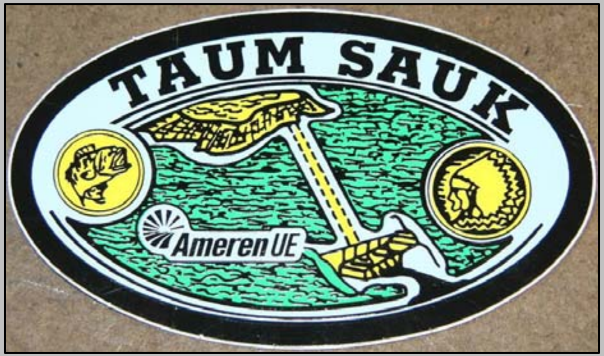
Water over the dam…

OVERVIEW OF THE TAUM SAUK UPPER RESERVOIR FAILURE

December 14, 2005

Reynolds County, Missouri



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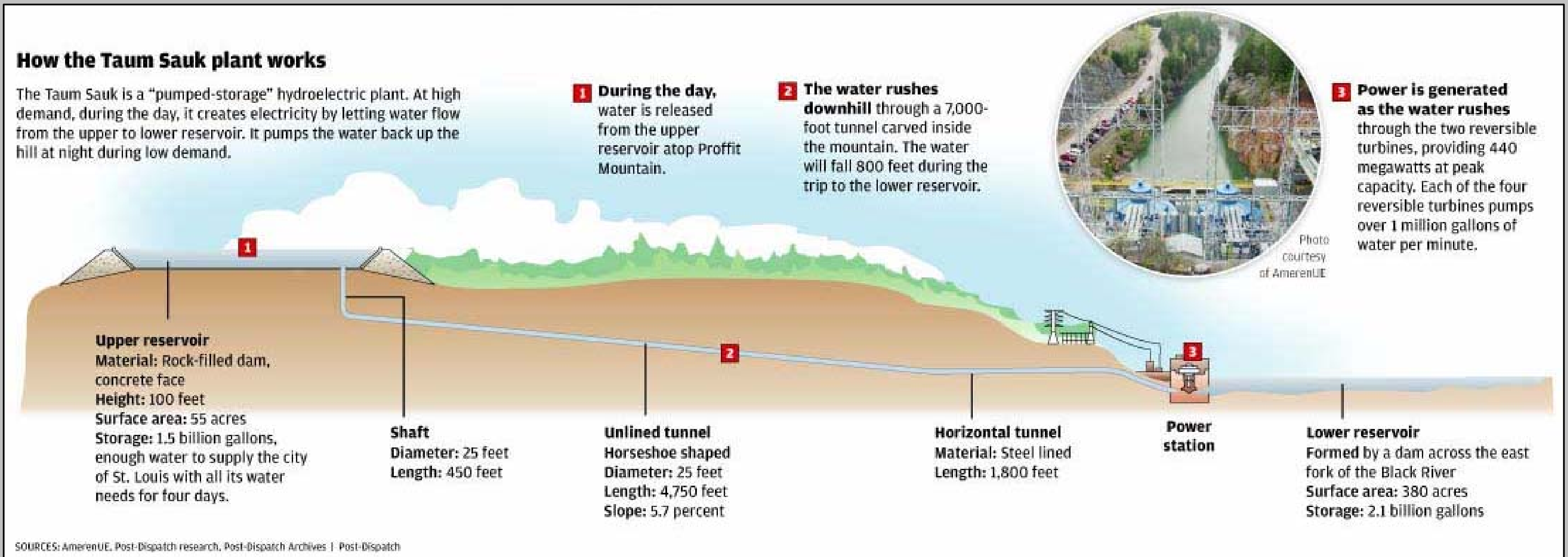
University of Missouri-Rolla

The Taum Sauk Pumped Storage Hydroelectric Plant's Upper Reservoir stored 1.5 billion gallons (~4600 ac-ft) of water.

PUMPED STORAGE SCHEME

- **Although the plant actually used more electricity than it generated, it served as a giant battery to store electricity generated at night that was required to maintain stability of the power grid, precluding wastage of this power.**
- **The plant generated power during daylight periods of peak demand, thereby reducing demand on primary generation plants.**
- **Upgrades and modifications to the plant continued through its life, increasing its operational efficiency to about 70%.**



The Taum Sauk project was designed and constructed by Fru-Con Construction Corporation of Clarkson Valley, Missouri.

- It was was one of the first pumped storage projects in the United States when it went into service in 1963.
- The lower storage reservoir was situated on the East Fork of the Black River, just downstream of Johnson’s Shut-ins State Park.
- Water was pumped uphill through a 7,000 ft long tunnel to the upper reservoir, an 800 ft lift.

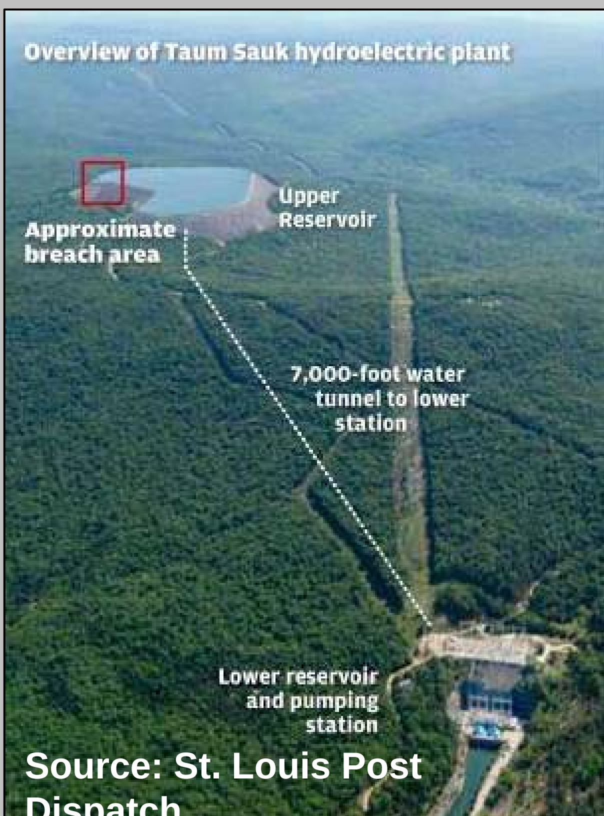
Layout and Proximity of the Upper and Lower Reservoirs

Source: Google Earth

Deregulation likely played role in trying to maximize utilization

- Prior to the deregulation of the electric power industry in the mid-1990's, Taum Sauk was operated approximately 100 days a year, mostly during the hot summer months.
- After 1995, power was allowed to be sold on the spot (open) market at non-regulated rates, making it profitable to operate Taum Sauk year-round. This provided an incentive to shut the plant down as little as possible.
- The generator/pump units were replaced in 1999 with increased capacity and more efficient units to increase profitability of the plant. Maximum output was increased from 350 MW to 440 MW.

The two generating units produced 440 Megawatts of power for up to eight hours before the upper reservoir emptied. As pumps, the two units could push up to 5,258 cfs into the upper reservoir through a 25 ft diameter conduit, an amount equivalent to the average flows of several Ozark rivers combined!

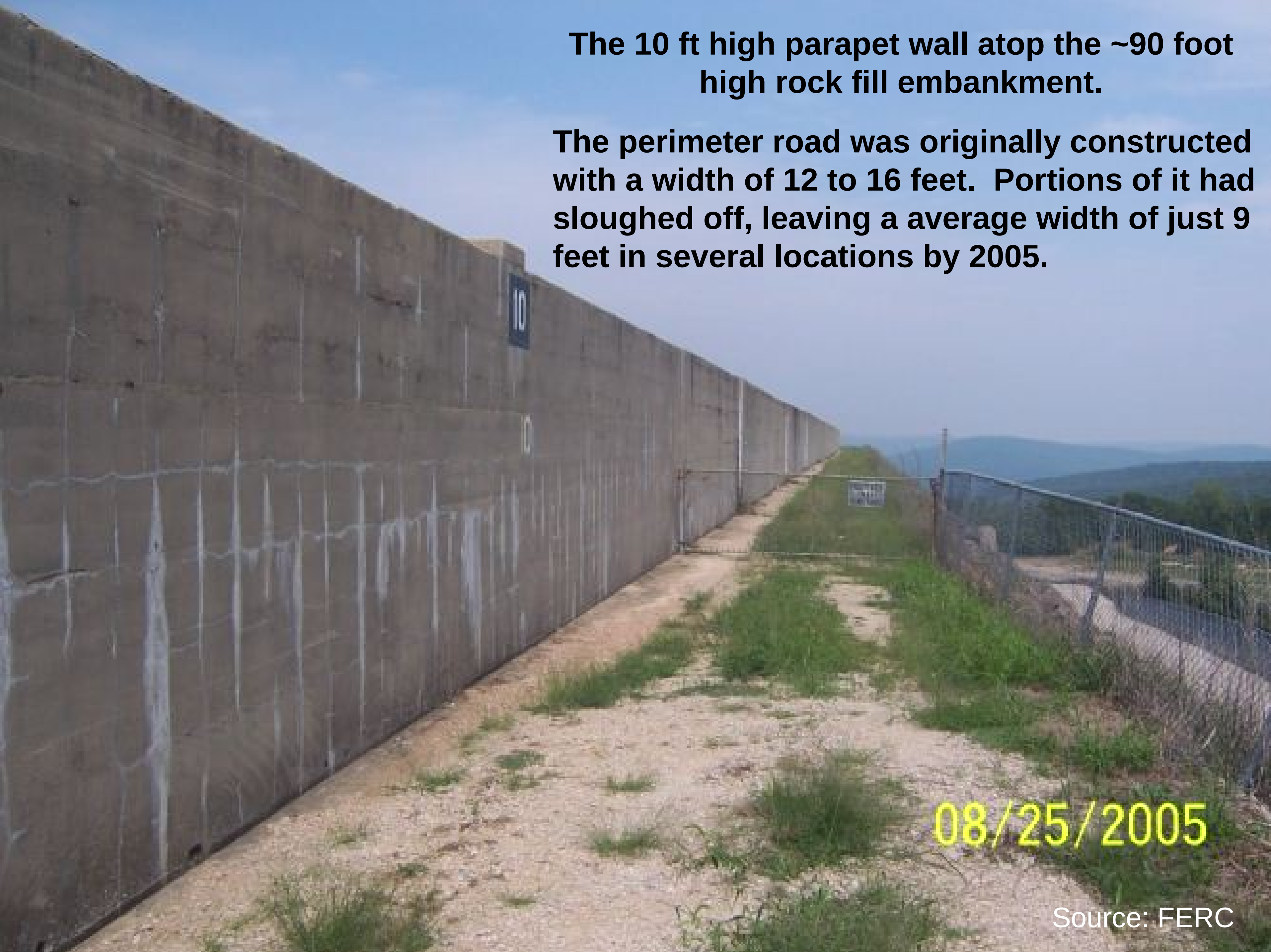


Source: St. Louis Post Dispatch

Source: FERC

The Upper Reservoir

- The upper reservoir was a ~90 foot tall rock fill embankment end-dumped and sluiced (to remove fines) and capped by a 10 foot tall concrete parapet wall and lined with reinforced concrete.
- Held 1.5 billion gallons (~4600 acre-feet) of water when completely full.
- Kidney-shaped dike was 6562 ft long.
- Sat 800 vertical feet above level of lower reservoir atop Proffit Mtn.
- No accommodation for spillage.


The 10 ft high parapet wall atop the ~90 foot high rock fill embankment.
The perimeter road was originally constructed with a width of 12 to 16 feet. Portions of it had sloughed off, leaving a average width of just 9 feet in several locations by 2005.
10
08/25/2005
Source: FERC

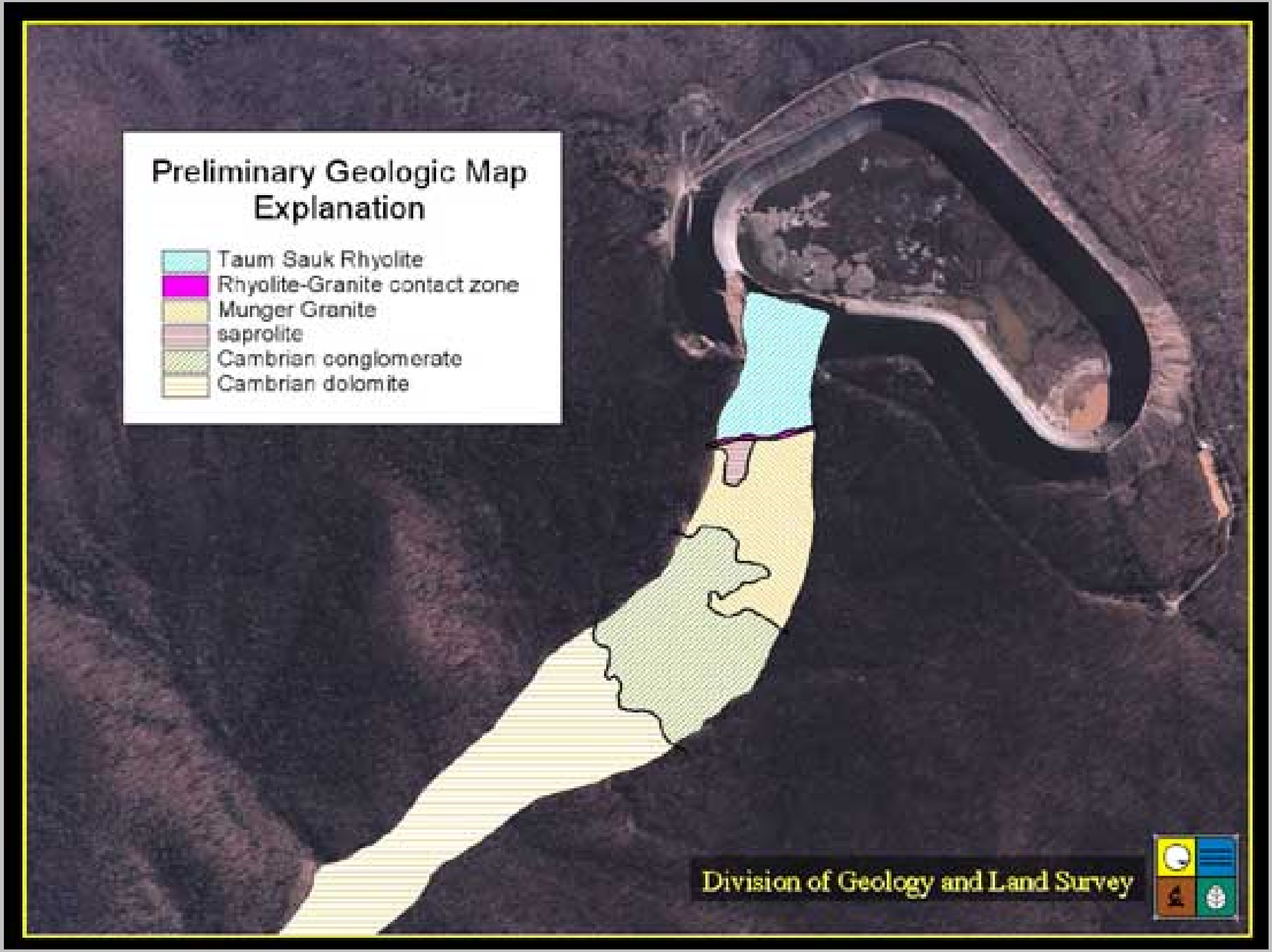
View across full Upper Reservoir

The upper reservoir held 1.5 billion gallons (~4,600 acre-feet) when filled. The pumps were originally programmed to allow two feet of freeboard against the 10-foot high parapet wall, seen here as the dark line between the water and the skyline.

Source: FERC

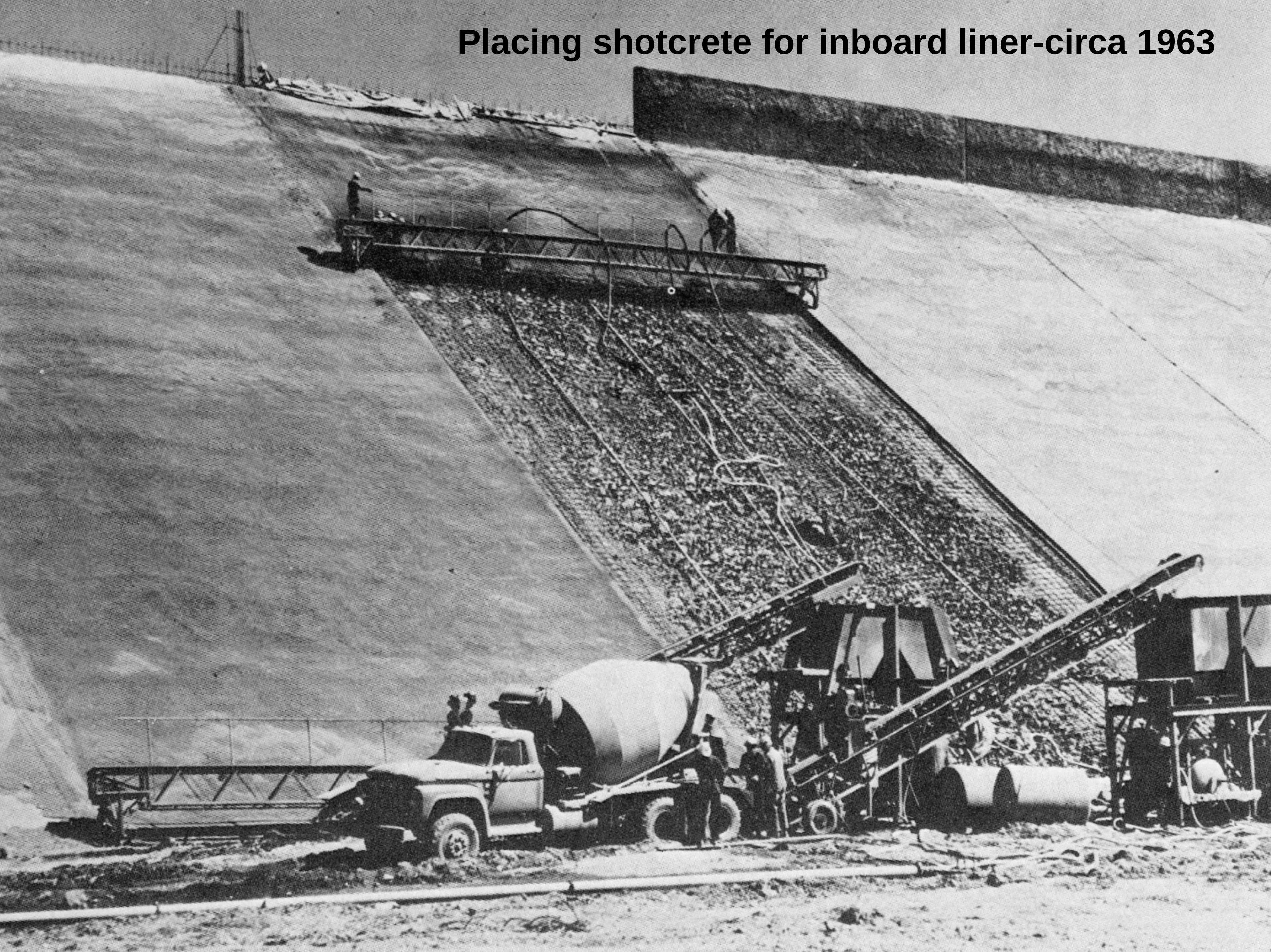
Geologic Setting and Construction

- The Taum Sauk Pumped Storage Hydroelectric Plant is located in in the St. Francois Mountains, about 50 mi SW of St. Louis.
- These mountains are underlain by Precambrian igneous knobs with margins draped in Cambrian & Ordovician sedimentary rocks, mostly carbonates.
- The Ozarks were not glaciated during the Pleistocene, allowing for the development of of deep weathering zones and extensive residuum.
- The steep topographic relief of this area made it attractive for pumped storage schemes.
- The lower reservoir was formed by damming the East Fork of the Black River near Lesterville, MO.
- The upper reservoir was constructed upon Proffit Mountain. The resulting materials were used to form a kidney shaped dike about 90 feet high, storing ~4600 ac-ft of water.



- **Geologic units exposed along path of the outbreak flood.**

Placing shotcrete for inboard liner-circa 1963



Most of the reservoir floor area was excavated into the underlying rock, in places, as much as 40 feet. The one exception was the northwest corner, where the presence of highly weathered rock required overexcavation. This is where the reservoir eventually failed.

