A.V. Watkins Dam Backward Erosion Piping Incident Update

National Dam Safety Program Technical Seminar | 2023

FEMA

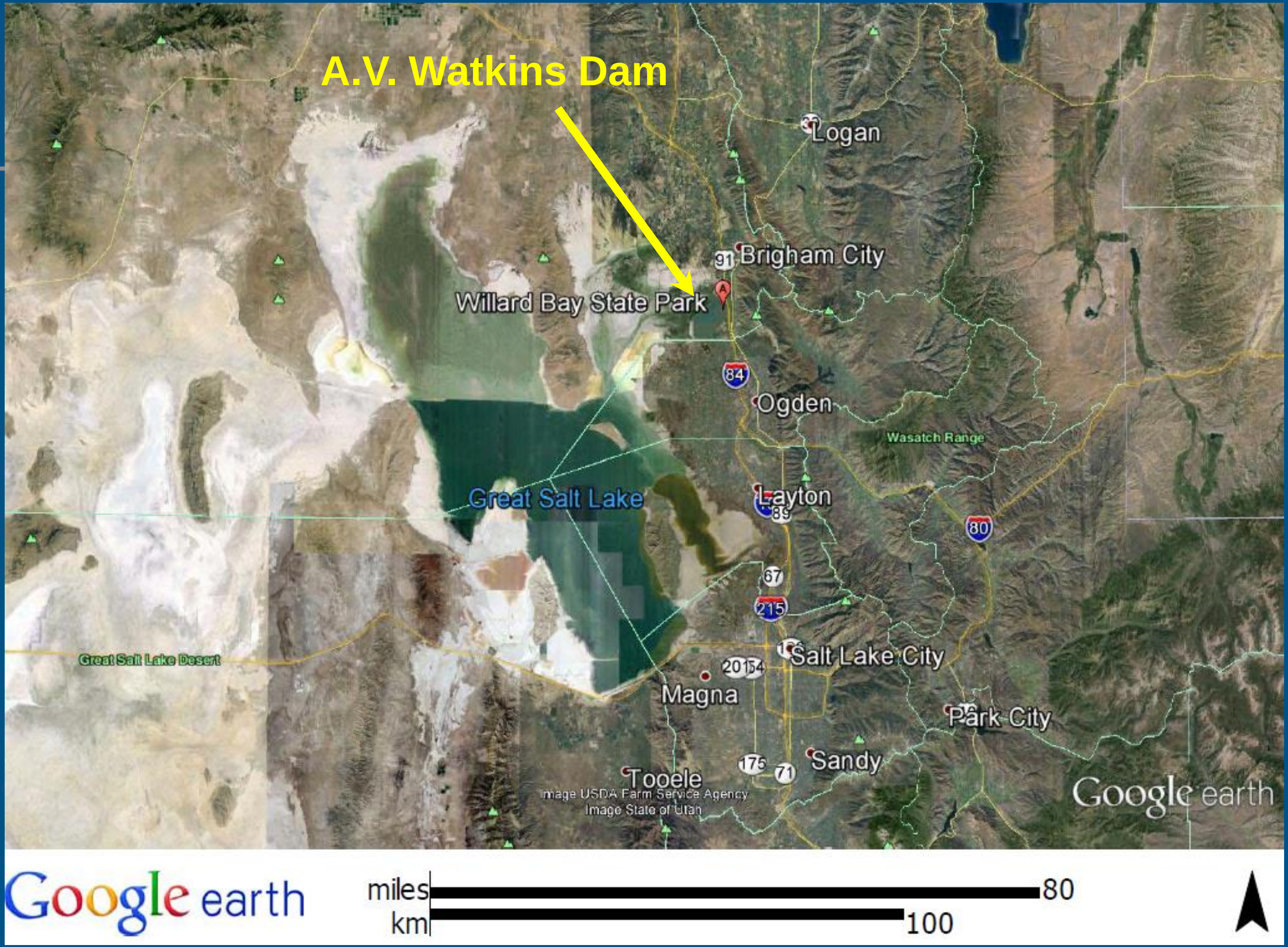
Outline

- Background
- Incident and Emergency Response
- Post-Incident Investigations
- Failure Mode Description
- Why did the Incident Occur after Decades of Successful Operation?
- Key Takeaways

Background

Background (1)

- Built on eastern edge of the Great Salt Lake
- Approximately 50 miles north of Salt Lake City



Background (2)

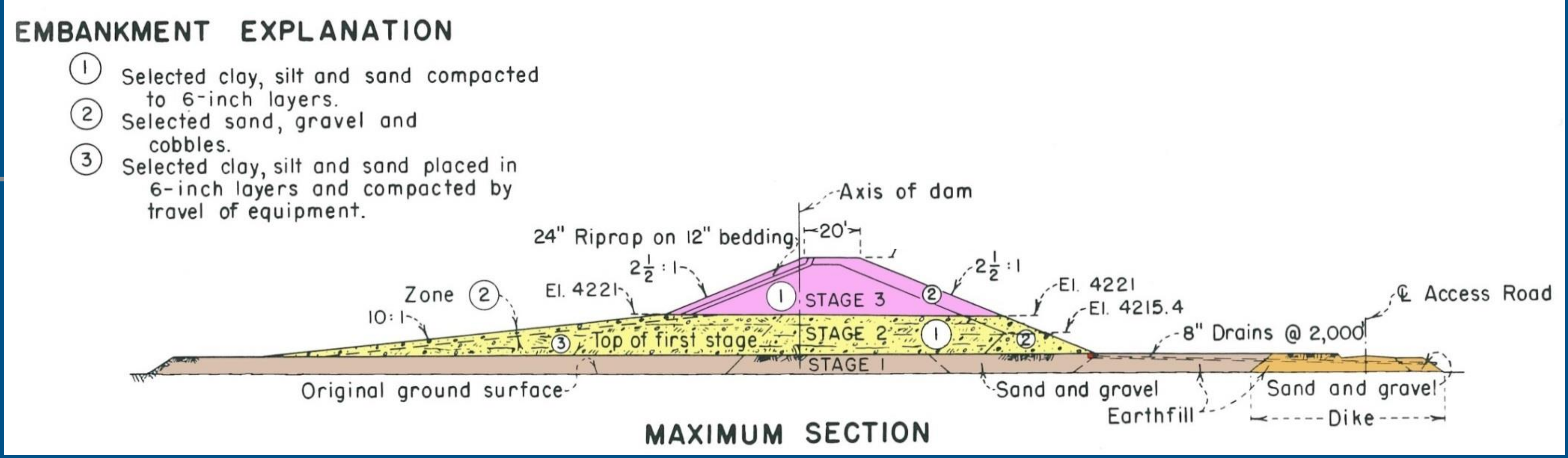
- Constructed from 1957 to 1964
- Dam Length: 14.5 Miles
- Height: 36 feet maximum originally
- Offstream storage facility
- Typically fills each year

Background (3)

Foundation Description

- Most of the dam foundation consists of highly compressible lake sediments (soft clay, ~10 miles)
- Foundation for southeast part of dam has up to about 30 feet of silt, sand, and silty sand over soft clay (~5 miles)
- No cutoff trench and no foundation treatment provided as part of dam construction

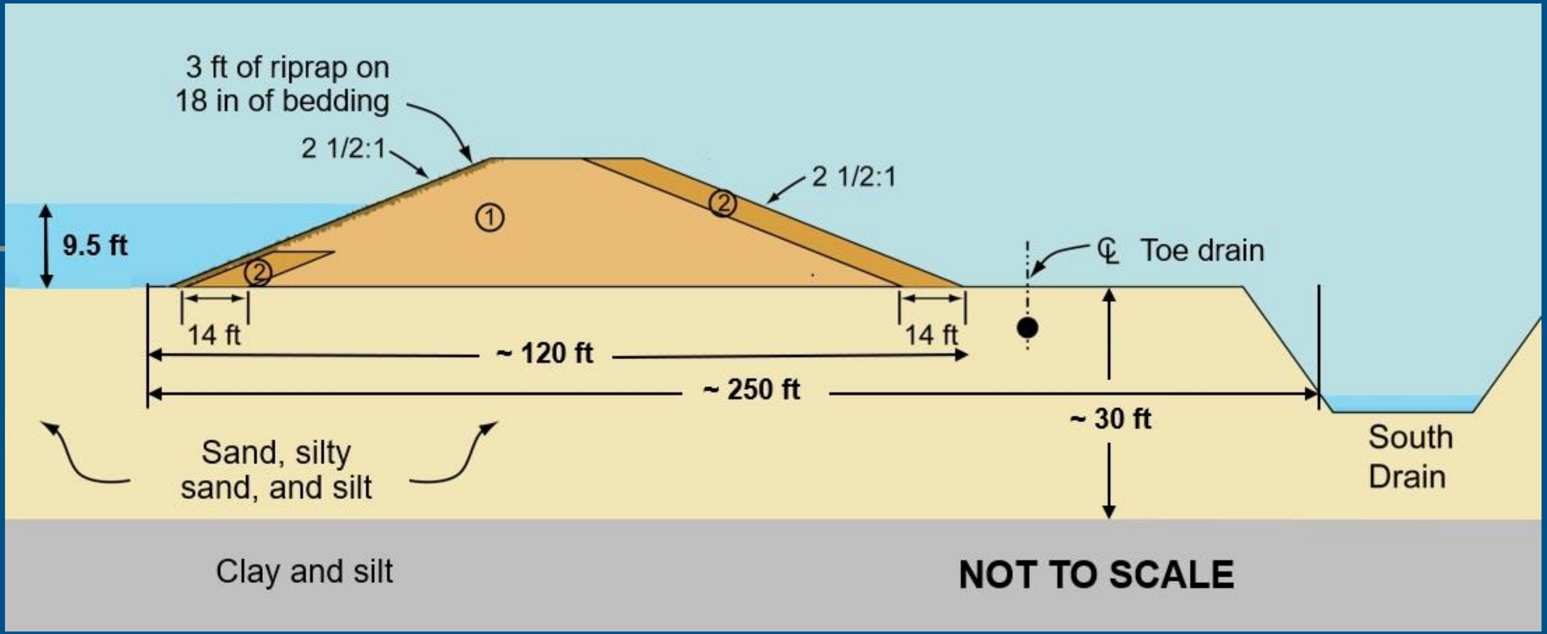
Background (4)



