

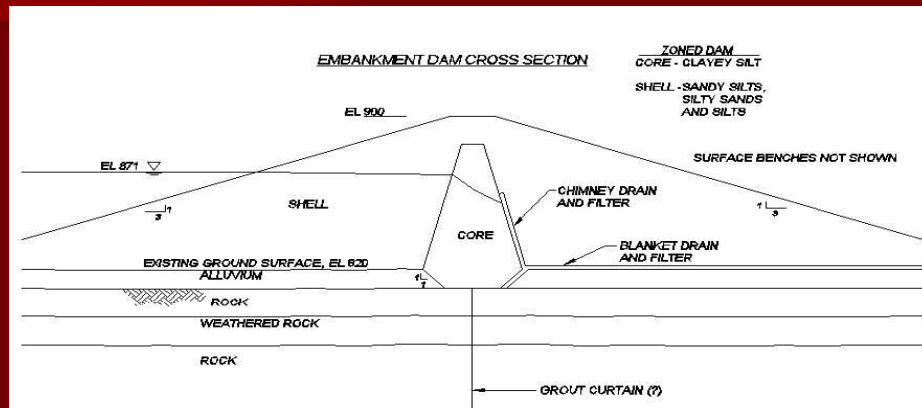
Seepage and Piping Dams

By
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Causes Of Catastrophic Failure

- Overtopping
- Uncontrolled Seepage and Piping
- Stability
- Liquefaction

Seepage Control



Types of Internal Erosion

- Segregation piping - Erosion of silts and sands from unstable gravel or larger size particles
- Continuing erosion - Erosion of silts and sands into an adjacent layer of gravel or larger size particles or open fractures in rock
- Piping - Erosion of cohesionless soils to form a "pipe" from downstream to source of seepage

Internal Erosion Enabling Criteria

- Gradient sufficiently high to cause soil particles to migrate
- Unfiltered exit
- Silts and sands most susceptible

Segregation Piping

- Unstable or non-self filtering sandy gravels
 - Skempton and Brogan (1994) - gradation curves typically gap graded or concave upward shape, $C_u > 20$
 - Fell and Foster (2000) - high permeability increases likelihood
- Can occur at very low critical gradients
 - Adel, et.al. (1988) - horizontal - 0.16 to 0.17
 - Skempton and Brogan (1994) - vertical - 0.20 to 0.34

Continuing Erosion

- Fell and Foster (2000) reported occurrence when D15 size of filter > 9 times D95 size of base soil
- Did not comment on required gradient
- Likely similar to Segregation Piping
- NRCS Gradation Design of Sand and Gravel Filters (1994)

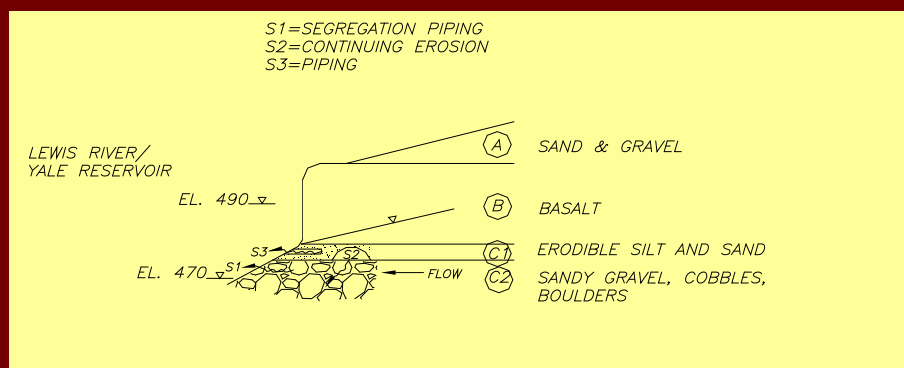
Piping

- Schmertmann (2001) – defined maximum global gradient, i_{pmt} , for failure in flume tests
 - $i_{pmt} = 0.05$ for $C_u=1.2$ to
 - $i_{pmt} = 1.00$ for $C_u=6.2$
 - i_{pmt} must be corrected for field conditions
- Field conditions included
 - layer depth, density, anisotropy and inclination
 - pipe length
 - permeability of layer below
 - roof above

