Dams and Reservoirs; Lessons Learned

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ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

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Outline of Case Histories

- Excavations in Reservoirs - **a really bad idea**
- Differing Foundation Stiffness – **expect differential settlement**
- Internal Erosion - **the number 2 cause of dam failures**
- Karst – **always a concern**

Karl Terzaghi

"---the principal function of theory consists in teaching us what and how to observe in the field."

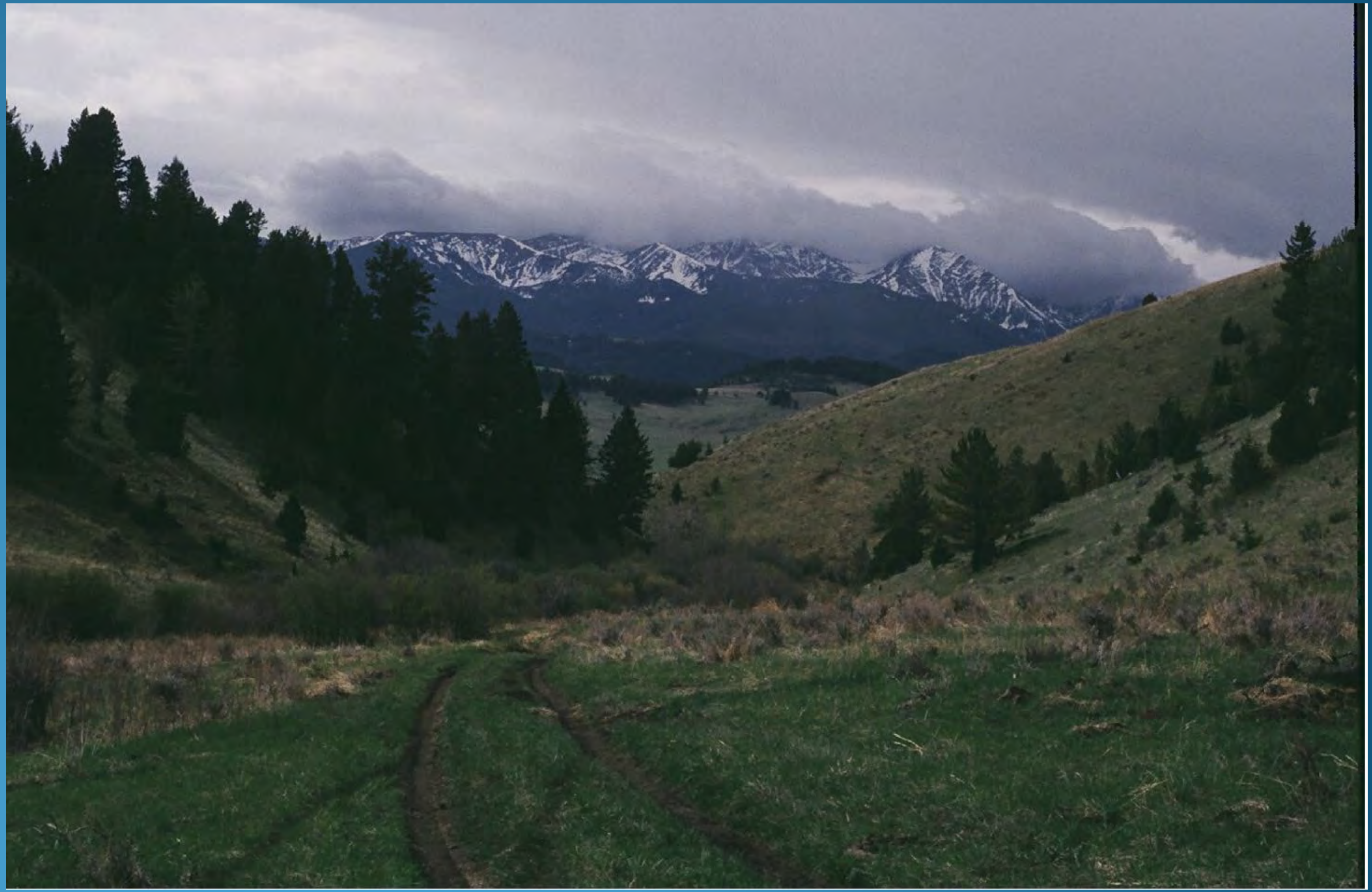
"I consider Engineering Geology an essential antidote against a too theoretical approach to practical problems."

Professor Dick Goodman on Terzaghi in The Engineer as Artist

"---he tried to see the whole of the problem, beginning with geology, and ending with measuring behavior during and after construction."

Excavation in Reservoir

Ted Turner Fishing Dam/Reservoir,
Flying D Ranch
(15 mi^2),
Gallatin Gateway, MT
(1996)



Montana Dam Design

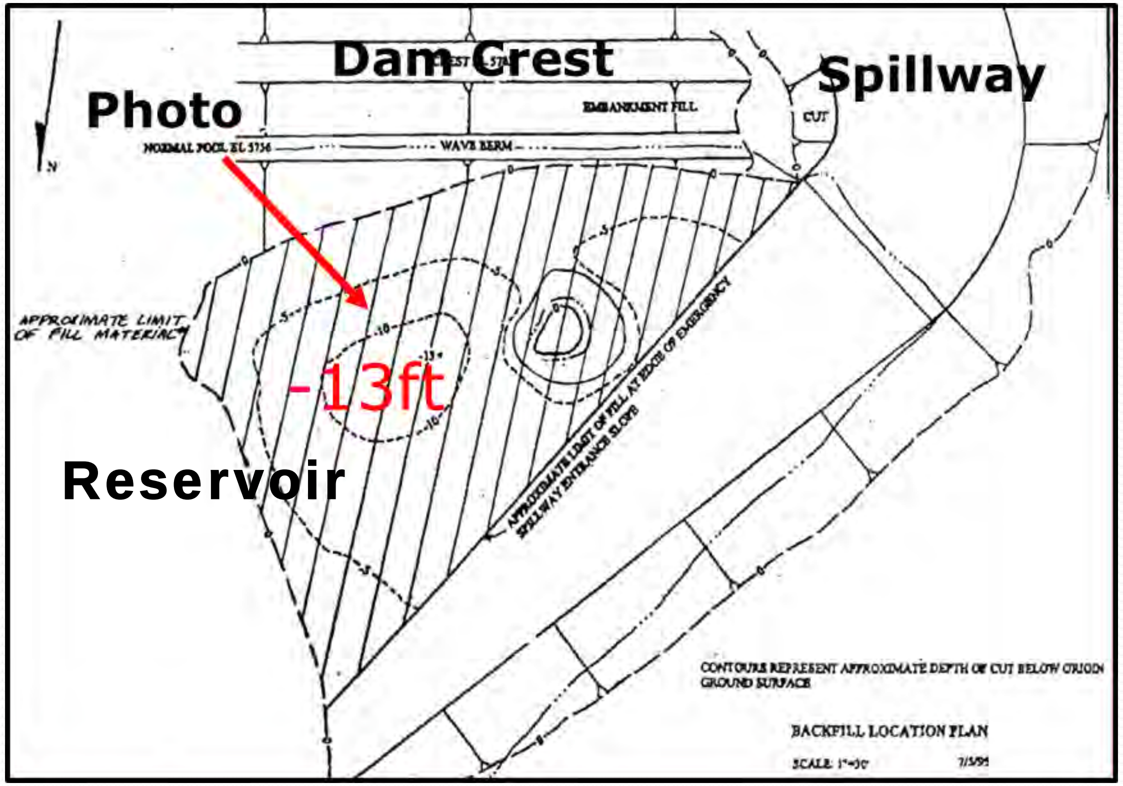
- 40 ft high homogeneous dam - sandy clay and clayey sand
- Surface of reservoir – 6 to 10 ft of clay over sand/gravel
- Borrow pit about 1 mile from reservoir site
- Technician sent home with 7ft of fill needed to reach crest
  - Budget for observation and testing expended
- Contractor then excavated remaining fill from reservoir

After Reservoir Filled – Urgent Call

- Ranch manager called: “seepage flowing from toe of dam on right side of outfall pipe”
- Ray: “Drain the lake ASAP”
- What caused the seepage?

Repair

- Backfill excavation with compacted fill from borrow pit
- Construct inverted filter-drainage blanked over seepage area

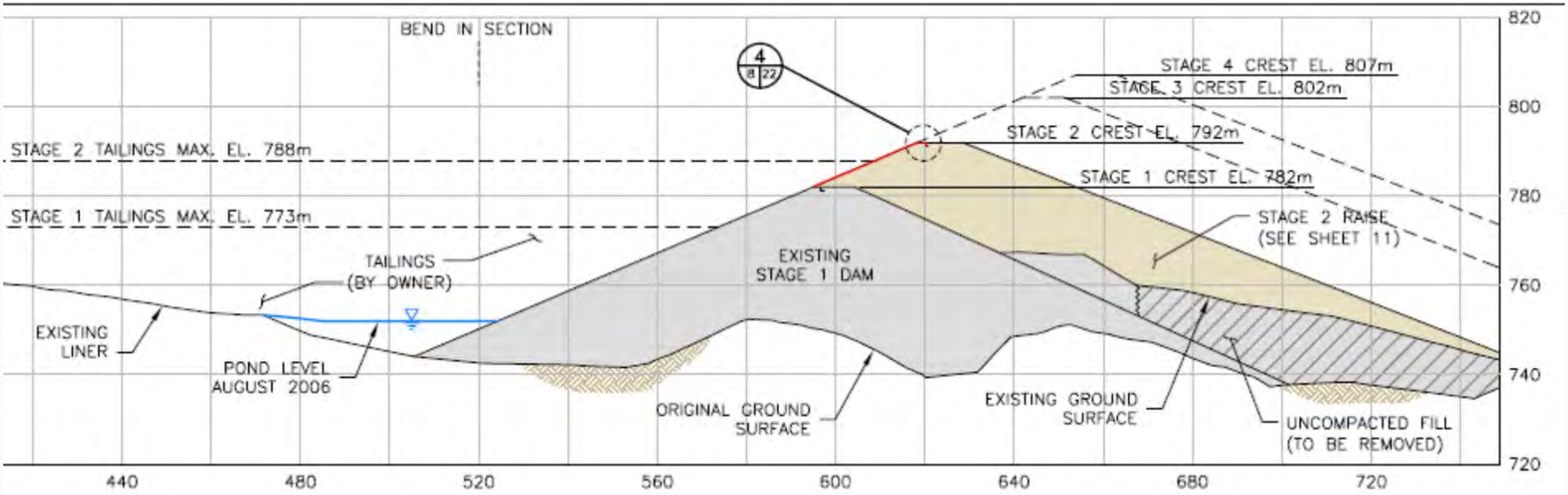


Excavation in Reservoir

Soledad Gold Mine Tailings Dam/Reservoir, Honduras (2007)