Original Design and Construction

- Primary concern was settlement of soft foundation soils
- Accounted for highly compressible, low-strength foundation soils by building the dam in stages to allow time for pore pressures to dissipate while soils consolidated and gained strength before additional fill added
- Embankment in incident area constructed mostly in Stage 3 (no wide base in that area)

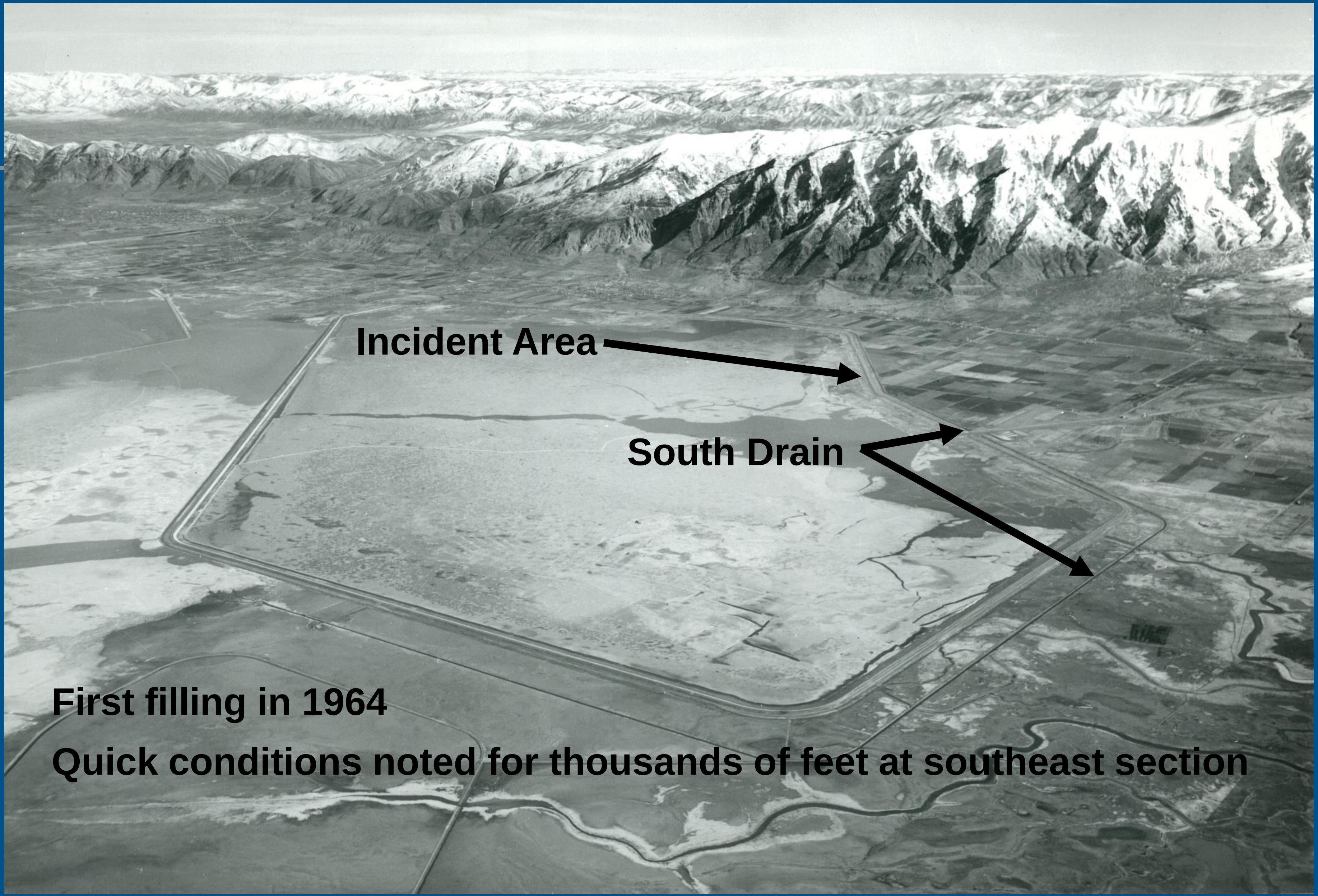
Background (5)



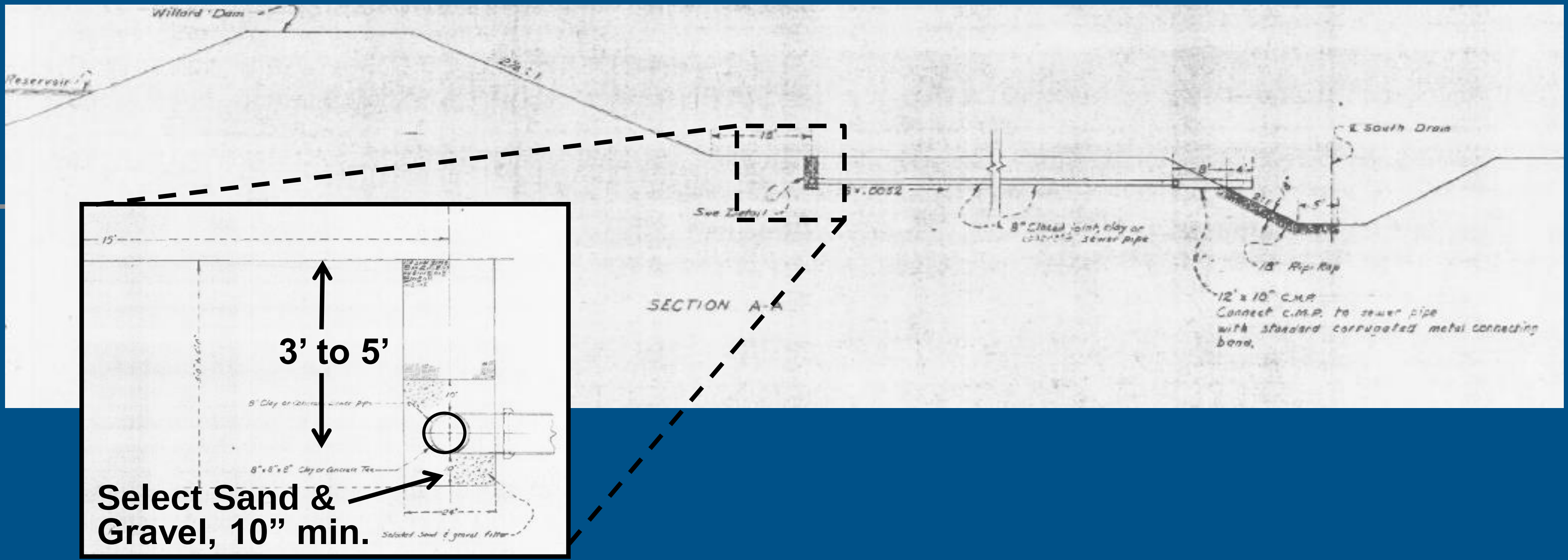
Typical section in area of incident

- Zone 1 is a sandy to silty clay (~70% fines content)
- Zone 2 was finer than intended by the design in the incident area with essentially no gravel and 20% to 50% fines content
- Foundation consists of ~30 ft of sand, silty sand, and silt overlying very soft lacustrine clay and silt that is hundreds to thousands of feet deep
- Hardpan was encountered during construction of portions of the South Drain

Background (6)



Background (7)



Toe Drain

- "Quick conditions" occurred at RWS El. 5224.5 feet
- Decision made to install toe drain along approximately 4 miles
- 8" diameter open joint concrete pipe along dam toe
- 15' downstream and pipe is 3 to 5 ft deep
- Outfalls at 1,000 ft intervals into the South Drain
- Toe drain sloped at 0.13%; outfalls sloped at 0.52%
- Dam filled successfully in 1965

Incident and Emergency Response

Detection of the Incident

- 9.5 ft of head on upstream toe at time of incident
- Feed lot operator noticed cloudy seepage and sand eroding into South Drain (piping) on November 11, 2006
- Feed lot operator notifies water district of concerns on Monday-November 13 when seepage increased and “dark clay” observed exiting into South Drain
- Monday evening – November 13
  - Foundation piping observed by Reclamation and water district staff
  - Sand boils at toe of dam, sand deposits in South Drain and at toe of dam, sinkholes, cracking, and slope failures on downstream slope, transverse cracks in crest

Incident and Emergency Response (1)

Initial Observations

- ~200 gpm seepage flowing into the South Drain.
- ~250 CY of sediments
- This is ~130 ft downstream of the downstream dam toe

