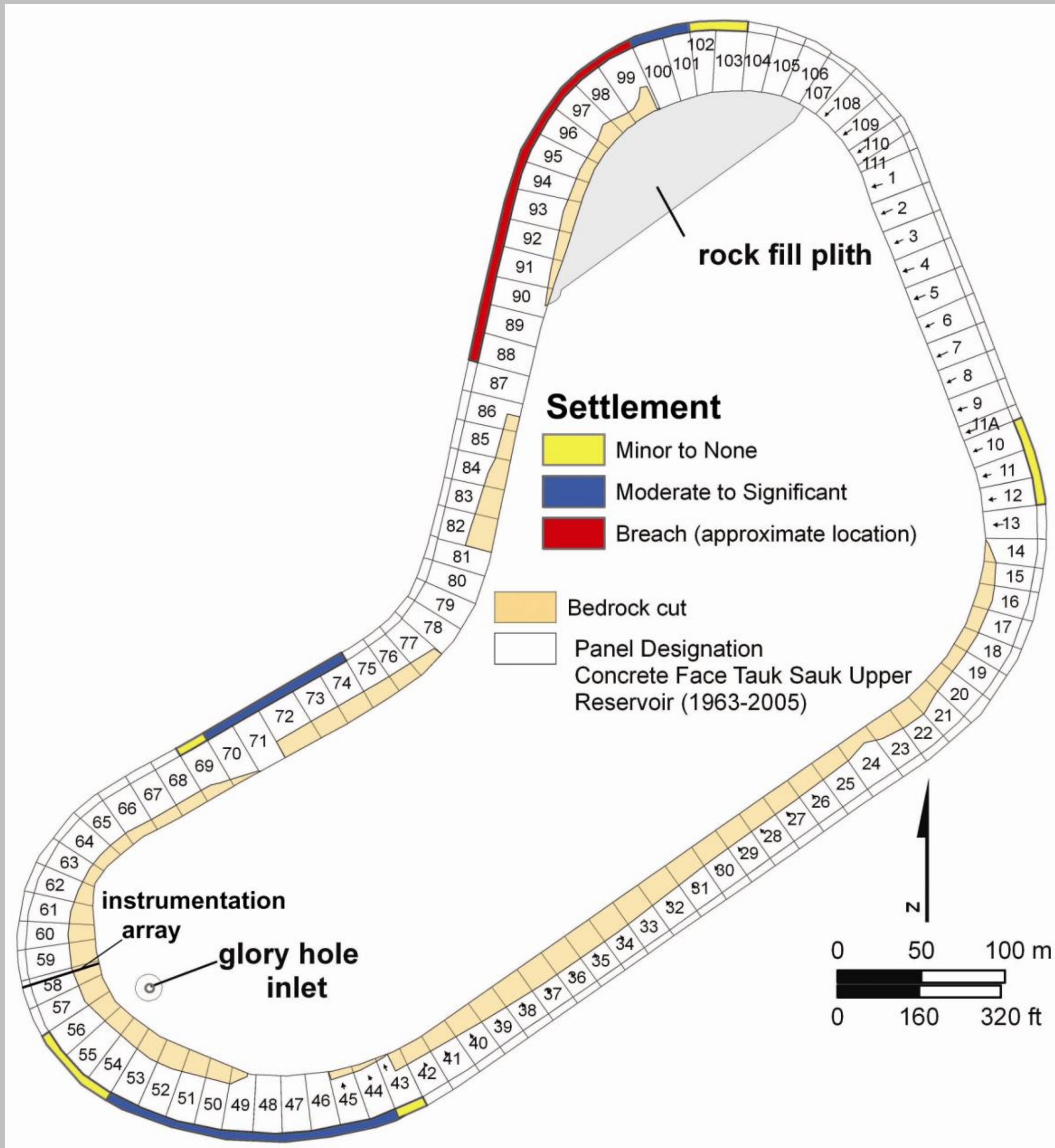
Zones of deeply weathered granite and diabase were exposed on the upper slopes of Proffit Mountain during the flood. Materials similar to this may have ended up in the embankment fill during construction, contributing to its contamination by fines, which led to the high rates of settlement.

This diabase dike (or sill) on the upper slopes of Proffit Mountain weathered to a weak soil-like material, yet retained the rock’s original fabric and fracture pattern.

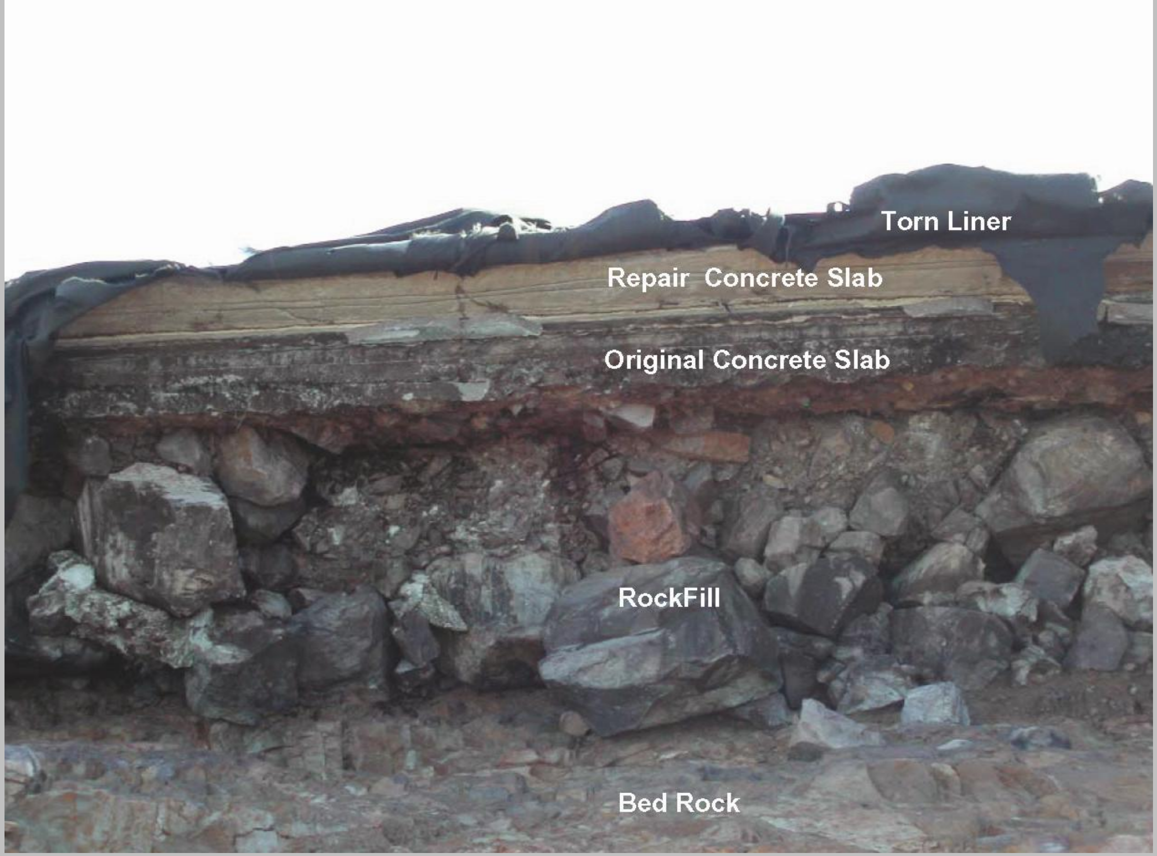
Core stone and remnant spheroidal weathering rind in the saprolite matrix.