Piping

- Can occur at very low critical gradients
 - Sherard, et.al. (1979) – boils – 0.5 to 0.8
 - Schmertmann (2001) - boils - 0.3 to 0.6
 - Fell and Foster (2000) - as low as 0.05

Types of Internal Erosion



Washington Power Canal

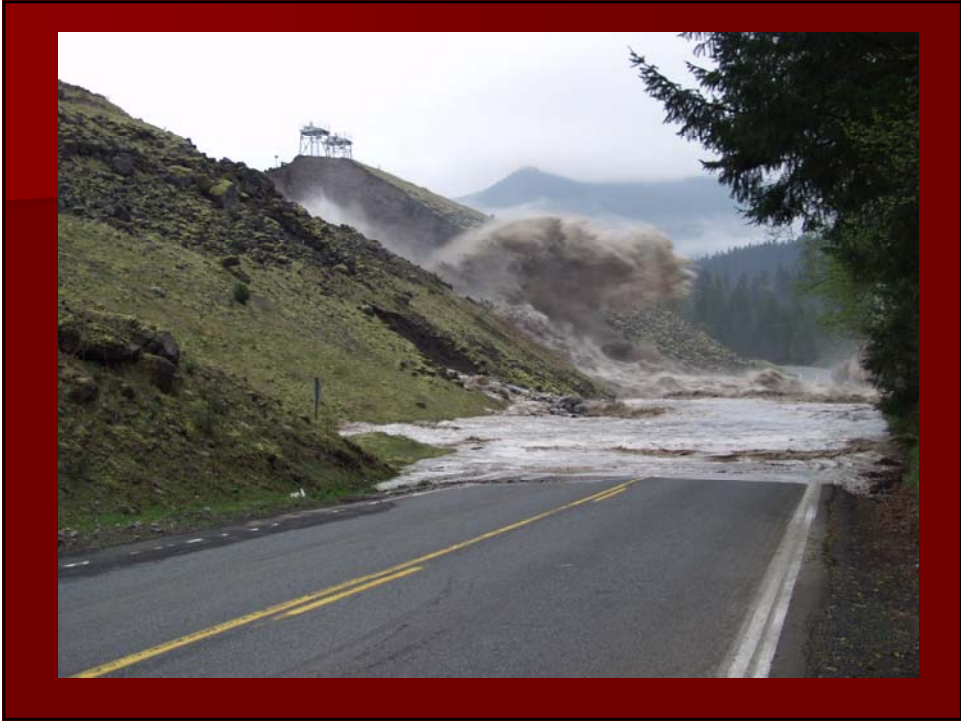
- Constructed - 1957 – 1958
- Length of water supply canal – 3 miles
- Impoundment - 2400 ac-ft
- Embankment height in forebay – 93 ft
- Maximum water depth – 53 ft
- Forebay operating pool level – El 603
- Operating tail race levels – El 470 to 490



April 21, 2002 Failure

- Sinkholes developed in forebay at about 3:00 AM
- Blowout followed at toe of embankment
- Orifice expanded upstream causing breach of the embankment at about 6:30 AM
- Flooding destroyed downstream facilities
- Discharge contained in downstream reservoir