Incident and Emergency Response (2)

Initial Observations

- View from dam embankment of sand boils immediately at the downstream toe

Incident and Emergency Response (3)

Initial Observations

- Large sand boils at the downstream toe

Incident and Emergency Response (4)

Initial Observations

- 150-200 gpm coming from 1 large sand boil at the toe and several smaller sand boils a short distance from toe
- ~ 12 CY of sand sediment at downstream toe
- Sand deposit indicates that higher flows existed prior to Reclamation staff arrival
- Note embankment slump that indicated the downstream portion had dropped into a void in the foundation

Incident and Emergency Response (5)

Initial Observations

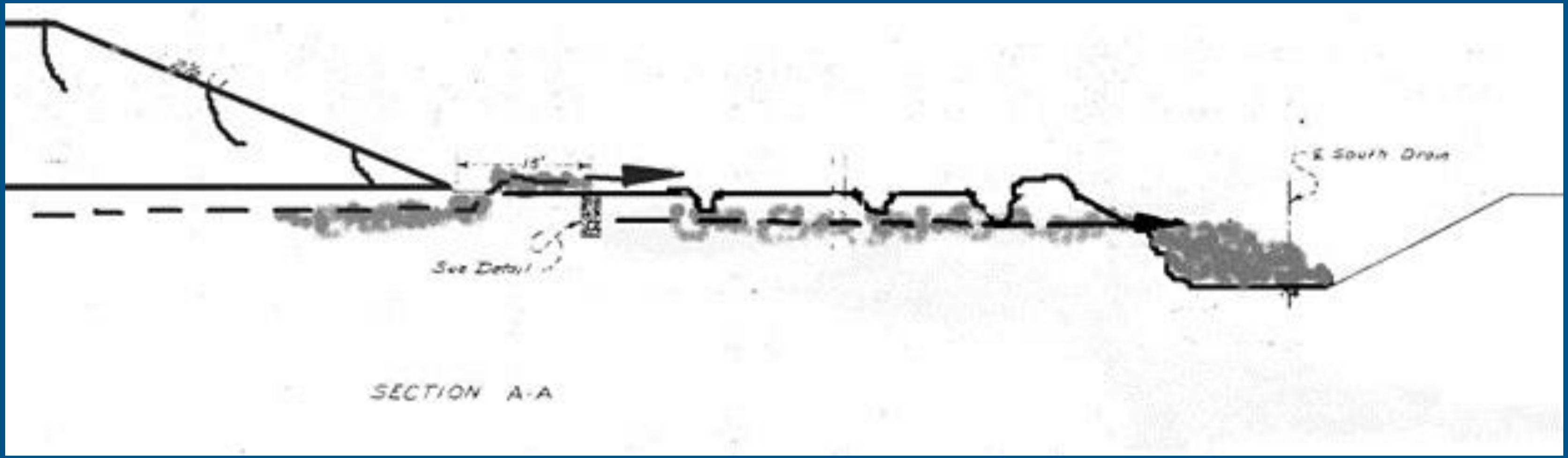
- Transverse crest crack in wheel path on crest
- Upstream of embankment slump area

Incident and Emergency Response (6)

Initial Observations

- Longitudinal crack in crest.
- Upstream of embankment slump area
- Additionally
  - Numerous sinkholes and depressions between the toe and the South Drain
  - Approximately 2 to 5 ft in diameter

Incident and Emergency Response (7)



Sketch of Conditions Upon Arrival (D. Grundvig, 2006)

- Blowout at dam toe with foundation soils being coming out of boils
- Concentrated flows carrying eroded soils over the ground surface and into sinkholes
- Transported sediments re-emerged in the South Drain

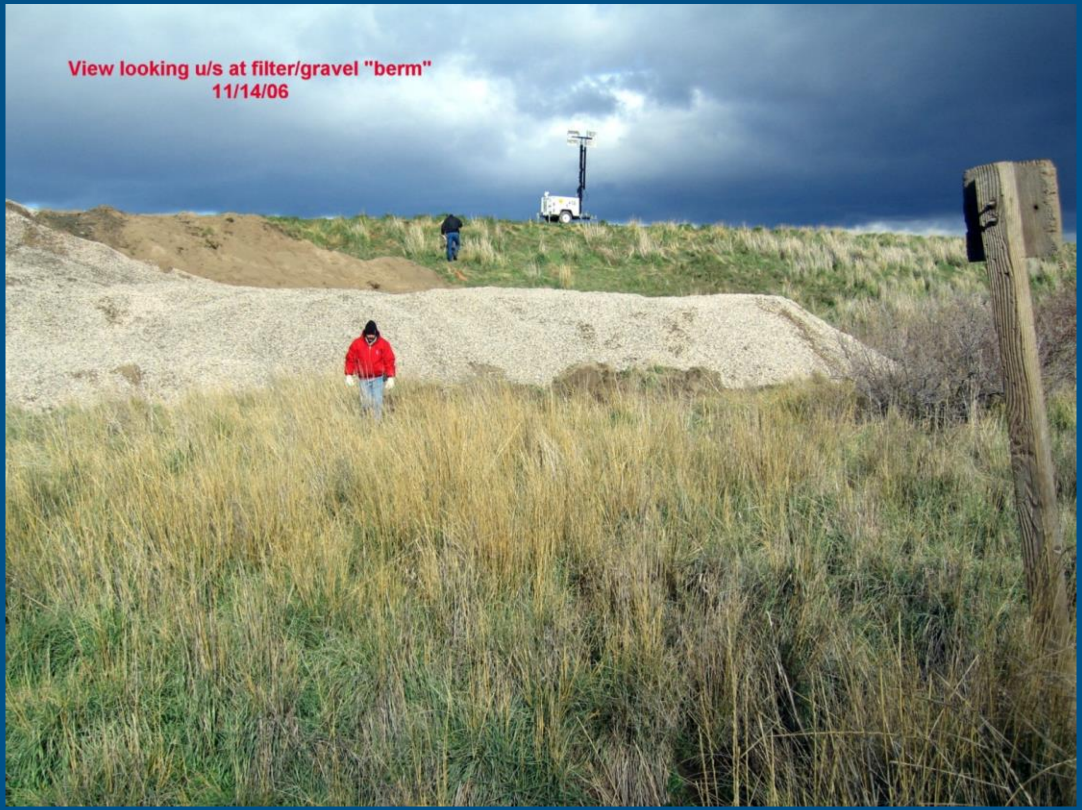
Incident and Emergency Response (8)

Emergency Response

- Decision made within minutes of arriving to construct a filter and berm at the downstream toe area
- Work was complicated by heavy rain and darkness
- Initial filter placement efforts were unsuccessful
  - Seepage volume and velocity too high; filter sand was washed away immediately
  - Flow velocity reduced by placing gravel on sand boils first, then placing filter sand

Incident and Emergency Response (9)

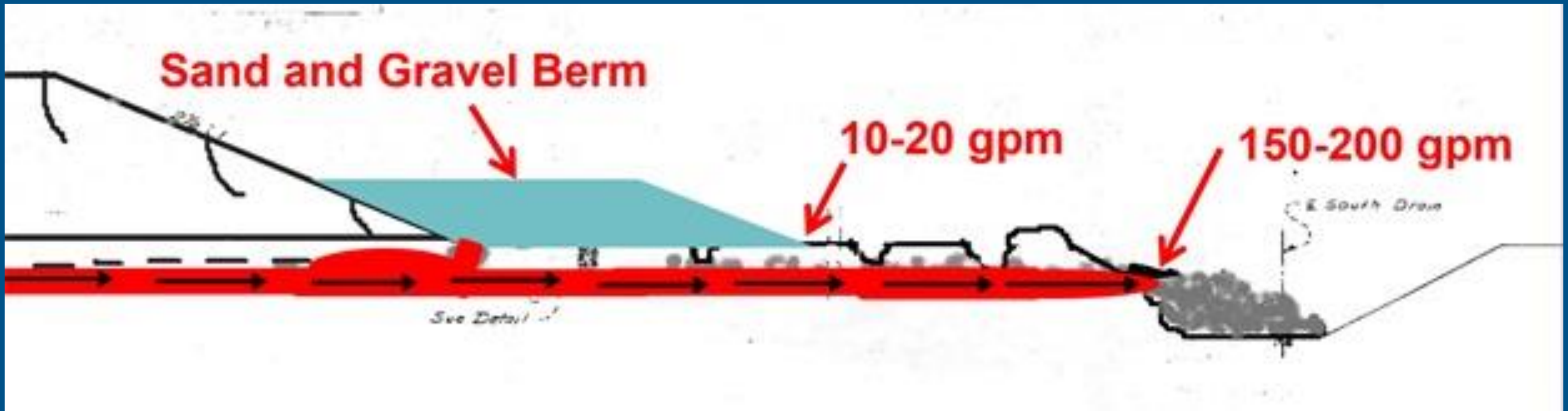
Photos of downstream filter berm



Incident and Emergency Response (10)

Conditions and Concept of the Failure Mode in Progress After Downstream Berm Construction

- 10 to 20 gpm of filtered seepage exiting toe of filter berm
- AND still 150-200 gpm cloudy seepage into South Drain
- Failure Still in Progress!