Tailings Disposal Facility Dam Design

- Downstream construction of a tailings dam – 43m high
- Appeared well designed–borings/seepage/stability analysis



Reservoir Design

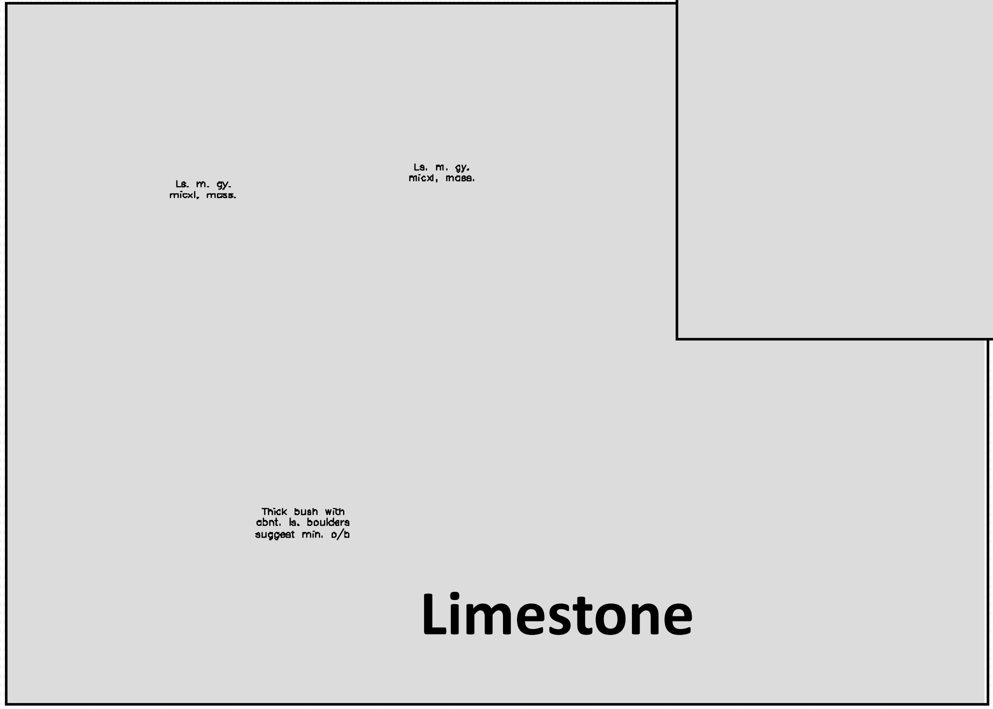
- Reservoir underlain by lean clay residual soil/limestone rock
- Test pits and geologic mapping in reservoir
- No reservoir seepage analysis - impermeable liner
- Pond 1.5mm-thick LLDPE liner underlain by geogrid
- Designed to span sinkhole 20ft in diameter 5ft deep
- Decant structure limited pond water volume to 50,000m^3
- Two borrow areas for dam construction within reservoir
- Do you see a potential problem?

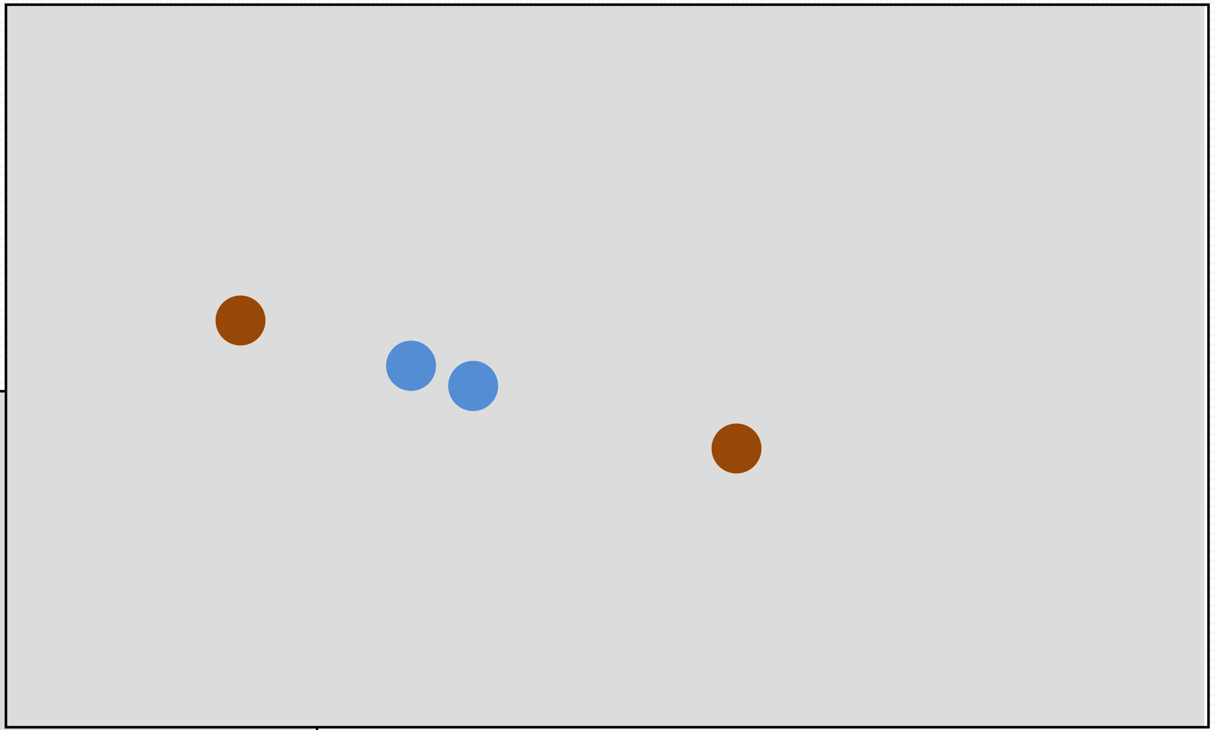
Construction

- Several sinkholes opened in reservoir during construction
  - Some borrow material had been removed over limestone
  - Occurred during wet weather periods
- Geogrid and geosynthetic liner placed over
  - Residual soil
  - Exposed rock – unrelated to borrow excavations

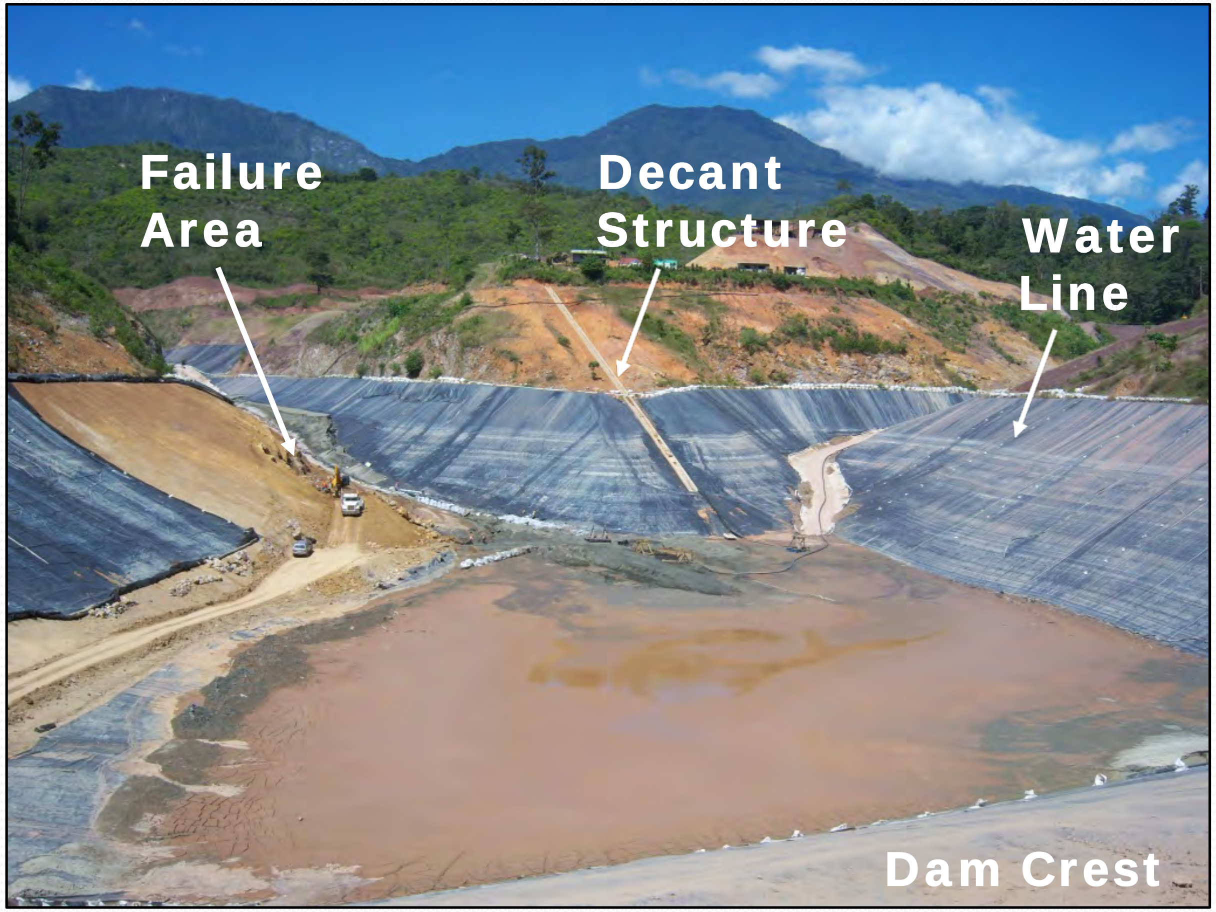
Adverse Geologic Conditions

- Borrow area expanded to include failure area





Failure


Failure
Area
Decant
Structure
Water
Line
Dam Crest


Failure
Area

Failure

- Liner seams likely failed - differential movement?
- Seepage entered soils reduced in thickness by excavation
- Soil piped into limestone solution features
- Sinkhole formed
- Liner/geogrid failed to support water load over sinkhole
- Pond drained into subsurface and exited downstream
- A large environmental problem in stream

Excavation in Reservoir

Marlin Gold Mine Tailings Dam/Reservoir – San Miguel, Guatemala (2006)

Gold Mine Tailings Dam Design

- Height – 80 m
- Constructed in three stages – centerline construction
- Rock fill dam with clay core and cutoff trench
- Grout curtain
- Internal filter drainage system (chimney drain)
- Dam appears to be well designed
- Reservoir was unlined

Covering Tailings with Geosynthetic/1.5m Soil

Tailings Reservoir

- Shallow residual soil cover over rock
- Rock is highly fractured tuff and metamorphic rock
- Groundwater reported 200m below surface
- Statement from design review document:

  "Suitable dam core material occurs in relatively small pockets scattered within the reservoir."
- Tailings contain heavy metals
- What problem could occur given the geologic setting?