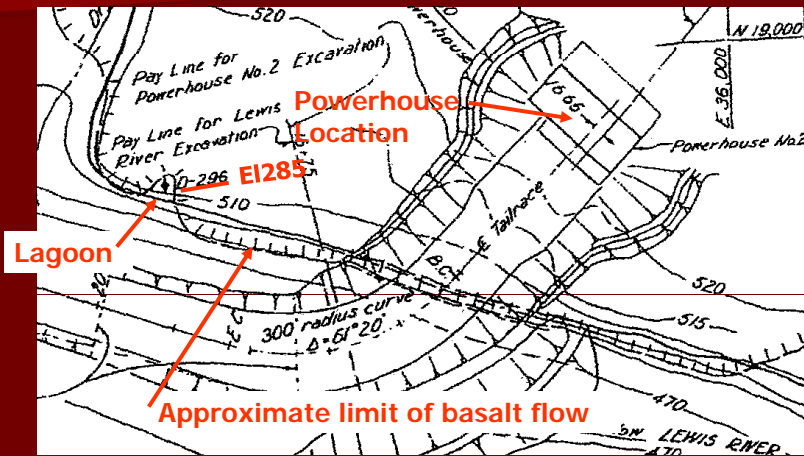




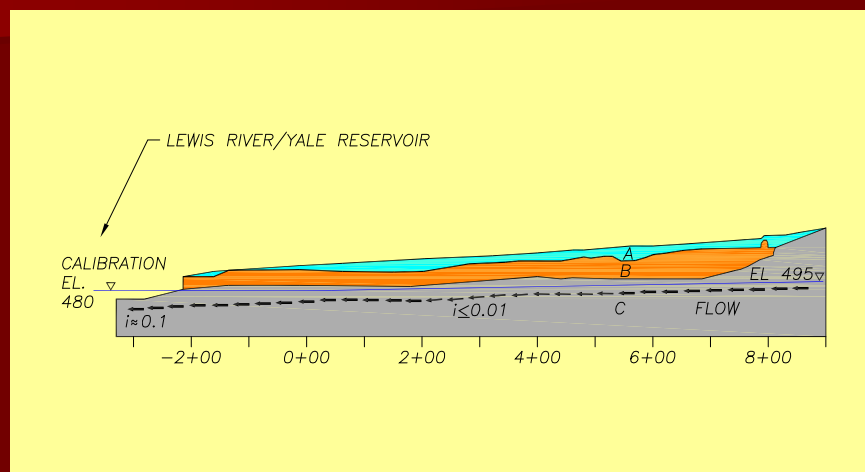
Foundation Stratigraphy

- Stratum A - alluvium/colluvium – sand and gravel (10 to 20 ft thick)
- Stratum B – vesicular to massive highly jointed basalt rock (8 to 50 ft thick)
- Stratum C – alluvium - silt, sand, gravel, cobbles, boulders (> 200 ft thick)
 - Stratum C1 - silt and sand
 - Stratum C2 - gravel, cobbles, boulders (< 5 percent silt/sand)

Design Topography



Preconstruction Groundwater Conditions



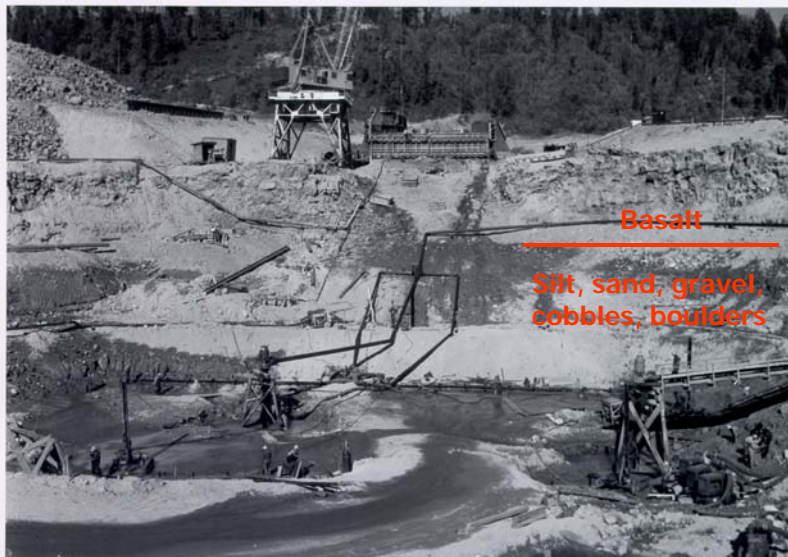
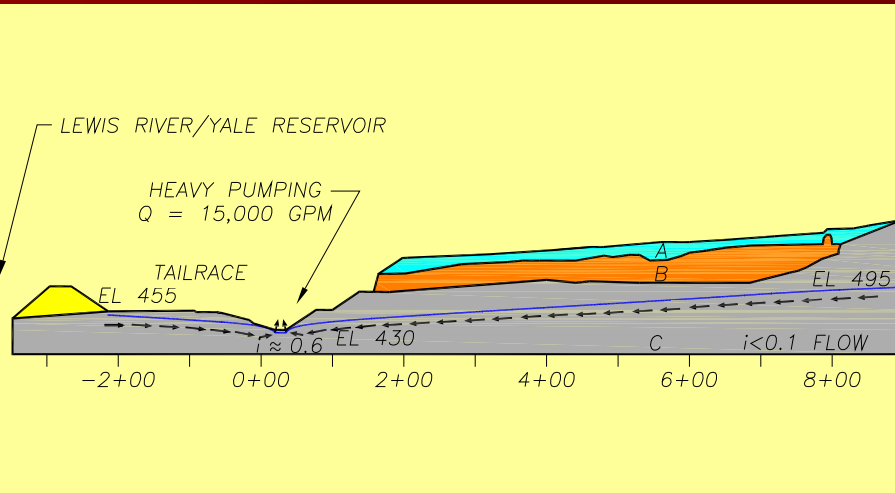
Groundwater Conditions