OVERTOPPINGS PRIOR TO DECEMBER 2005 FAILURE

The “Niagara Falls” incidents of September 25th and 27th

The Institute of Electrical and Electronics Engineers (IEEE) Declares The Taum Sauk Plant An *Engineering Milestone* on September 26, 2005

The plant was recognized for:

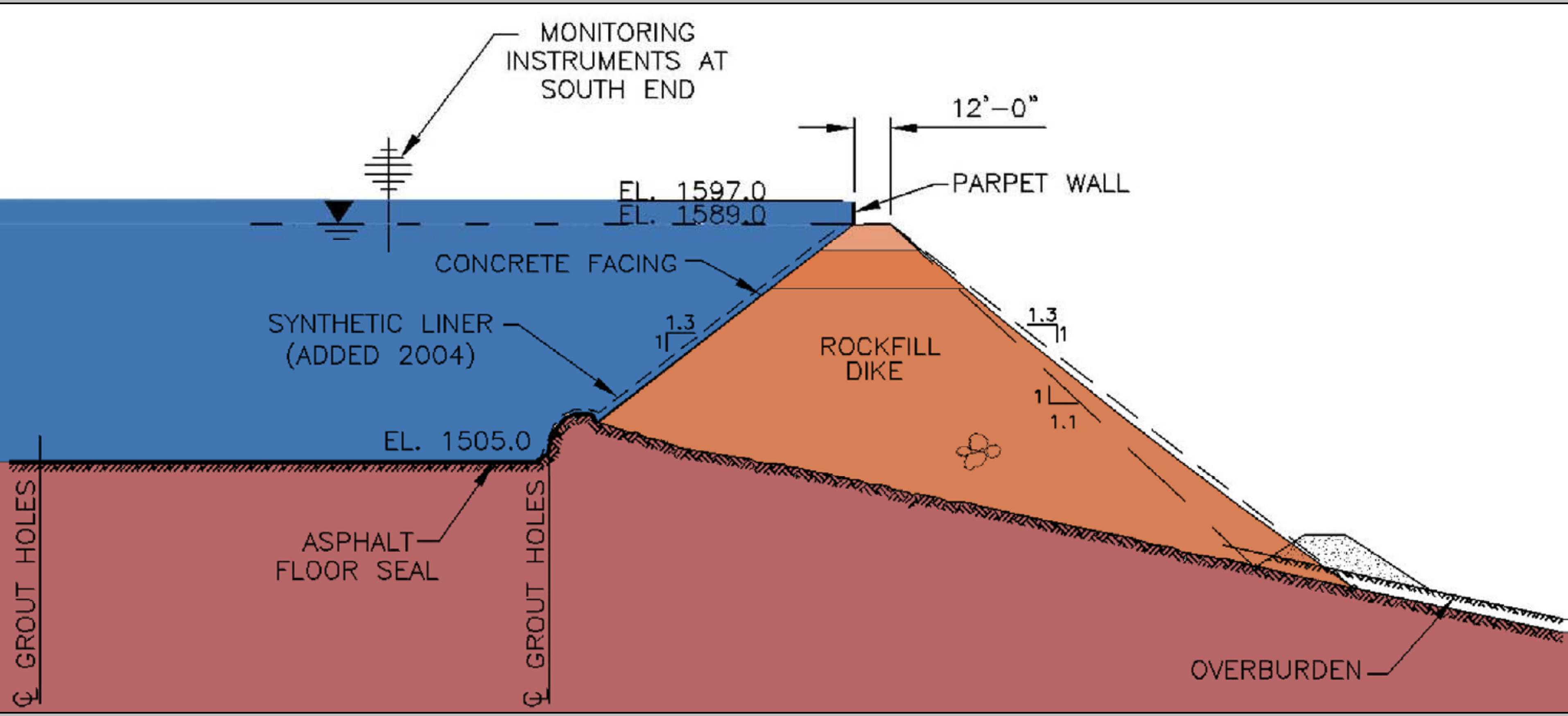
- **The plant was the largest in North America and one of the first of its type when it was constructed in 1963.**
- **Used high capacity turbine generators/pumps.**
- **Ability to be run remotely from St. Louis or Osage/Bagnell Dam Power Plant or automatically WITHOUT HUMAN INTERVENTION.**
- **Ability to help restart the power grid in the event of a complete blackout as coal and nuclear plants need outside power to start.**
- **Only ~75 engineering projects worldwide have received this award.**

- **Plant operators first experienced trouble with upper reservoir water levels on September 25, 2005, as they were preparing the facility for the awards ceremony to be held the next day. A large quantity of water was observed pouring over the NW portion of the reservoir wall in what was described as "Niagara Falls." Inspections revealed scour up to 1' deep.**
- **Pumps were manually turned off and the generators turned on to lower the reservoir level. Operators warned of catastrophic failure if such an occurrence was repeated and maximum water levels were reduced by 3 feet by recalibrating the controls.**

Warnings Sent By Plant Operator After Second Overtopping on Sept. 27, 2005

- **Water levels were observed 4" from the top of the parapet wall two days after the initial incident and wetness on the outside of the panels indicated minor overtopping occurred that morning.**
- **Richard Cooper, Plant Operator, sent an e-mail to his supervisors warning about continued overtopping of the upper reservoir after the second incident.**
- **"*Overflowing the upper reservoir is obviously an absolute 'NO-NO,'*"**
- **"*The dam would severely erode and cause eventual failure of the dam. Those kinds of headlines we don't need.*"**
- **If water continued to spill over the top of the wall, it could cause a section to collapse and "*then it would be all down hill from there — literally.*"**
- **Divers were summoned and they ascertained that the new sensor conduits were loose at the bottom of the reservoir. Maximum water levels in the reservoir were reduced by 3 feet to provide a margin of error. Permanent repairs would be postponed until regularly scheduled maintenance to avoid an additional shutdown of the facility.**

As - Built Section

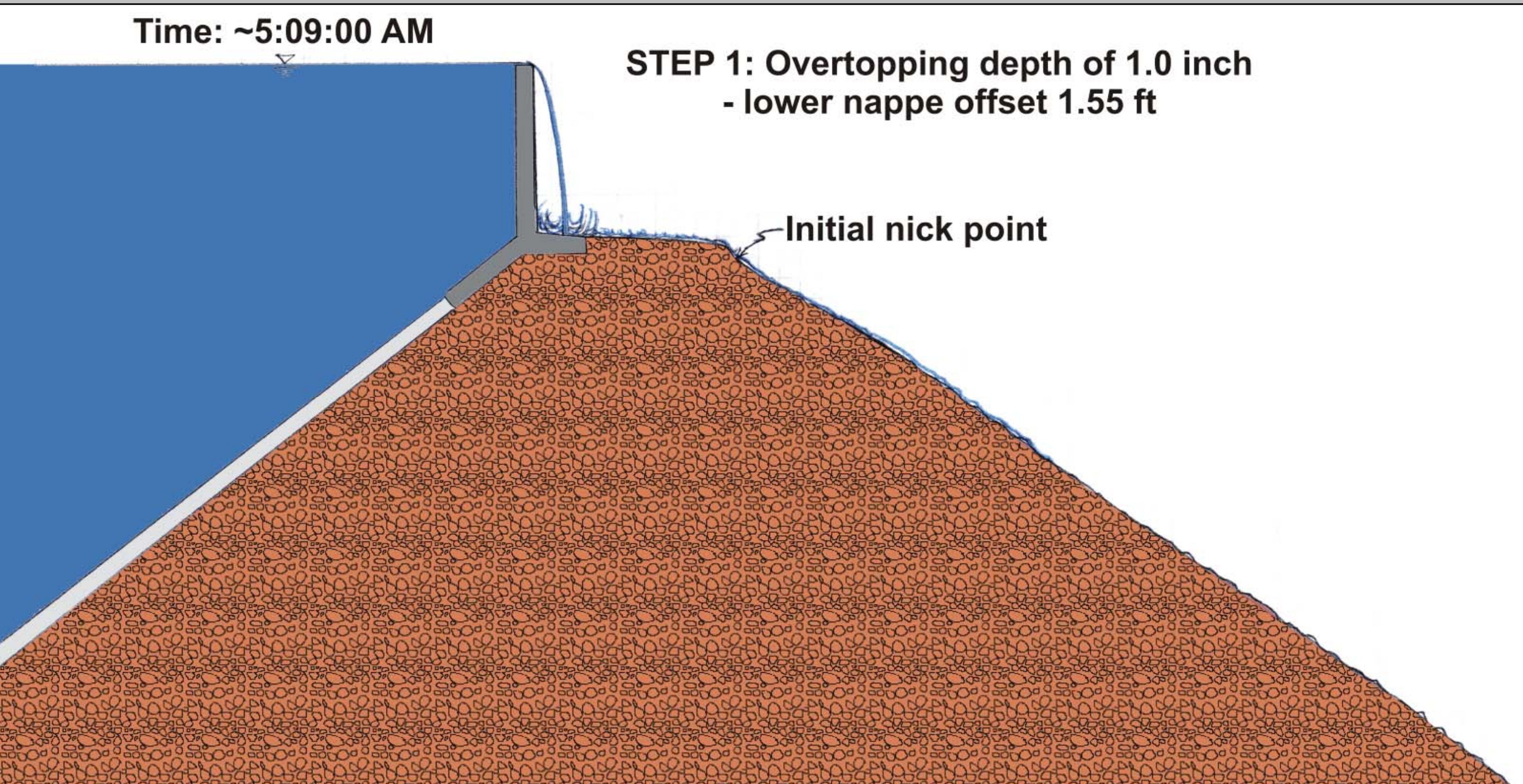


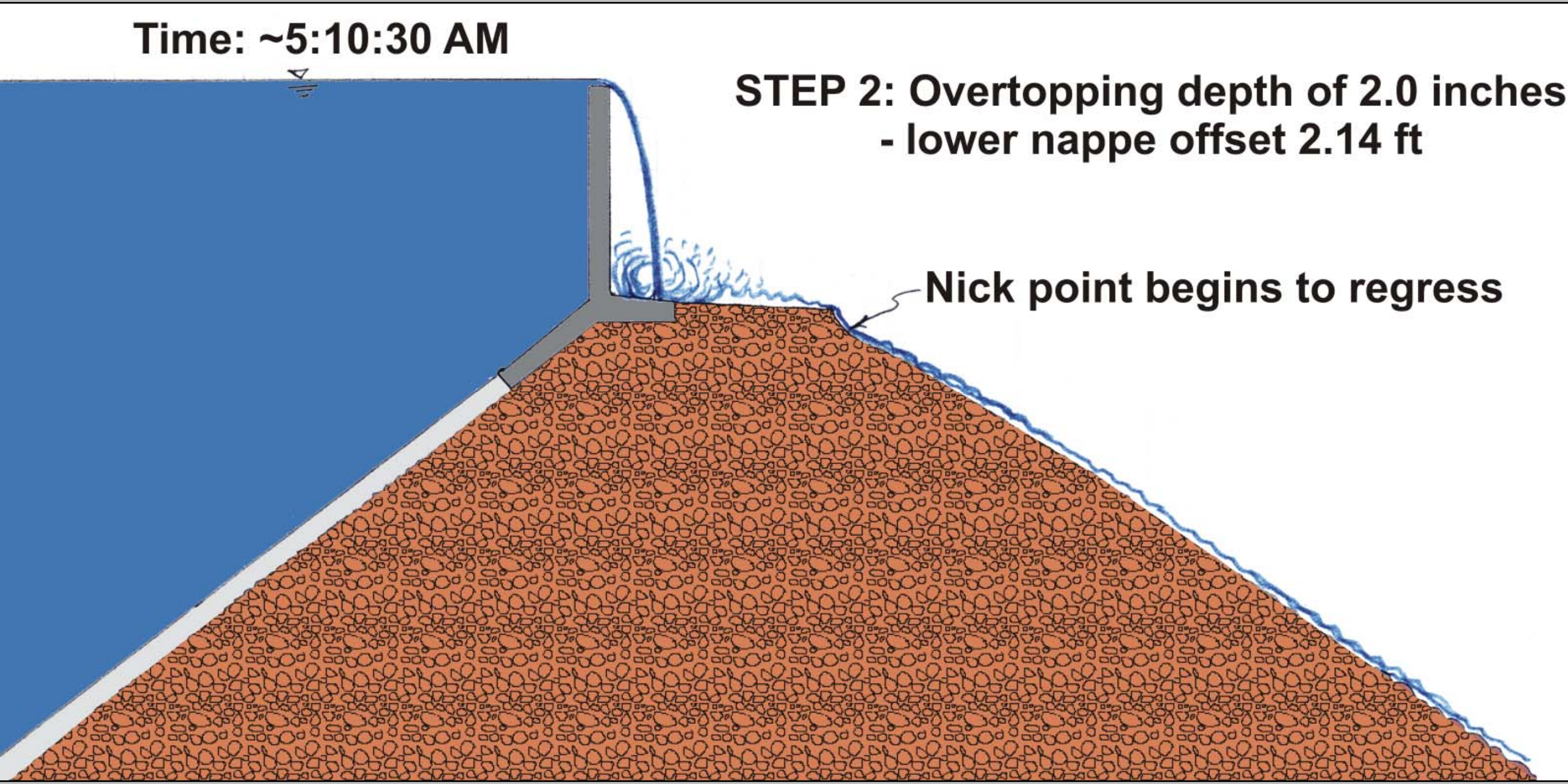
RECONSTRUCTED FAILURE SEQUENCE

using the outflow hydrograph constructed by the Federal Energy Regulatory Commission (FERC)

The Upper Reservoir Failure Sequence ~5:09 to 5:32 AM

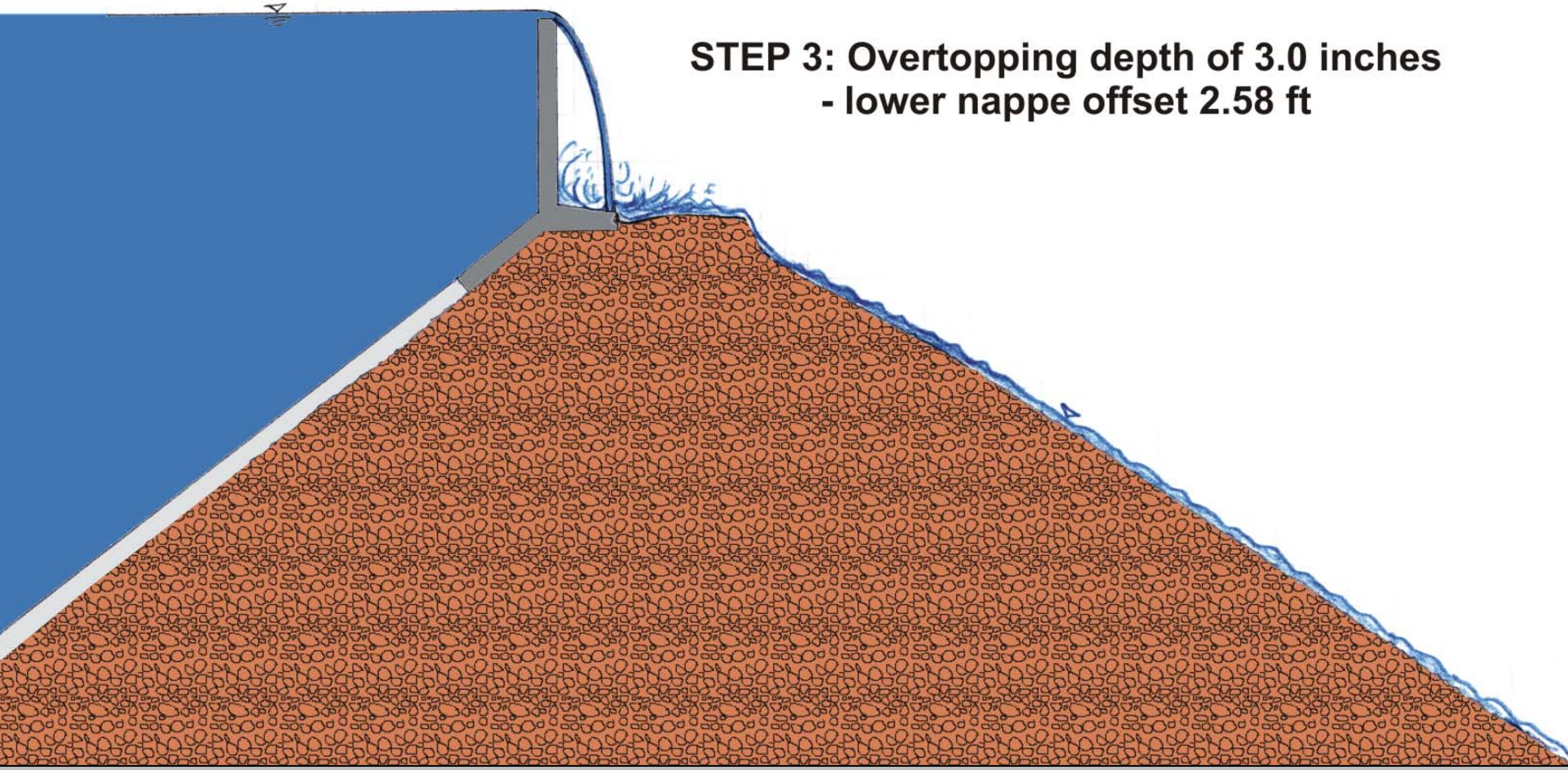
- During the morning of Dec 14th, the upper reservoir was completing its nightly filling. Faulty sensors and "fail safe" backups failed to turn the pumps off soon enough, allowing water to be pumped over the reservoir's parapet wall in at least four locations, where it scoured away the rockfill embankment. Records show the last pump did shut-off automatically, but the reservoir was already overflowing and near failure at this time.
- The failure occurred at the NW portion of the dike where the Sept. 25th "Niagara Falls" incident occurred.
- Instruments at the reservoir suggest it emptied in approximately 12 minutes, with a peak outflow of 289,000 cubic feet per second. This is a larger than the average flow of the Mississippi River above the Ohio River at Cairo, IL (200,000 cfs).
- Ironically, an emergency drill was scheduled to be conducted at the facility on Dec 14 and responders assumed that initial reports were part of this planned drill and not an actual incident.


Time: ~5:09:00 AM
STEP 1: Overtopping depth of 1.0 inch
- lower nappe offset 1.55 ft
Initial nick point


Time: ~5:10:30 AM
STEP 2: Overtopping depth of 2.0 inches
- lower nappe offset 2.14 ft
Nick point begins to regress