Differing Foundation Stiffness

Upper Tamakoshi Hydropower Dam, Lamabargar, Nepal (2015)

Overall Project Characteristics

- Peaking, “run of the river” facility
- Construction began in 2012, stopped by 2015 earthquakes
- Estimated cost = US $441 Million
- Components impacted by earthquake
  - 22 m high concrete gravity dam (abutments, intake, spillway)
  - Two 225 m long desanding basins
- Little or no damage
  - 8.4 km long power tunnel, penstock with 822 m head drop, 456 MW in-mountain powerhouse, tailrace tunnel

Location Map

Panel of Experts (POE) Called to Evaluate Headworks Area - Displacements

- Binod Tiwari, Ph.D., P.E., Cal. State Fullerton
- James K. Mitchell, Sc.D., P.E., D.GE, Chairman
- Izzat M. ‘Ed’ Idriss, PhD, P.E.
- William F. Marcuson, III, PhD, P.E.
- Ray E. Martin, Ph.D., P.E., D.GE

Earthquake History/Landslides

- Historically, 10 earthquakes >M7.0 since 1255
- Two major recent events:
  - M_w = 7.8 on April 25, 2015
  - M_w = 7.3 on May 12, 2015
- More large earthquakes will occur
- Several landslides occurred in valley during recent earthquakes
- Potential for future major landslides was not investigated in design of headworks facilities

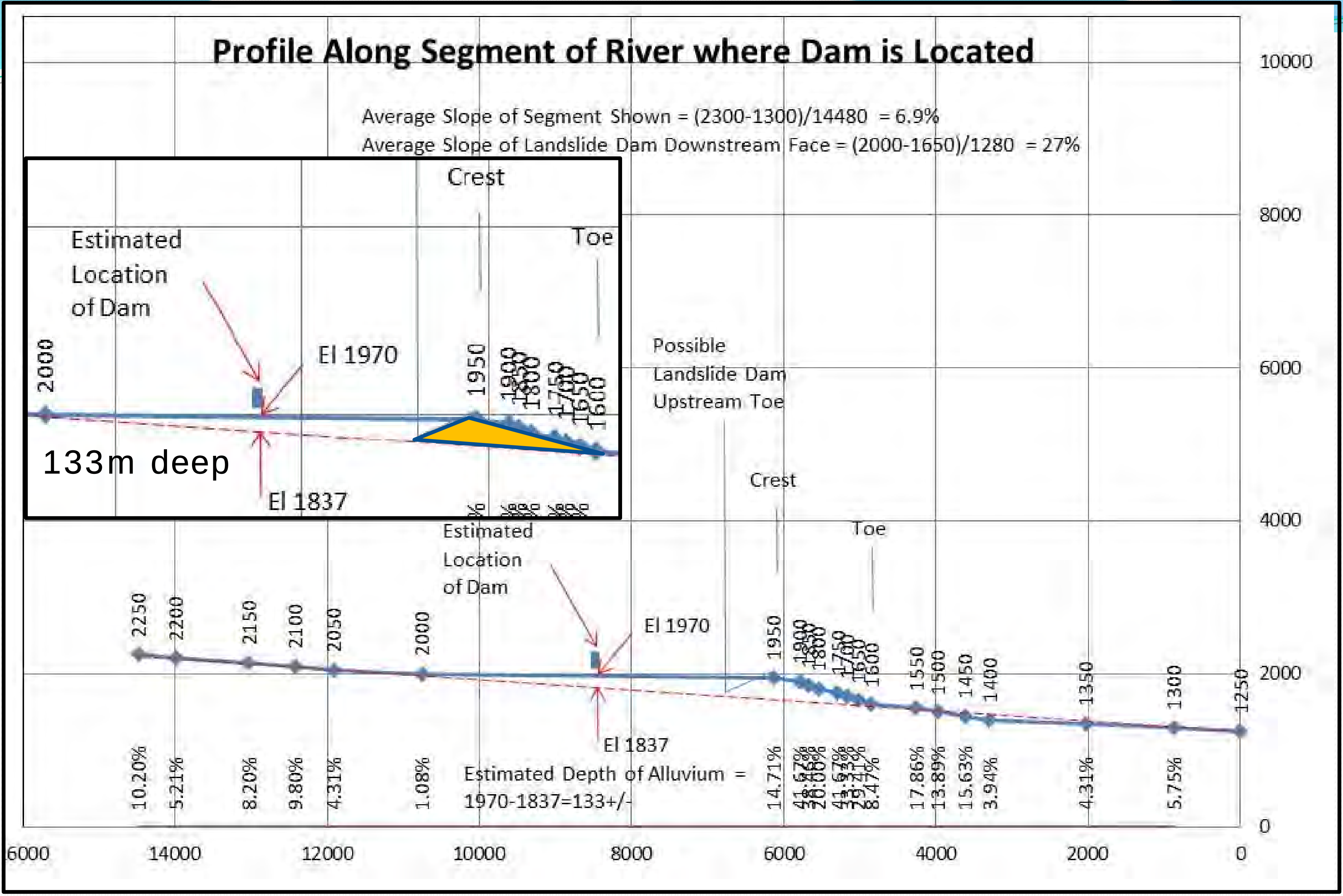
Local Geology

- Gneiss rock at dam site abutments - strongly foliated/ highly fractured
- Deep river alluvium exists under dam
- Deposited behind ancient landslide dam
- Landslide dam – 2.5km downstream of new dam
  - Estimated age – 2000 years
  - Most landslide dams are not stable – usually eroded by river
  - Perhaps stable because large boulders armor downstream surface

Landslide Dam

- 39 M m^3 in landslide dam
- 18 M m^3 of alluvium behind landslide dam
- 300 m high

Dam Foundation



- Illustrates estimated depth of alluvium under center of dam

Summary of Foundation Conditions

- Right abutment - monolith anchored to rock
- Intake and spillway monoliths
  - 8 m of alluvium removed
  - Replaced with 5 m of compacted fill
  - Shallow cutoff wall
  - ~120 m of alluvium below fill
  - Maximum investigation depth = 46 m

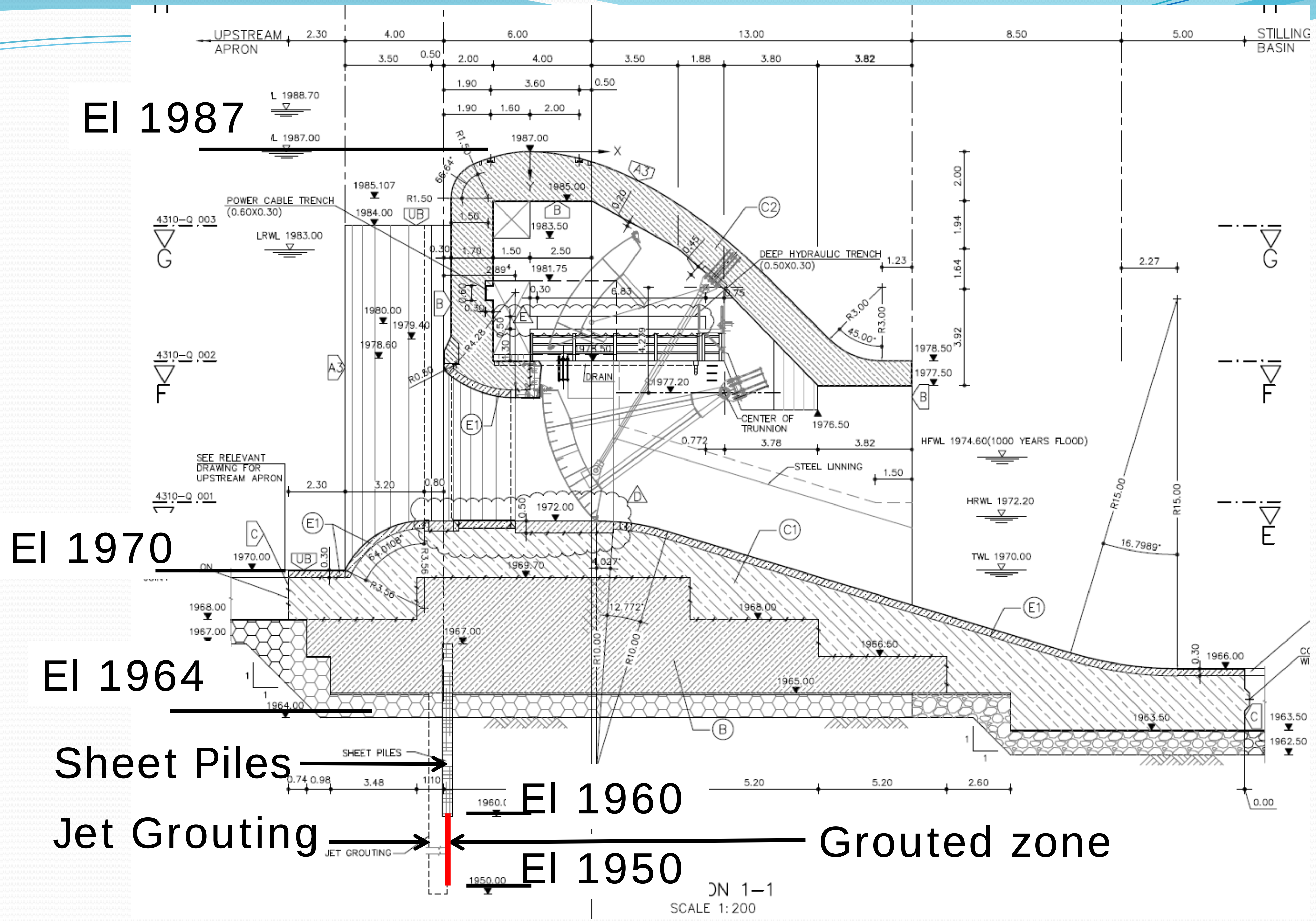
- Left Abutment – planned to be anchored to rock - actually a very large boulder