- Groundwater surface generally at about interface of basalt and underlying alluvium [test borings - 1956]
- Due to low preconstruction gradient, ($i = < 0.01$ to 0.1) erosion likely did not occur below basalt before canal was constructed

Powerhouse Construction

- Groundwater lowered about 60 ft
- Pumping rates – 7,000 to 15,000 gpm (4 mo)
- Estimated 4,000 ac-ft of groundwater pumped
- Unfiltered discharge
- Pumping imposed gradient – 0.6
- Heavy pumping caused internal erosion of silts and sands from Stratum C gravel, cobbles and boulders below Basalt

Construction Groundwater Conditions



2145-111
SEPTEMBER 23, 1957

SWIFT HYDROELECTRIC PROJECT
EXCAVATION FOR POWERHOUSE NO. 3, LOOKING UPSTREAM.



Construction Change

- Subdrain installed upstream of powerhouse due to heavy flow coming from below basalt
- Unfiltered 18 in dia. perforated CMP placed just below interface of basalt and underlying alluvium



2145-158
FEBRUARY 18, 1958

SWIFT HYDROELECTRIC PROJECT
POWERHOUSE NO. 2, LOOKING UPSTREAM. POWER INTAKE STRUCTURE AND STEEL PENSTOCKS
IN LEFT BACKGROUND. NOTE INITIAL CONSTRUCTION OF SERVICE BAY IN LEFT FOREGROUND.





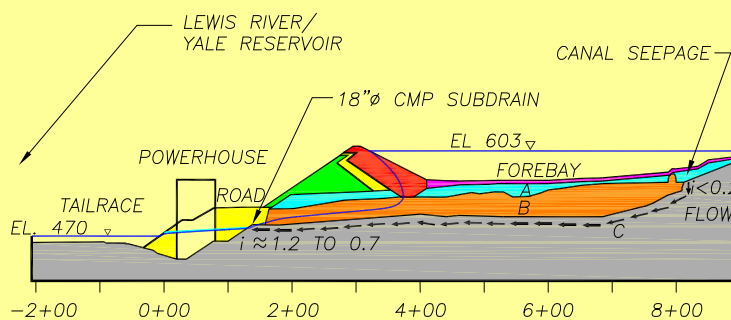
Summary Construction Seepage Impacts

- Silts and sands in the gravel, cobbles and boulders of Stratum C were removed during the pumping process by internal erosion due to high gradients
- Unfiltered spring discharges existed just below the basalt during construction and also allowing removal of silts and sands

Construction of Embankment

- Cutoff trench 300 ft - both sides of intake structure through alluvium/colluvium
- Grout curtain partially penetrated basalt
 - Typically - 20 ft deep
 - Five holes penetrated basalt, 40 to 45 ft deep
 - No seepage barrier was formed below basalt
- Forebay blanket – silty sand with gravel (SM)
- Zoned Embankment

Construction of Embankment



Filling Canal

- Canal filling increased water head by 108 ft
- Preconstruction seepage gradient under basalt increased significantly

Conditions Favorable for Internal Erosion

- Basalt provided "roof" over Stratum C
 - Collapse not possible
- Bottom of basalt sloped slightly downward
 - Facilitated internal erosion
- Stratum C1 consisted of silt and sand
 - Highly erodible
- Stratum C2 consisted of gravel, cobbles and boulders
 - Open graded non-self filtering