Incident and Emergency Response (11)

Upstream Berm

- Needed to cover/plug the upstream entrance of the seepage
- 5-inch minus pit-run material pushed into reservoir
- Seepage into South Drain reduced to 20-30 gpm (clear)
- Seepage from toe stopped completely

Post-Incident Investigations

Post-Incident Investigations (1)

Purpose

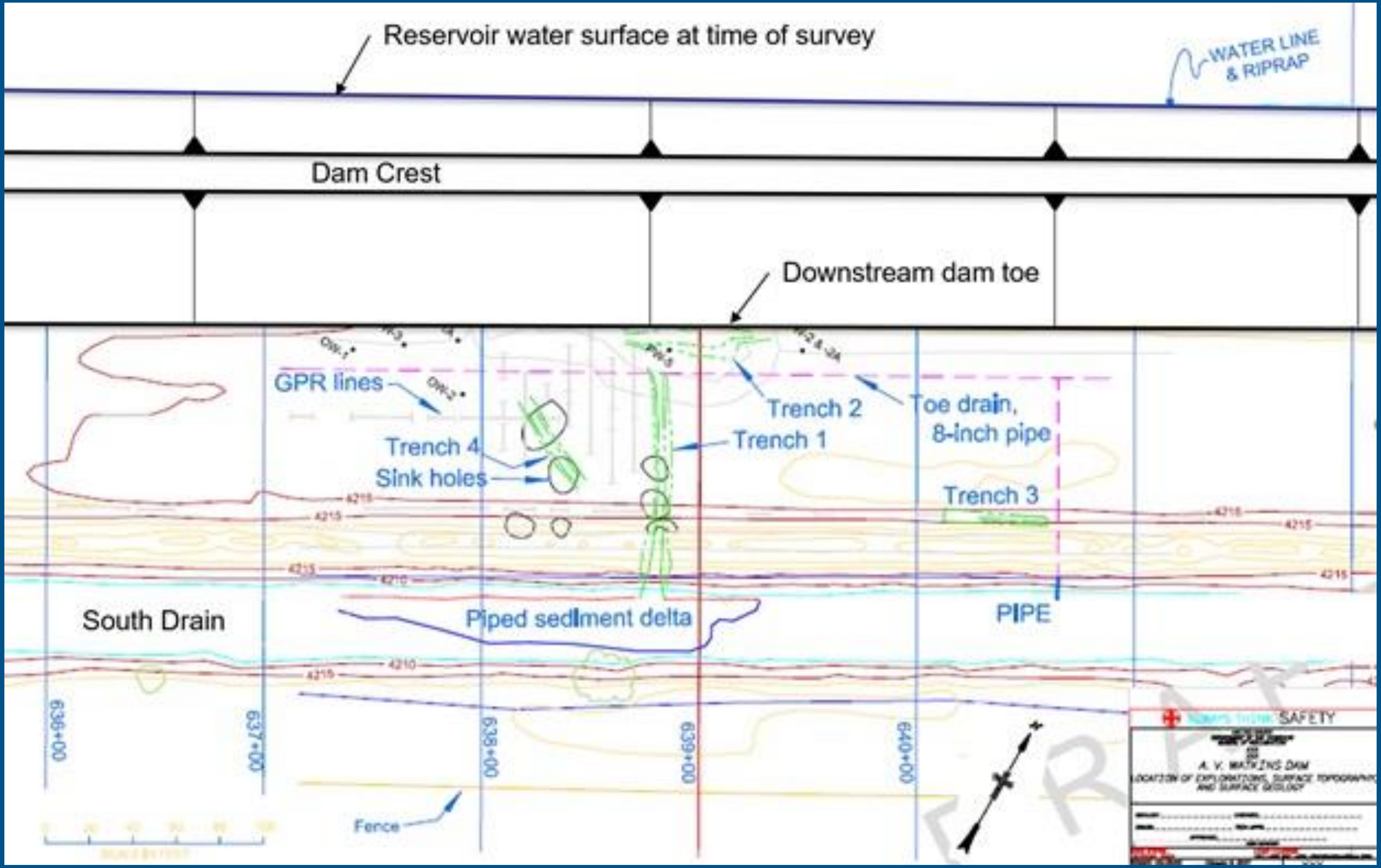
- Primary purpose: design of interim and permanent dam safety modifications
- Limited forensic study conducted
  - Dewatering efforts for the investigations were unsuccessful
  - Feasible depth of investigations was limited

- **Investigations**
- Visual examinations
  - Entire southeast reach of the dam
  - Upstream toe area to look for sinkholes
- Trenches, test pits, boreholes, and CPT's
- Geologic mapping of trenches in the incident area
- Examination of the toe drain
- Conducting topographic surveys and ground penetrating radar (GPR)

Post-Incident Investigations (2)

Plan of Incident Area

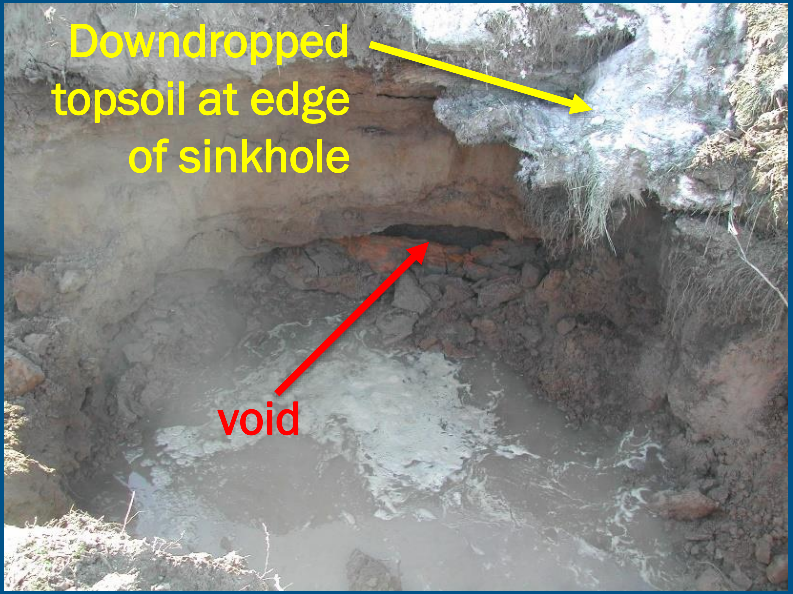
- Locations of Explorations
- Sinkholes
- Survey including sediments in South Drain



Post-Incident Investigations (3)

Hardpan layer several inches thick in the incident area on the dam side of South Drain

Steel rod used to break through the hardpan layer exposed in a trench. Note upward flowing water under pressure.

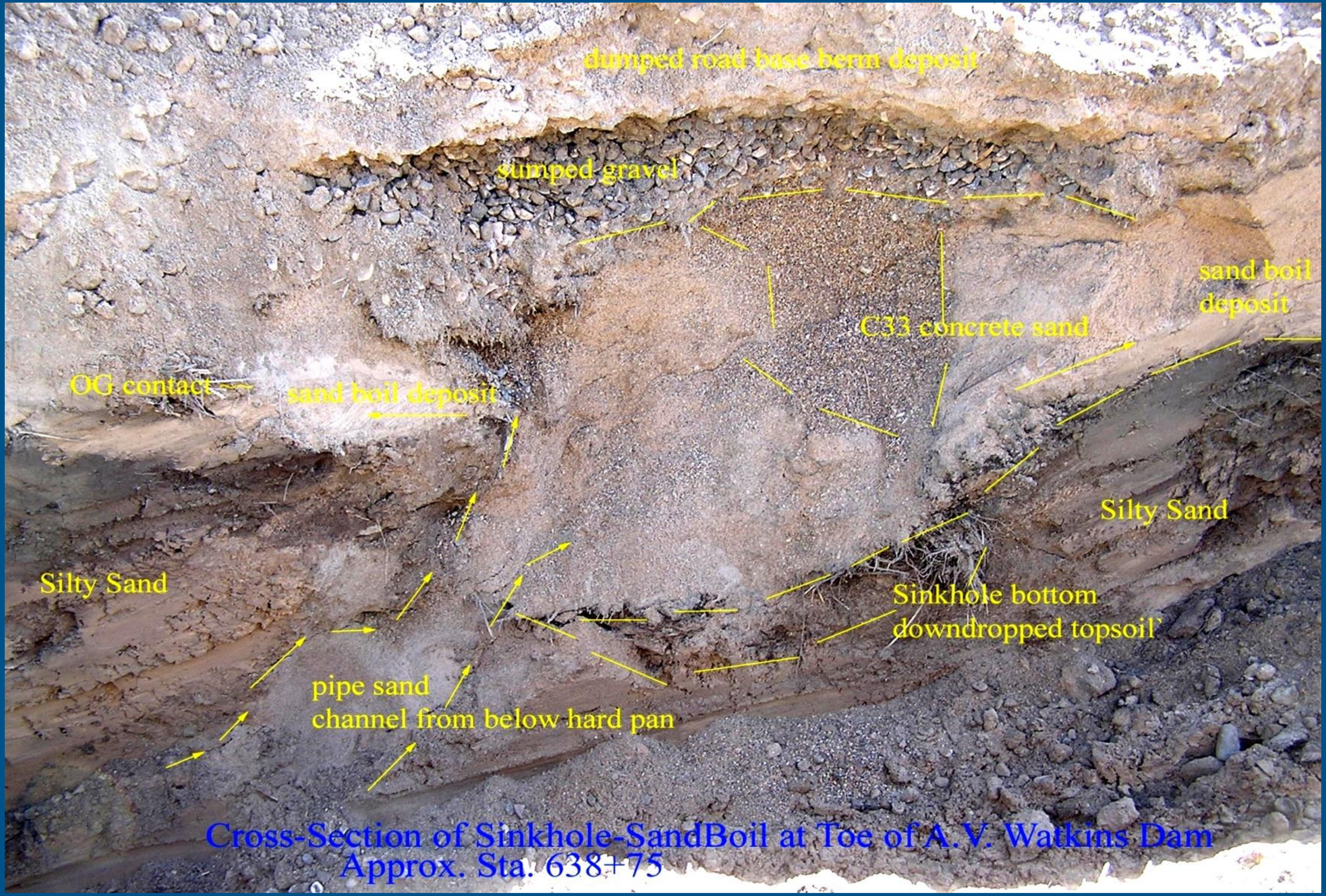


Shallow, wide void under hardpan exposed in test pit at a sinkhole

Post-Incident Investigations (4)

- Photo of trench excavated at the downstream toe showing down-dropped topsoil, piped sand from below the underlying hardpan.