Right/Left Abutments

Spillway Cross Section

Spillway and Inlet Monoliths supported on compacted fill from about

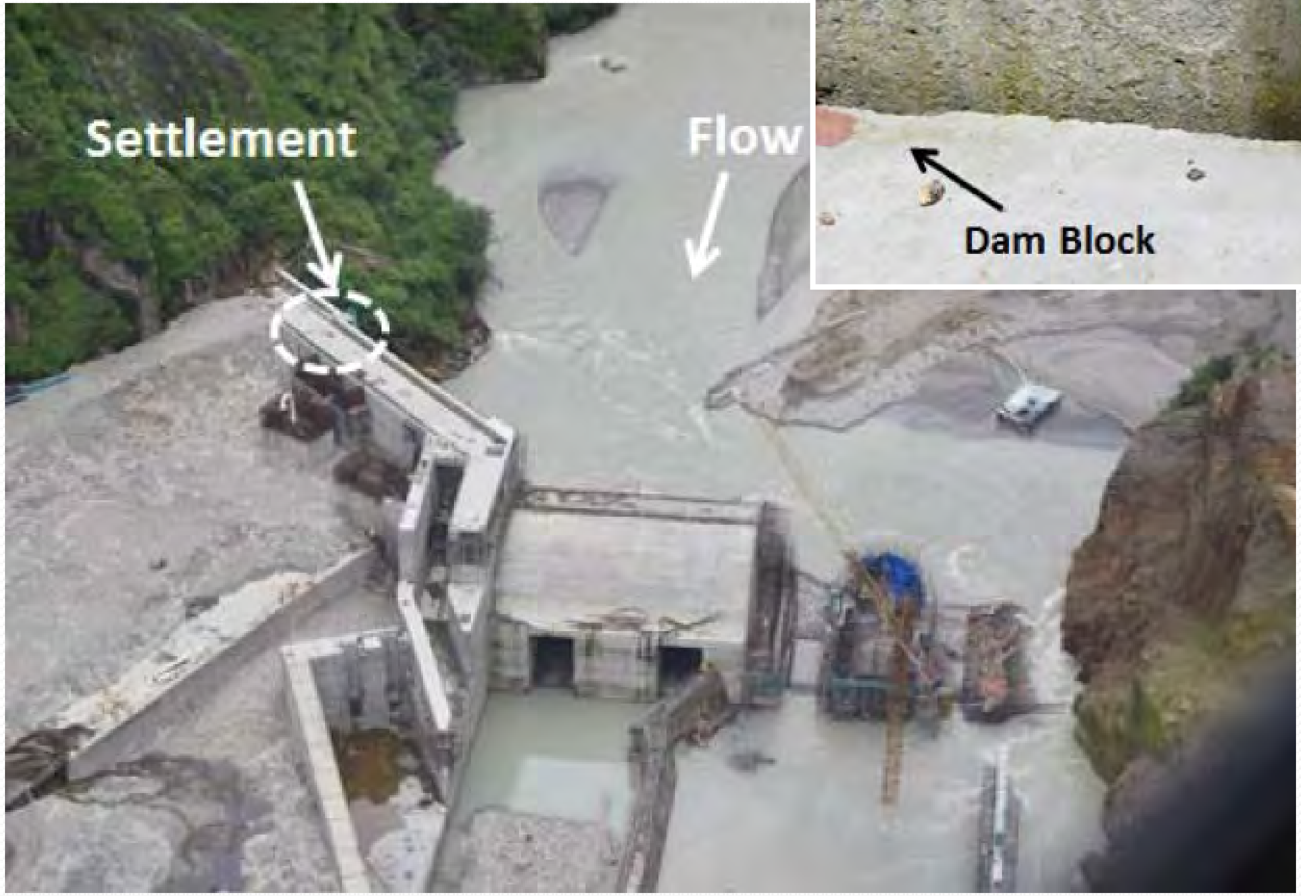
El 1964 to 1959

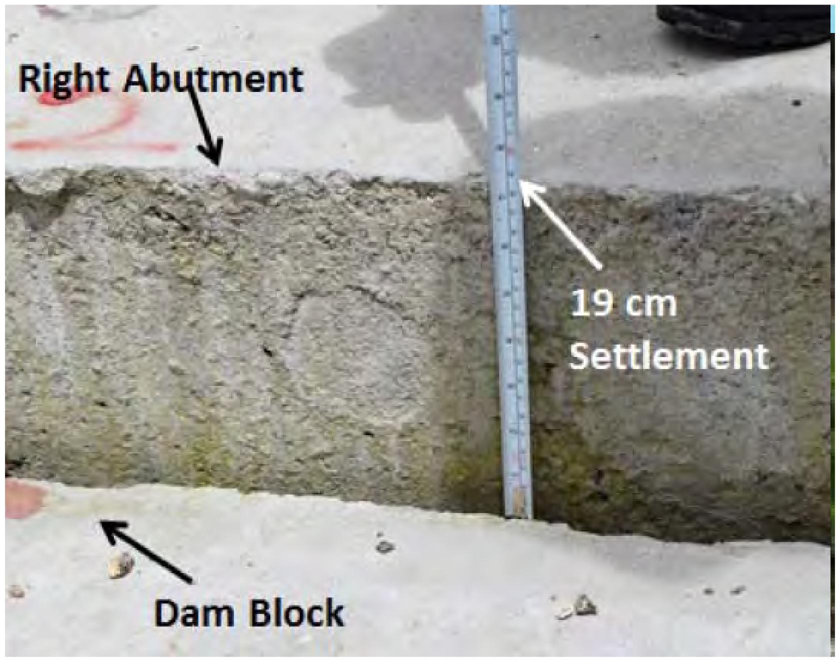


Foundation Questions

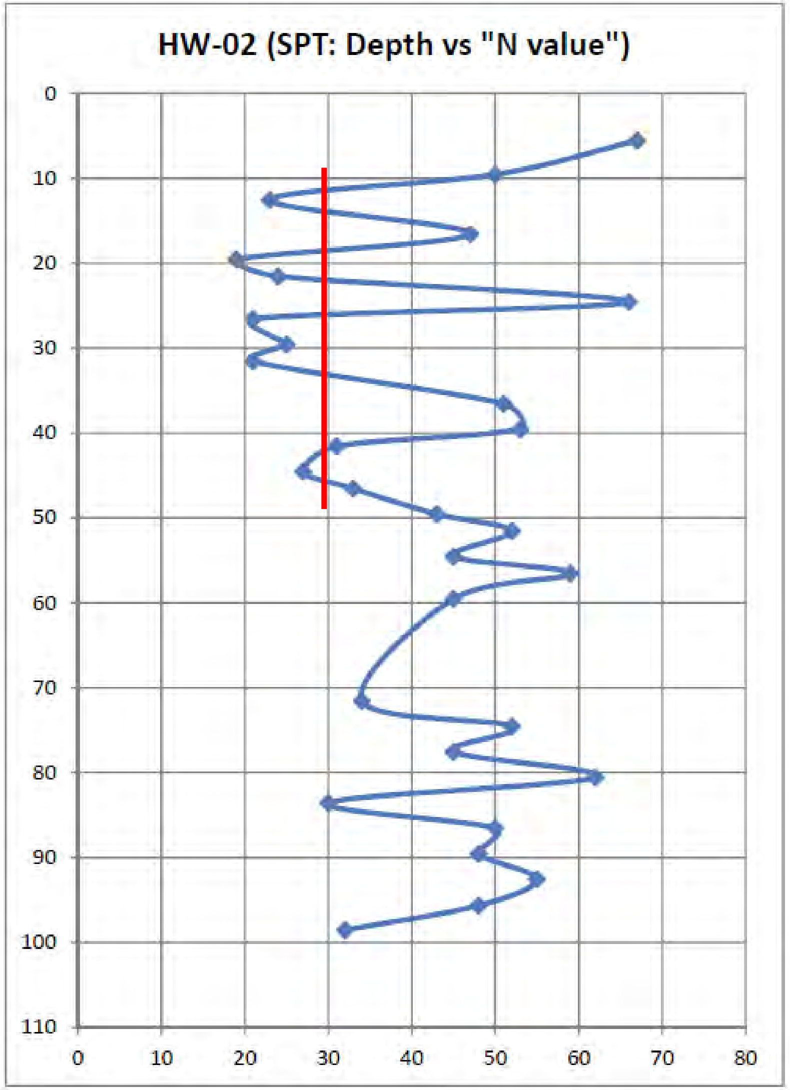
- What impact would you expect earthquakes to have on dam?
- Did previous earthquakes densify alluvium?
- Will future earthquakes continue to densify alluvium?