Time: ~5:11:55 AM

STEP 3: Overtopping depth of 3.0 inches
- lower nappe offset 2.58 ft



Time: ~5:12:55 AM

STEP 4: Overtopping depth of 4.0 inches
- lower nappe offset 2.95 ft

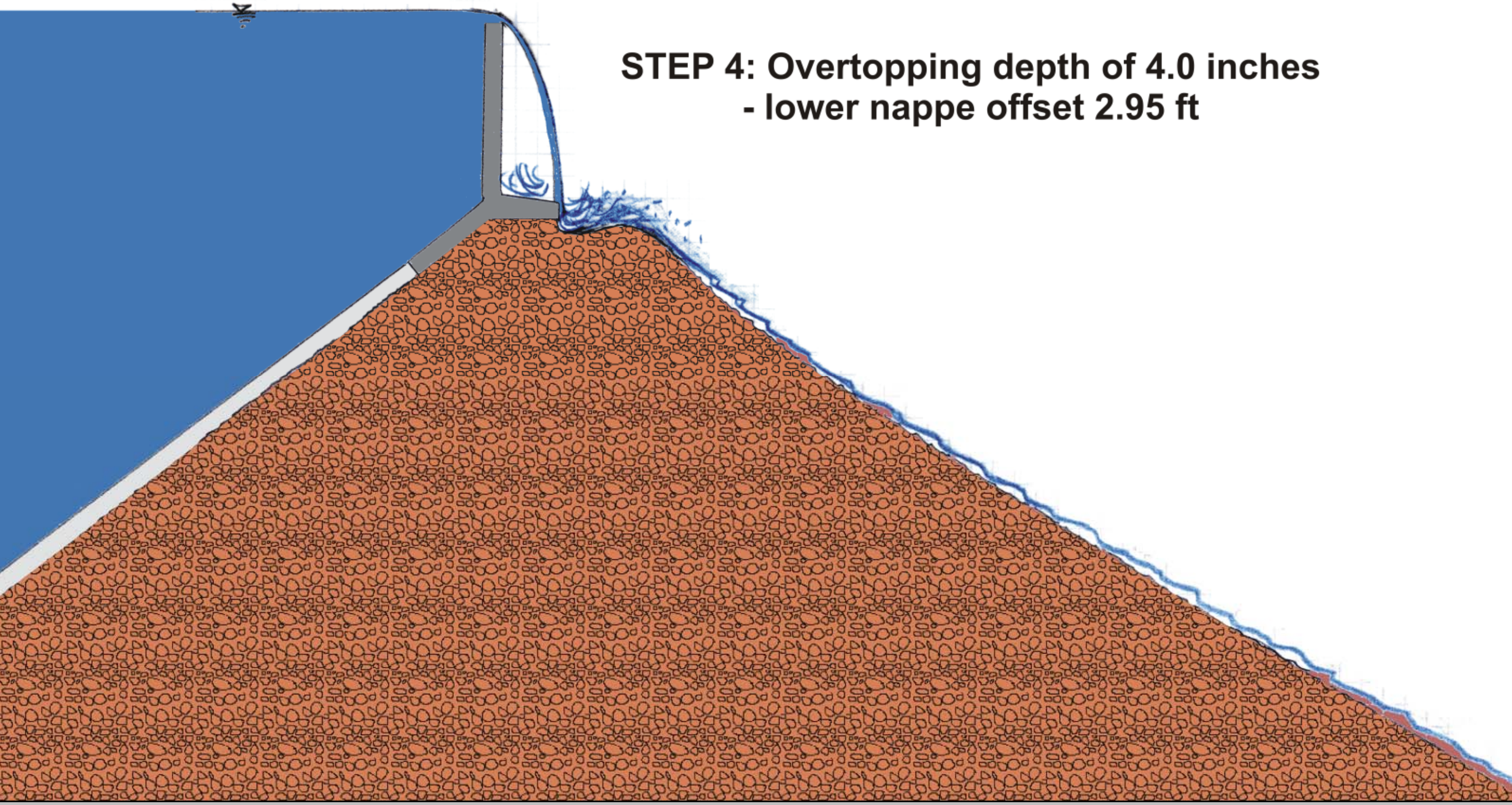


Photo by David Hoffman

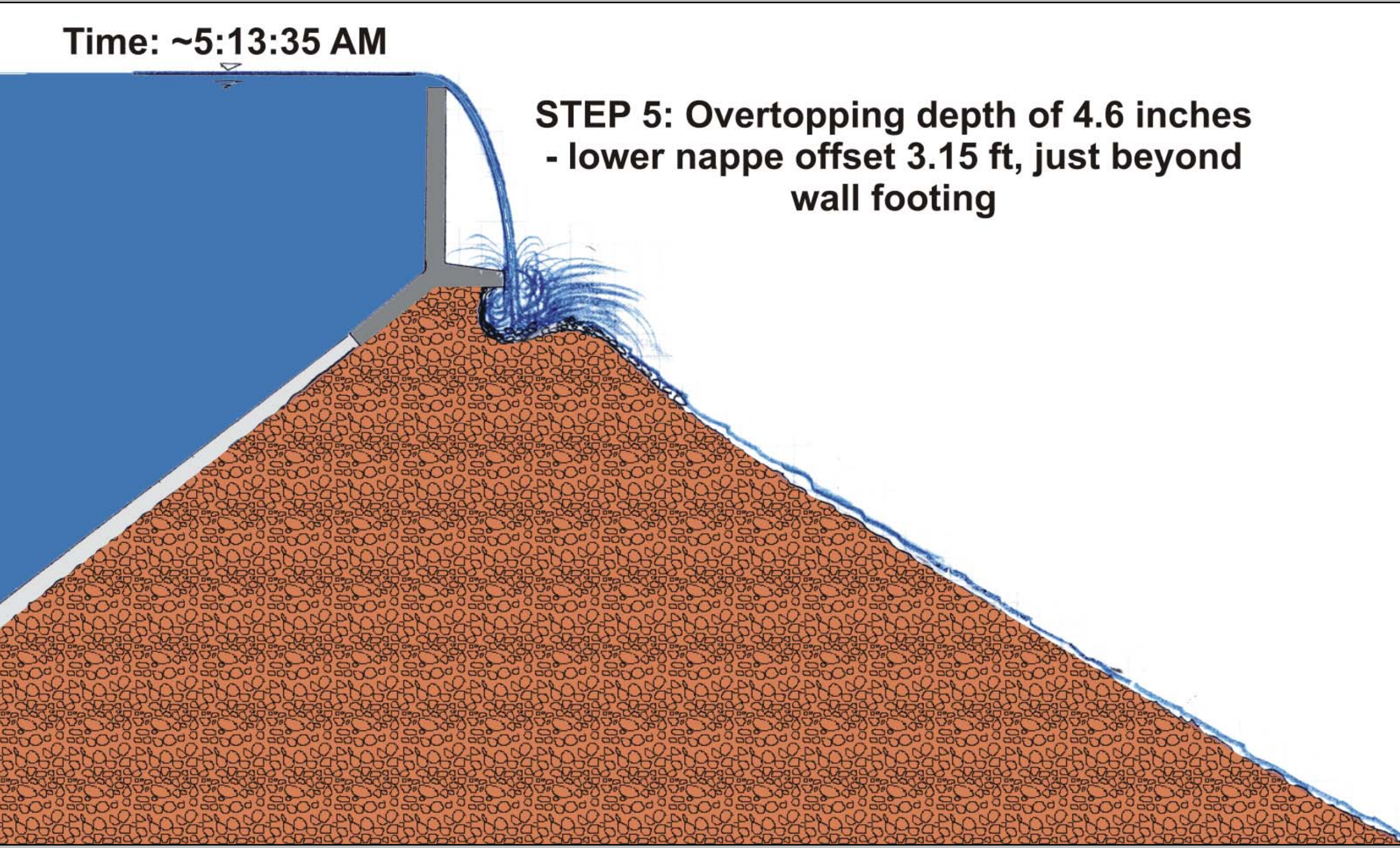
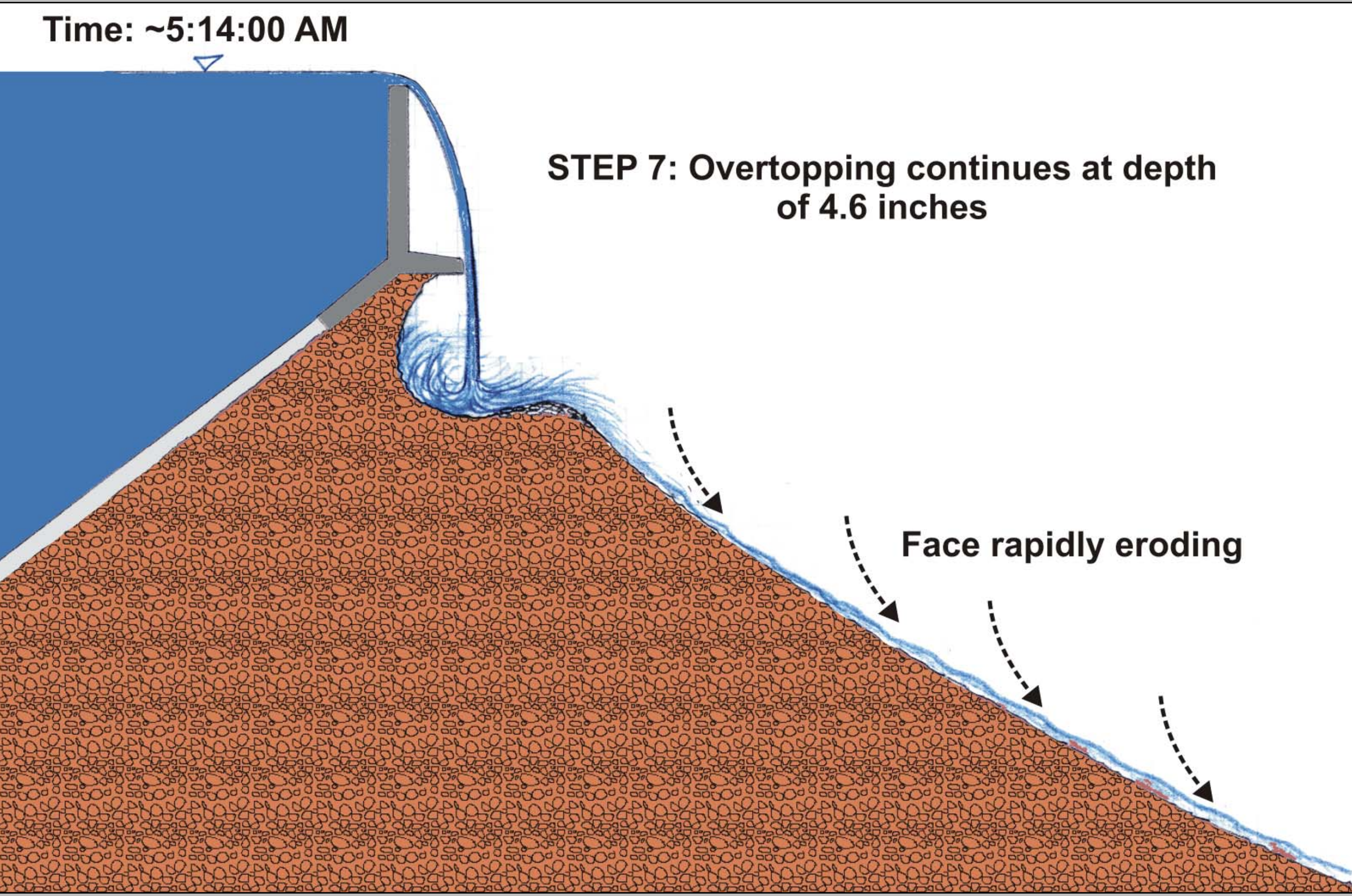
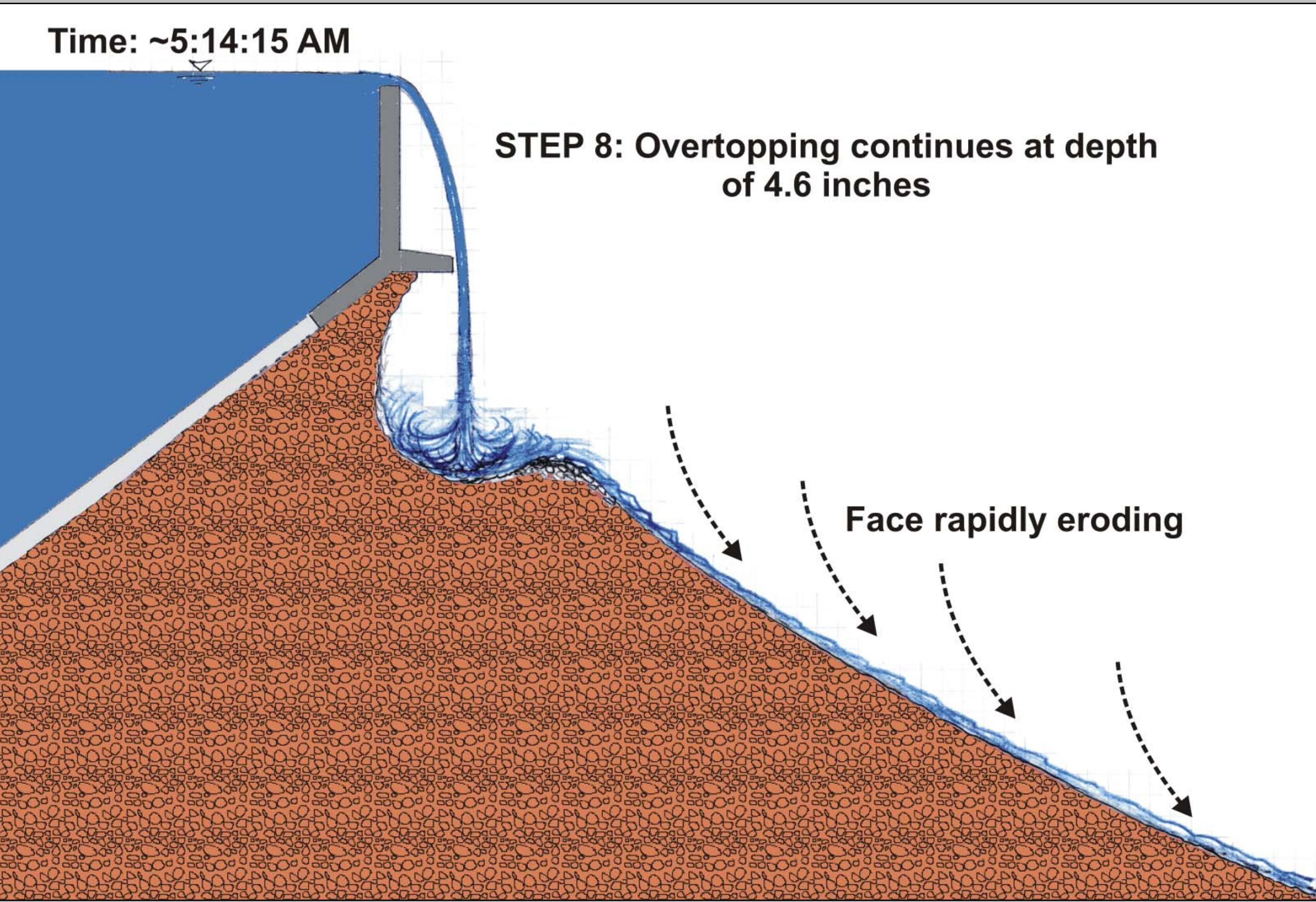
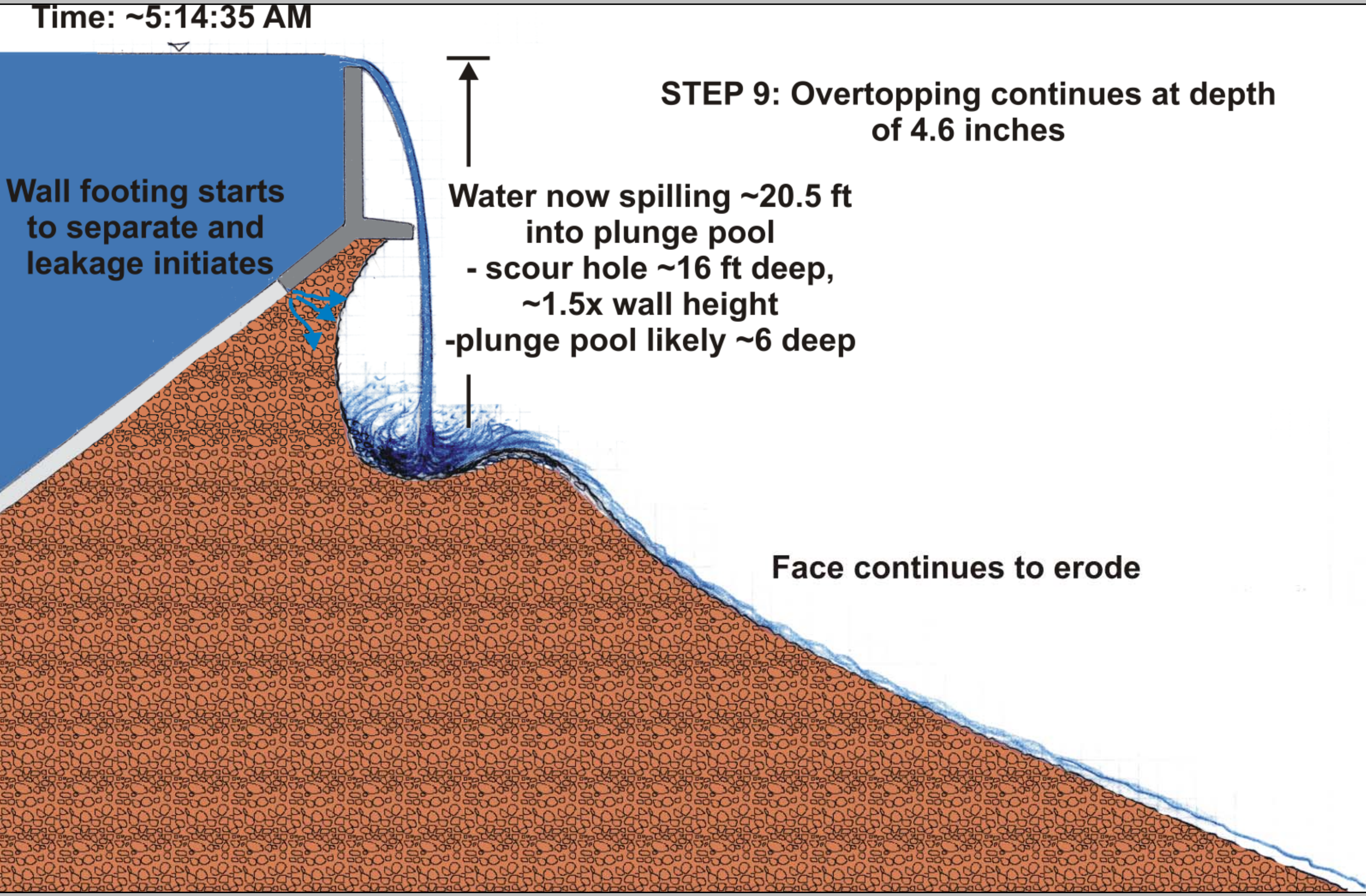

Time: ~5:13:35 AM
STEP 5: Overtopping depth of 4.6 inches
- lower nappe offset 3.15 ft, just beyond
wall footing


Photo by David Hoffman


Time: ~5:14:00 AM
STEP 7: Overtopping continues at depth of 4.6 inches
Face rapidly eroding

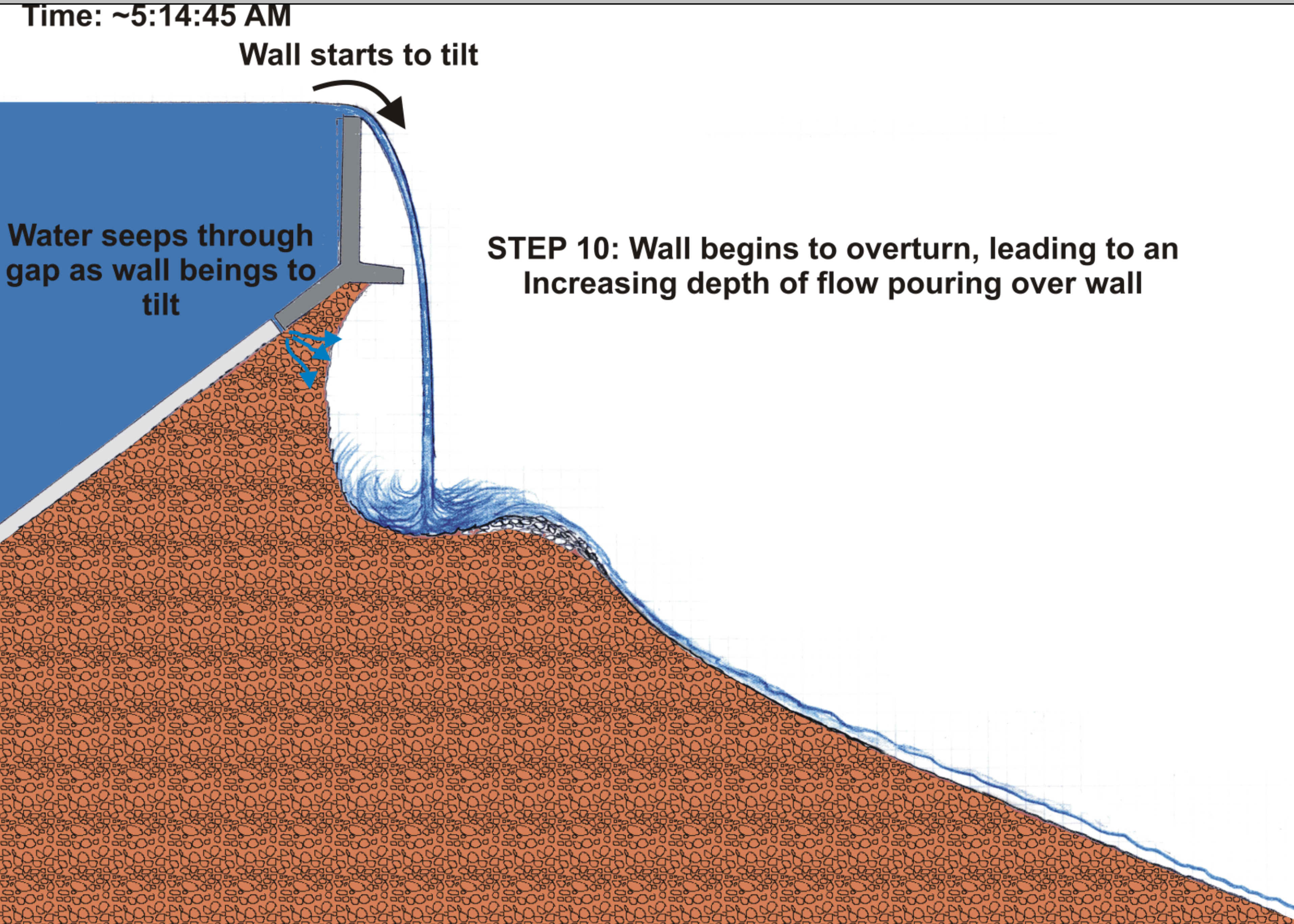


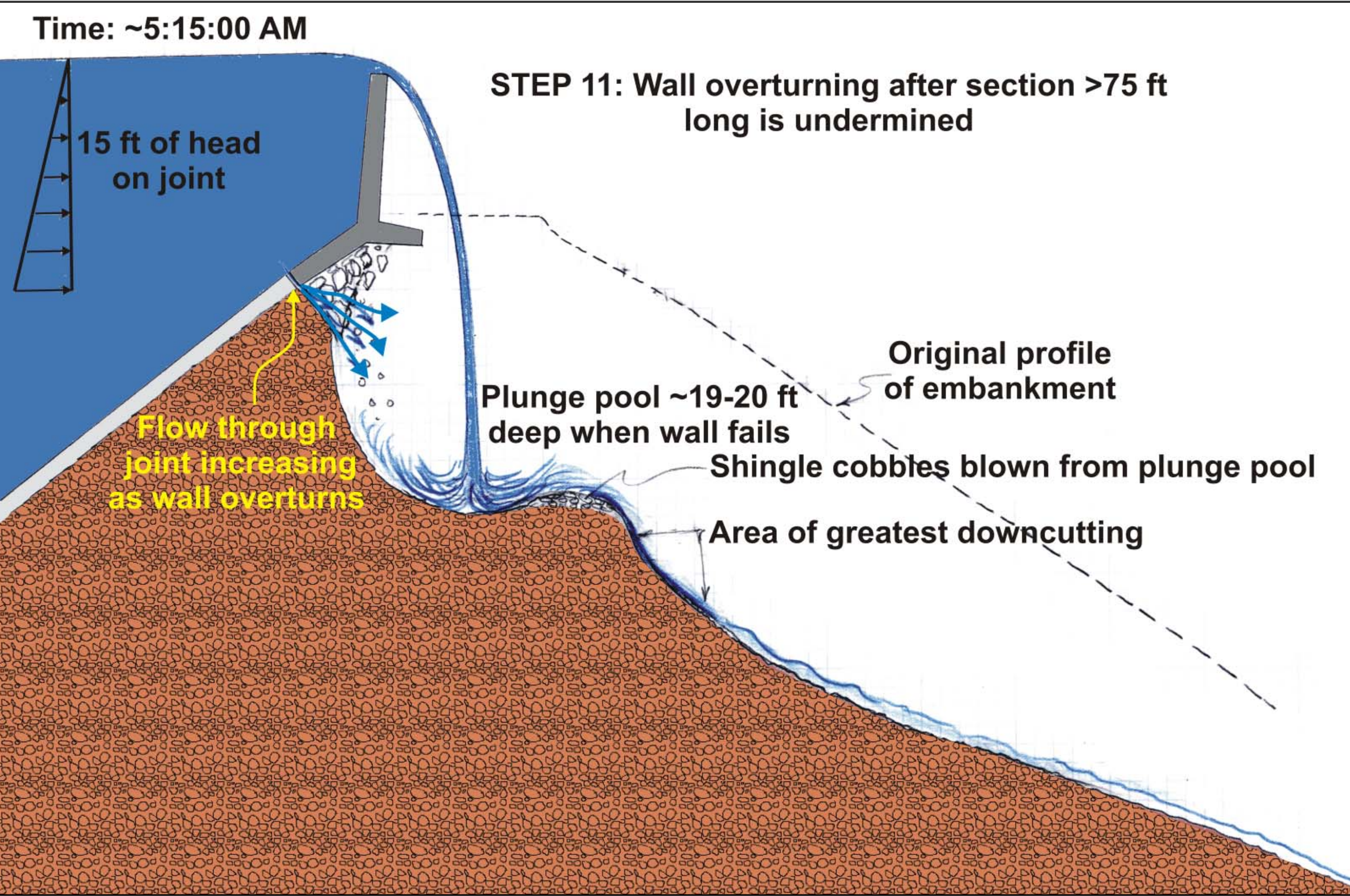
3 Dimensional effects allowed wall to stand with extensive undermining


Time: ~5:14:35 AM
STEP 9: Overtopping continues at depth of 4.6 inches
Wall footing starts to separate and leakage initiates
Water now spilling ~20.5 ft into plunge pool
- scour hole ~16 ft deep, ~1.5x wall height
-plunge pool likely ~6 deep
Face continues to erode

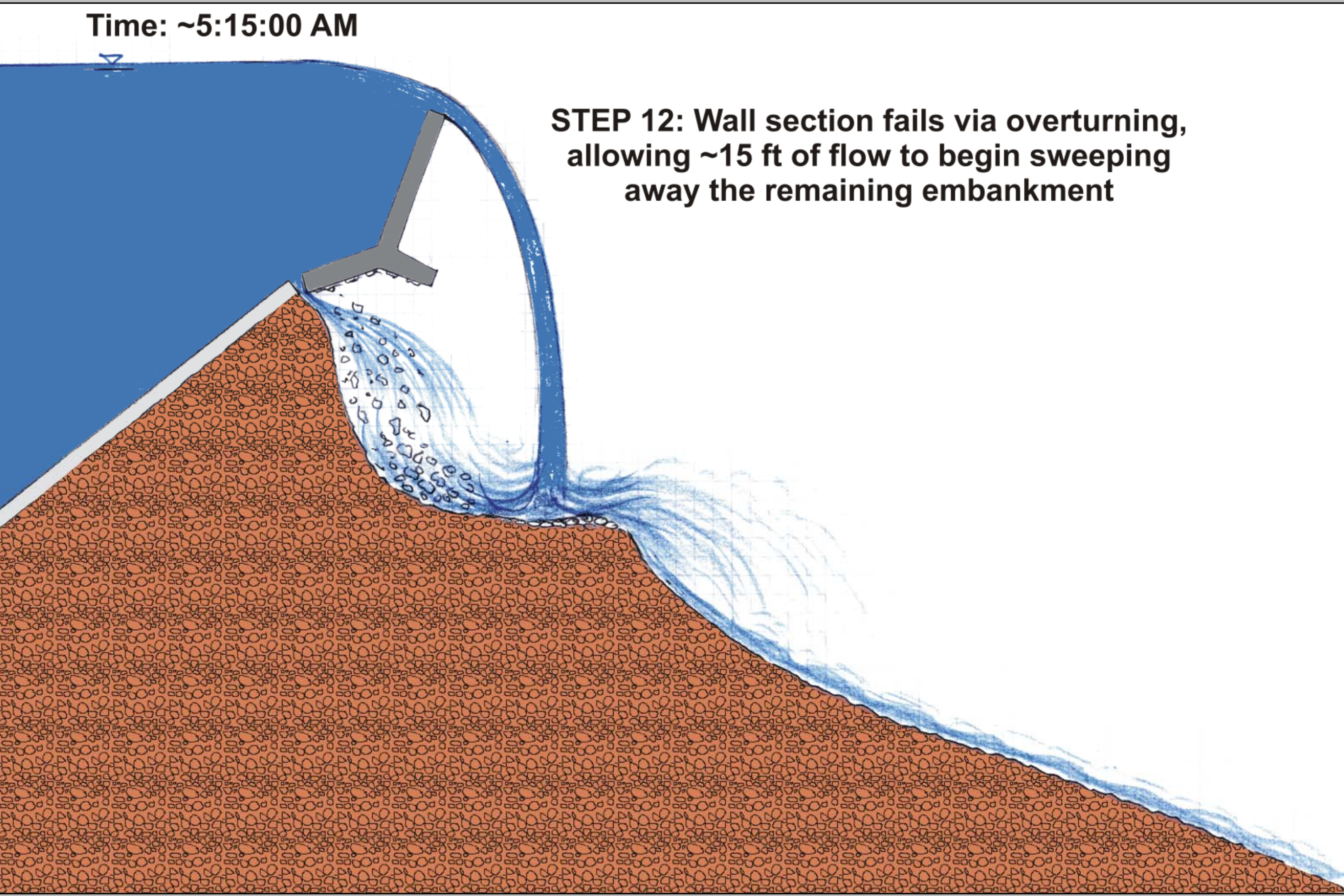
Water pouring over the parapet wall scoured away the fill supporting the wall's foundation. A portion of the wall appears to have toppled, unleashing a flow of water that catastrophically eroded a 680 foot wide section of the embankment, emptying the reservoir in ~12 minutes.