INSUFFICIENT FOUNDATION PREPARATION

- **Specifications called for the removal of all soil beneath the rockfill embankment. Any remaining soil should have been no greater than 2 inches in thickness and '*well saturated*' before placement of the rockfill.**
- **Up to 18" of native residual soil was found beneath the embankment during drilling.**
- **This may have contributed to the shifting/settlement of the embankment and likely resulted in lower strengths at the rocfill/foundation interface.**



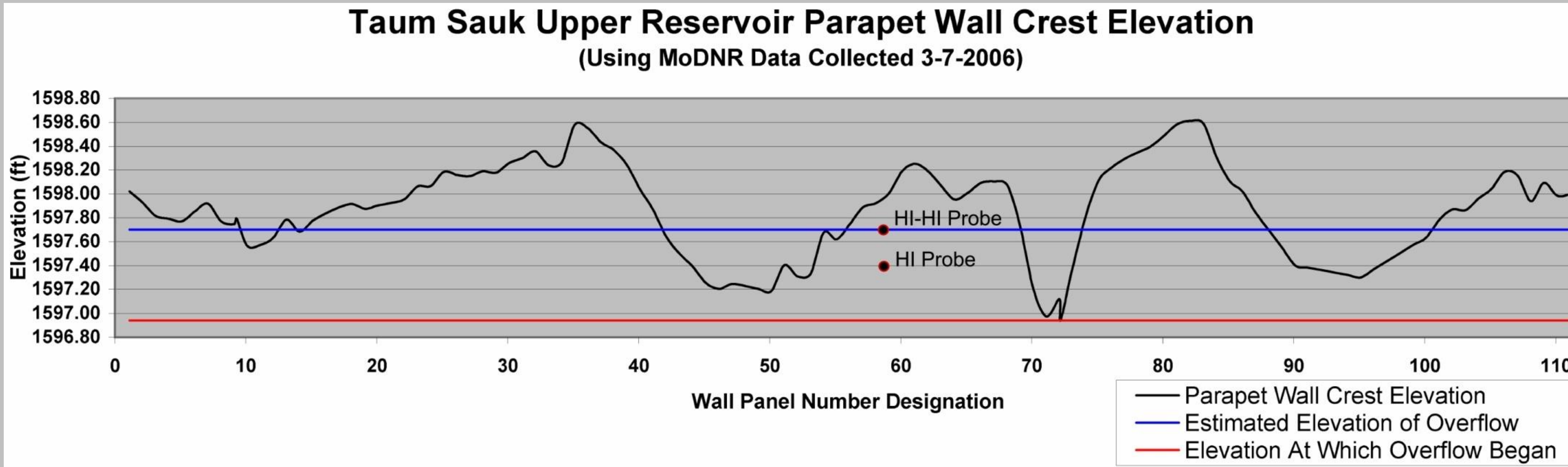
- **The most nagging leakage and settlement problems were at Panels 89-107 in 1963-64, in the vicinity of the 'rock fill plinth.'**
- **The cut-fill wedge at the northwest corner of the reservoir, which experienced extra-normal settlement. This area should have been overexcavated and replaced.**



- Rockfill exposed in the plinth beneath the northwest corner of the Upper Reservoir.
- Several feet of clean rockfill were placed over the rhyolite bedrock, then covered with a 4-inch thick asphalt liner, which failed miserably under uplift when the reservoir was initially filled in 1963.
- The asphalt was replaced by several generations of reinforced concrete mats in 1963 and 1964, which were subsequently covered by the HDPE geomembrane liner in 2004.

Much of the residual soil cover and organic debris (shown here) was left in-place, beneath the northwest corner of the reservoir, and exposed *after* the failure.

DIFFERENTIAL SETTLEMENT OF THE RING DIKE



- **This figure illustrates the differential settlement along the crest of the upper reservoir parapet wall and the positions of the Warwick probes at the parapet wall at Panel 58.**
- **Four segments of the parapet wall were almost two feet (61 cm) lower than their original elevation.**
- **The elevations of the breached Panels (shown here in red) were estimated by AmerenUE after the failure (data from MoDNR, 2006).**

Settlement of the rockfill dike during first five years of operation

- **In the first 4.5 years of operation the Taum Sauk embankment settled 0.50 to 0.80 ft; between 0.53% and 0.73% of the embankment height.**
- **In 1967, J. Barry Cooke noted that the observed settlements were without precedent for a rockfill embankment, concluding that "*frequent zones of soft weathered rock"…"could not have been selectively wasted"* and that *"I believe that a fill of 100% competent rock would have stabilized and that the percentage of weathered rock in the Taum Sauk is the cause."***
- **According to Cooke's 1967 review, the average settlement of 0.1 ft/year during the first 4-1/2 years was unexpectedly high and "*without precedent*."**