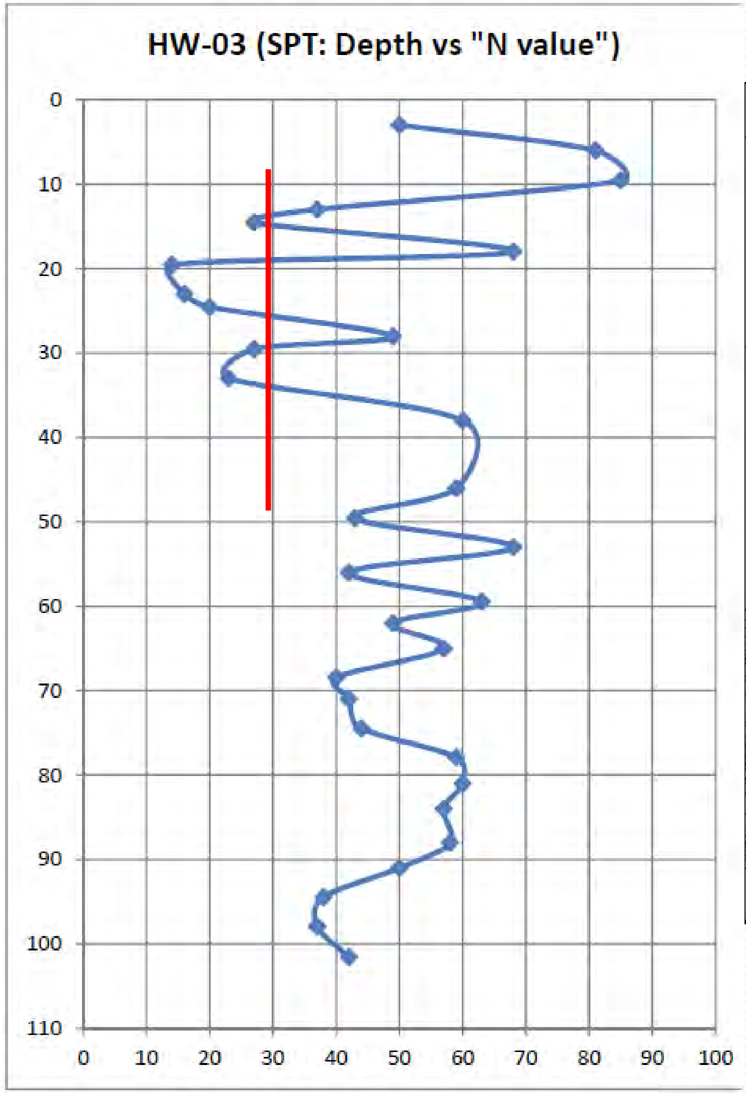
Headworks Movements

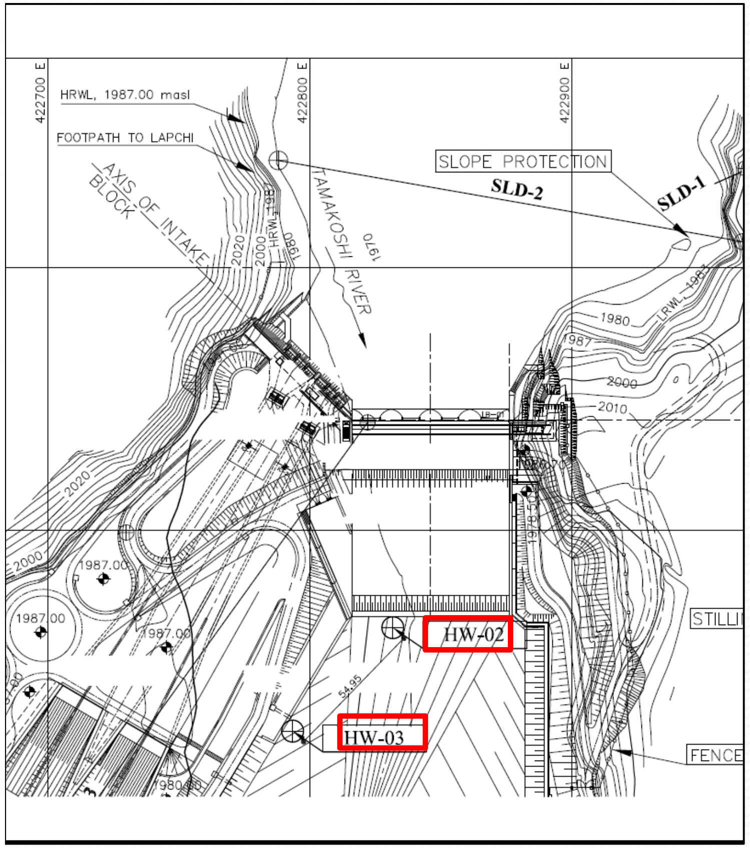




Post Site Visit Borings – Rock 121 m (2016)







Cause of Settlement/Displacement

- Liquefaction
  - Volumetric strain ~ 1% - limited depth of liquefiable soil
- Volumetric compression (densification)
  - Volumetric strain ~ 0.15%
- Tectonic movements
  - Possible strike-slip movement on fault in valley
  - Evidence not supportive
- Panel conclusion - densification was likely cause
- How would you have designed the dam?

Internal Erosion - General Comments

Piping is the number 2 cause of dam failures worldwide

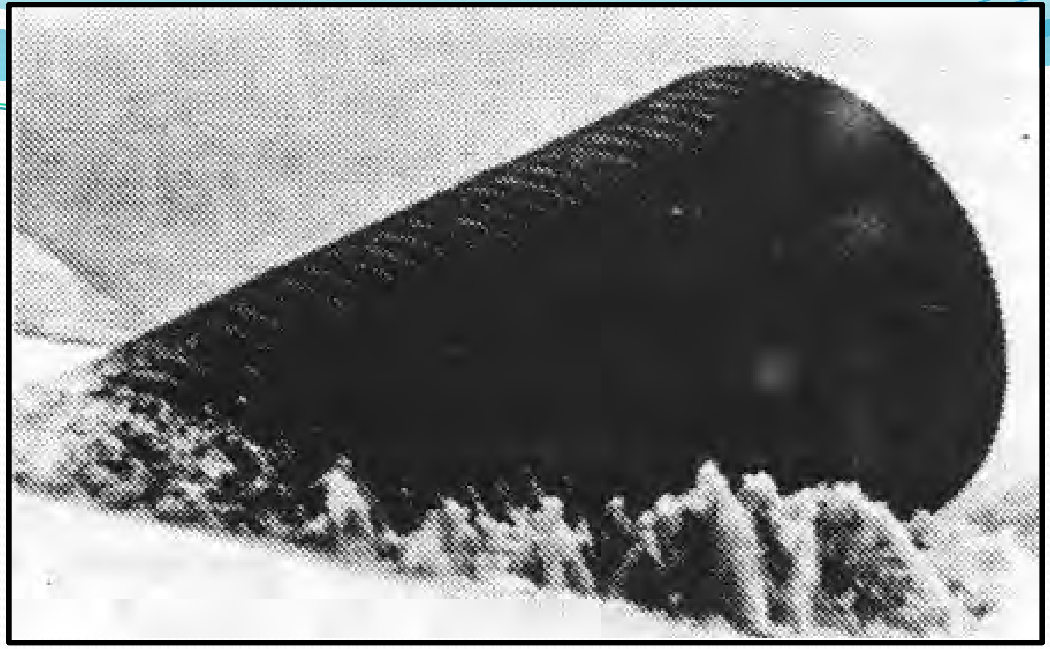
Internal Erosion/Piping

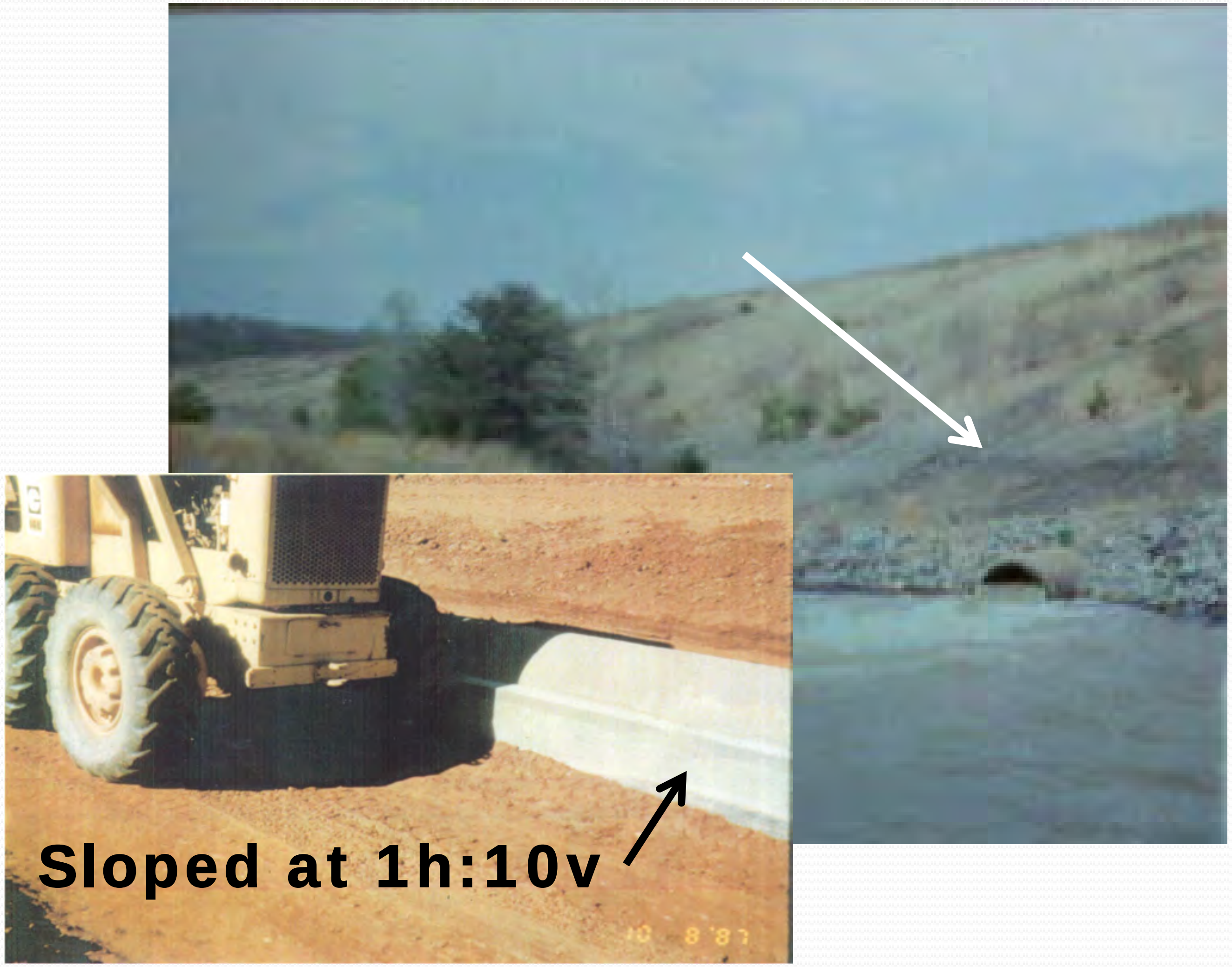
- Piping - backward erosion of soils from and unfiltered exit under a sufficiently high exit gradient to cause soil particles to erode and form a “pipe” to the upstream source of seepage
- Silts and sands most susceptible
- Gravel and larger size particles are susceptible if gradients are sufficiently high

Critical Gradient/Roofing

- Gradient which initiates soil particle movement
- Upward vertical critical gradient, $i_{cr} = \Upsilon'_m/\Upsilon_w$
  - Often assumed to be 1
  - Depends on the unit weight of the soil – for example Υ = 112.4pcf is: $i_{cr} = \Upsilon'_m/\Upsilon_w = (112.4 - 62.4)/62.4 = 0.8$
- i_{cr} can be lower when flow is sloping down – 0.6 to 0.3
- Piping enabled by material that provides "roof" over pipe