- Upper materials are C33 concrete sand and gravel of the filter berm.

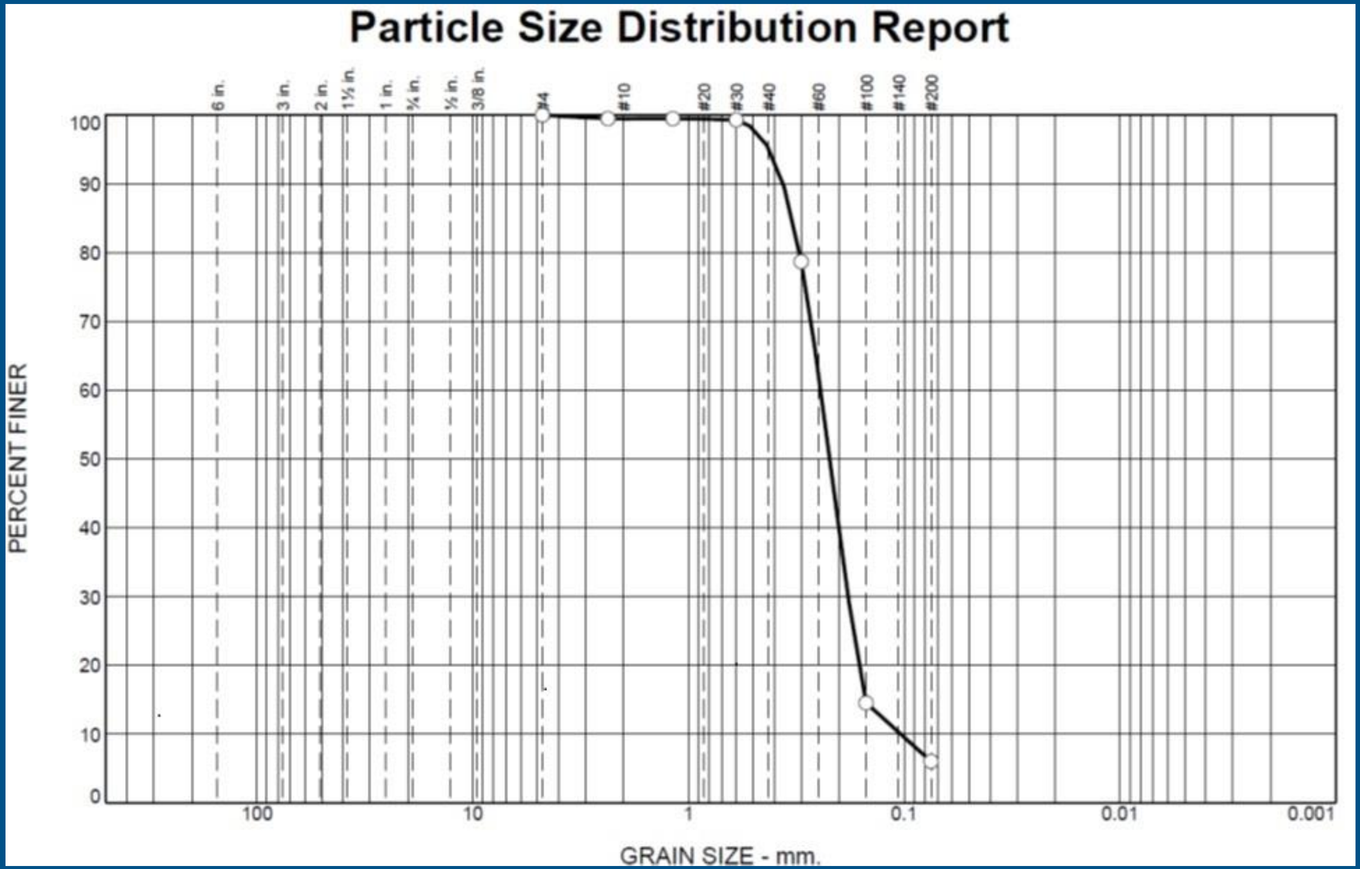


Post-Incident Investigations (5)

- Photo of trench sidewall below the hardpan
- Sand Deposited in erosion pathway after flow was choked off by collapse of the hardpan downstream of this location

Post-Incident Investigations (6)

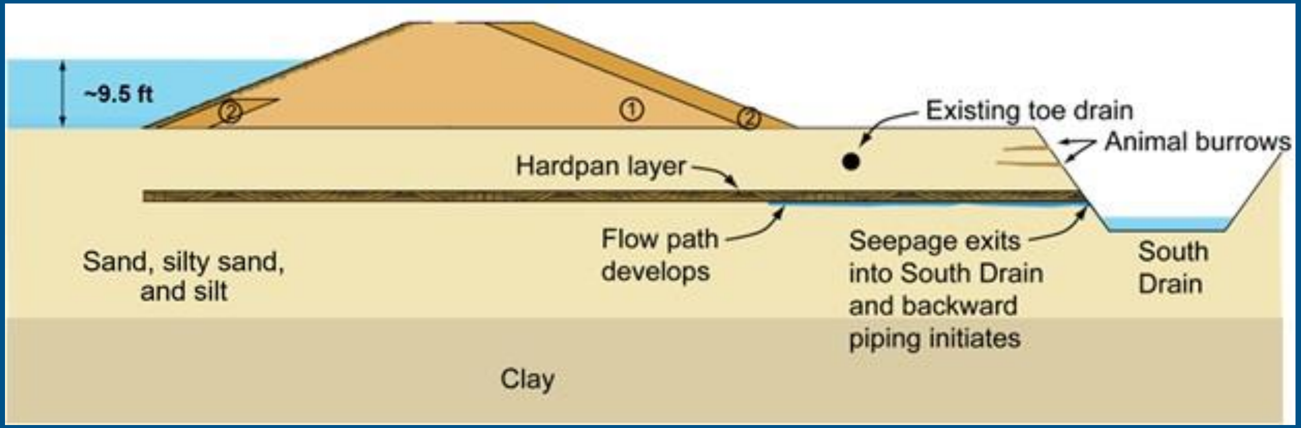
- Representative gradation of eroded soils collected in a forensic trench
- Relatively uniform, fine sand very susceptible to backward erosion piping



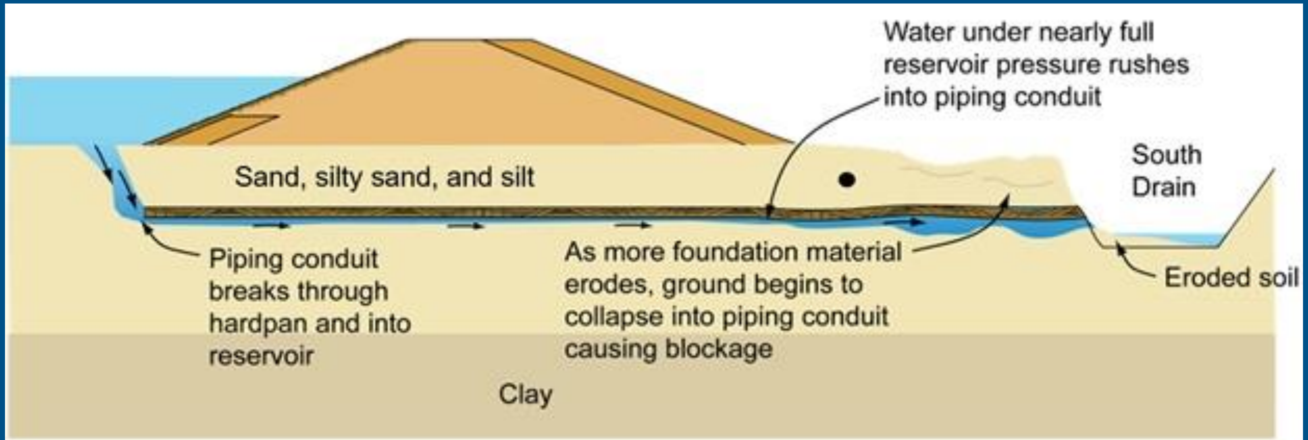
Failure Mode Description

Failure Mode Description (1)

Step 1. Unfiltered Exit and Initiation of Piping
Backward erosion piping initiates into south drain beneath continuous hardpan layer