Photo by David Hoffman

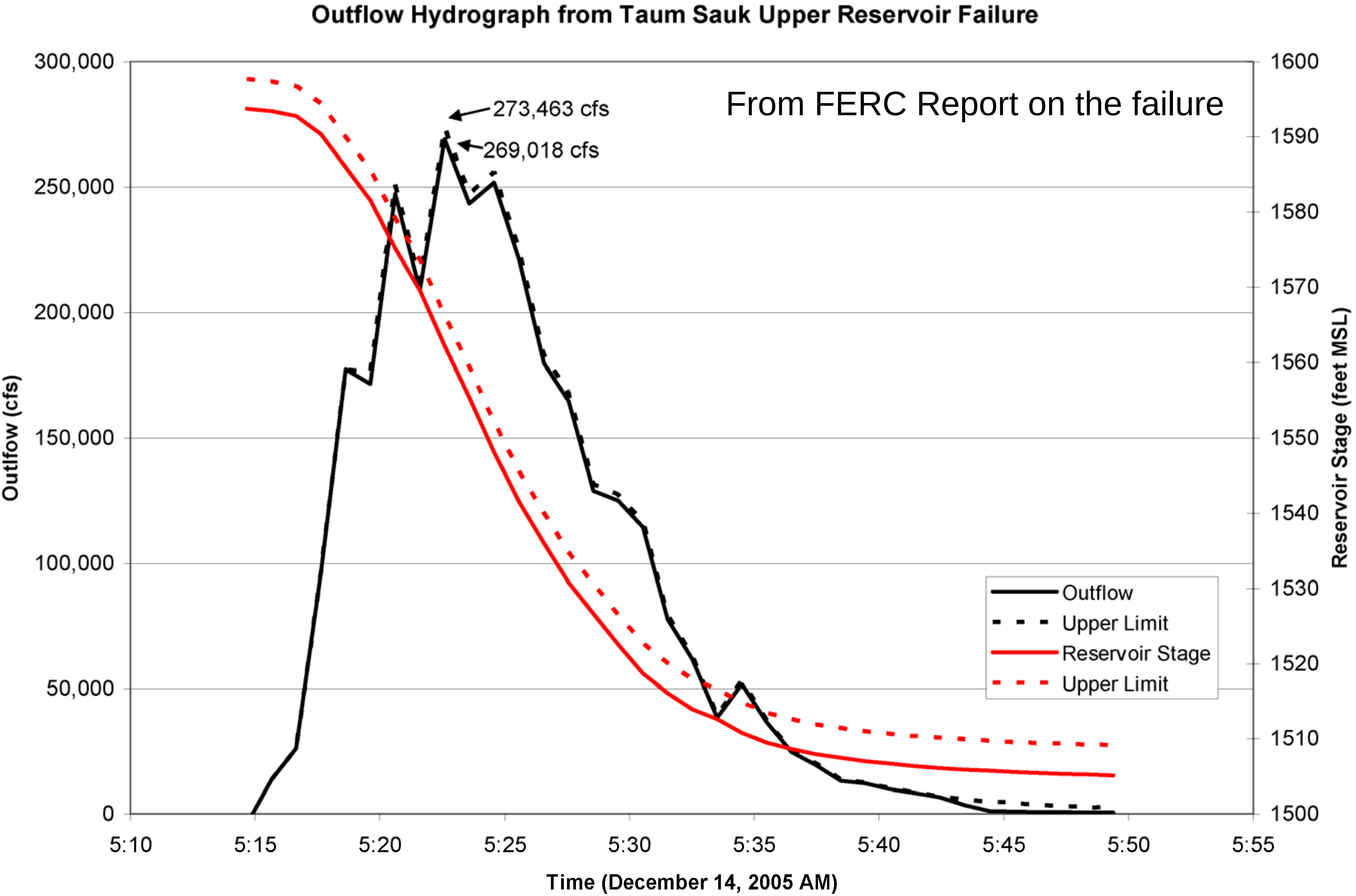

Time: ~5:14:45 AM
Wall starts to tilt
Water seeps through gap as wall beings to tilt
STEP 10: Wall begins to overturn, leading to an Increasing depth of flow pouring over wall


Time: ~5:15:00 AM
STEP 11: Wall overturning after section >75 ft long is undermined
15 ft of head on joint
Flow through joint increasing as wall overturns
Plunge pool ~19-20 ft deep when wall fails
Original profile of embankment
Shingle cobbles blown from plunge pool
Area of greatest downcutting

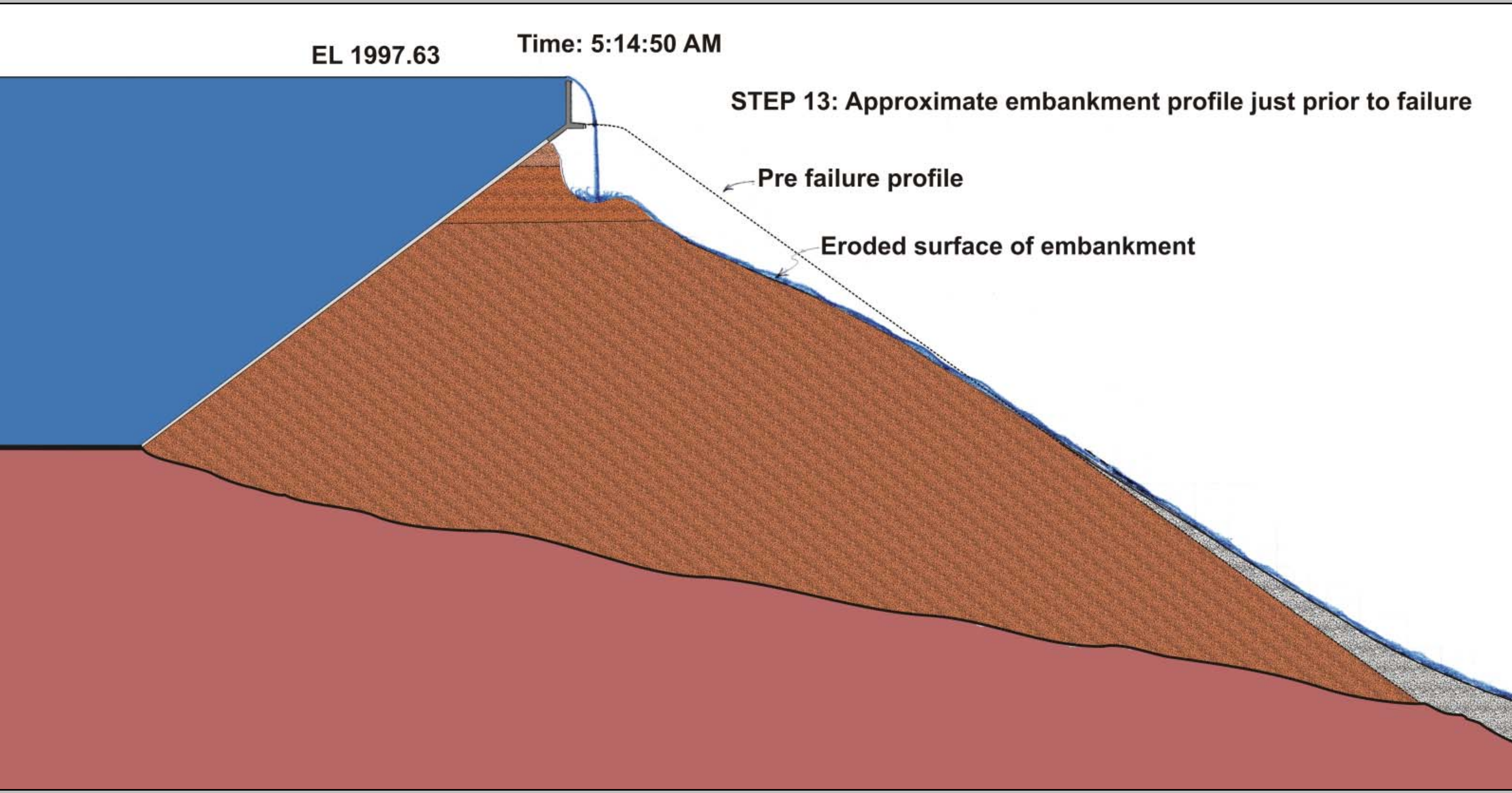

Exposed foundation
of parapet wall
72
Photo by David Hoffman


Time: ~5:15:00 AM
STEP 12: Wall section fails via overturning, allowing ~15 ft of flow to begin sweeping away the remaining embankment

Wall panels toppled over after extensive undercutting, initiating the catastrophic failure sequence.

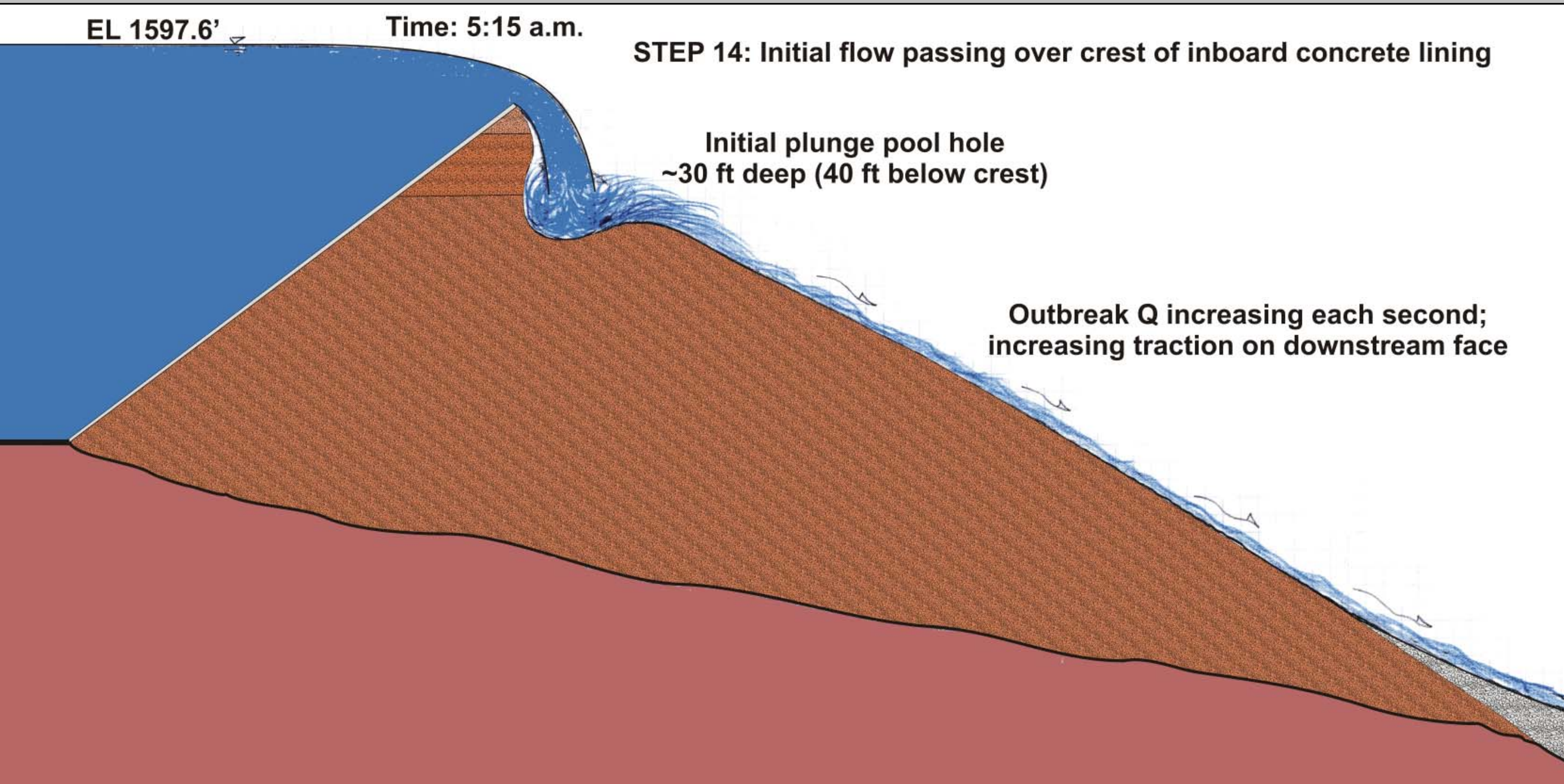


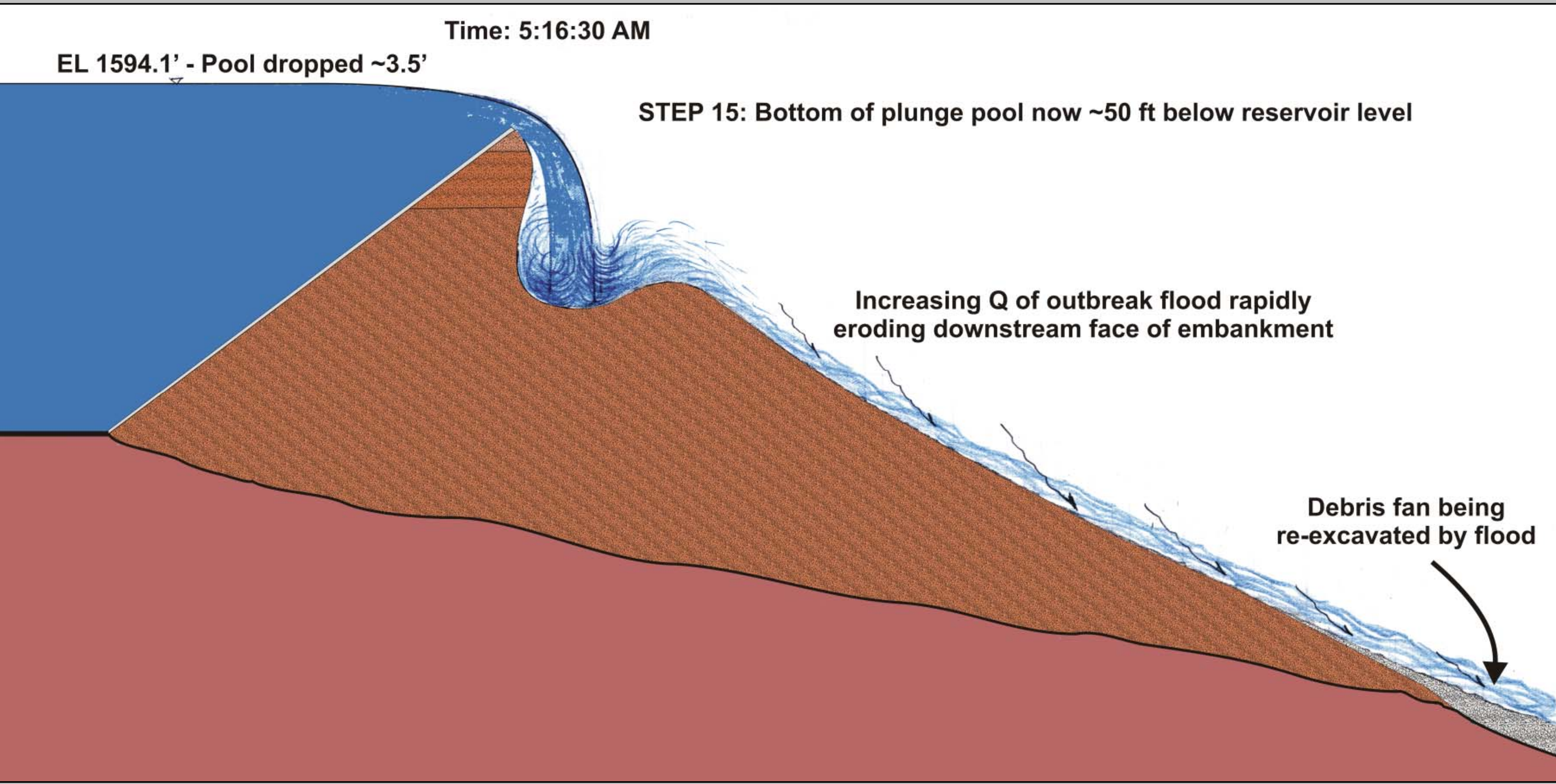
Calculated Outflow Hydrograph for Taum Sauk Breach

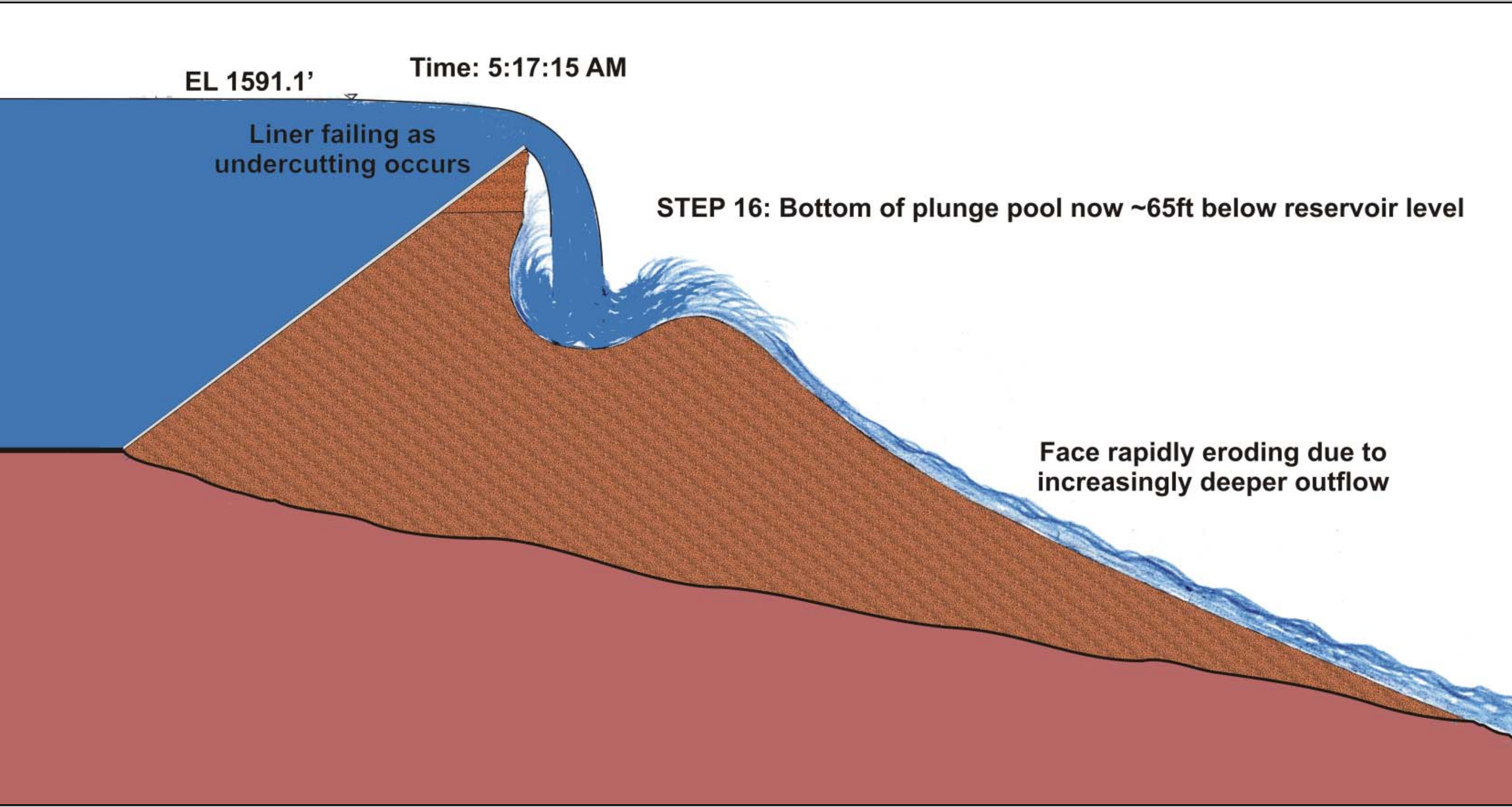


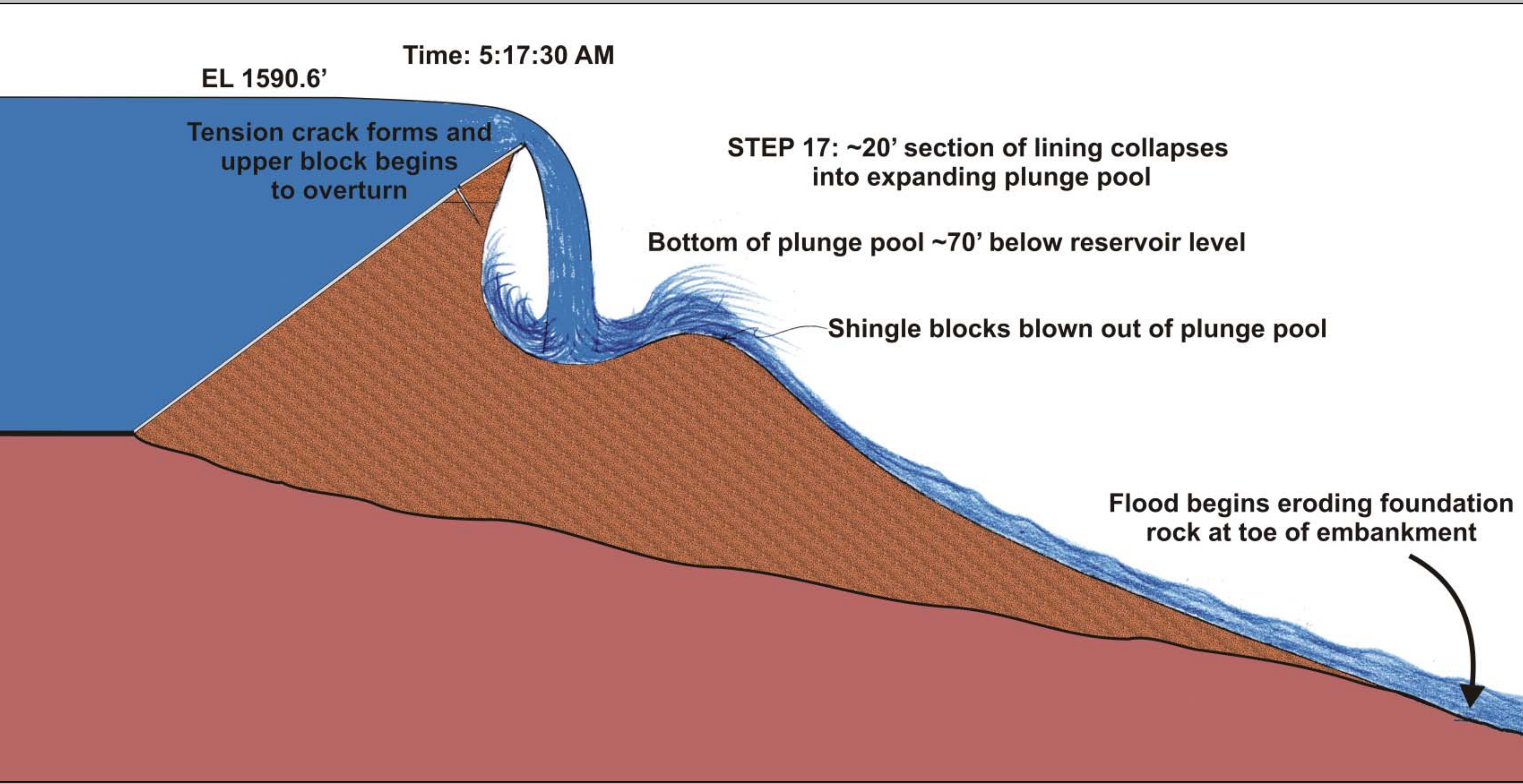
EL 1997.63
Time: 5:14:50 AM
STEP 13: Approximate embankment profile just prior to failure
Pre failure profile
Eroded surface of embankment