Surface of Seepage/ Internal Erosion/A Failure

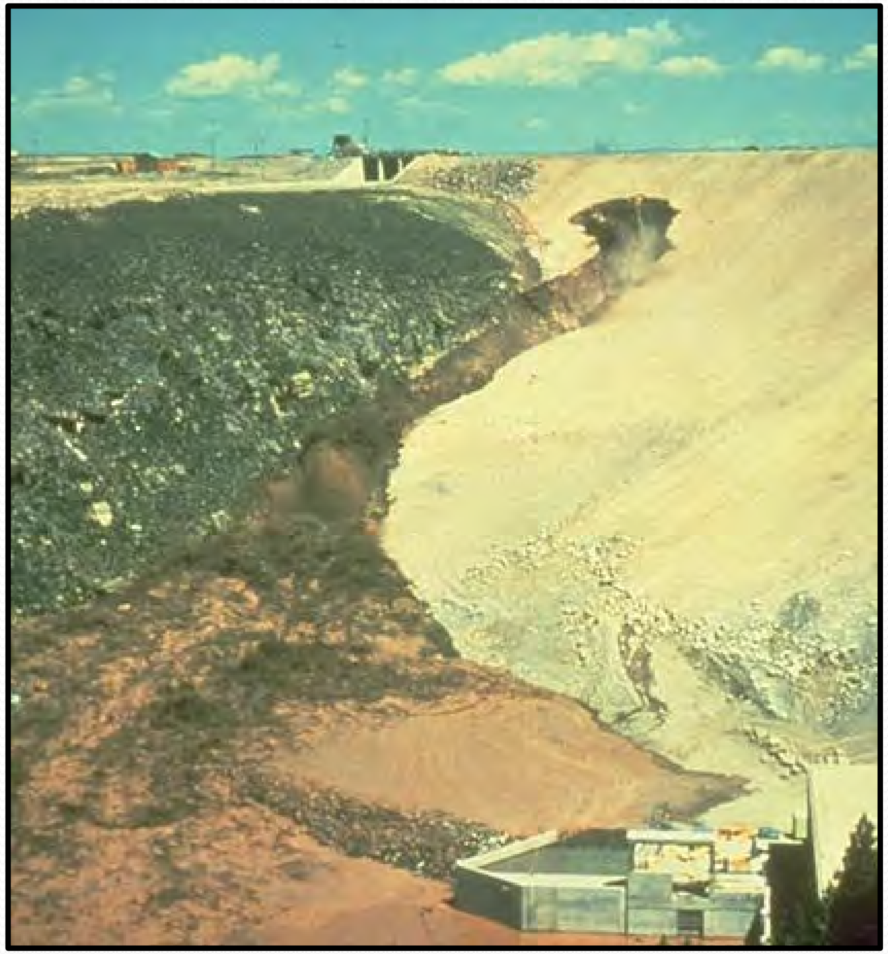




Internal Erosion

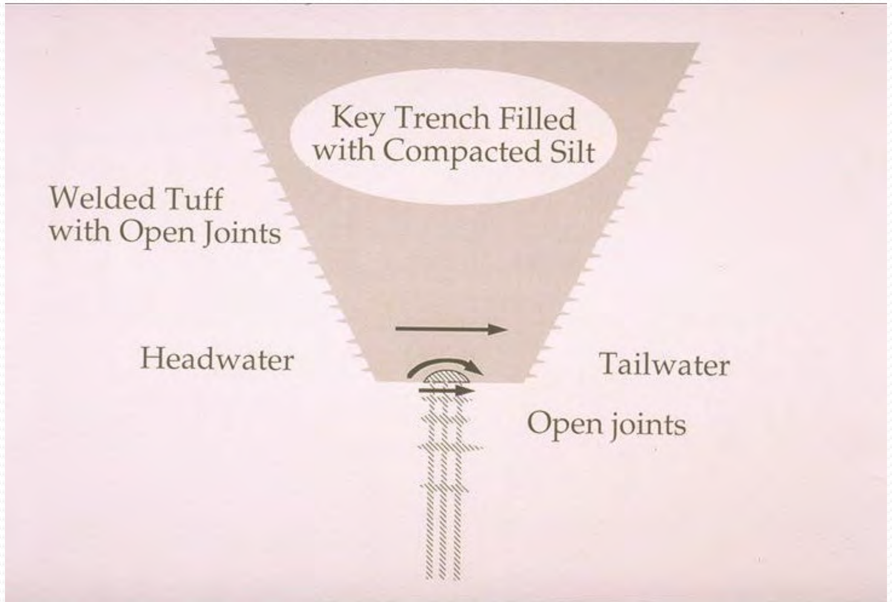
Teton Dam, Fremont & Madison Cos. Idaho

Teton Dam Piping Failure – 1976 -14 Deaths



Cross Section Looking Down Stream

- Fractured rock excavated in upper portion of Core Trench
- <u>How erodible is silt?</u>



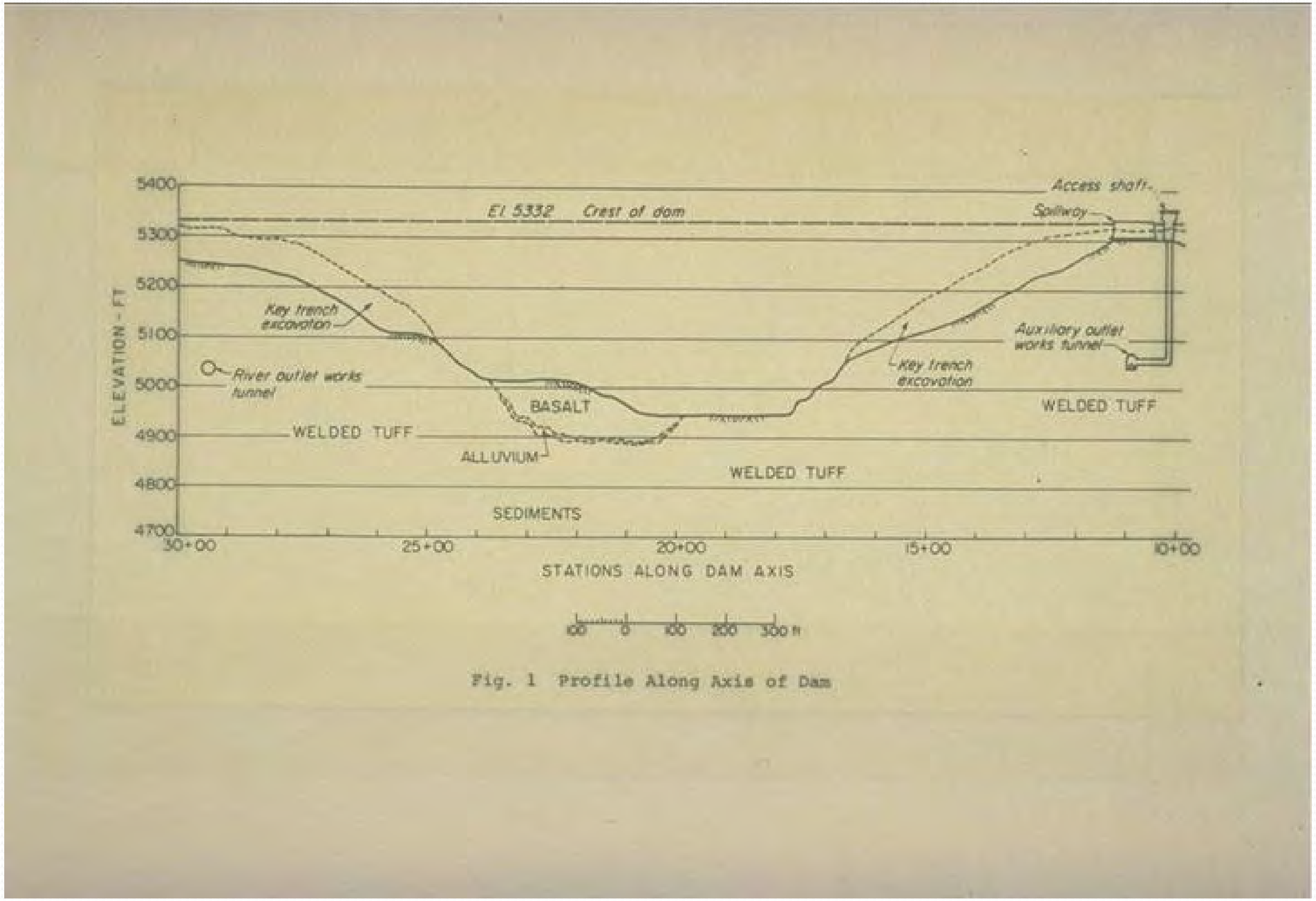


Fig. 1 Profile Along Axis of Dam

Internal Erosion

Golf Course Dam, Williamsburg, VA (1980’s)

Williamsburg Golf Course Dam

- Small dams can fail by piping
- Homogeneous 15ft high embankment dam constructed of sandy clay/clayey sand
- Cradle in lower 10 percent of pipe
- Reservoir filled – 10ft of head
- Failed over night along pipe

Failure

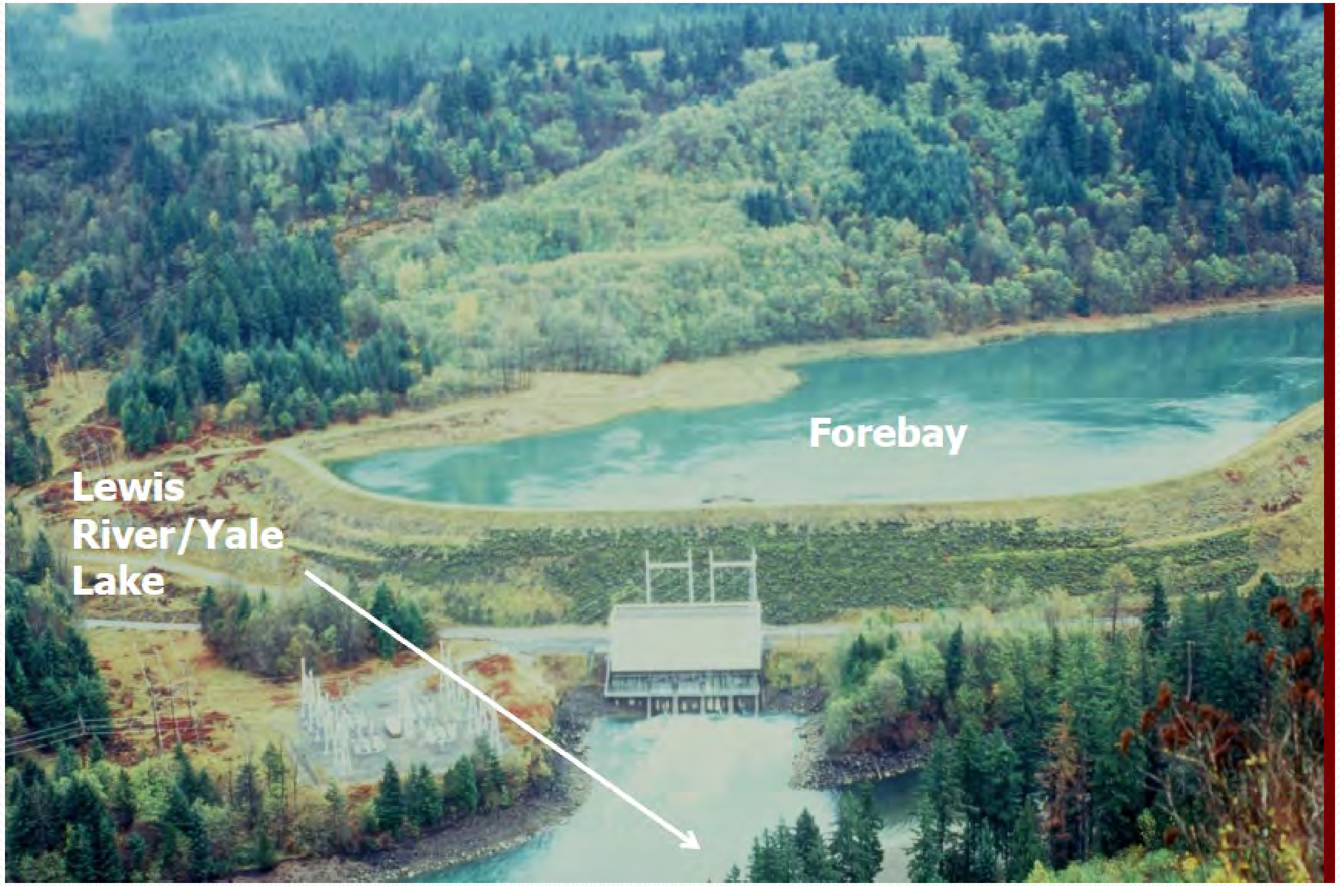
- How did it fail?