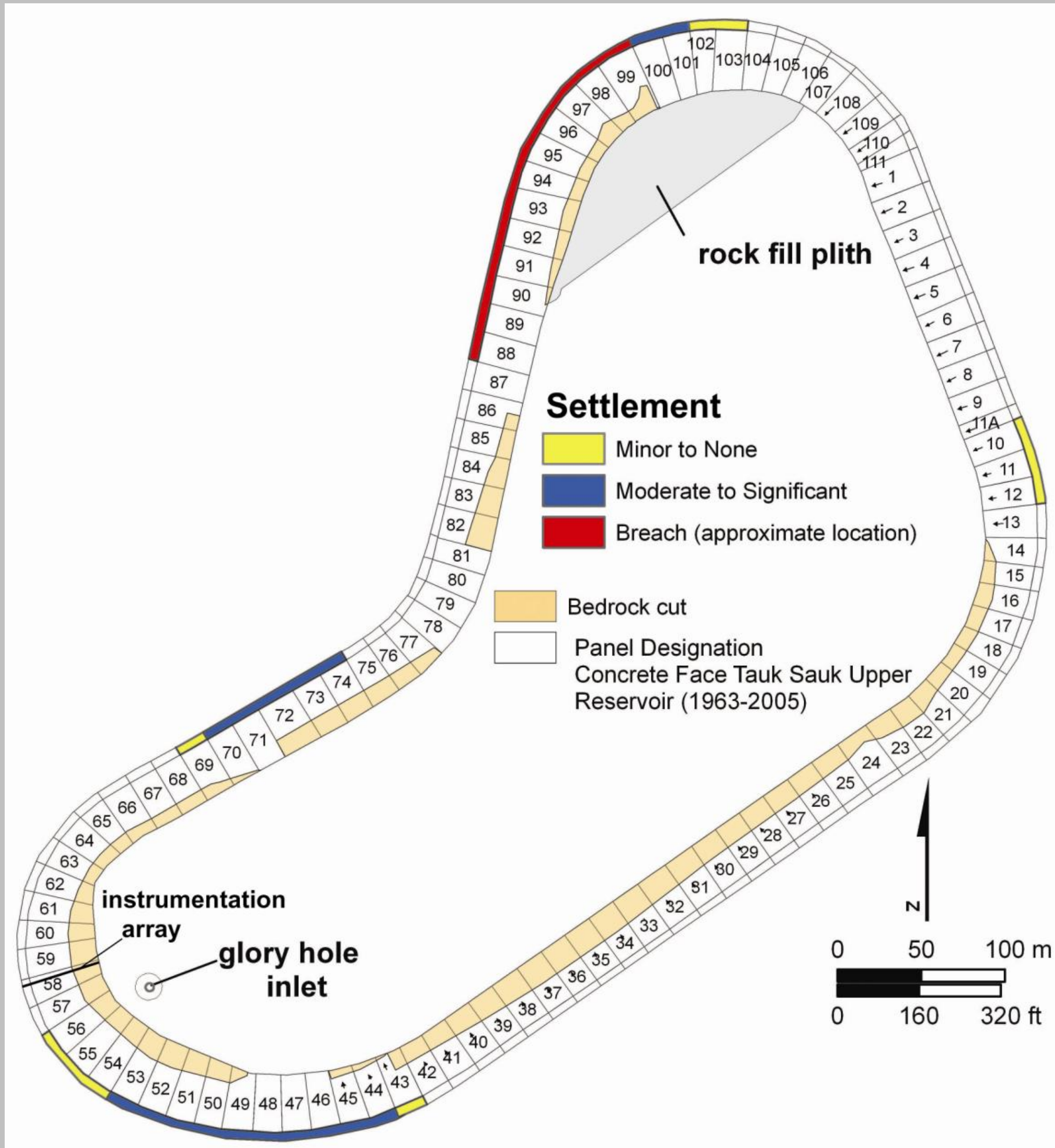
ELEVATION DISCREPANCIES INTRODUCTED DURING THE 2004 LINING/UPGRADE

- The upper reservoir was designed to have 2 feet freeboard, from the water surface to the top of the parapet wall.
- The staff gauge re-attached to the inside of the concrete parapet wall in 2004 had previously settled ~1 foot, but this was not verified by onsite survey. This was because the office engineers simply assumed that the crest elevation (1598 ft) shown on the design drawing was valid, and did not consider the impacts of dike settlement.

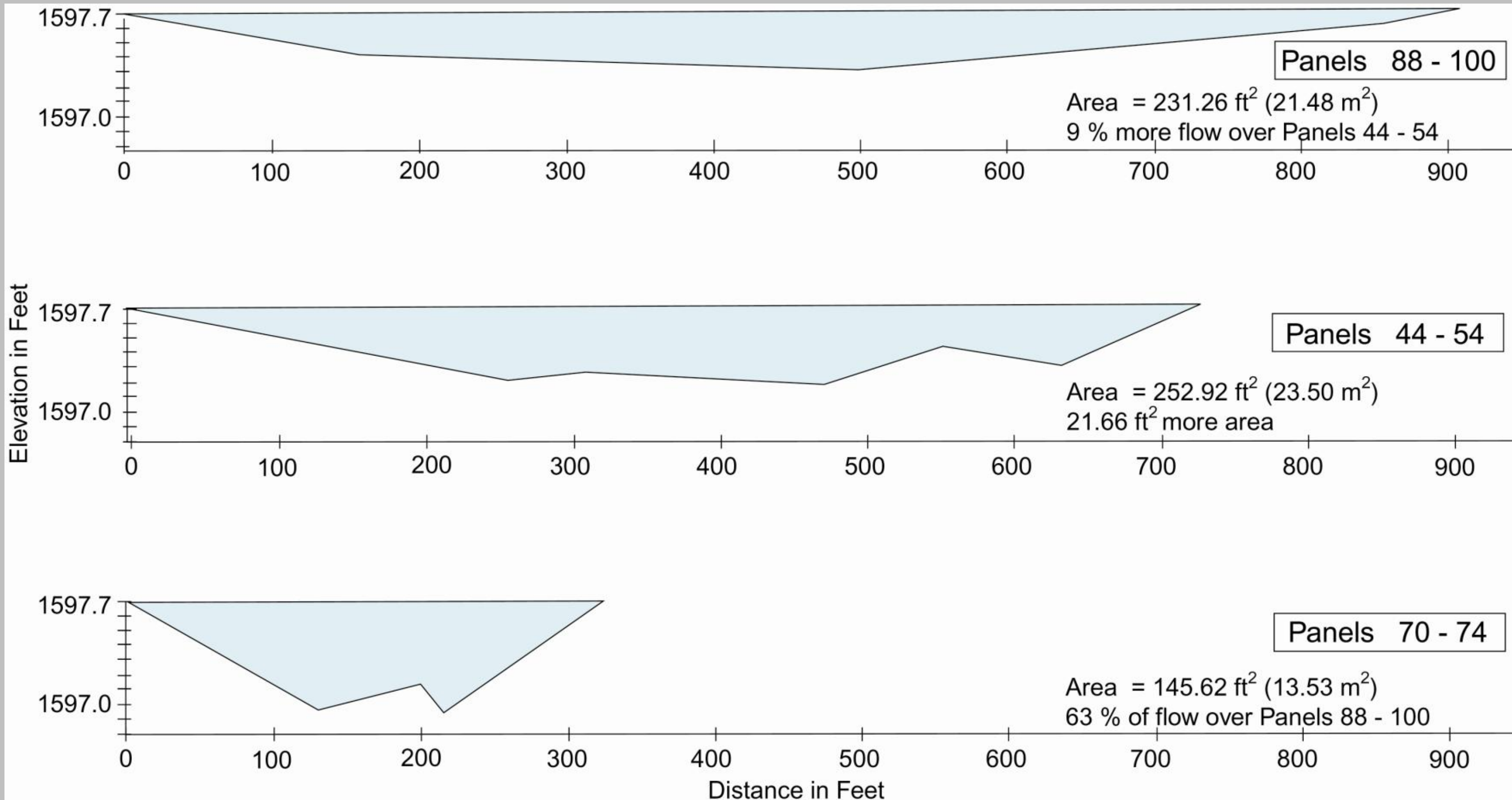
MORE ELEVATION DISCREPANCIES

- The old gauging system had been operated relative to the staff gage affixed to the parapet wall, so the freeboard remained constant throughout the years, even though the dike settled up to 2.2 ft. in other areas.
- The NEW gauging system was operated in terms of absolute elevation, which was 1’ higher than the elevations stated on the staff gage. This resulted in a 1’ reduction of freeboard, without the operator’s knowledge.