Conditions Favorable for Internal Erosion

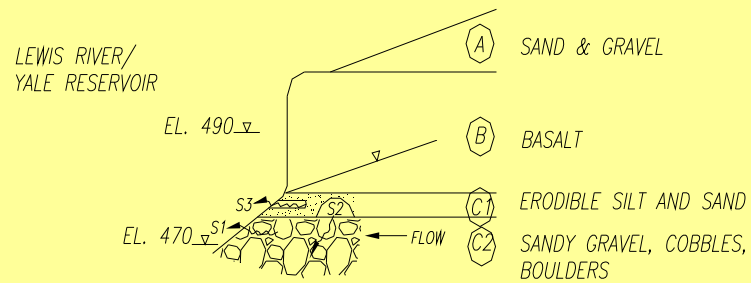
- No grouting (barrier) present under basalt
- Unfiltered discharge locations downstream
 - Powerhouse 18 inch subdrain
 - Exposed Stratum C1 soils under basalt in tailrace and tailrace canal

Impacts of Filling Canal

- High gradients caused internal erosion (segregation piping, continuing erosion and piping) of silts and sands from
 - Stratum C2 gravel, cobbles and boulders
 - Stratum C1 into Stratum C2, and
 - Within Stratum C1

Beginning Internal Erosion Process

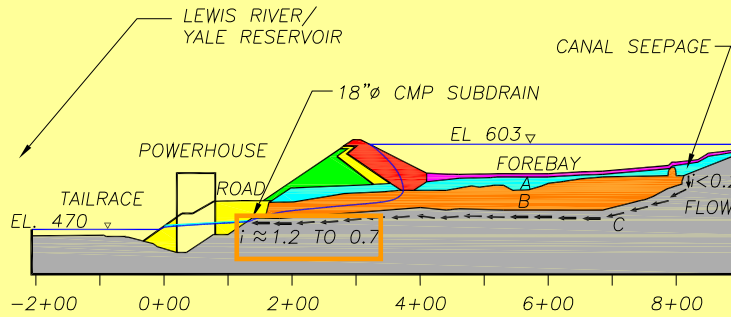
S1=SEGREGATION PIPING
S2=CONTINUING EROSION
S3=PIPING



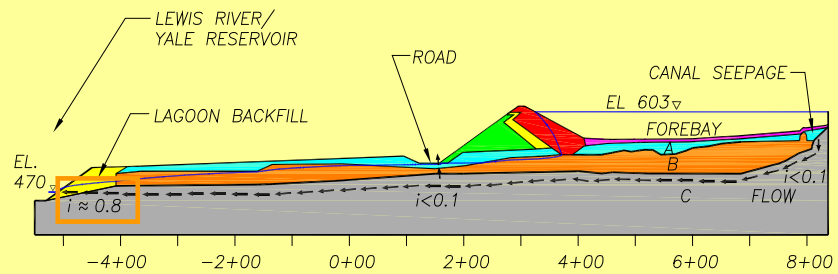
Stratum C1 Silt and Sand Under Basalt of Stratum B



Post Construction – Powerhouse Seepage



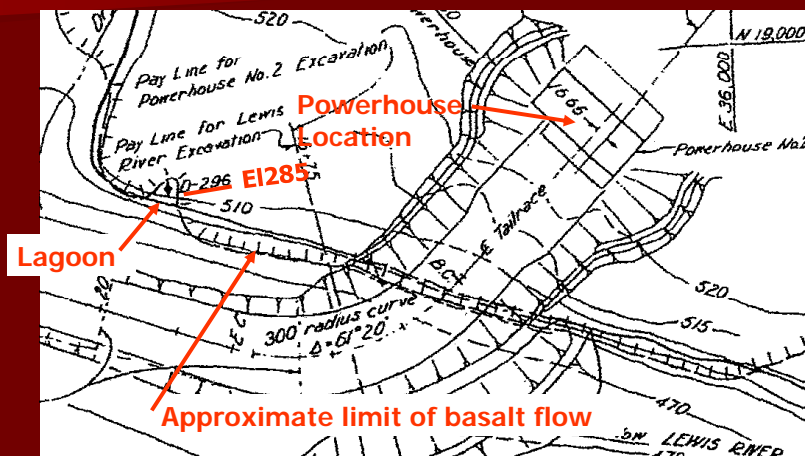
Post Construction – Lagoon Seepage



Impacts of Filling Canal

- Gradients increased below basalt
 - At unfiltered 18 in dia. perforated subdrain pipe – 0.7 to 1.2
 - At unfiltered springs along tailrace/at lagoon – 0.3 to 0.8