Internal Erosion

Swift No. 2 Dam, Lewis River, Skamania County, Washington (2005)

Swift No. 2 Hydropower Project

- Constructed - 1957 – 1958
- Length of water supply canal – 3 miles
- Impoundment - 2400 ac-ft
- Embankment height in forebay – 93 ft



Foundation Stratigraphy

- Stratum A - alluvium/colluvium – sand and gravel (10 to 20 ft thick) – Recent
- Stratum B – vesicular to massive highly jointed basalt rock (8 to 50 ft thick) – from Mt. St Helens (about 2000 years old) - Recent
- Stratum C – alluvium - silt, sand, gravel, cobbles, boulders (> 200 ft thick) - Pleistocene
  - Stratum C1 - silt and sand
  - Stratum C2 - gravel, cobbles, boulders (< 5 percent silt/sand)

Post-Construction Canal Leakage

- 1958 - Seepage loss from canal ~100 cfs (45,000 gpm)
- 1959 - Canal drained twice, numerous sinkholes repaired
- 1974 - Boils at downstream toe of the forebay embankment
  - *"An inspection of the river bank---several places where water was cascading into Yale Reservoir---appeared to be clear."*
  - Canal drained; numerous sinkholes repaired
- 2000 - Seepage observed along Lewis River/Yale Reservoir
  - *"The flow appeared to be clear, but has been reported to be turbid during periods of high runoff.---seepage gradient should be small"* [FERC Report]

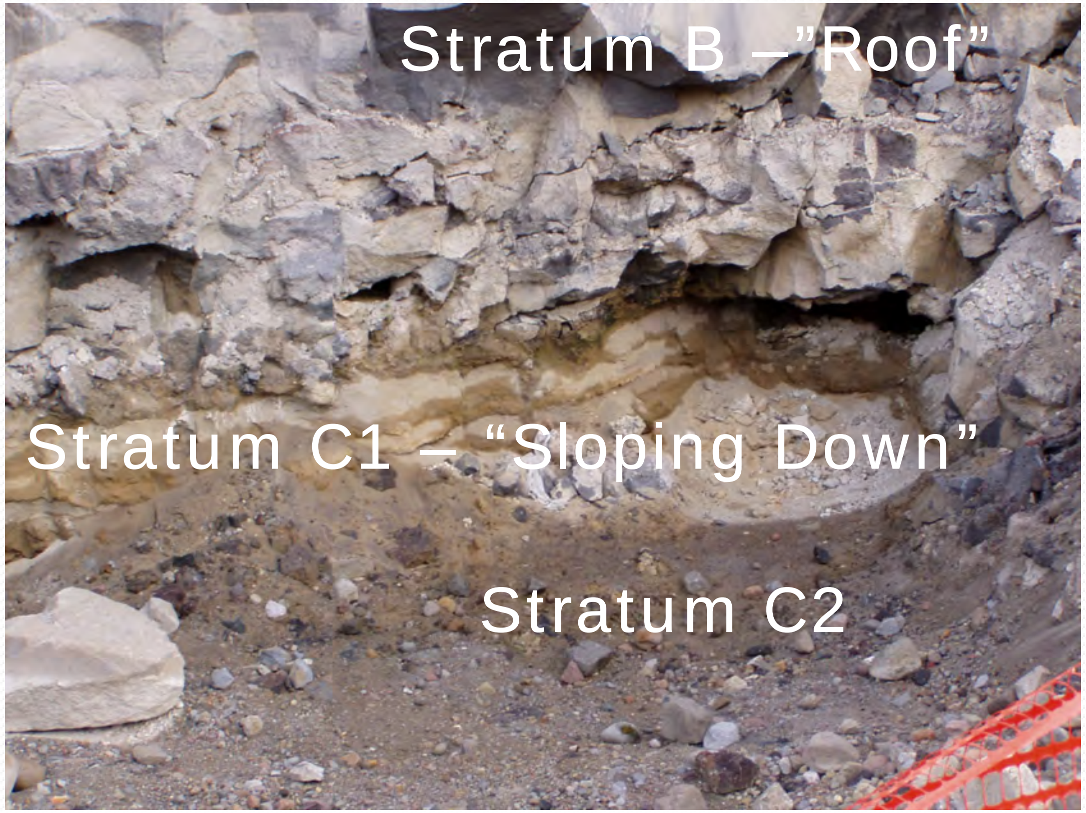
April 21, 2002 Failure

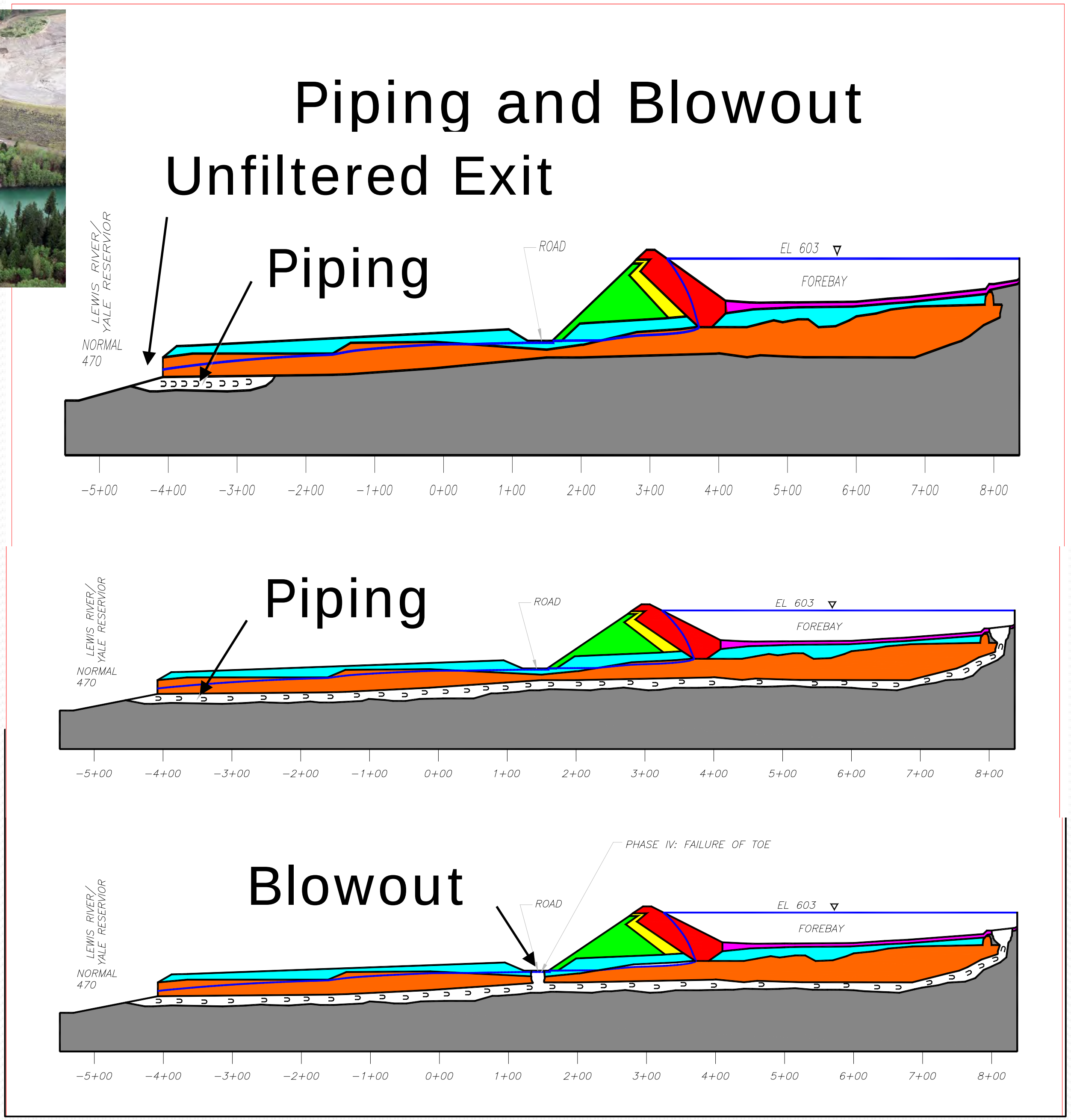
- Blowout occurred at toe of embankment at about 3:00 AM
- Orifice expanded upstream causing breach of the embankment at about 5:20 AM
- Flooding destroyed downstream facilities
- Sinkholes discovered in forebay
- Discharge contained in downstream reservoir

Failure in Progress

Post Construction View/Post Failure View

Piping Failure





- <u>Why did it take 44 years to fail?</u>

Internal Erosion

Tailings Reservoir Rim Failure, Sand Mine, Camden, TN (2014)

Tailings Pond Rim Piping Failure

Failure on October 26, 2014

- A 911 call at 9:51PM from home north of CSX track – “flooding”
- A CSX Railroad train derailed at about 10PM
- The Pond contained about 79.6 million gallons of water at failure
- In use for about one year

Breach Geology

- A - Fill – for access road
- B – Clayey sand
- C - Upper McNairy fine sand
- D - Lower McNairy cemented sand/silt/clay
- Note head cut blocky area in cemented soil
- Water depth at rim – 25.7 ft

Ground Surface Left of Breach

- Ground Surface 3.5 ft higher than at breach
- Head – 22.2 ft or 3.5 ft less than at breach
- Pushed stick in ground 3 ft at location of flow
- <u>How did failure occur?</u>

Dam/Reservoir in Karst

Zongolica Hydropower Dam/Reservoir, Veracruz State, Mexico (2015)