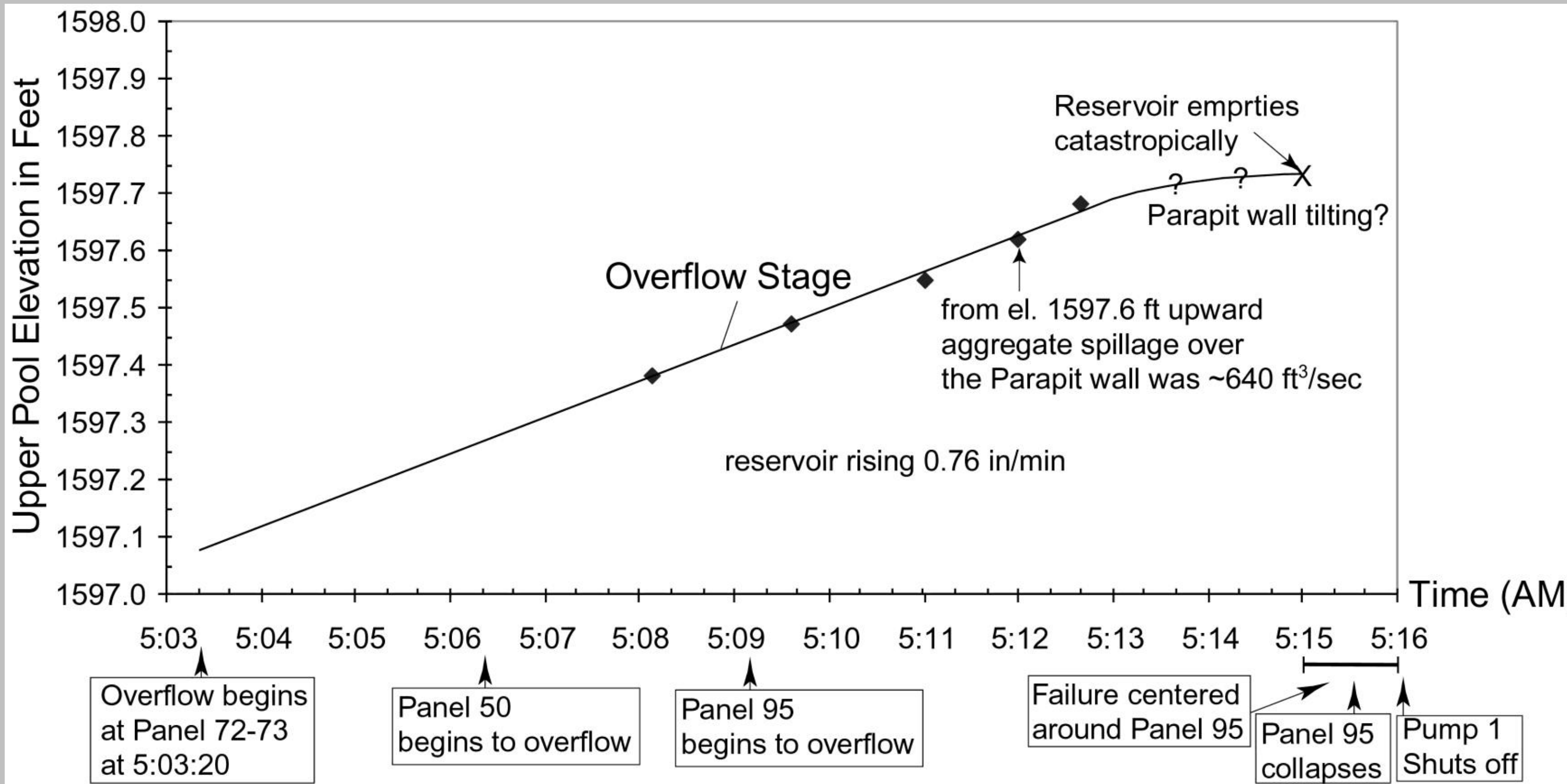
PREFFERENTIAL SURFICIAL EROSION OF THE UPPER EMBANKMENT



- **Plan view of Taum Sauk Upper Reservoir, showing all 111 concrete panels lining the inside face of the circular dike, which was capped by a 10 ft (3 m) high cantilever retaining wall.**
- **The colored areas denote those portions of the wall that were overtopped on the morning of Dec 14, 2005.**
- **Note the variable height of cut on the inboard toe of the dike and height of embankment, on the outboard side.**
- **The most nagging leakage and settlement problems were at Panels 89-107 in 1963-64, in the vicinity of the ‘rock fill plinth.’**



- **Comparative cross sections along the crest of the Upper Reservoir between Panels 70-74, 44-54, and 88-101. Note how the greatest cross sectional area and volume of spillage appears to have occurred between Panels 44-54, *not* where the breach occurred, between Panels 88-99.**



- **Reconstruction of Upper Reservoir stage versus time during the interval when the reservoir breached, between 5:03 and 5:16 AM on December 14, 2005.**
- **Note how the three principal zones of spillage began at 5:03, 5:06, and 5:09, with the last zone being the one that undercut the parapet wall first. The wall toppled over just about the same time that the last pump shut down.**

- **Aerial oblique view of the southeastern side of the Upper Reservoir embankment, taken the morning after the failure.**