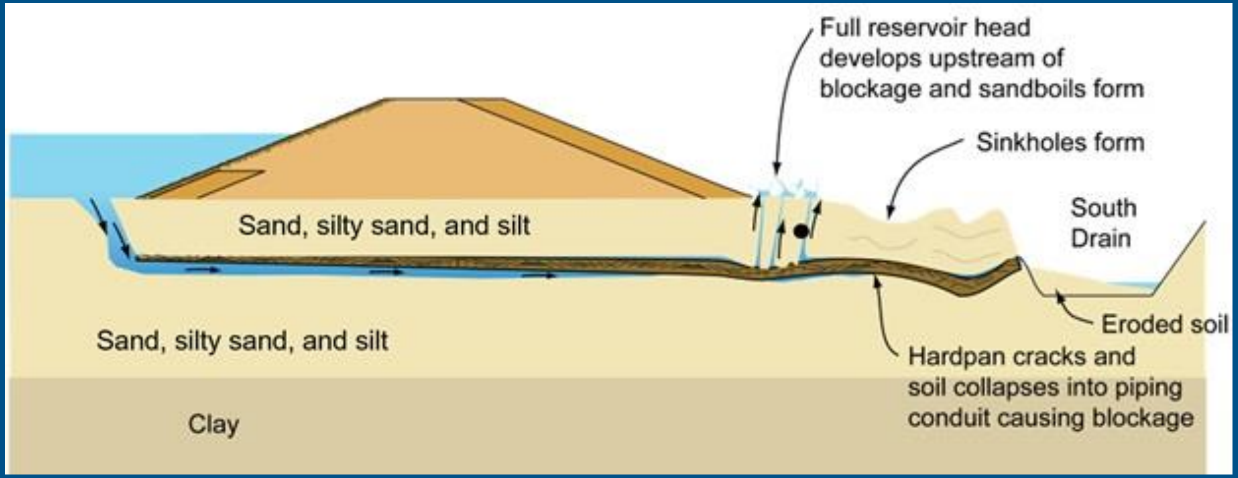


Step 2. Progression of Erosion
Erosion progresses upstream beneath hardpan, eventually reaching the reservoir

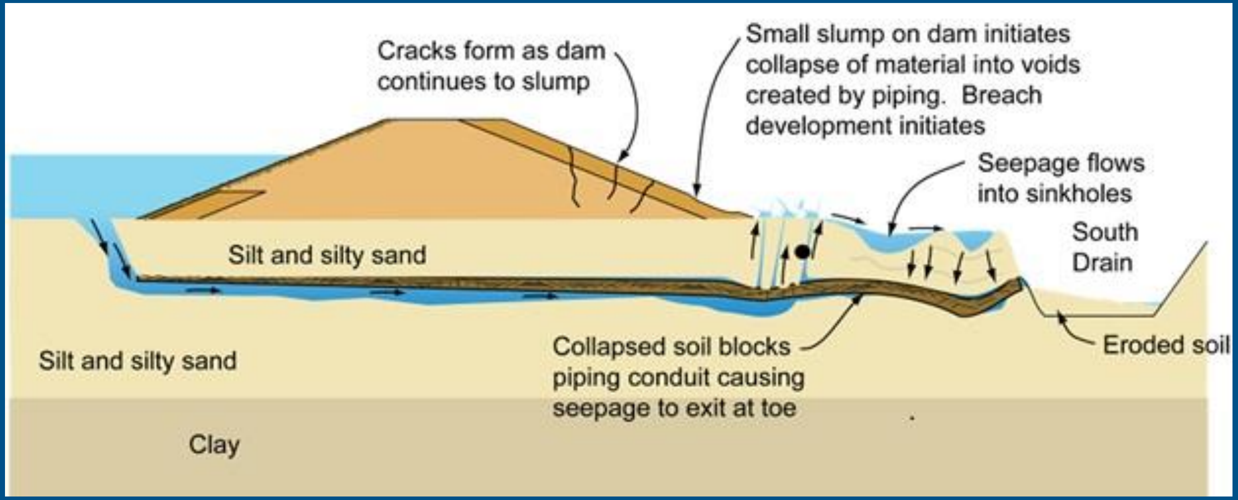


Failure Mode Description (2)

Step 3. Collapse of Hardpan and Boil Formation at Downstream Toe
Voids enlarge and hardpan collapses, causing seepage and sand boils at the downstream toe



Step 4. Distress to Overlying Embankment
Erosion and enlargement of voids cause the hardpan to collapse upstream of the downstream toe, causing slumping and cracking of the dam

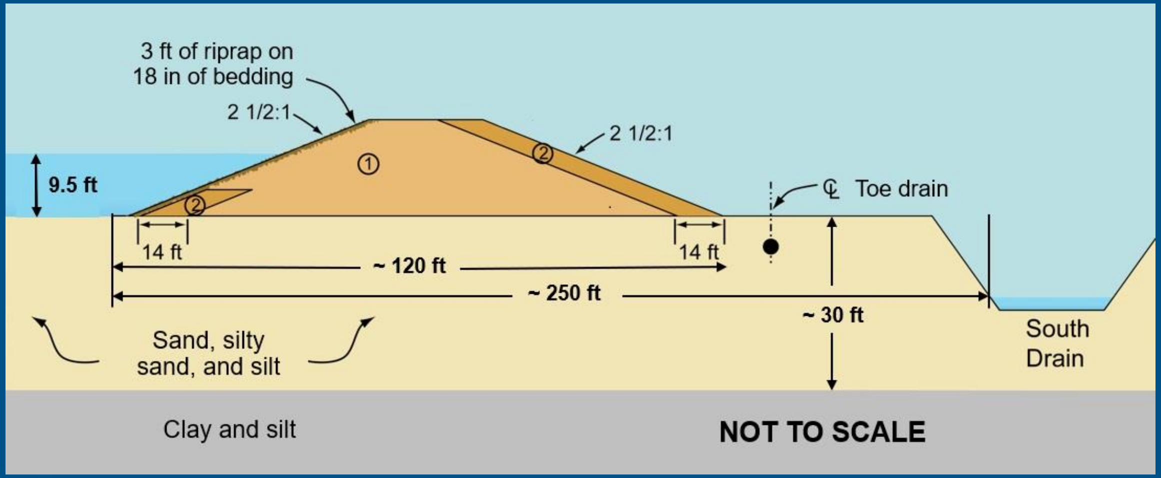


Why did the Incident Occur after Decades of Successful Operation?

Why did the Incident Occur after Decades of Operation? (1)

Adverse Site Conditions Existed Since Original Construction (although not fully recognized)

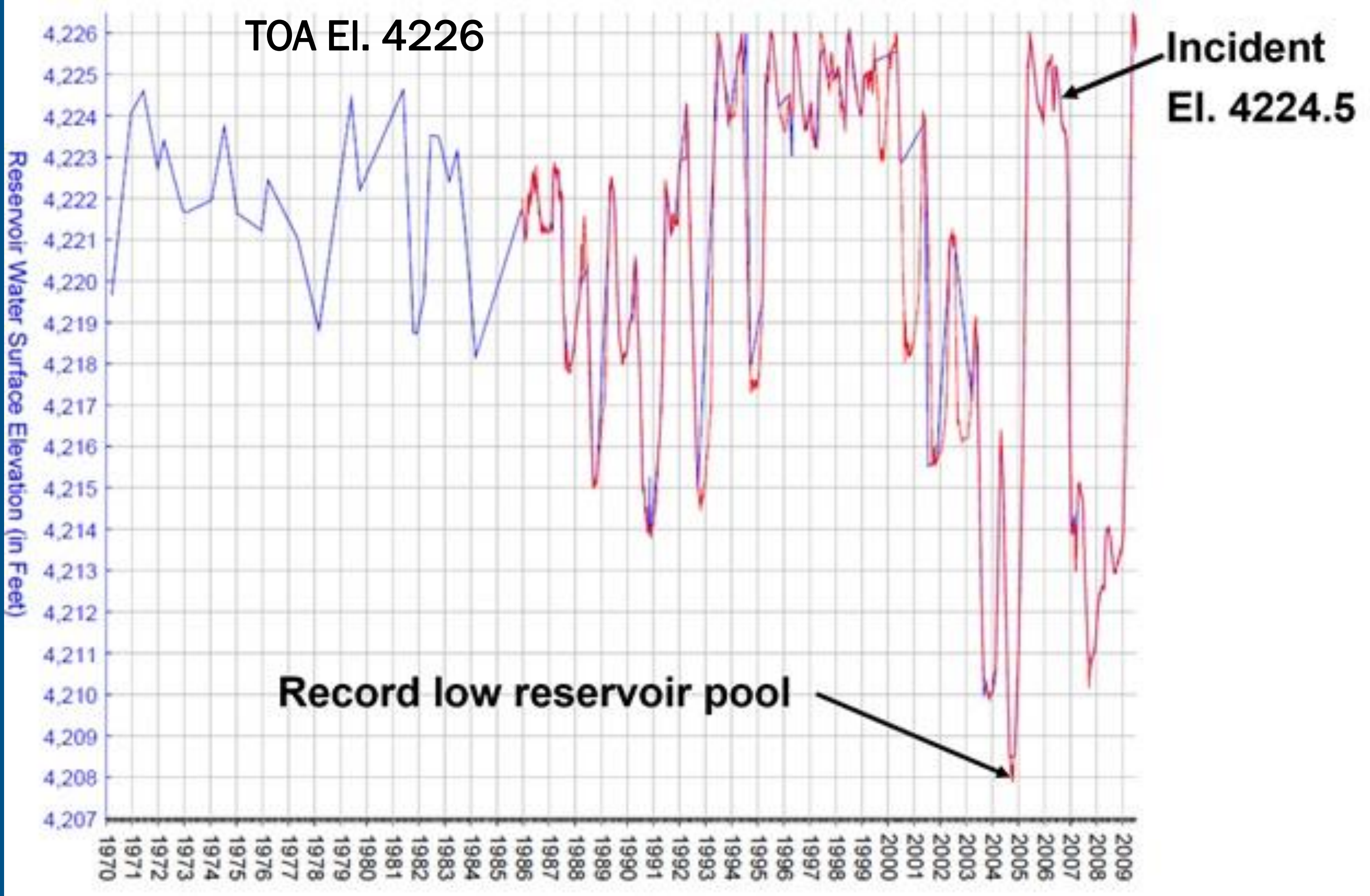
- Highly erodible foundation materials
- Unfiltered horizontal seepage exit into the South Drain
- Continuous hardpan layer that acted as a roof over the developing pipe
- Filled to top of active conservation El. 4226 many times without any problems