Design Topography



1952 USGS Photo



Backfilled Lagoon - 1980



Canal leakage, 1958

- Seepage loss in 1958 estimated at about 100 cfs (45,000 gpm)
- *“---on both sides of powerhouse --- there are very large springs at the bottom of the basalt” “---along the riverbank---it is expected that seepage from springs at the bottom of the basalt will have been increased.”* [Special Consultants Memo]
- Canal drained twice in 1959, numerous sinkholes repaired

Canal leakage 1974

- Boils found at downstream toe of the forebay embankment
- *“An inspection of the river bank ---indicated several places where water was cascading into Yale Reservoir” “Close inspection of these flows was not made; however, they appeared to be clear.”* [Construction Report]
- Canal drained, numerous sinkholes repaired
- Major water flow out of canal

Canal leakage, 2000

- *"The flow appeared to be clear, but has been reported to be turbid during periods of high runoff. This seepage is probably coming from the canal, --- and the seepage gradient should be small" [FERC Part 12 Report]*
- Springs provided unfiltered seepage discharge locations for migrating soils
- Small gradients can produce internal erosion

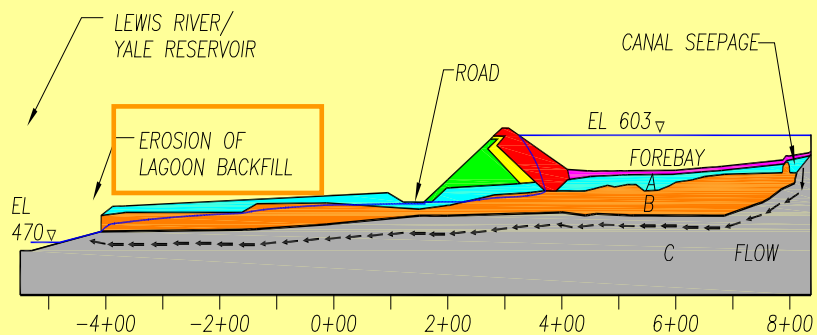
Pre- and Post Failure Lagoon



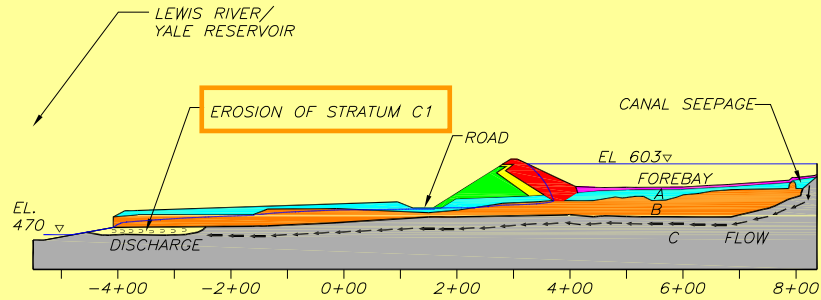
Summary of Excessive Canal Seepage

- Seepage gradients and forces increased below the basalt after the canal was filled with water
- Internal erosion can occur at small gradients under favorable conditions
- The presence of turbid (cloudy) water was indication that soil particles were being eroded from under the basalt
- Erosion of lagoon was indication of internal erosion