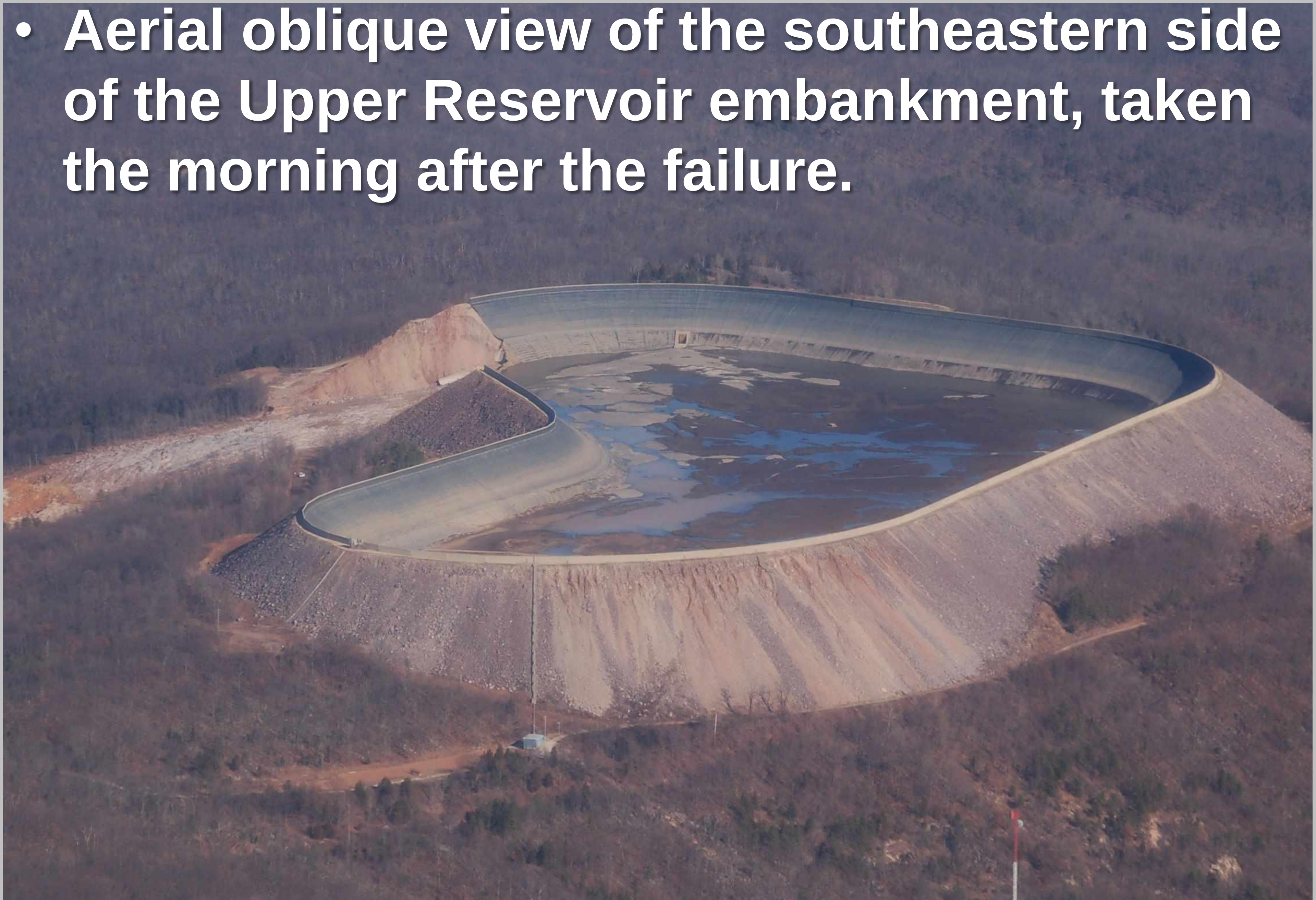
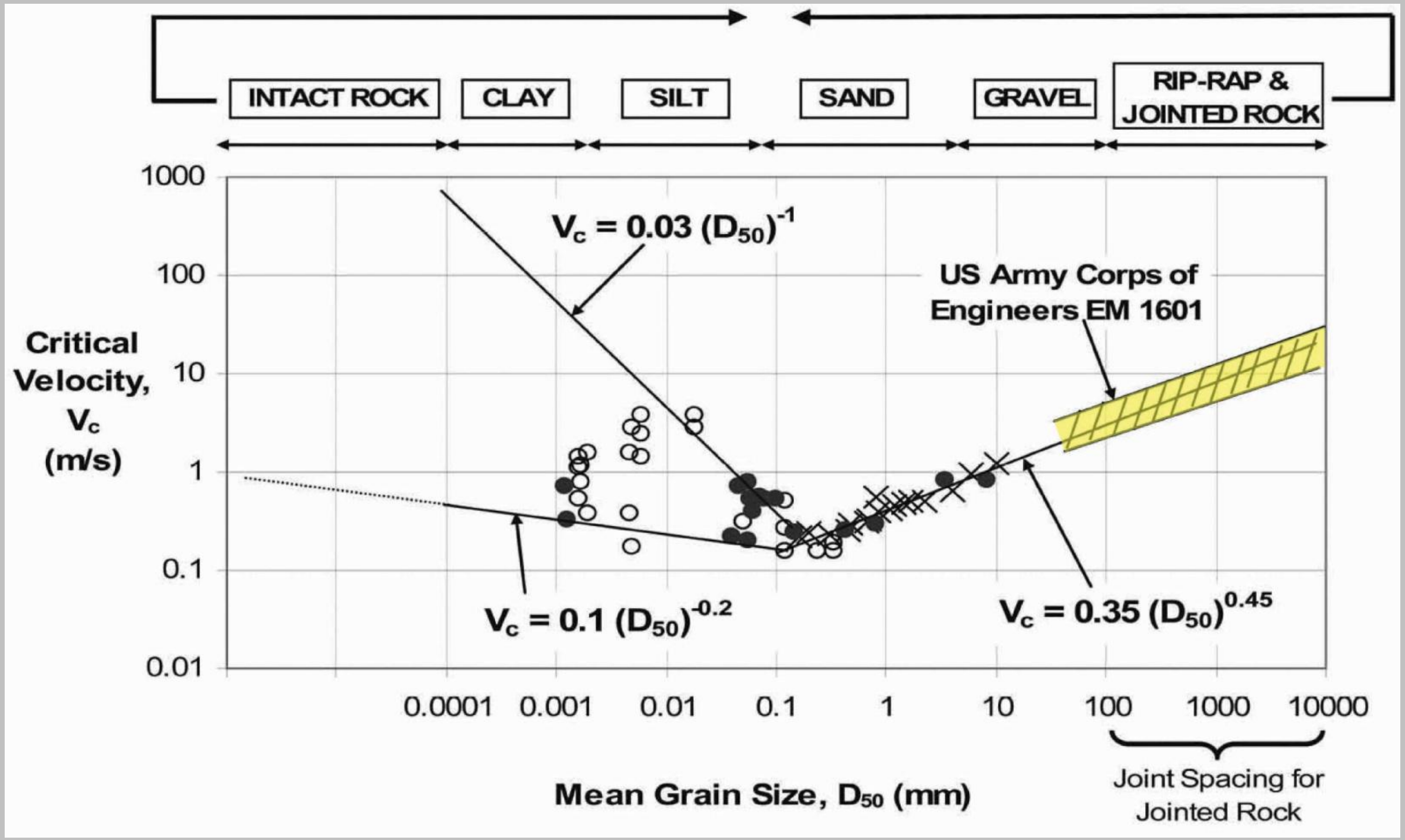