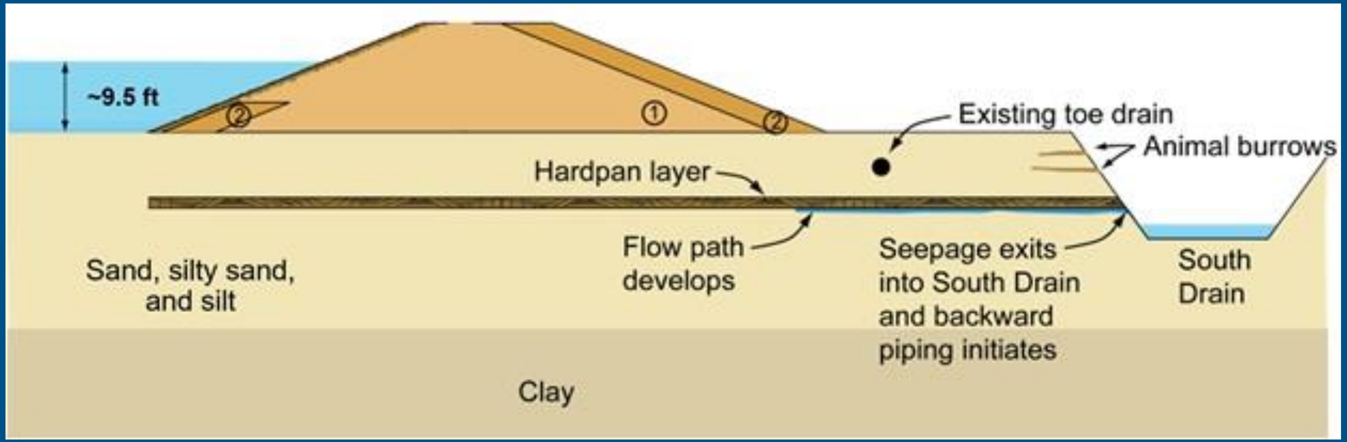
Why did the Incident Occur after Decades of Operation? (2)

Factors that were <u>Different</u> at Time of Incident (i.e. Triggering Event)

- Increased gradient
  - Drought conditions
  - Reduced toe drain capacity (plugged)
  - Possible presence of animal burrows beneath the hardpan
- Stress changes during drought in the years prior to 2005 could have altered foundation conditions and seepage behavior upon refilling of the reservoir



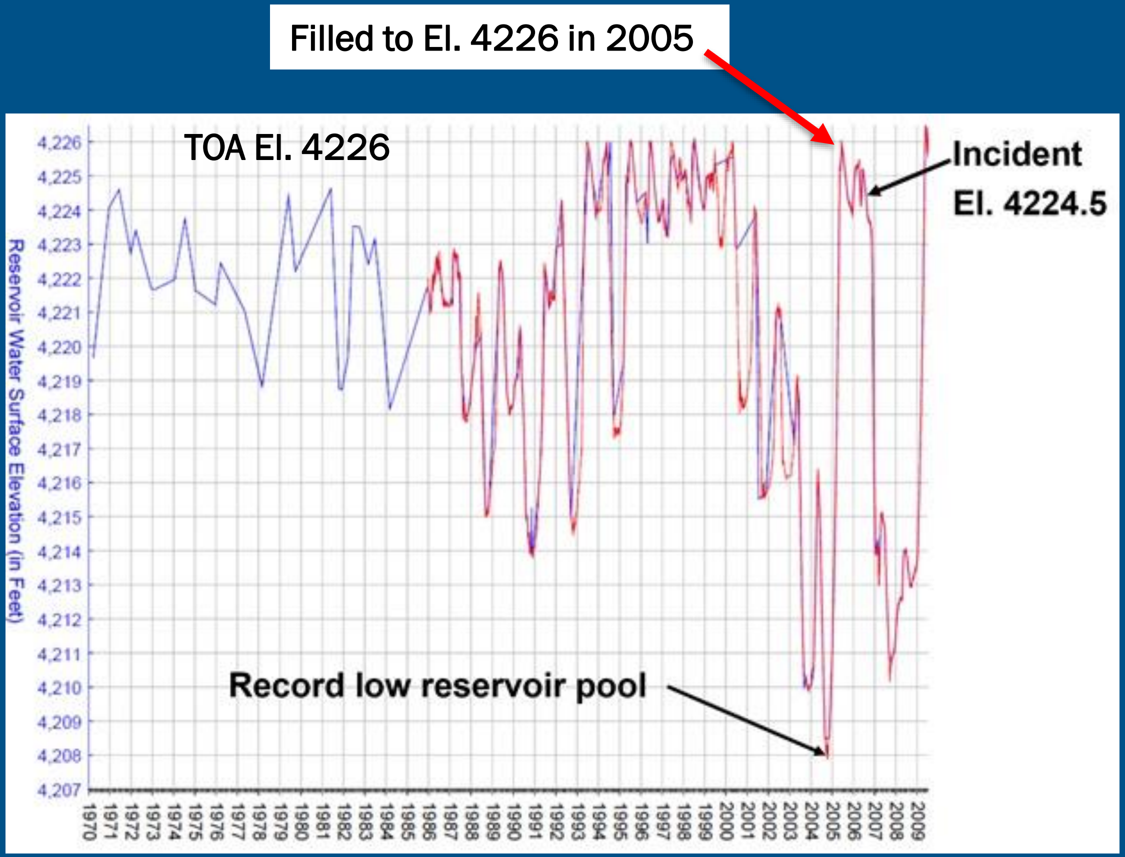
Why did the Incident Occur after Decades of Operation? (3)



Average (Global) Gradient Calculations at Time of Incident

- Average gradient from upstream toe to exit at South Drain = 0.06
- Average gradient from upstream toe to downstream toe = 0.08
- Functioning toe drain: average gradient from toe drain to South Drain = 0.04
- Plugged toe drain: average gradient from toe drain to South Drain = 0.06
- Postulated average gradient from upstream dam toe if the unfiltered exit occurred into an animal burrow that extended 20 ft upstream of South Drain = 0.08

Why did the Incident Occur after Decades of Operation? (4)



Record low reservoir pool in 2004 and refilling of reservoir

- During multi-year drought and record low pool, tailwater in the South Drain was likely at its lowest historic level
  - Upon refilling, highest historic avg. gradient likely occurred
- Filled to El. 4226 in 2005 but no incident detected
- A partial pipe may have been created in 2005
  - Avg. gradient to South Drain was 0.07 (vs 0.06 at time of incident)
  - Undetected erosion could have occurred in 2005, but stopped when pool was lowered, or self-healing occurred
  - Shorten seepage path to the pipehead in a partial pipe would increase the avg. gradient calculation upon filling in 2006, and may explain why piping initiated at 1.5 ft lower pool

Why did the Incident Occur after Decades of Operation? (5)

Plugged Toe Drain

- Standing water at downstream toe developed over time, indicating loss of functionality over time
  - General notations of seepage presence noted during exams
  - No detailed monitoring of changes to extents of wet areas, e.g., no staking or flags to delineate
- Test pits found the toe drain was plugged in the incident area
- Average gradient to South Drain was higher with plugged drain (0.06) compared to a functioning toe drain (0.04)
- Plugging of toe drain not likely to be the triggering event
  - Constructed above the hardpan layer
  - Ponded water at toe had existed for at least several years prior to the incident

Why did the Incident Occur after Decades of Operation? (6)

Animal Burrows

- Drought period could have allowed animals access to soils beneath the hardpan that would normally be saturated
- Any burrow length toward the dam would have shortened seepage path making initiation of erosion more likely
  - Increased average gradient
  - 3D seepage toward the burrow would tend to concentrate flows
- Some burrows observed elsewhere observed above the hardpan
- No way to know if any burrows existed below the hardpan in the incident area
- Considered less likely to be the triggering event

Why did the Incident Occur after Decades of Operation? (7)

Stress Increase During Drought

- Lower phreatic surface during the drought could have increased stresses in the foundation by several hundred psf
- Increased stresses could have caused settlement of the foundation soils, possibly cracking hardpan
- Possible that previously established seepage paths were altered
  - Preferential seepage paths
  - Higher pore pressures farther downstream than previously
- May have contributed to the event occurring in 2006, but the stress increase was relatively small and may not have affected foundation seepage