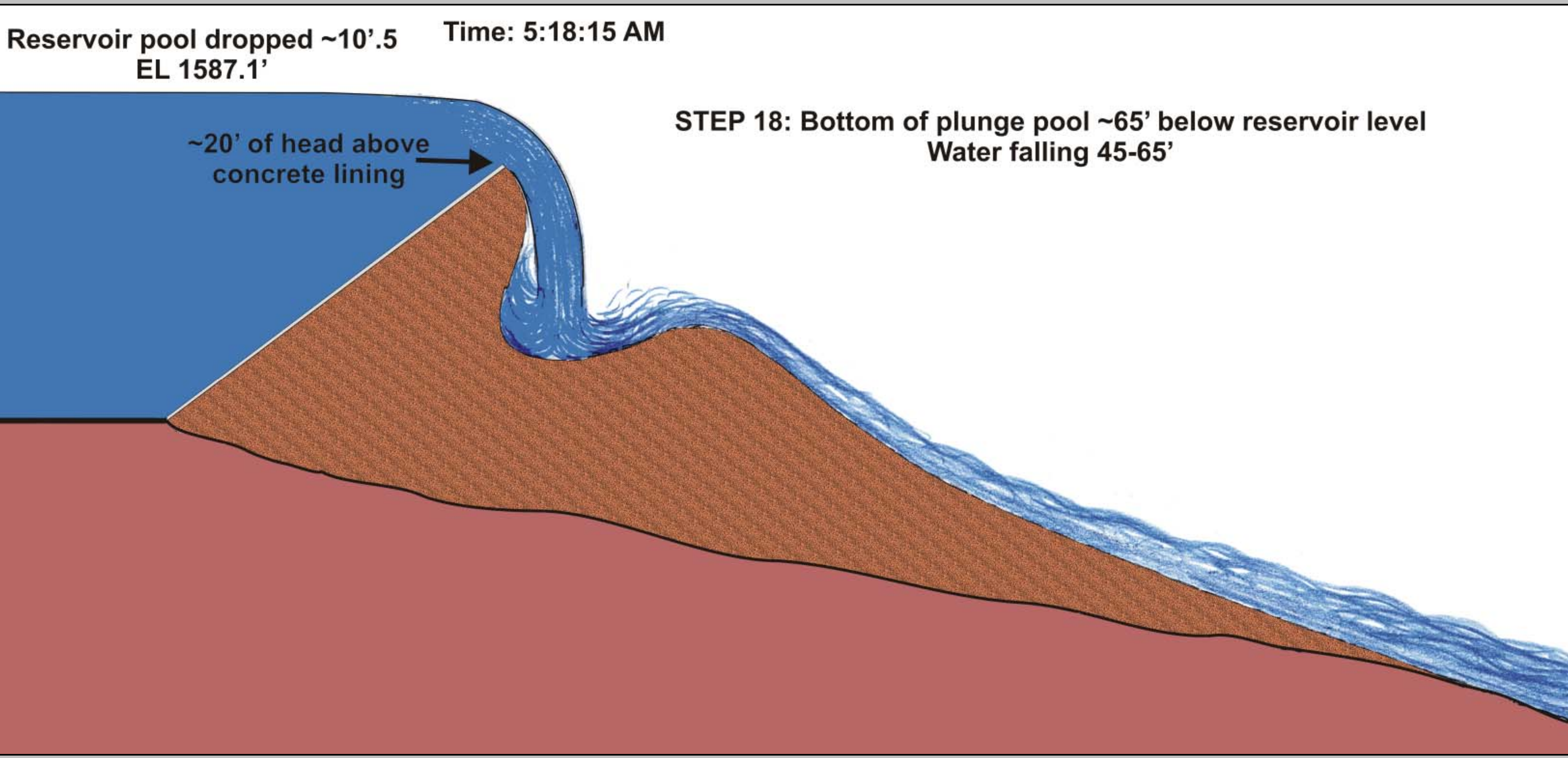

Debris cone at toe
of embankment

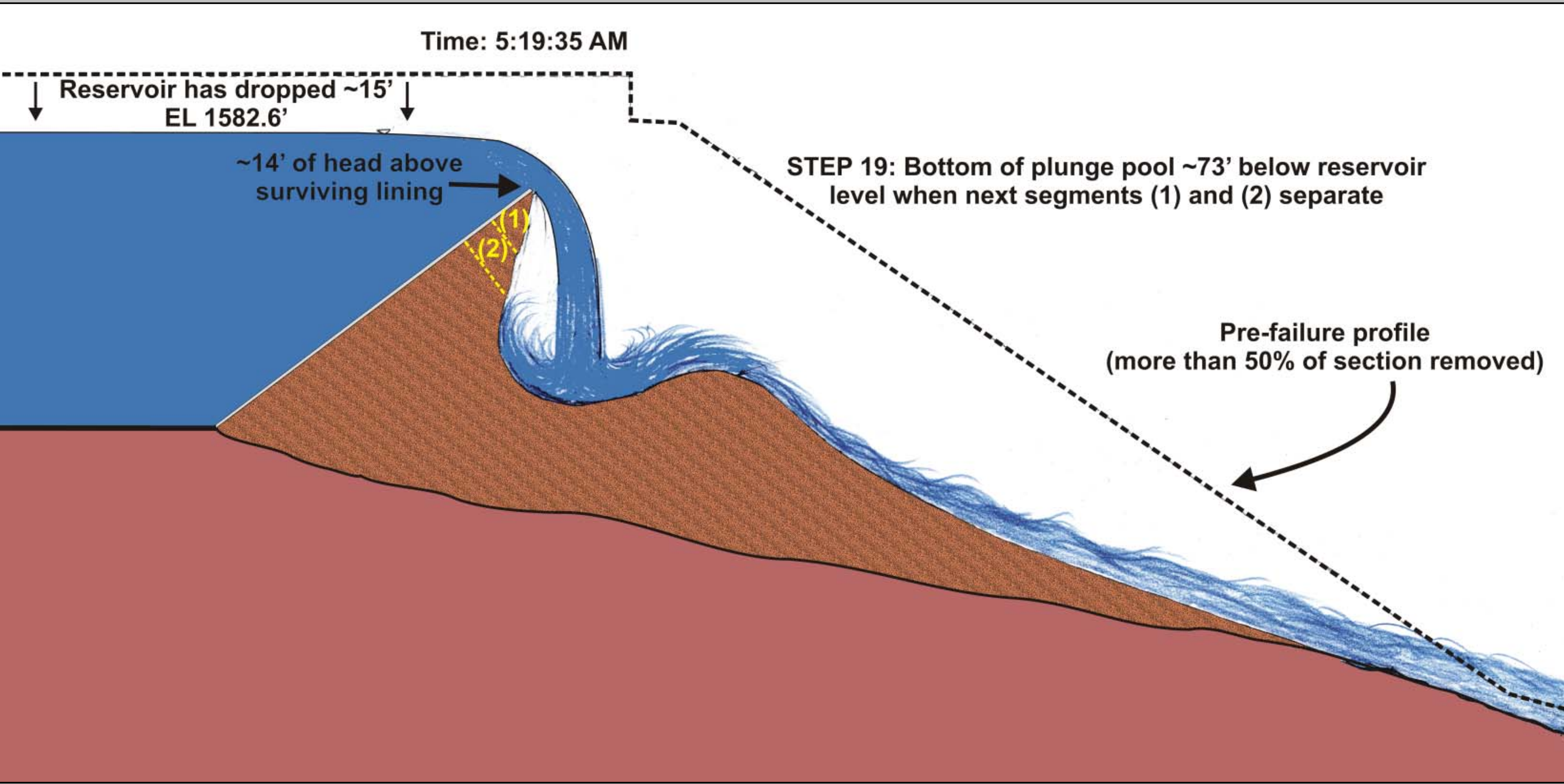

EL 1597.6'
Time: 5:15 a.m.
STEP 14: Initial flow passing over crest of inboard concrete lining
Initial plunge pool hole
~30 ft deep (40 ft below crest)
Outbreak Q increasing each second;
increasing traction on downstream face

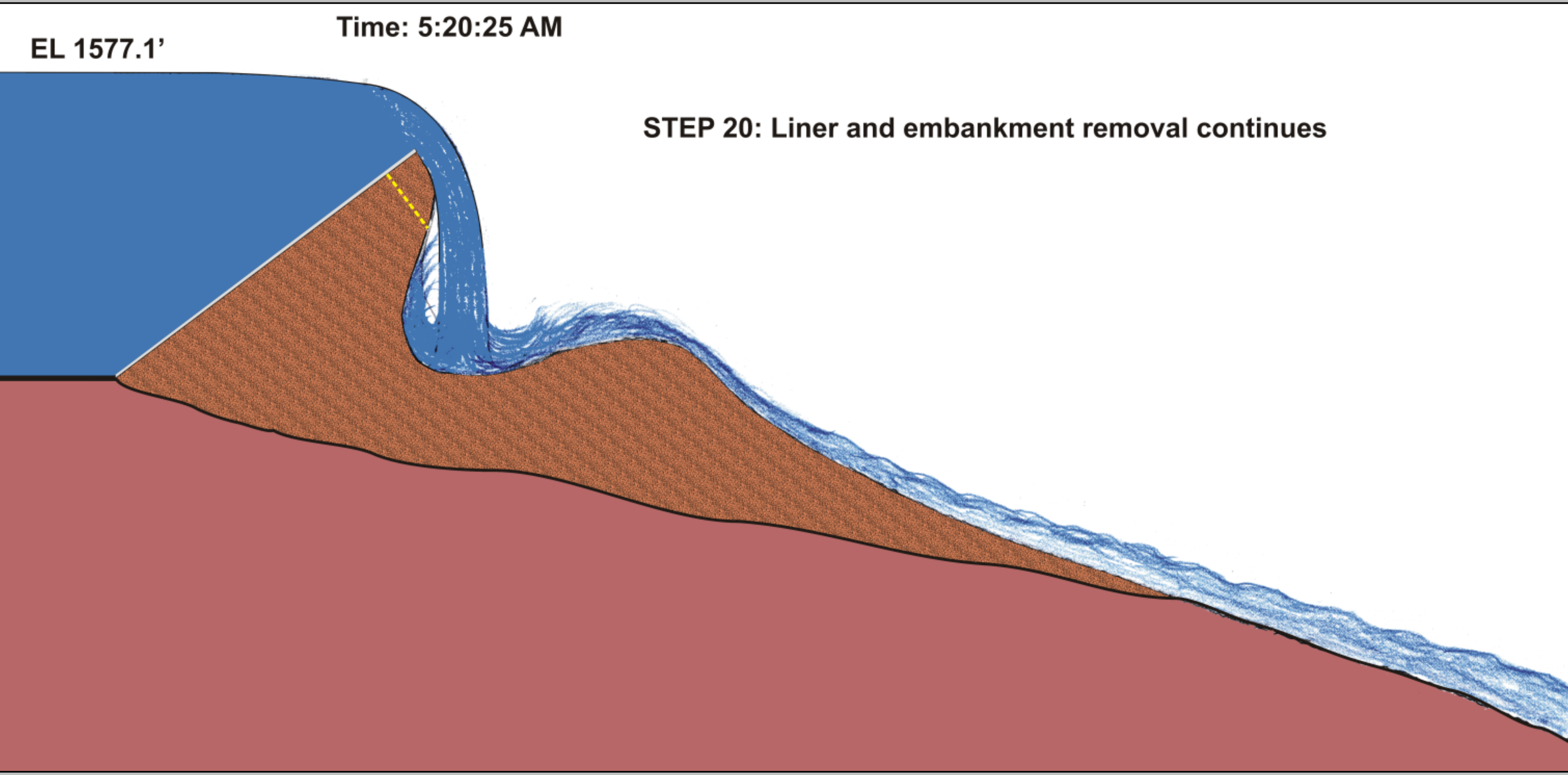

Time: 5:16:30 AM
EL 1594.1' - Pool dropped ~3.5'
STEP 15: Bottom of plunge pool now ~50 ft below reservoir level
Increasing Q of outbreak flood rapidly
eroding downstream face of embankment
Debris fan being
re-excavated by flood

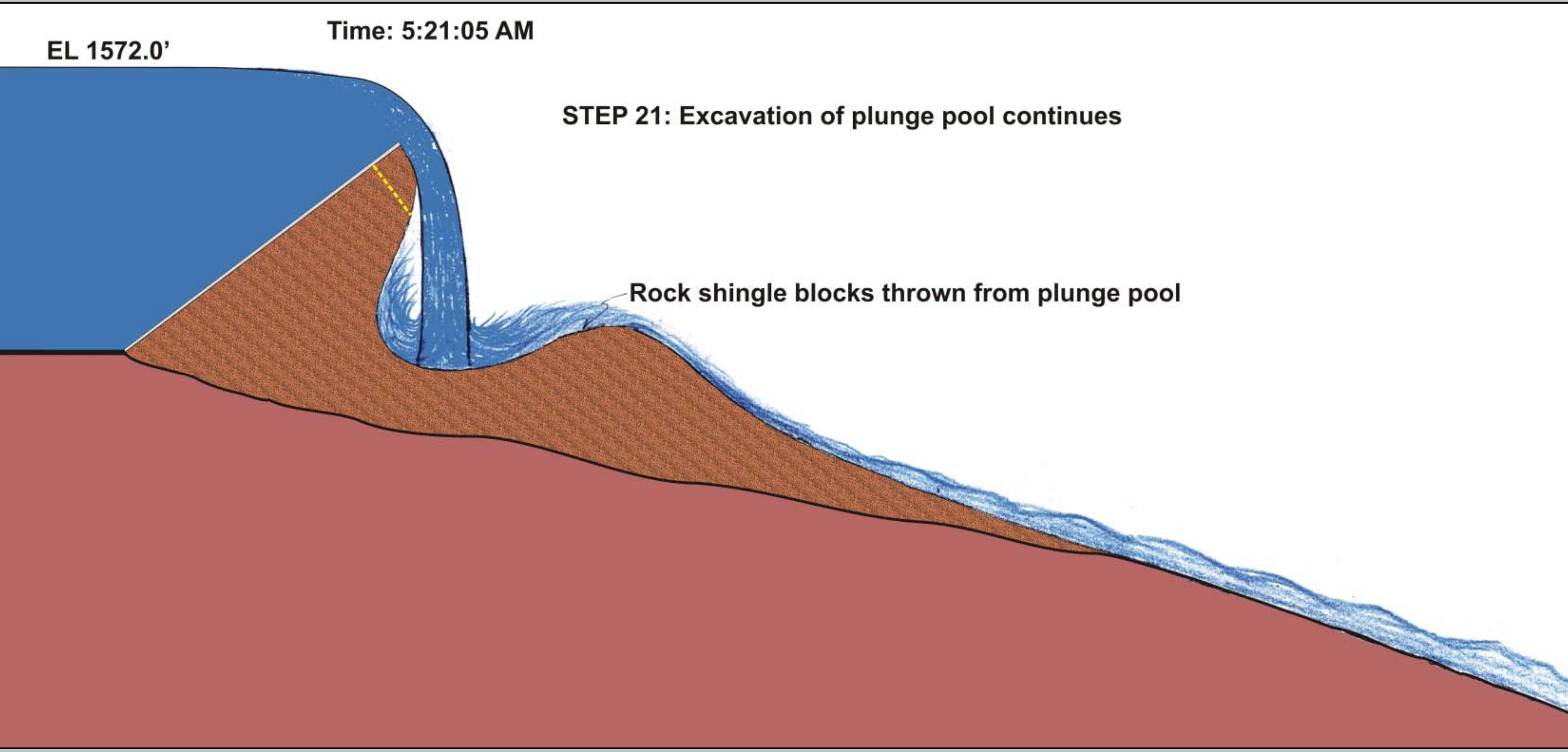

EL 1591.1'
Time: 5:17:15 AM
Liner failing as
undercutting occurs
STEP 16: Bottom of plunge pool now ~65ft below reservoir level
Face rapidly eroding due to
increasingly deeper outflow

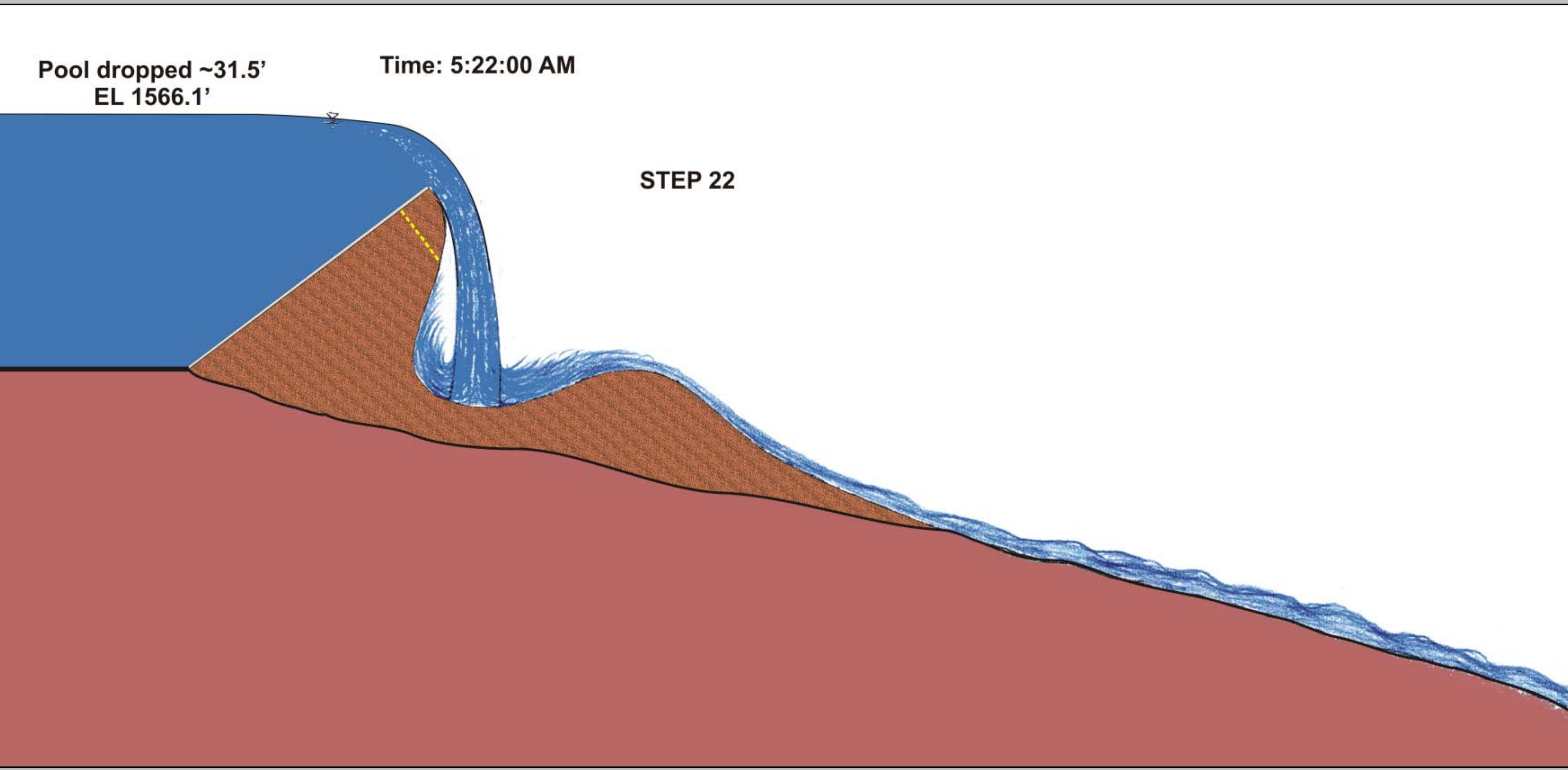

Time: 5:17:30 AM
EL 1590.6'
Tension crack forms and upper block begins to overturn
STEP 17: ~20' section of lining collapses into expanding plunge pool
Bottom of plunge pool ~70' below reservoir level
Shingle blocks blown out of plunge pool
Flood begins eroding foundation rock at toe of embankment

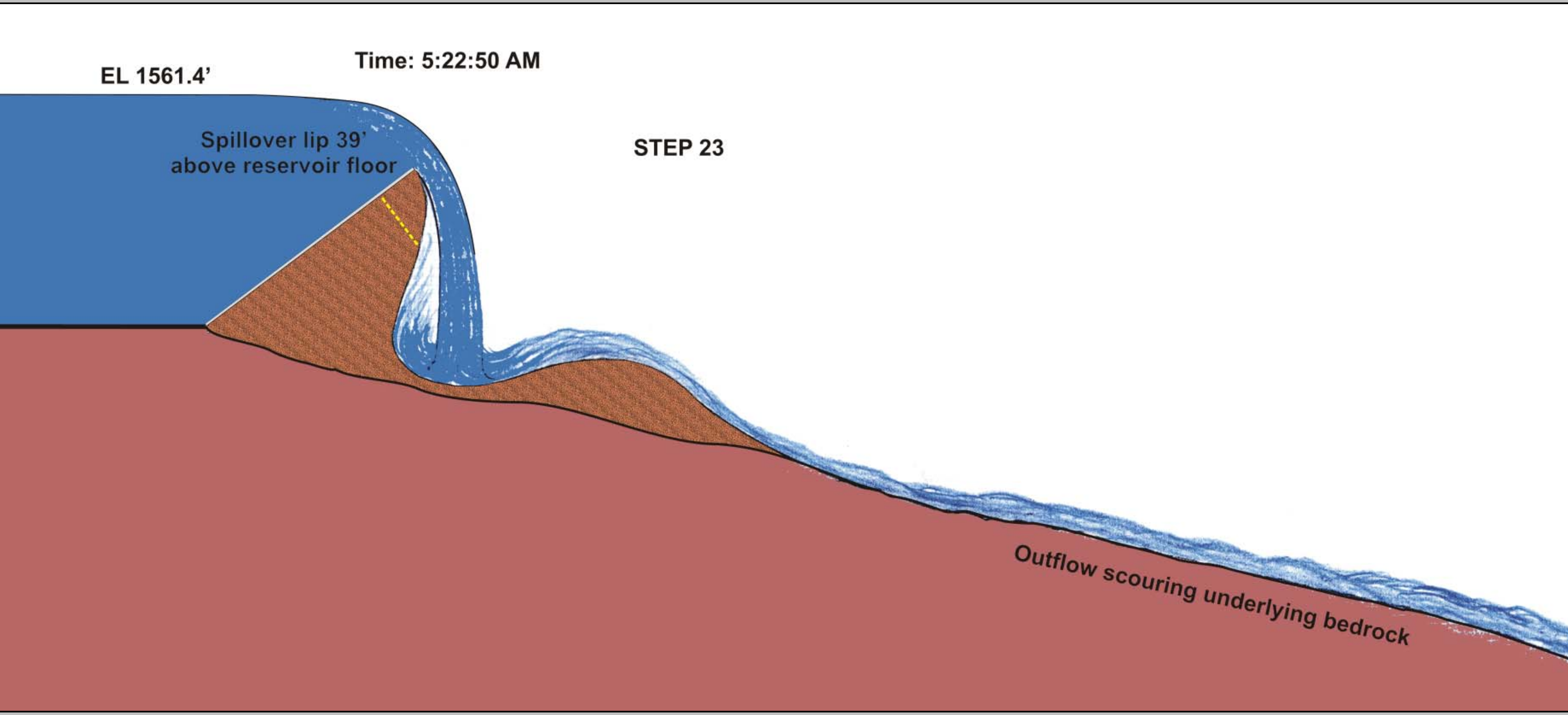

Reservoir pool dropped ~10'.5
EL 1587.1'
Time: 5:18:15 AM
~20' of head above
concrete lining
STEP 18: Bottom of plunge pool ~65' below reservoir level
Water falling 45-65'