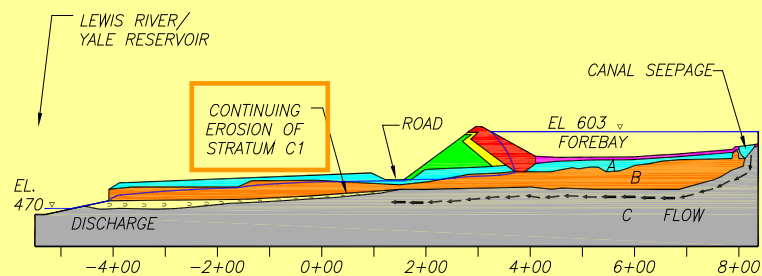
Initial Erosion of Lagoon



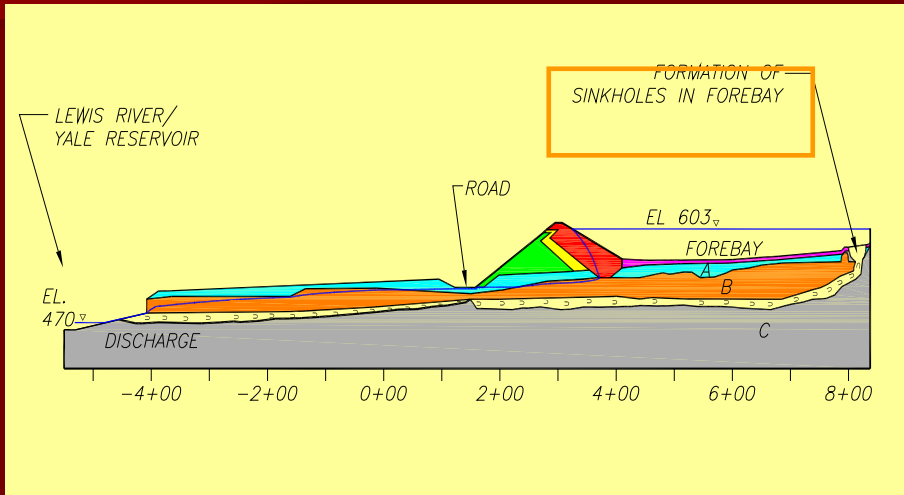
Erosion Tunnels Begin to Form Under Basalt



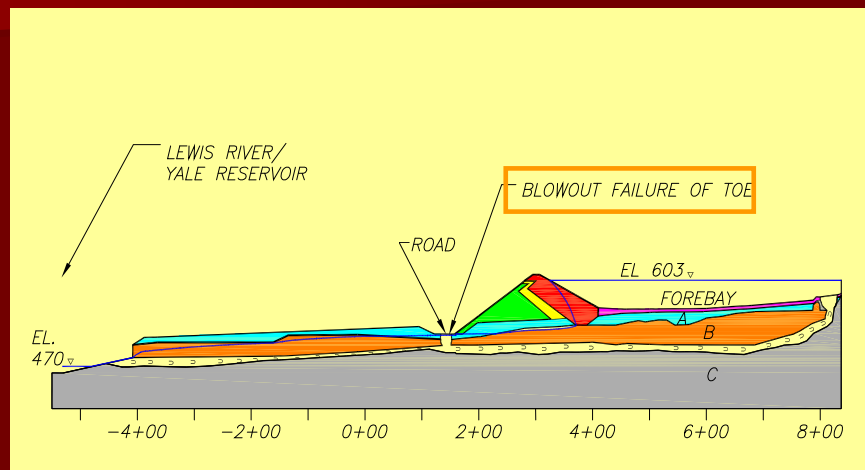
Continuing Erosion Under Basalt



Sinkholes Form



Ultimate Blowout



Evolution of Failure

- Internal erosion progressed to canal bottom over 45 years of operation
- Sinkholes developed and water pressure under basalt rose to about 6100 psf
- Basalt and colluvium/alluvium thinnest at downstream toe – 8 and 10 ft, respectively
- Blowout occurred - maximum flow through expanding failure orifice about 3500 cfs
- Breach peak discharge - about 80,000 cfs
- Damage > \$100 million

What went wrong?

- Historical assumptions
 - Seepage gradients small, internal erosion could not occur
 - Internal erosion can't occur under basalt in dense soils
 - Catastrophic failure not possible
- Reports of turbid discharges were not related to ongoing internal erosion
- Erosion of lagoon prior to failure was not related to excessive seepage discharge

Summary of Failure

- Internal erosion was a long term process that commenced with construction excavation and pumping and continued due to excessive canal leakage until failure 45 years later