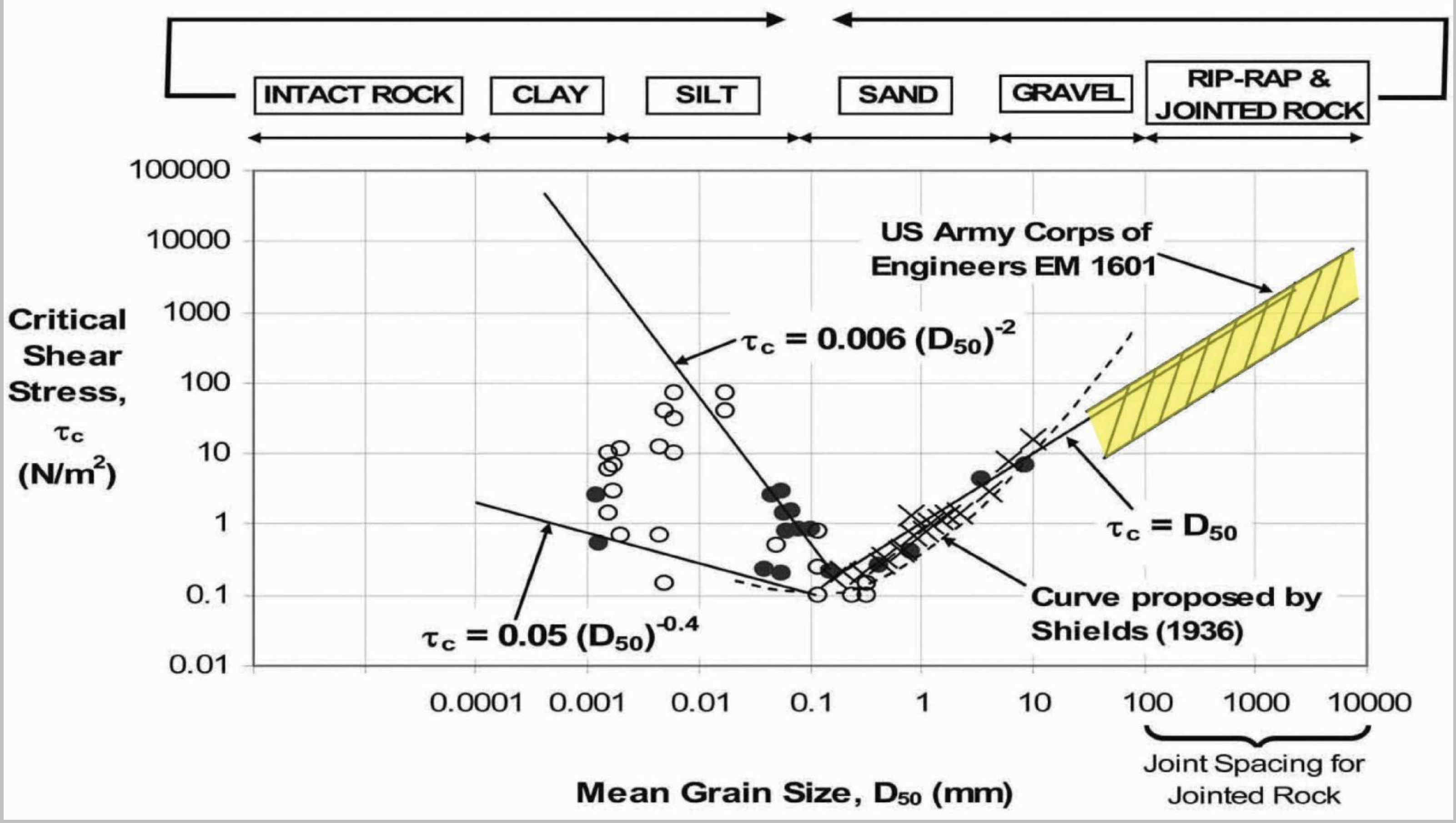
Photo by Jeff Spooner, USGS

- **Extensive erosion of the Upper Reservoir embankment near at Panel 47, on the southeastern perimeter.**
- **Right view shows erosion of the perimeter road to the footing of the parapet wall. Note gunite facing that had been placed on the upper slope to arrest surficial raveling, prior to the failure.**
- **Left view shows the extensive gully erosion in this same area, extending to depths of 15 feet. Note the sluicing of finer grained materials by the large volume of runoff.**

(Photos by David Hoffman)



- Critical velocity triggering erosion versus mean grain size, taken from Briaud (2008).
- The yellow shaded zone represents data for coarse gravel, rip-rap, and jointed rock. Sediment carrying capacity of noncohesive materials like sand and gravel is a power function of velocity.
- Data points from measurements at Texas A&M and Army Corps of Engineers Waterways Experiment Station, described in Briaud (2008).

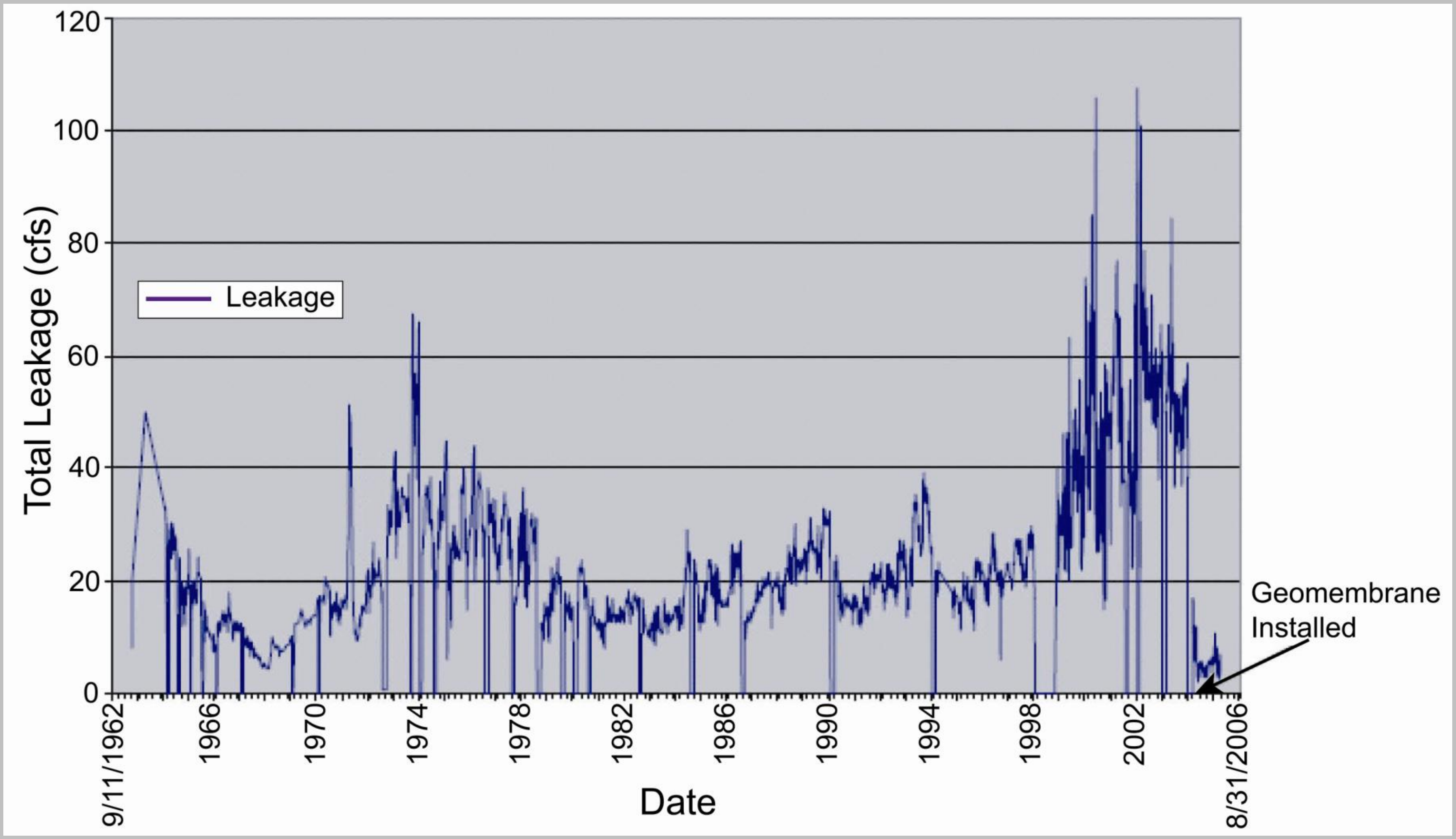


- Critical boundary shear stress as a function of mean grain size, taken from Briaud (2008). The yellow shaded zone represents data for coarse gravel, rip-rap, and jointed rock.
- Data points from measurements at Texas A&M and Army Corps of Engineers Waterways Experiment Station, described in Briaud (2008).

CHANGES TO RESERVOIR STAGE SENSOR SYSTEM DURING THE 2004 LINING/UPGRADE

Upper Reservoir Experienced Persistent Leaks

- Throughout its life, the upper reservoir leaked. This leakage helped provide Johnson's Shut-ins with a steady source of water during dry summers.
- Some leaks were serious and resulted in the shut-down of the plant for repairs.
- Most leaks were related to the cracking of the reinforced concrete liner as the underlying rockfill settled differentially.
- Leakage was reducing the efficiency of the operation by about 2%, so the reservoir was lined with an HDPE geomembrane in fall 2004. This stabilized the seepage losses.



- **Leakage from the Upper Reservoir exhibits a gradual upward trend until the basin was lined in 2004, dramatically reducing seepage losses (FERC Independent Panel of Consultants Report, 2006).**

In 2004 AmerenUE installed an HDPE geomembrane liner to retard ongoing seepage losses from the upper reservoir, at a cost of ~$2.4 million.

GSI supervised the placement of 1.3 million square feet of 80 mil HPDE textured geomembrane and geocomposite material. They also covered five rock outcroppings on the side slope with 80 mil textured LLDPE material.

- The reservoir stage sensors were comprised of the four perforated HDPE conduits shown here; two were to hold pressure transducers, one was an extra, and one was to be filled with concrete as ballast. This was to be anchored to the liner using welded HDPE straps.

- The liner contractor pointed out that this design would reduce the performance and life of the liner and suggested that some alterations be made.