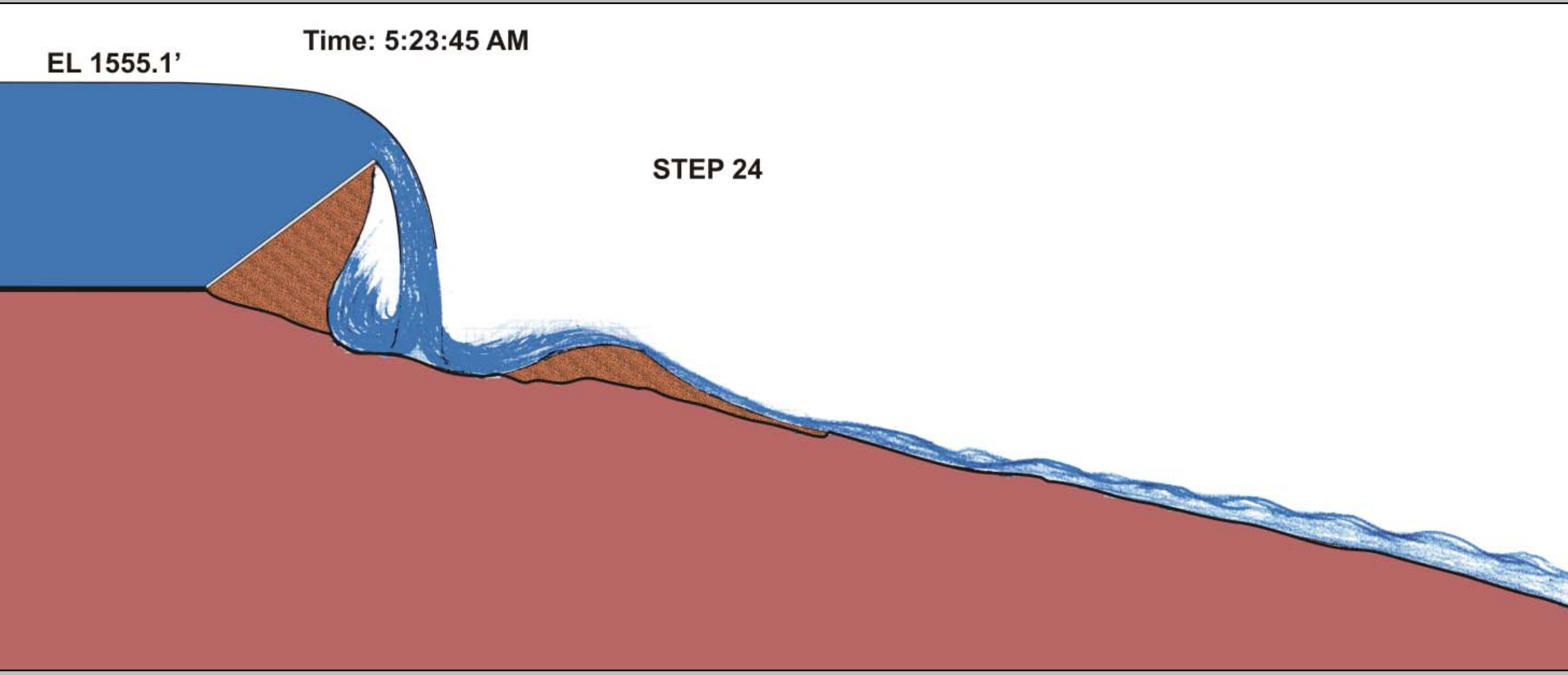

Time: 5:19:35 AM
Reservoir has dropped ~15'
EL 1582.6'
~14' of head above surviving lining
(1)
(2)
STEP 19: Bottom of plunge pool ~73' below reservoir level when next segments (1) and (2) separate
Pre-failure profile
(more than 50% of section removed)

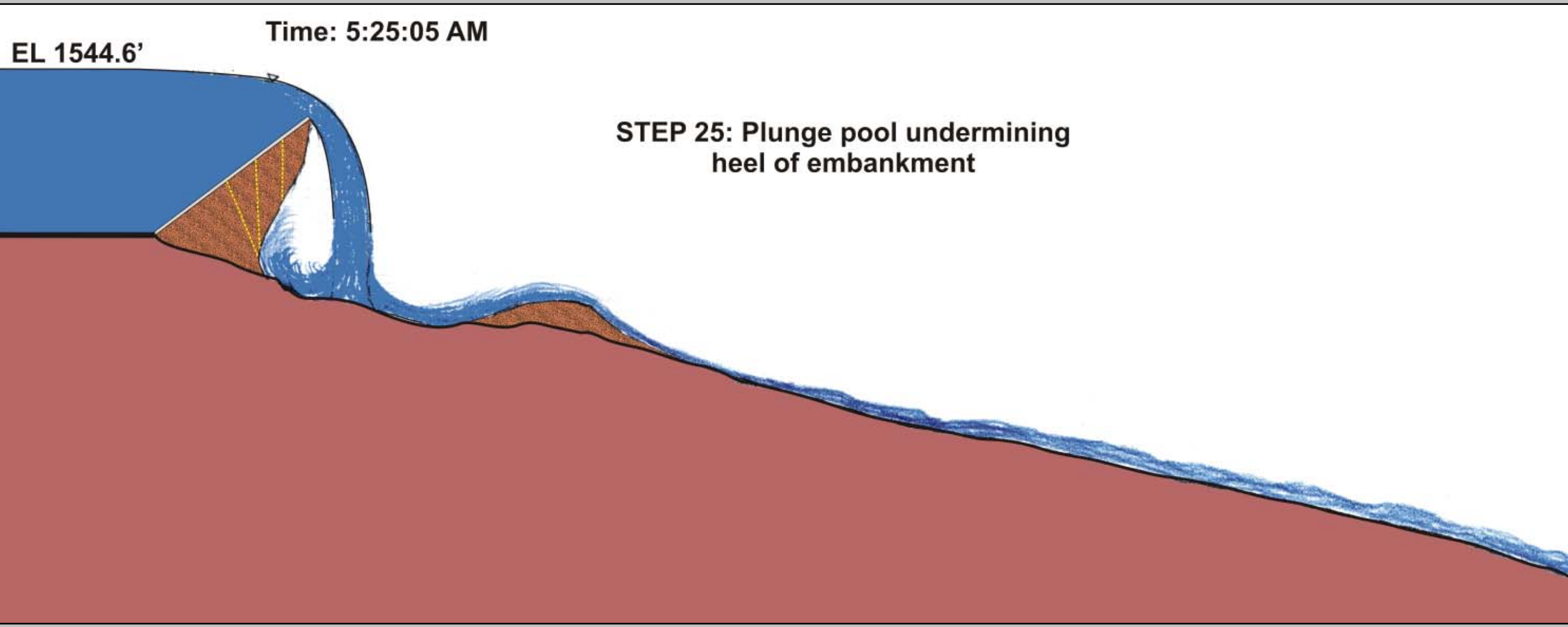

Time: 5:20:25 AM
EL 1577.1'
STEP 20: Liner and embankment removal continues

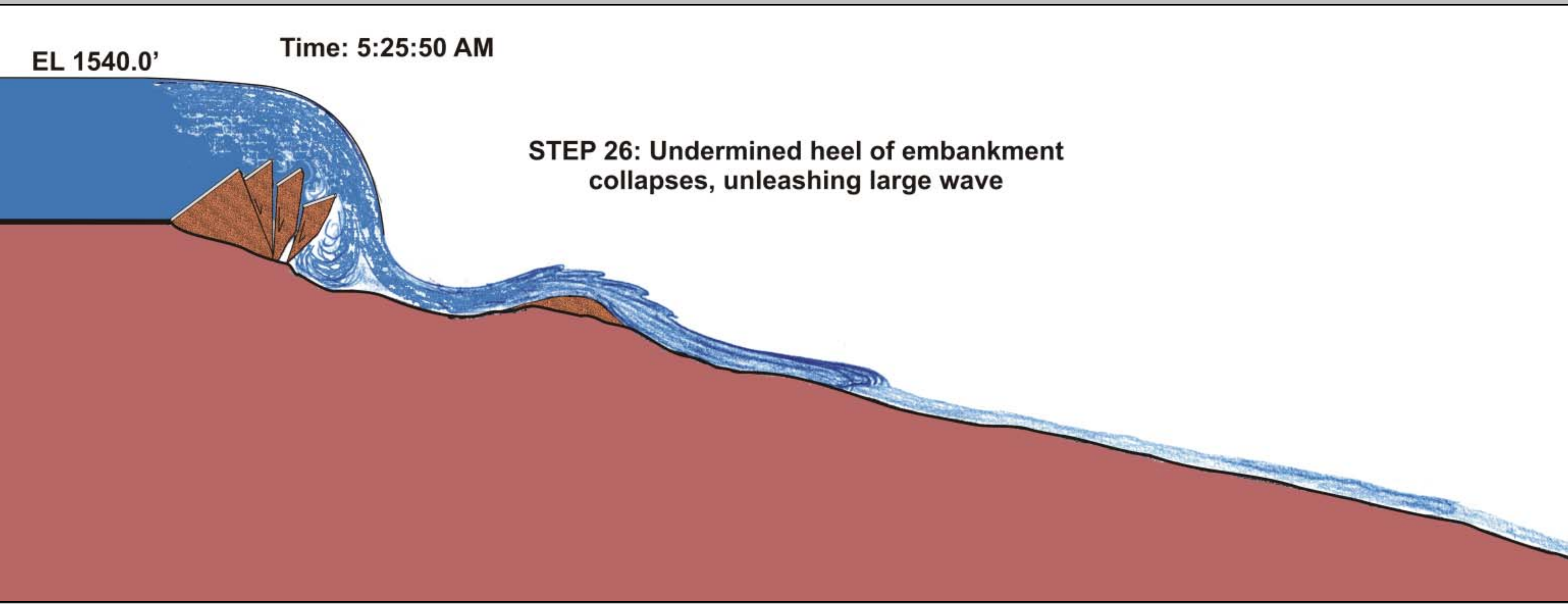

Time: 5:21:05 AM
EL 1572.0’
STEP 21: Excavation of plunge pool continues
Rock shingle blocks thrown from plunge pool


Pool dropped ~31.5'
EL 1566.1'
Time: 5:22:00 AM
STEP 22

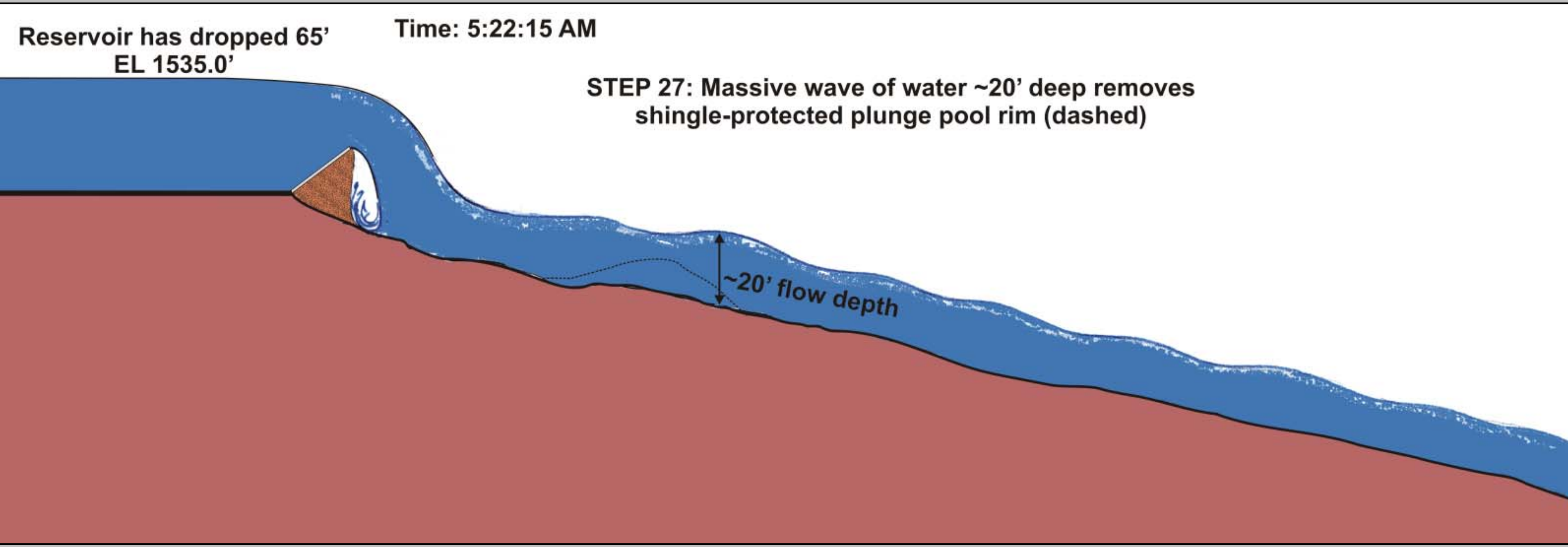

EL 1561.4’
Time: 5:22:50 AM
Spillover lip 39’
above reservoir floor
STEP 23
Outflow scouring underlying bedrock


Time: 5:23:45 AM
EL 1555.1'
STEP 24


Time: 5:25:05 AM
EL 1544.6'
STEP 25: Plunge pool undermining
heel of embankment

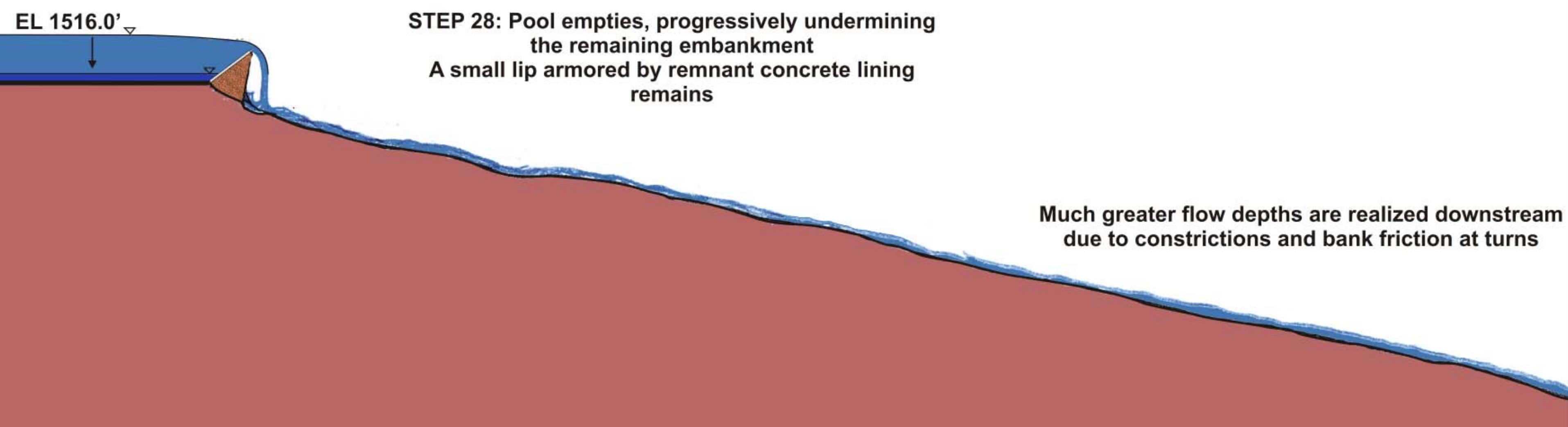


EL 1540.0'
Time: 5:25:50 AM
STEP 26: Undermined heel of embankment
collapses, unleashing large wave


Reservoir has dropped 65’
EL 1535.0’
Time: 5:22:15 AM
STEP 27: Massive wave of water ~20’ deep removes shingle-protected plunge pool rim (dashed)
~20’ flow depth

Time: 5:32:10 AM to ~5:50 AM (Reservoir essentially empty)

STEP 28: Pool empties, progressively undermining the remaining embankment
A small lip armored by remnant concrete lining remains



A small lip of material armored by portions of the concrete liner remained in a few locations at the breach site.

SCENES ALONG THE PATH OF THE OUTBREAK FLOOD

- **0.7 m LiDAR “bare earth” image of the Upper Reservoir area flown for MoDNR after the failure.**

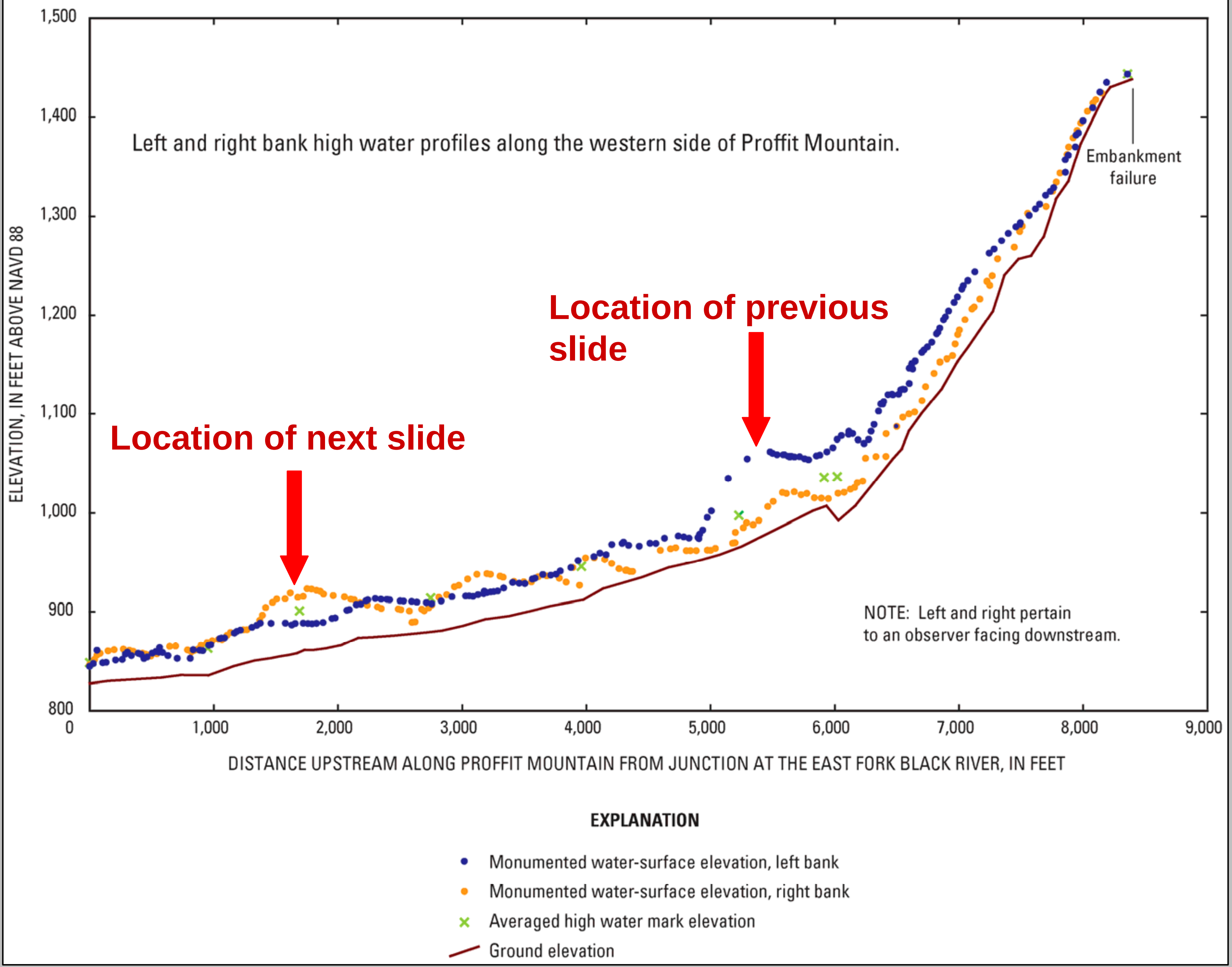
- **Note details in LiDAR derived digital elevation model, and scour of the outbreak flood path.**

Standing on residuum looking at exposures of the Munger Granite.

The flow path down the slope of Proffit Mountain was stripped down to the underlying bedrock (photo by Jeff Spooner (USGS).

The raging flood incorporated soil, rock, concrete, rebar, and HDPE liner, forming a very turbid flow. This flood accumulated soil, rock, and thousands of trees. The momentum of the water allowed it to ramp up the side slopes around the bends.

The momentum of the surging waters allowed them to flow up and over this hill (an old landslide) constricting the valley ~100’ above the valley floor.



Flows reached almost 100’ in depth as the flood banked around turns.

A massive hydraulic jump (near center) developed as the gradient of the slope decreased where Ordovician carbonates onlap onto Precambrian igneous formations of Proffit Mountain. The water dropped over 400 feet down the now bare slope of Proffit Mountain.

A massive scour hole >20 feet deep formed at the hydraulic jump where the gradient suddenly decreased, shifting to a lower flow regime. The coarse fraction of the bedload began to drop out of the flow, although the bed of the channel was still very active. This transition appears to have been “rinsed” by one final wave of water.

Huge pieces of rock and concrete were carried down the slope by the turbid debris flow. A large section of a concrete wall panel is shown here.

Toppled wall panel at north end of breach. The stem was 10 feet high.

Lower portion of the scour channel and precipitous drop, immediately below the reservoir.

Much of the coarse debris fraction appears to have been reworked and sluiced of fines by tail flows, as the flood waters subsided. Note the coarsening upward nature of this deposit and the inclusion of rebar from the shotcrete liner.

The upstream side of two trees had all bark abraded away by the turbid flow.

Reworked boulders, cobbles, and gravel fill the lower portion of the scour channel along with twisted remnants of concrete and rebar.

Concrete and rebar from the dam littered the scour channel.

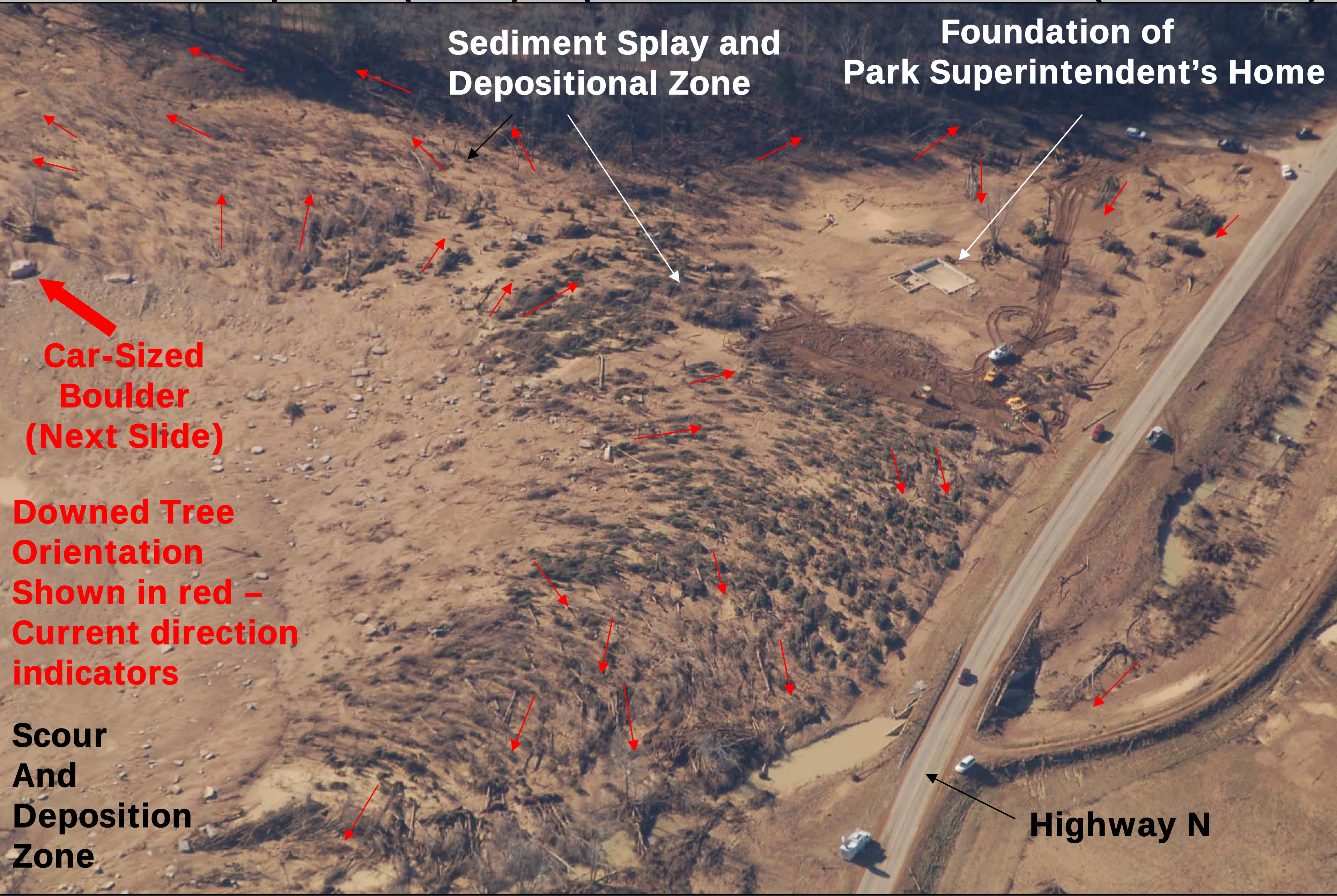
The flood waters surged into the East Fork of the Black River, just upstream from Johnson's Shut-ins State Park, and about 700 ft below the reservoir.