Why did the Incident Occur after Decades of Operation? (8)

Episodic Erosion Over a Long Period of Time

- Cattleman on the adjacent property reported that he had observed episodes of cloudy seepage in the years before the drought
- His observations of tan to light brown sediments entering the South Drain during the 2006 incident were consistent with his previous observations
- He did not notify the water district until the color change occurred (from tan to dark brown)
- Progressive erosion over many years may have gradually worsened foundation conditions, and in combination with historic high gradients during refilling after the drought contributed to the incident occurring in 2006

Key Takeaways

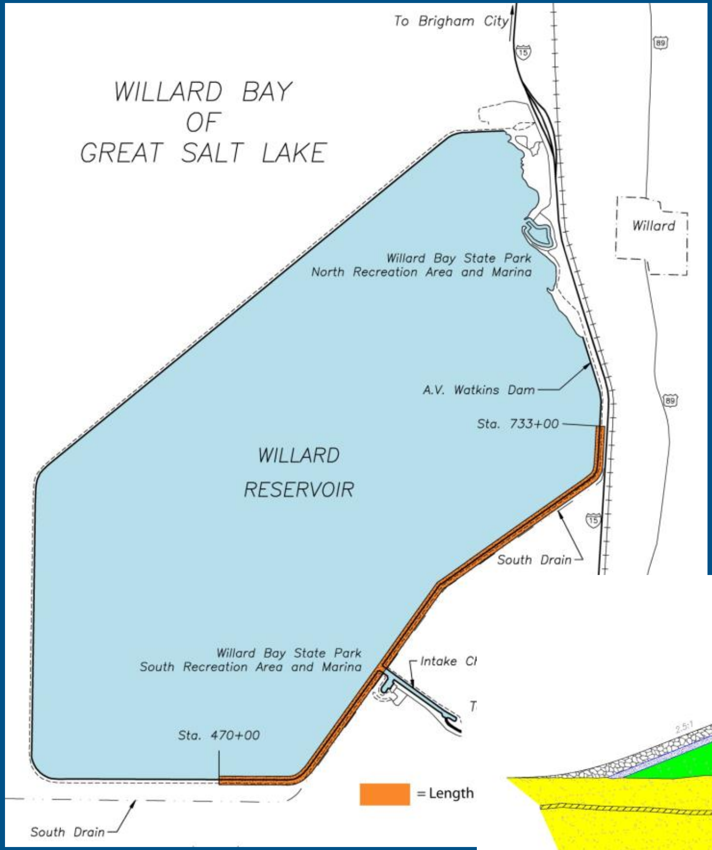
Key Takeaways (1)

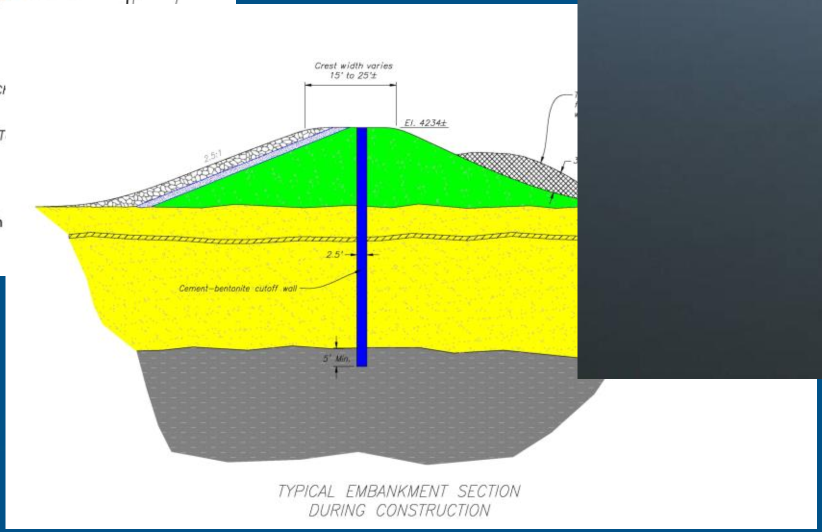
1. Horizontal unfiltered seepage exits are a concern
   - Easier for erosion to initiate relative to vertically upward seepage
   - Ditches downstream of water impounding structures provide an unfiltered condition
2. Backward erosion piping can initiate and progress with very low average gradients
   - Average gradient from the upstream toe to the seepage exit into the South Drain was approximately 0.06 at the time of the incident
3. Filling after prolonged low reservoir levels should be a time of increased awareness and monitoring due to opportunity for changed conditions such as:
   - High gradients not previously experienced
   - Increased effective stresses leading to altered seepage paths
   - Opportunity for animal burrowing

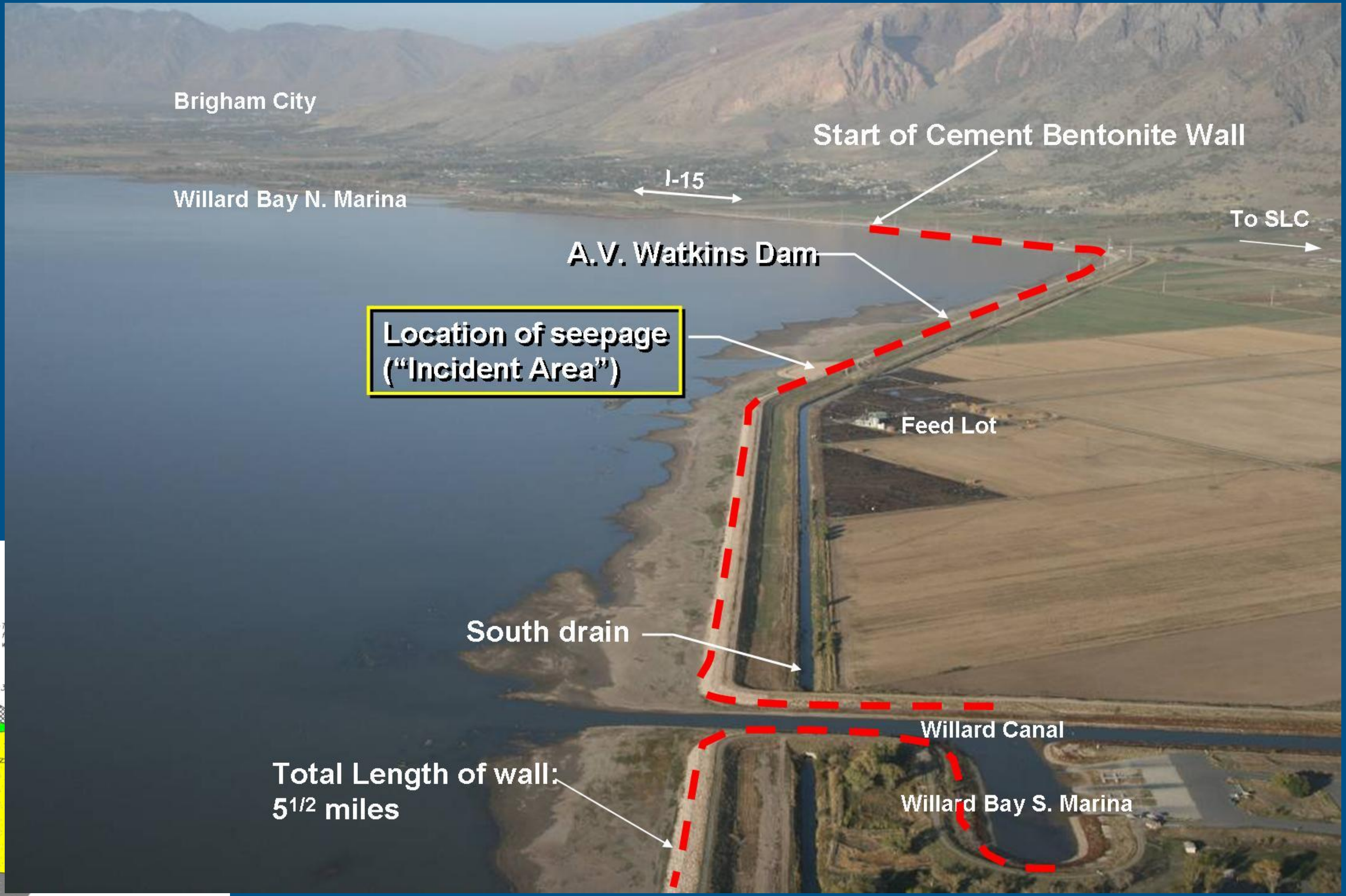
Key Takeaways (2)

4. New or changed seepage conditions, even if they occur very slowly over time, require a detailed evaluation of the potential causes and implications (i.e., toe drain, geologic conditions)
   - Watch out for recency bias. Gradual changes became normal
   - Don't be hesitant to perform field investigations to better understand conditions
5. Backward erosion piping may occur episodically, possibly over long periods of time
   - Past performance is not a guarantee of future good performance
   - If piping initiates and progresses followed by self-healing or reservoir drawdown that stops the process, subsequent piping events may occur under lower average gradients than had been experienced previously.
6. Progression of a piping erosion pathway could be wide and shallow, not a round "pipe"
   - Voids below the hardpan appeared to have been very wide and relatively shallow at A.V. Watkins Dam.
7. During initial response efforts to mitigate erosion, concentrated flows may need to be slowed down by placing gravel prior to placing filter sand as part of a weighted filter berm.

Dam Safety Modifications: Cement-Bentonite Cutoff Wall







Thank You

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