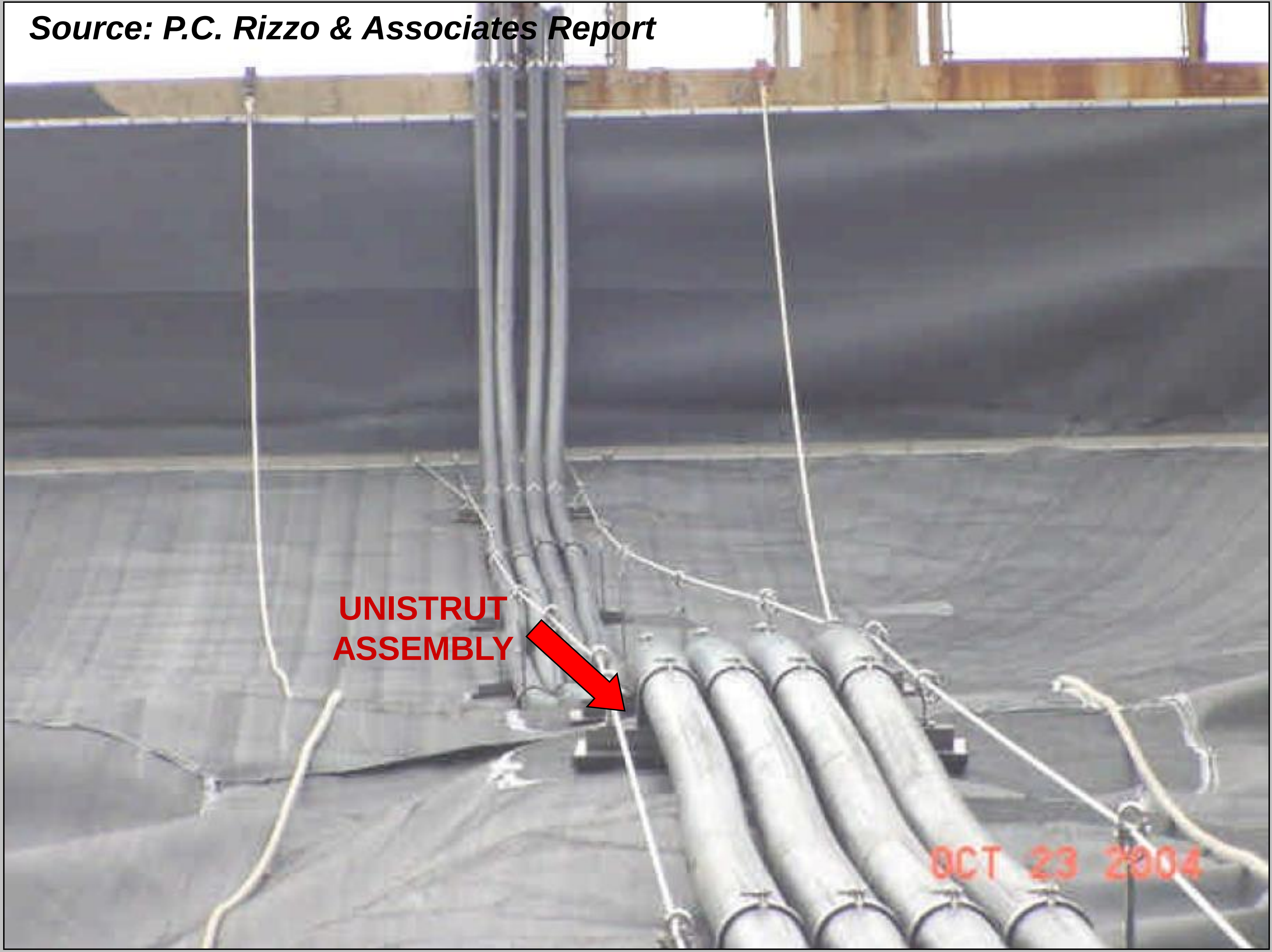
Eye Bolt

Turnbuckle

- **An untensioned steel cable was to be anchored to the top and bottom portions of the concrete lining with eye bolts, like that shown left above. The concrete ballast pipe was removed. Since a fourth pipe was already on site, it was installed as a spare, without any ballast.**
- **During placement, the eye bolts were discarded in favor of turnbuckles (right above), so the steel cable could be tensioned. 1). During the twice-daily filling and emptying of the reservoir, the turnbuckles loosened and allowed the sensor tubes to work themselves free. 2). The omission of a ballast pipe allowed the sensor tubes to deflect much more easily.**
- **These attachment details were not subjected to external peer review. Last minute connection details often prove to be problematic.**

FAILURE OF THE UNISTRUT ASSEMBLIES

- **The four sensor pipes were held bound together by four U-bolts, fastened to a piece of hardware called a *unistrut*. This hardware came apart as the turnbuckles loosened, allowing the pipes to separate. This reduced the cumulative stiffness of the pipe group, allowing them to deflect more easily under the twice-daily cyclic loading of the reservoir filling and draining.**



Sensor pipe array emplaced at Taum Sauk Upper Reservoir in 2004

Detached UNISTRUT Assemblies and deflected sensor conduits – as seen after the failure