Scour holes were excavated into the residuum and weathered carbonate rock near the junction with the flood plain of the Black River.

As the flood roared into the Black River flood plain, it scoured a deep hole, seen here. The sudden drop in gradient caused the flood waters to drop its sediment, forming a debris dam that backed up this six acre lake (photo by Jeff Spooner USGS-MCGSC).

Source: Missouri Attorney General's website

Sources: Jeff Spooner (USGS) Airphoto, Dr. David Wronkiewicz (Annotations)



Had the Park Superintendent's Home been 200 feet to the south (left), the family would have been washed down into the shut-ins and almost certainly killed.

This boulder was carried over a down the slopes of Proffit Mountain and was deposited just a few hundred feet from the Superintendent’s home.

The Family of Five That Survived

- Park Superintendent Jerry Toops and his family lived near the entrance of Johnson’s Shut-ins.
- At ~5:20 a.m., Jerry awoke to his wife Lisa screaming about a loud rumble she thought was a tornado heading their way.
- Jerry was aware of the reservoir and realized that it had broken and that the family was in grave danger.
- He began to get out of bed to gather his family when the wall of water and debris hit their house, ripping it to pieces.
- The family was caught in a back eddy and carried upstream across Hwy N (road to Johnson’s Shut-ins).
- All three of their children survived and their most serious injuries were caused by rescuers burning them while attempting to assuage their hypothermia.

A hydraulic jump formed as the flow changed from an upper to lower flow regime between the upper and lower shut-ins. Gravel was deposited in this once open hole after the transition to a low flow regime.

A pile of trees was deposited 40 feet above the main channel by the flood. If anyone had been in the shut-ins at the time of the flood, they would have likely not realized there was a problem until it was too late to get out.

Deposition of boulders, mud, and trees in the campground at Johnson's Shut-ins State Park.

Had campers been in the state park campground during the flood, they would have almost certainly been swept into the shut-ins and killed.

The trail leading to the shut-ins was covered by a thick layer of mud and other debris. The shut-ins below restricted the flow and slowed the waters in this portion of the park.

The boardwalks leading to the shut-ins were damaged and covered by debris.

Areas inundated by the flood, as mapped by the USGS-MCGSC team.

Chopper Video Taken by MO Attorney General Jay Nixon on Dec 28, 2005 (Click on Image to Play)

Before After Photos of Scour Zone

WHAT HAPPENED?

- The margin of error provided by recalibrating the controls disappeared as sensors at the bottom of the reservoir continued to pull loose, allowing them to float higher in the water column. This resulted in the failure to measure the full amount of water in the reservoir, causing the controls to believe the reservoir wasn’t full although it actually was.
- The pumps continued to operate, pumping water over the concrete parapet wall where it scoured the underlying rockfill foundation, causing the wall to topple.
- The failure occurred around 5:15 AM on Dec 14, 2005 as the reservoir was completing its nightly filling.

SEVERAL OTHER SHORTCOMINGS DISCOVERED DURING FORENSIC ANALYSIS

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.

1. "DIRTY" ROCKFILL

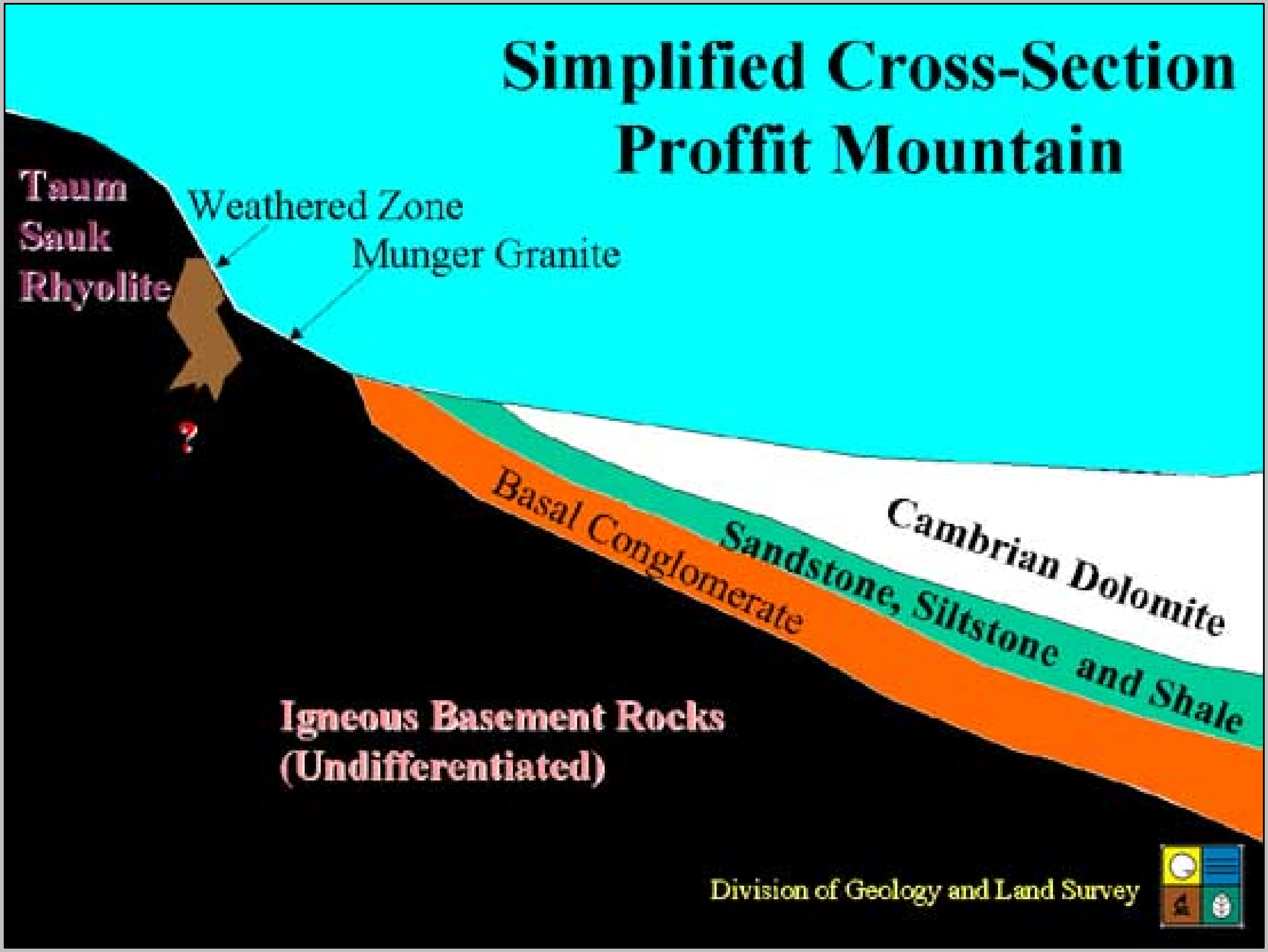
- The cross section of the dam exposed by its failure exhibited a high fines content. The rockfill contained about 20% fines while the project specifications limited the fines to 5% or less.
- This contributed to up to 2' of differential settlement, shifting of the concrete parapet walls, and a cracking of the concrete liner over the years. This also reduced drainage and thus, internal stability of the dam.

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

2. 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 while other areas consist of hydrothermally altered granite and rhyolite.
- A letter by Cooke (1967) states that settlement rates of the embankment are unprecedented but acceptable for the performance of the project. Up to 0.8 feet of settlement had taken place in the first few years of operation, leading him to assume this wasn’t a pure rockfill embankment.
- Cooke stated that it would have been impractical, if not impossible, to remove all of the weathered rock from the fill material during construction and that this weak material was likely responsible for the high rates of settlement at Taum Sauk.

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.**

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 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.

3. 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 resulted in lower strengths at the foundation interface.

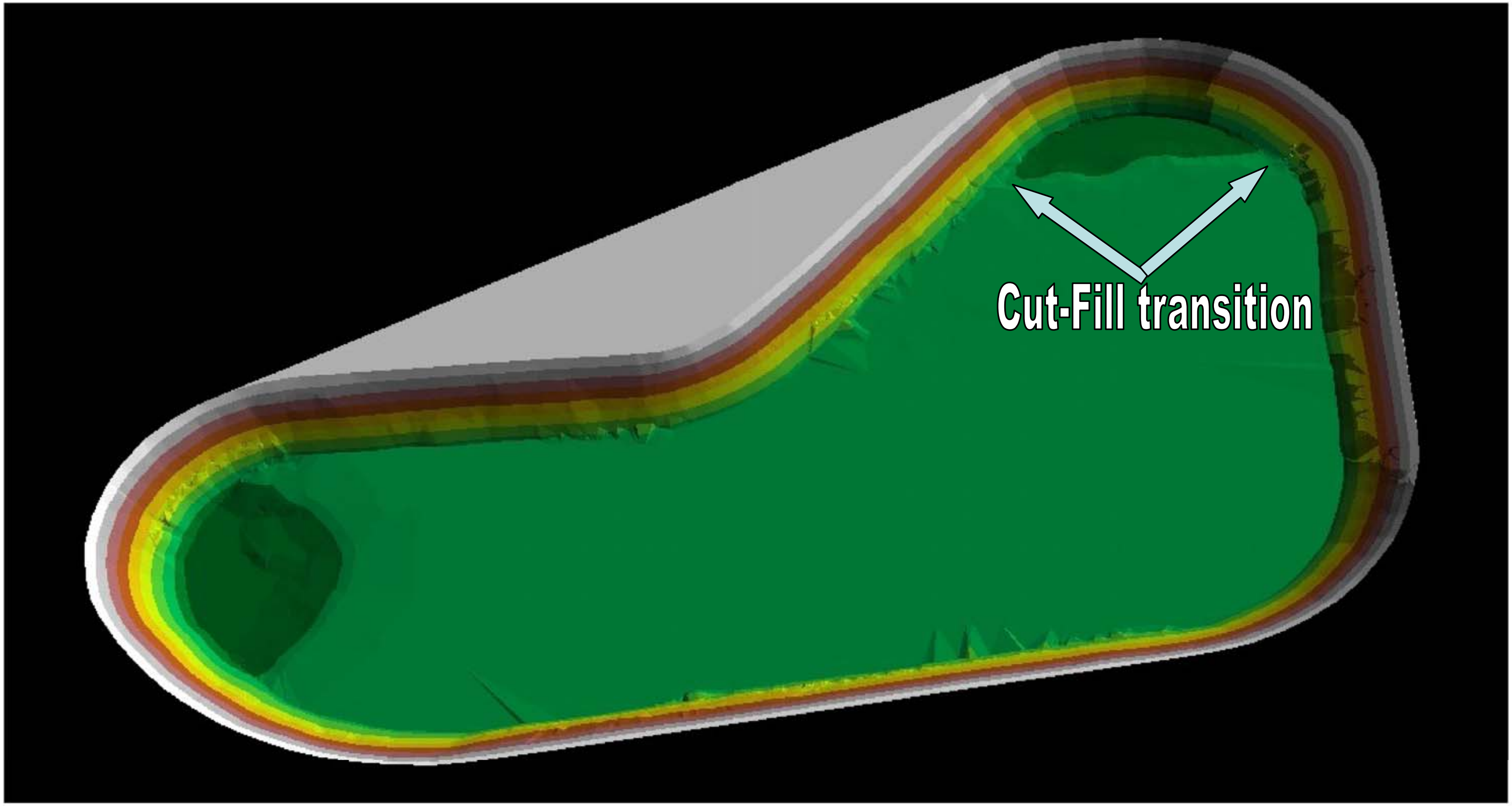


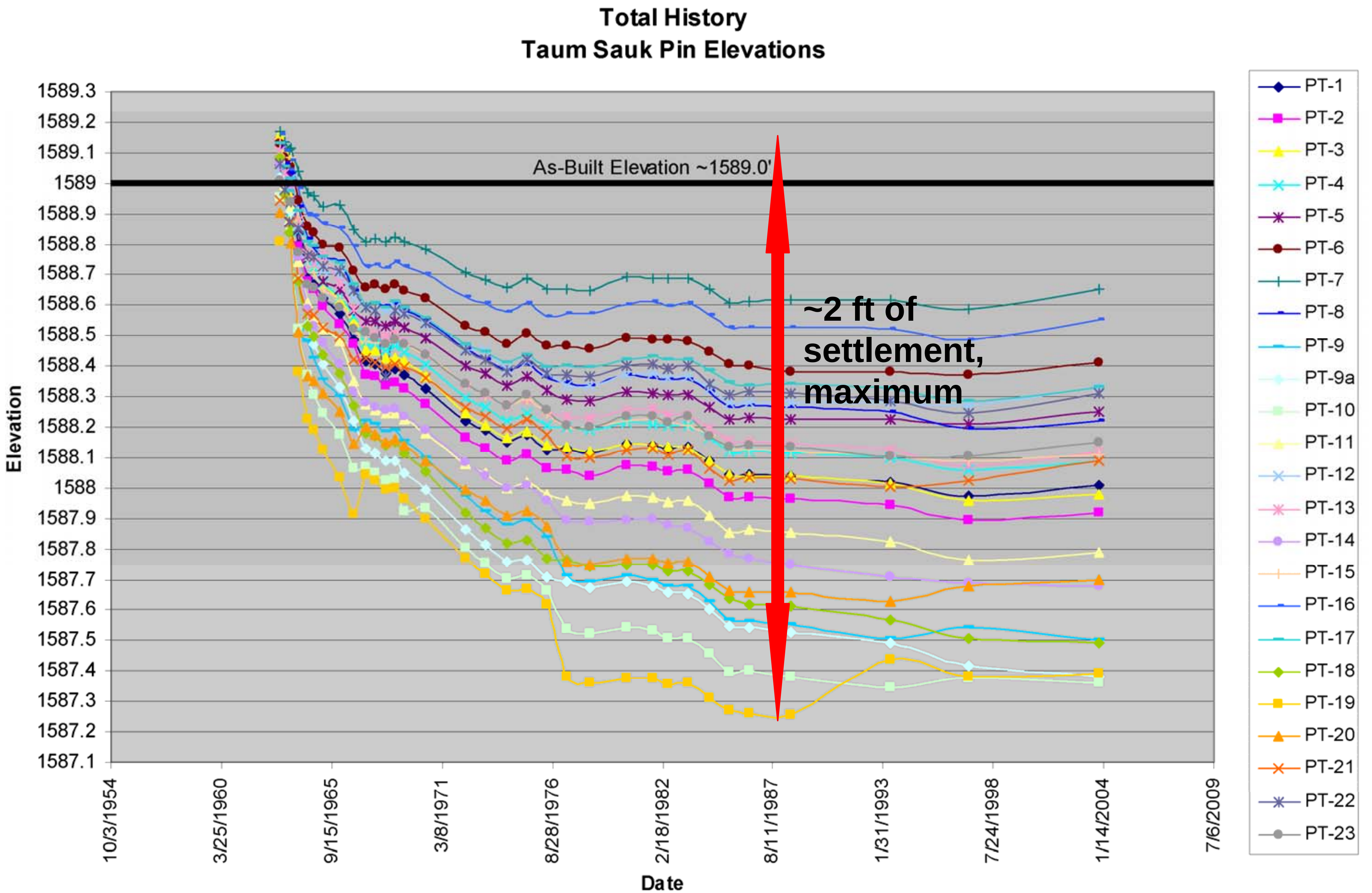
Figure 8.4 – Aerial Survey of empty upper reservoir

- **The cut-fill wedge at the northwest corner of the reservoir, which experienced extra-normal settlement.**

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.

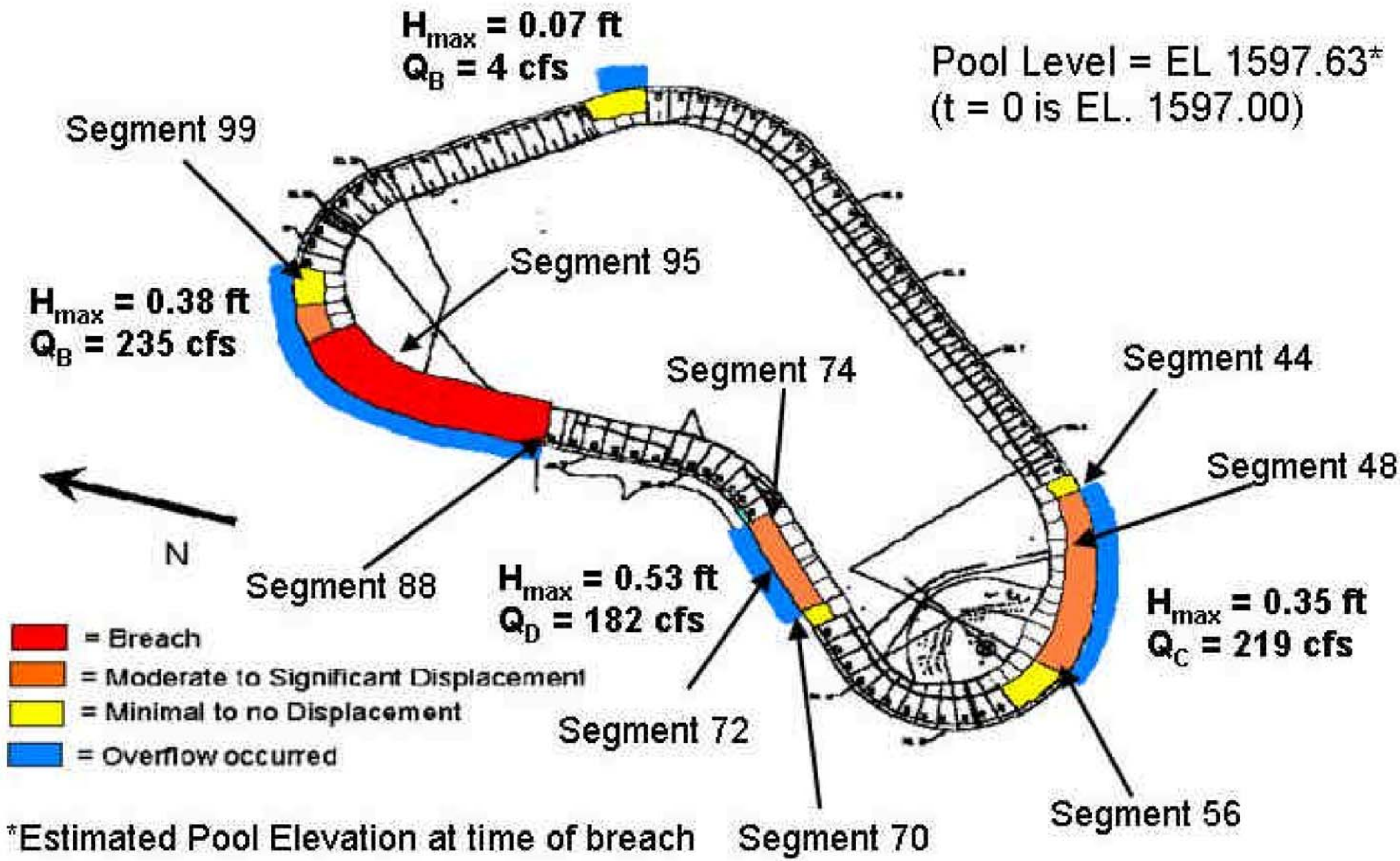
DIFFERENTIAL SETTLEMENT OF THE RING DIKE

SETTLEMENT OF THE EMBANKMENT

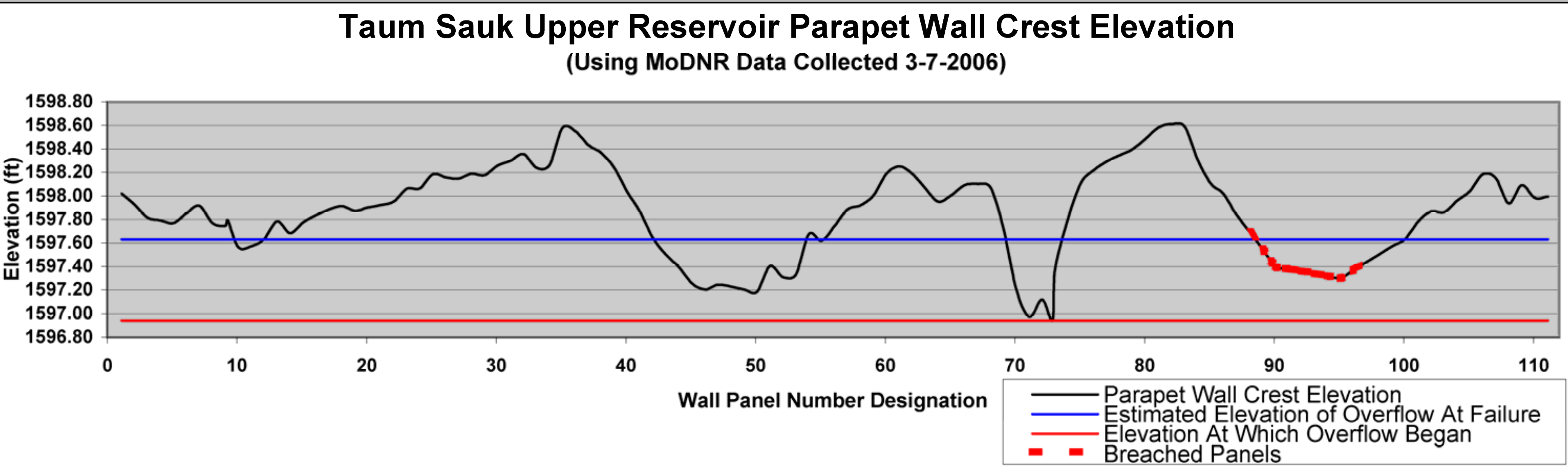


Settlement of the rockfill embankment during first five years of operation

- **The Taum Sauk embankment settled 0.50 to 0.8 ft in the first 4-1/2 years; 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.**



H_{max} = 0.07 ft
Q_B = 4 cfs
Pool Level = EL 1597.63*
(t = 0 is EL. 1597.00)
Segment 99
Segment 95
H_{max} = 0.38 ft
Q_B = 235 cfs
Segment 74
Segment 44
Segment 48
N
Segment 88
H_{max} = 0.53 ft
Q_D = 182 cfs
H_{max} = 0.35 ft
Q_C = 219 cfs
= Breach
= Moderate to Significant Displacement
= Minimal to no Displacement
= Overflow occurred
Segment 72
Segment 56
*Estimated Pool Elevation at time of breach
Segment 70


Taum Sauk Upper Reservoir Parapet Wall Crest Elevation
(Using MoDNR Data Collected 3-7-2006)
Elevation (ft)
1598.80
1598.60
1598.40
1598.20
1598.00
1597.80
1597.60
1597.40
1597.20
1597.00
1596.80
0
10
20
30
40
50
60
70
80
90
100
110
Wall Panel Number Designation
Parapet Wall Crest Elevation
Estimated Elevation of Overflow At Failure
Elevation At Which Overflow Began
Breached Panels

4. ELEVATION DISCREPANCIES INTRODUCTED DURING 2004 LINING/UPGRADE

- The upper reservoir was designed to have a 2' freeboard from the water surface to the top of the parapet wall.
- A staff gauge installed on the inside of the concrete parapet wall during construction had settled ~1 foot over the years.
- The old gauging system was operated relative to the staff gage so freeboard remained constant throughout the years, even with the settlement.
- The NEW gauging system was operated in terms of absolute elevation, which is 1' higher than the elevations stated on the staff gage. This resulted in the 1' reduction of freeboard.