Source: David Hoffman

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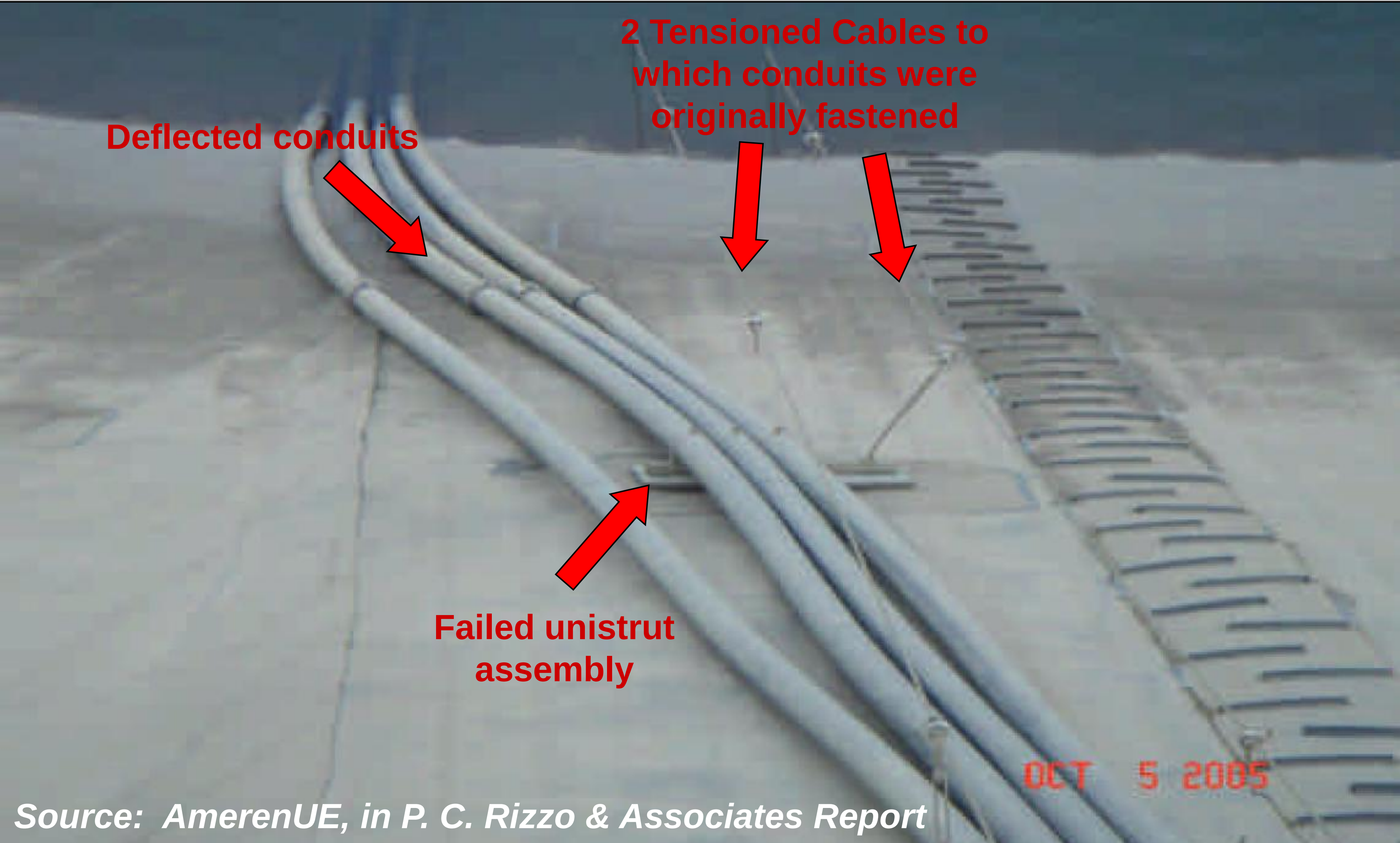
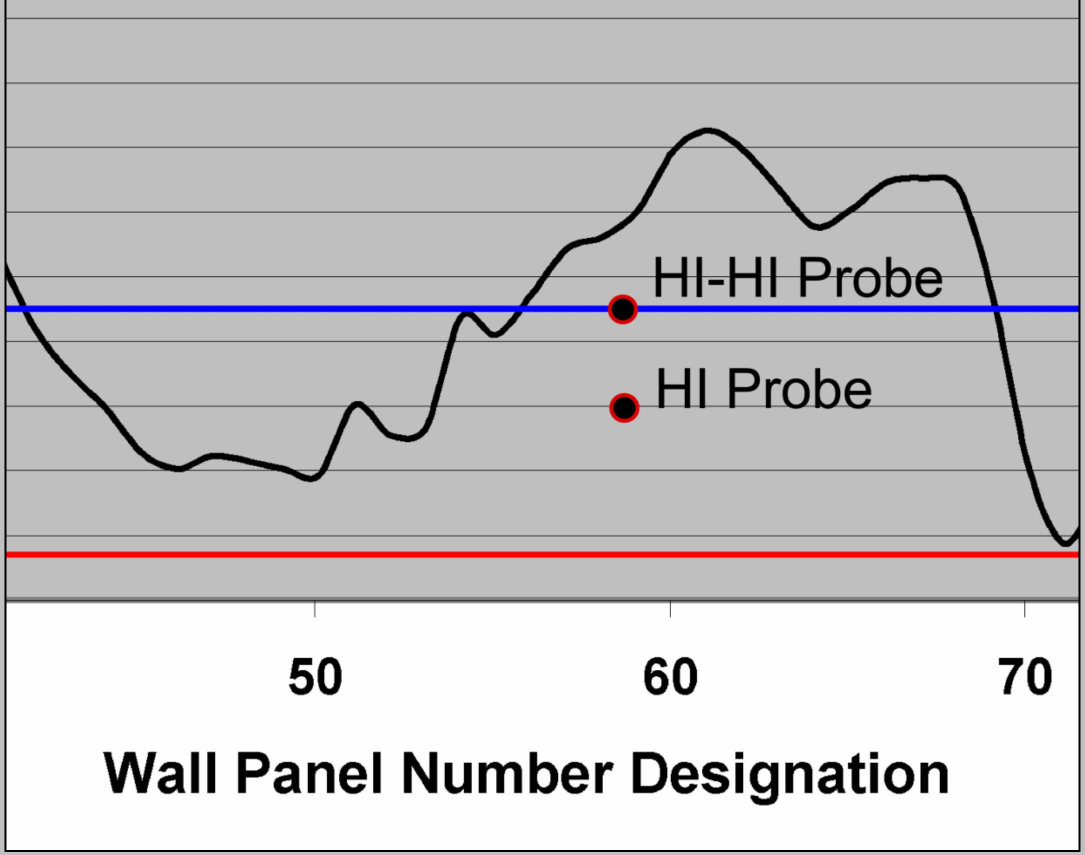
- The 35 ft diameter glory hole entry to the 25 ft diameter feeder line was located about 120 ft from the base of the instrumentation ducts.

Detached Unistrut assembly and deflected sensor conduits-as seen 2-1/2 months before the failure



Source: AmerenUE, in P. C. Rizzo & Associates Report

“FAIL SAFE” PROBES LOCATED TOO HIGH



- The upper reservoir included so-called fail-safe probes, intended to automatically shut down inflow if the reservoir stage monitoring system in the reservoir malfunctioned.
- Due to the wrong assumed elevation of the parapet wall (due to the differential settlement of the embankment), in 2004 these probes were fixed **ABOVE** the lowest crests of the parapet wall at other locations around the reservoir (which had dropped < 1598 ft).

- **The reservoir level was observed to have risen within 4 inches of the wall crest two days after the "Niagara Falls" overtopping (Sept 25th), and the fail-safe shut off probes failed to activate.**
- **Some wetness on the parapet walls indicated minor overtopping.**
- **The maximum level of these fail-safe probes was then lowered, but the reservoir stage conduits continued to deflect, so that sufficient freeboard was lost by the time of the fatal overtopping on Dec. 14th.**

CONCLUSIONS
PRIMARY FACTORS THAT TRIGGERED THE FAILURE

Primary Factors - 1

- 1. Failure to include an overflow spillway of some kind during the design process would seem to have been a naive presumption. It assumed that instrumentation would never malfunction, for any reason, such as aging or unforeseen circumstances.
- This shortcoming was pointed out in the first FERC peer review in 1967.

Primary Factors - 2

- 2. Continued operation of the plant when it was obvious that the sensors were malfunctioning. Safety should never be sacrificed in deference to business or convenience. Had the failure occurred 6 months later, it could have killed more than 1000 people.
- The owner also failed to notify the Federal Energy Regulatory Commission (FERC) of the instrumentation problem. FERC stated they would not have allowed continued operation of the facility until proper repairs had been effected.

Primary Factors - 3

- The impact of the differential settlement of the dike should have been appreciated by whoever was responsible for reservoir stage instrumentation. The dike is only as "high" as its lowest elevation; not the crest elevation where the instruments are located.
- Aging impacts are the most difficult to appreciate and/or anticipate. Hidden design and construction flaws caused operational and maintenance difficulties.
- The overflow incidents on September 25th and 27th should have triggered an active monitoring program at the very least, to ascertain whether the problem was worsening with each cycle of filing.

Primary Factors - 4

- The principal contributing factors appear to have been a series of ***critical component failures,*** which were accompanied by successive errors in managerial judgment. Ameren did not have a dam safety program in place.
- It only took 6 minutes of malfunction to foment the catastrophe.
- Critical engineering systems should employ ***sufficient redundancy*** to survive the failure of any single component facet, without suffering a catastrophic failure.

This lecture will be posted at

www.mst.edu/~rogersda/dams

in .pdf format for easy downloading and use by others.

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