5. CHANGES TO RESERVOIR STAGE SENSOR SYSTEM DURING 2004 LINING/UPGRADE

Upper Reservoir Experienced Persistent Leaks

- Throughout its life, the upper reservoir leaked. This leakage helped provide swimmers at 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 during their repair.
- 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% and the reservoir was lined with an HDPE geomembrane in fall 2004. This reduced leakage dramatically.

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 sensor network was comprised of 4 perforated HDPE conduits; 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 changes should be made.

Eye Bolt

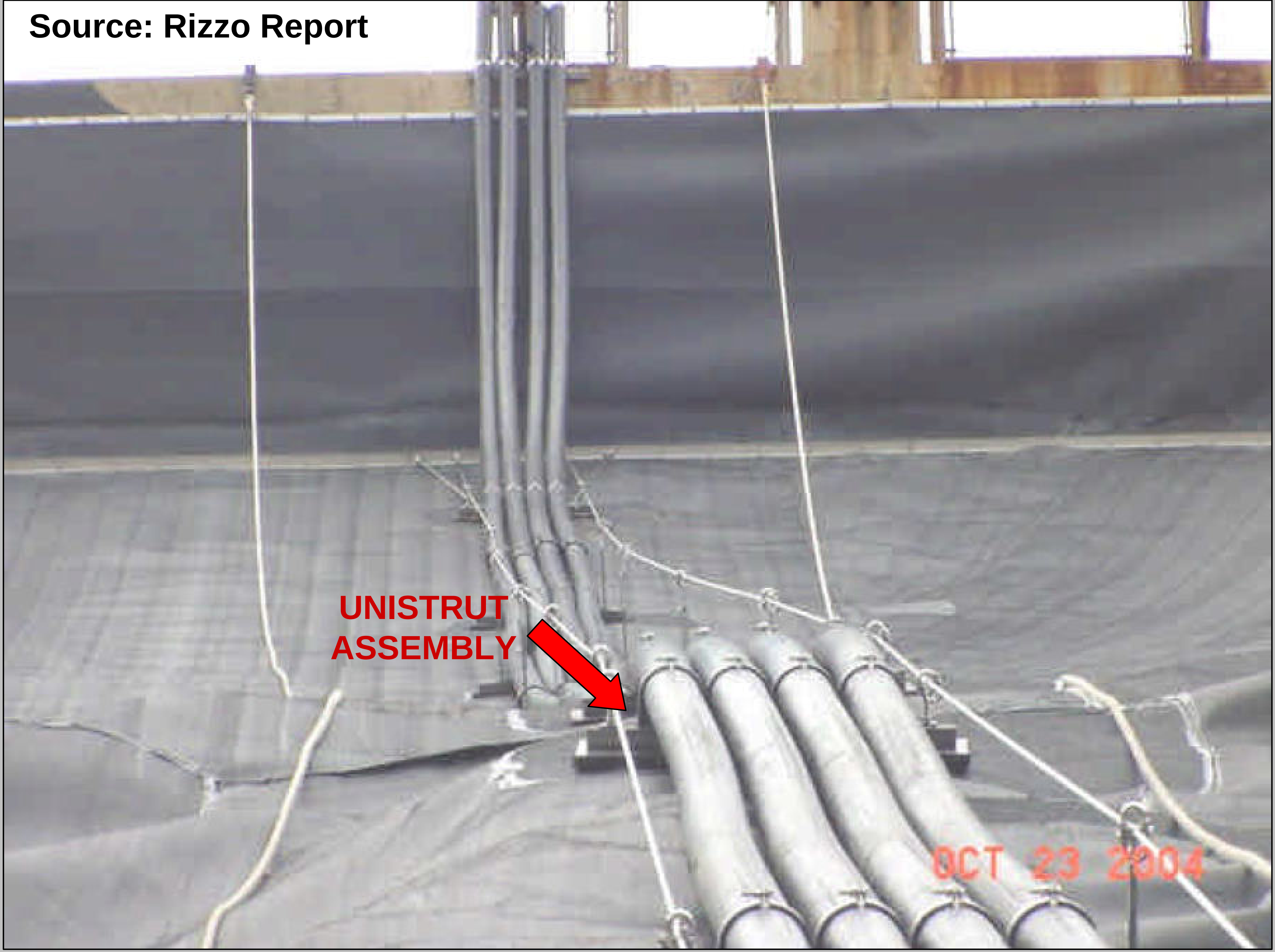
Turnbuckle

- **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 anything inside.**
- **During placement, the eye bolts were discarded in favor of turnbuckles (right above), so the steel cable could be tensioned. 1. The turnbuckles loosened during cyclic loading caused by the filling and emptying to the reservoir, allowing the tubes to work themselves free. 2. The omission of a ballast pipe allowed the sensor tubes to move and deflect much more easily.**
- **These attachment details were not subjected to external peer review. Last minute connection details often prove to be problematic.**

6. FAILURE OF THE UNISTRUT ASSEMBLIES

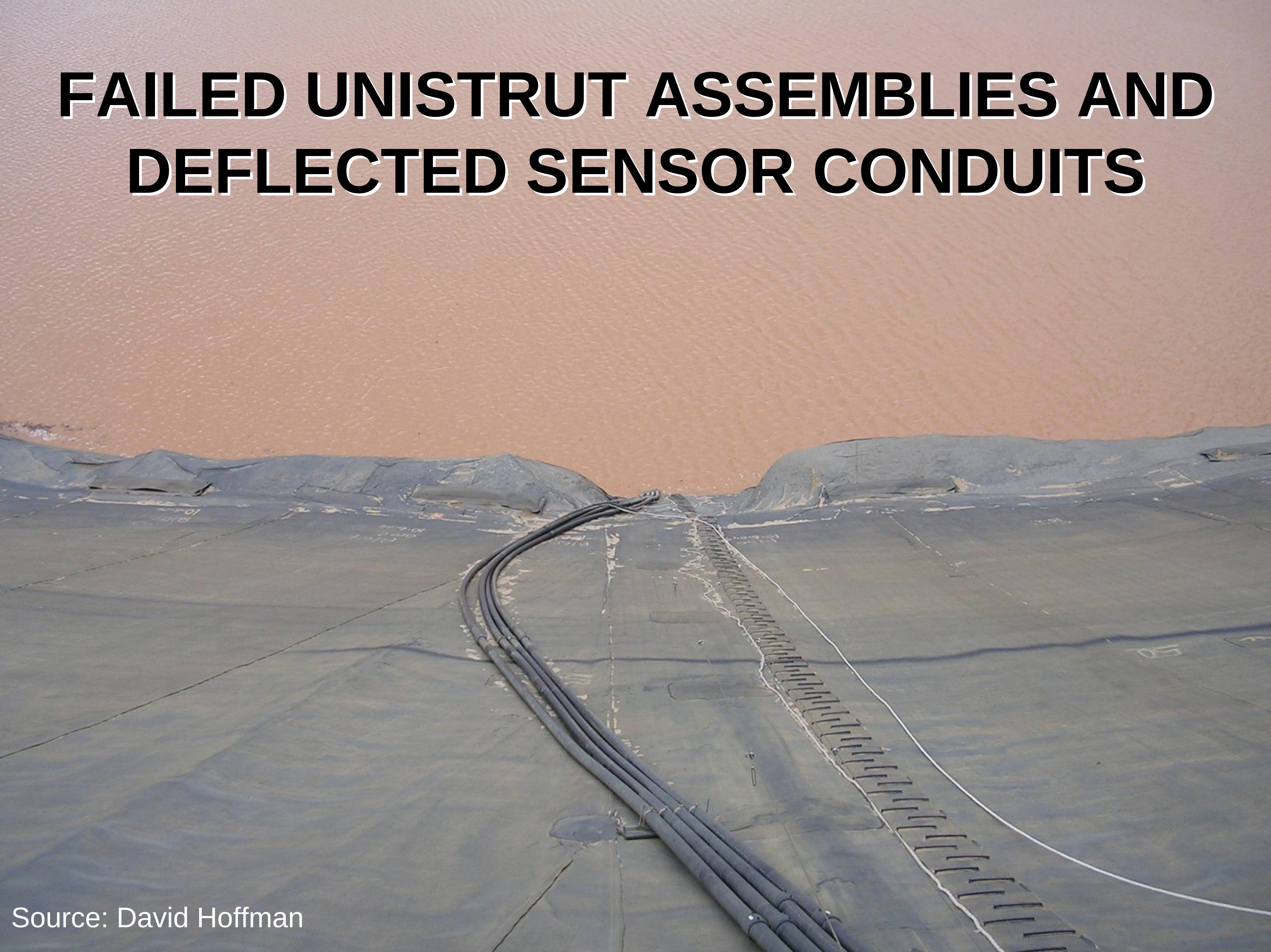
- The four pipes were held bound together by four U-bolts fastened to a piece of hardware called a unistrut. This hardware came apart as the turnbuckles loosened, allowing pipes to separate. This reduced the cumulative stiffness of the pipes, allowing them to deflect easier under the cyclic loading of reservoir filling/draining.

Source: Rizzo Report



Sensor pipes as constructed at Taum Sauk Upper Reservoir in 2004

FAILED UNISTRUT ASSEMBLIES AND DEFLECTED SENSOR CONDUITS

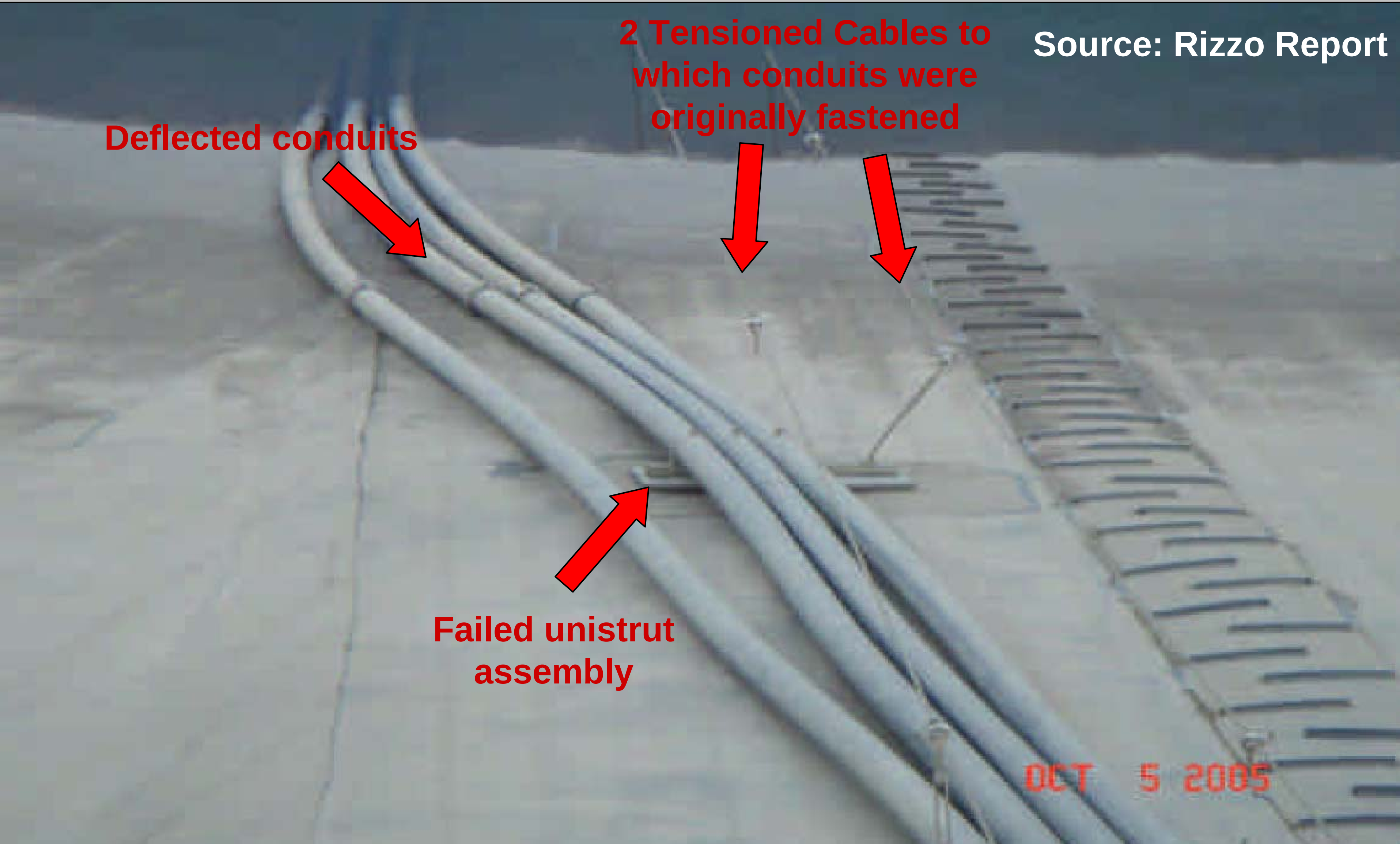


Source: David Hoffman

Source: David Hoffman

- **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.**

FAILED UNISTRUT ASSEMBLY AND DEFLECTED SENSOR CONDUITS



7. “FAIL SAFE” PROBES LOCATED TOO HIGH

- The upper reservoir included fail-safe probes to automatically shut down inflow in case the water level indicators within the reservoir malfunctioned.
- Due to the differential settlement of the embankment and parapet wall, these probes were located ABOVE the lowest points along the crest of the parapet wall at other locations.
- The reservoir level was observed to have risen within 4 inches of the wall crest two days after the “Niagara Falls” overtopping, but the auto-stop 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 conduits likely continued to deflect, so that sufficient freeboard was lost by the time of the fatal overtopping on Dec. 14th.

PRIMARY FACTORS BEHIND THE FAILURE and CONCLUSIONS

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 incident on September 25th 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 errors in judgment.
- 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, without suffering a catastrophic failure.

RESULTS AND CHANGES MADE DUE TO FAILURE

- The Governor and state legislature looked into passing a revised dam safety act to improve inspection and maintenance of dams deemed to be a danger if they were to fail. Legislators from rural counties worried about violating private property rights and voted against the act, defeating the measure. Agricultural interests also lobbied against the bill.

CHANGES EFFECTED BECAUSE OF THE FAILURE

- AmerenUE examined its internal policies and pledged to make changes to operating and maintenance procedures at ALL their facilities to prevent future problems.
- A full-time dam safety officer has been hired to oversee all dam-related projects within the company.
- AmerenUE is paying for clean-up and repair of Johnson's Shut-ins State Park.
- FERC has approved AmerenUE's plan to rebuild the upper reservoir.
- The Federal Energy Regulatory Commission fined AmerenUE $15 million; the largest fine ever accessed by FERC and is 30x larger than the previous record fine of $500,000.
- Investigation is ongoing by the FBI and the Missouri Highway Patrol to decide if other fines/penalties should be accessed. The State Attorney General's office is also conducting its own investigation, based on information that surfaced after release of the FERC and Rizzo forensic investigations.

REASONS BEHIND RECORD FINE

- FERC assessed its record fine based on the following aspects:
  -Failure to report the Sept. 25, 2005 overtopping to FERC
  -Failure to report unusual instrument readings on Sept. 27th
  -Failure to report the release of the transducer retention system
  -Addition of 0.4 feet to the water level in the programmable logic controller to compensate for inaccurate readings
  -Failure to repair the loose transducers
  -Operation of the reservoir with insufficient freeboard (too close to the top of the parapet wall)
  -Fail-safe probes moved to an elevation higher than the lowest point on the reservoir parapet wall
  -System programmed to have a 1 minute delay in pump shutdown after activation of probes
  -Probes reprogrammed to operate in series instead of in parallel
  -Lowest of two probes not programmed to sound alarm when activated
- All of the listed modifications to the system required the notification of FERC by AmerenUE prior to such changes being implemented.

WHAT COULD HAVE HAPPENED?

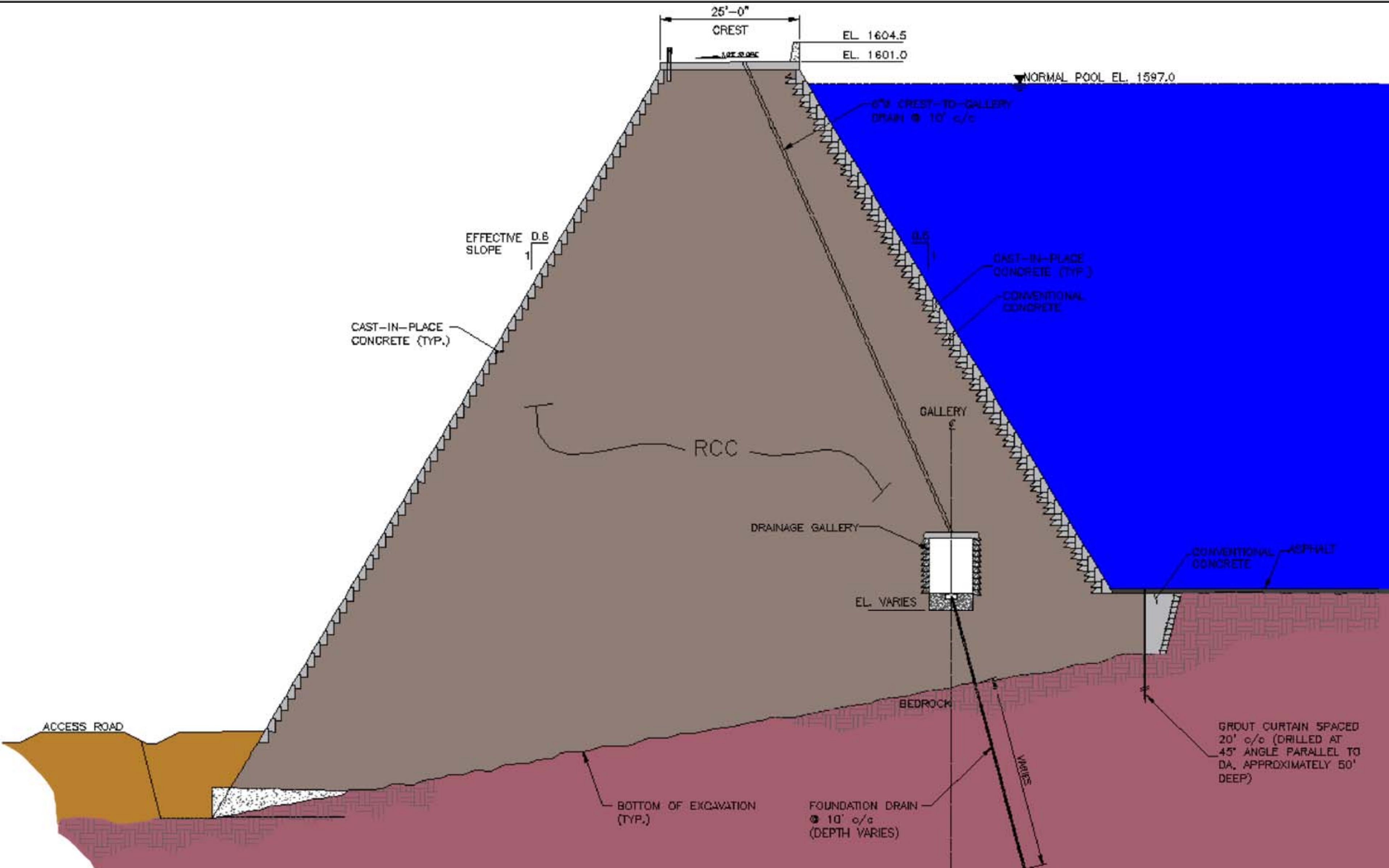
- **The results from this disaster could have been FAR worse!**
- **The reservoir failed during the early morning hours of a weekday in the middle of December. The campground at Johnson's Shut-ins State Park was empty that night/morning.**
- **If the reservoir had failed on a popular summer weekend such as Memorial Day or July 4th, the campground and shut-ins would have been AT CAPACITY with campers and swimmers filling this natural water park. Those in the campground and shut-ins would have had little time to react to the rushing torrent of water. Visitors would have noticed a loud roar but might have wondered about the noise and not realized its significance until it was too late to escape.**
- **This could have killed nearly as many people as the failure of the South Fork Dam near Johnstown, PA (2,209 dead) or the New Orleans levee failures induced by Hurricane Katrina (~1,600 dead), now recognized as the worst engineering failure in U.S. History.**

The lower reservoir had been pumped down to fill the upper reservoir the night before. The partially empty lower reservoir captured much of the flood and associated debris, saving downstream towns such as Lesterville from the devastation although muddy water clouded the normally clear Black River. Had this reservoir not been present or also failed, downstream damage would have been much worse.

UPPER RESERVOIR REBUILD

- **AmerenUE is awaiting approval from various state agencies before the rebuild can begin.**
- **If approved, construction will span two years with power generation resuming in 2009.**
- **The new reservoir will be constructed of roller compacted concrete (RCC) using aggregate recycled from the failed reservoir dike.**
- **RCC is more resistant to overtopping and the new reservoir will include a spillway capable of handling the maximum inflow (5,358 cfs), along with video monitoring systems and multiple redundant sensors capable of detecting overflow in case the primary system fails.**
- **The spillway would direct any overflow down the SE side of the mountain into Taum Sauk Creek and then the lower reservoir, away from Johnson's Shut-ins State Park.**

SECTION THRU PROPOSED ROLLER COMPACTED CONCRETE DIKE



CABIN CREEK PUMPED STORAGE PLANT

Georgetown, CO

- One year after the completion of Taum Sauk, a similar project began in Colorado. Construction spanned from 1964 to 1967.
- Similar generating capacity with two generating/pump units (324 MW vs. 350 MW at Taum Sauk). Taum Sauk was later upgraded to 440 MW in 1999.
- The project used a compacted rockfill embankment lined with reinforced concrete.
- Maximum water levels were set 6 ft. below the crest of the dam and 9 ft. below the top of a 3 ft. parapet wall on the crest. This gave 9 ft. of freeboard vs. 2 ft. at Taum Sauk.
- This reservoir was also overpumped but did not fail. Details of this incident are not specified in reports.

CONCLUSIONS

- **The Tauk Sauk failure could have been far worse had it occurred on a different date.**
- **The failure of the Taum Sauk Upper Reservoir was due to a combination of several contributing factors. Had JUST ONE of these factors been absent, the failure would probably not have occurred.**
- **Engineered projects generally have redundancy built in to prevent failures so it is unusual for one factor to bring down an entire system. Often, certain combinations of factors were unforeseen by the original designers.**
- **Most major engineering failures share the commonality of experiencing multiple smaller failures leading to a complete failure of the system. Human error is almost always a main contributing factor.**

REFERENCES & ACKNOLEDGEMENTS

The following resources were consulted during the creation of this presentation.

- **Field trips to the site with the USGS, UMR, and MACTEC after the failure provided opportunities to photograph and study the failure**
- **Various articles and figures from the St. Louis Post Dispatch, KMOV TV, KSDK TV, KTVI TV, The Springfield News-Leader, The Daily Journal (Park Hills, MO newspaper), and other media sources following the incident**
- **Operation reports pertaining to the project on FERC's website http://elibrary.ferc.gov/idmws/search/eSave.asp?fd=11/22/2004&td=12/22/2007&cat=submittal,%20issuance&dkt=P%2D2277%2D&ft=fulltext&dsc=description**
- **Forensic Reports on the failure including**
  -FORENSIC INVESTIGATION AND ROOT CAUSE ANALYSIS DECEMBER 14, 2005 INCIDENTUPPER RESERVOIR DIKE TAUM SAUK PLANT **published by Paul D. Rizzo & Associates, Apr. 5, 2006**
  ***-FERC Staff Report*, April 28, 2006**
  ***-FERC Independent Panel of Consultants (IPOC) Report*, May 25, 2006**