Project Location

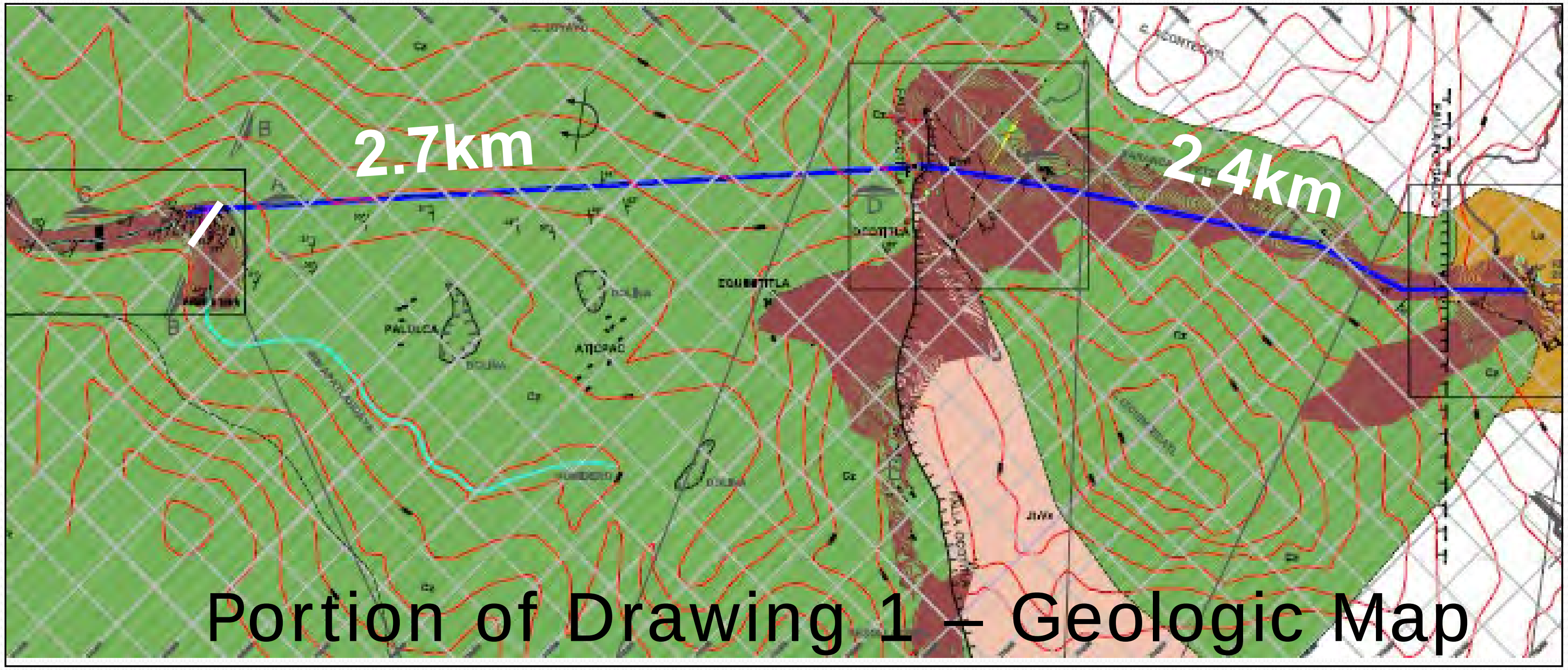
Project Site

Understand the Site Geology

- 2008 Geotechnical Report, Section 4.5 – Local Geology

  " [The formation includes]---limestones and some dolomite horizons --- of the Orizaba formation---."

- <u>What geologic features can be observed?</u>



Portion of Drawing 1 – Geologic Map

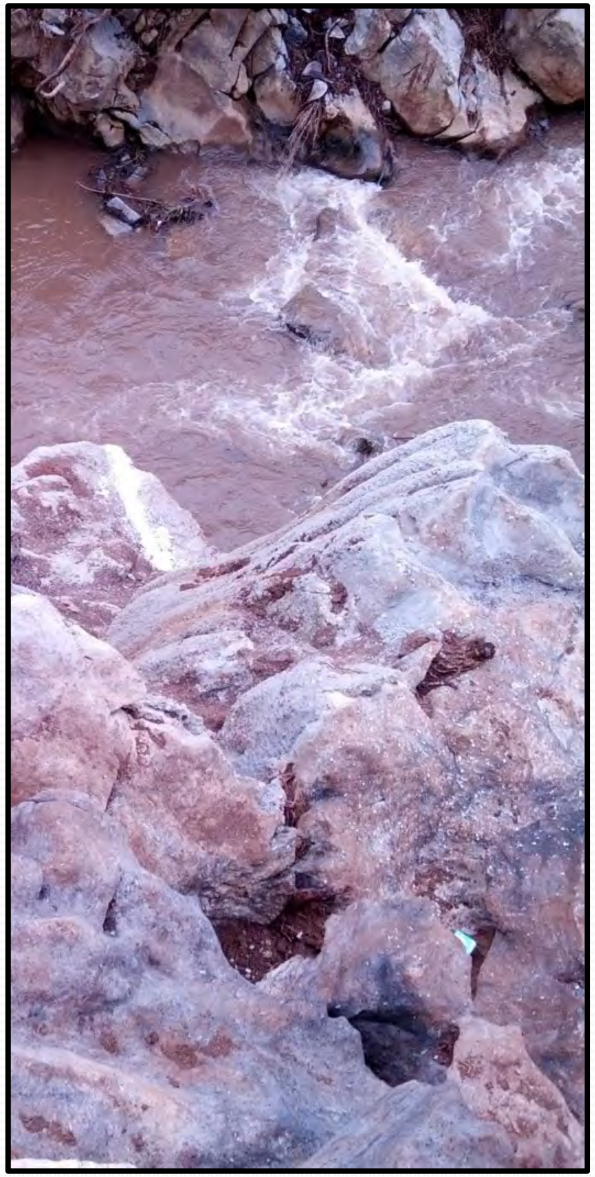
2008 Field Investigation/Geology

- Reservoir - limestone
  - No investigation or borings until after dam was constructed
- Dam (30 m high) - limestone
  - 2 borings - little solutioning indicated on logs
  - Water pressure test data: $k = 10^{-4} - 10^{-5}$ cm/sec
- What does this range of k-values indicate?
- Power tunnel (2.7km long) - limestone
  - 1 boring - little solutioning indicated on log, no pressure tests
- Powerhouse – sandstone and shale
  - 6 borings
- Why?

2012 Geotechnical Report Prior to First Filling of Reservoir

- Gray limestone, contains minor interbedded red shale
- Rock is of very good quality
- Concave rock structures generated by dissolution
- Discontinuous small cavities observed along fractures

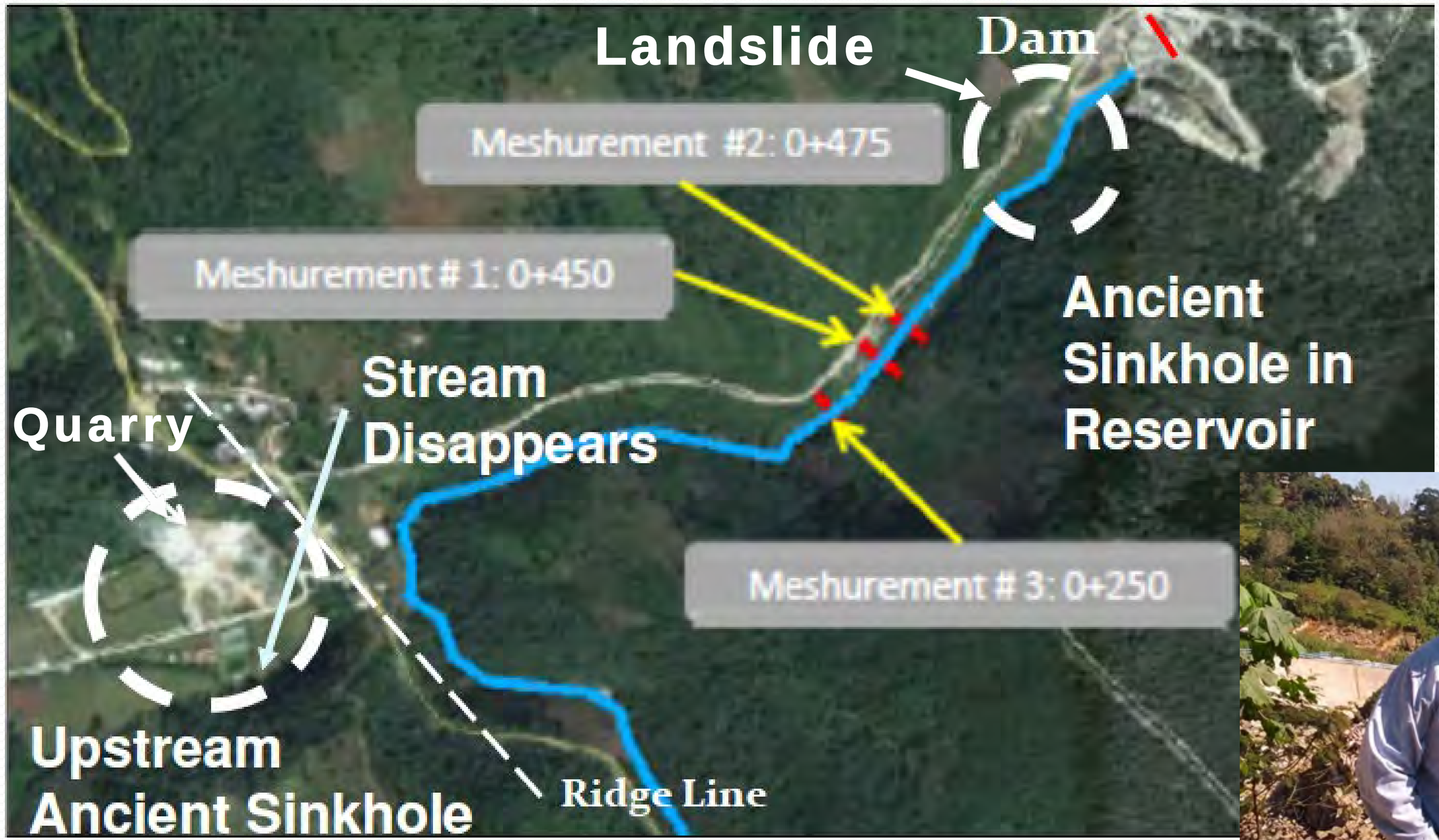
"Neither karstic sinkholes nor visible infiltration that could affect the water reservoir were observed."



First Filling of the Reservoir

- Problem – *“the reservoir is leaking so much we can’t operate in dry season”* - reservoir could not be **<u>filled</u>** at 1.5 m^3/sec stream flow
  - Flow ranged from 0.5 m^3/sec in dry season to >4.5 m^3/sec in wet season
- We needed a local geologist!

Carlos Garcia, Geologist - Comments



- It is likely that groundwater is well below river
- River is perched
- Landslide in reservoir is a remnant of an ancient sinkhole

- 75% of wells installed found groundwater below stream

Upstream Ancient Sinkhole from Ridge Line

Vertical Shaft in Limestone Quarry in Upstream Ancient Sinkhole

Remedial Alternatives – 8 Months to Finish

- Grouting Reservoir - **risks with grouting too high**
  - Upside cost of grouting unknown – how deep – 200m
  - Need to create a bathtub – not likely possible
  - Maximum available for remedial repair - $10 million
- Lining Reservoir
  - Line portions of reservoir side walls with shotcrete
  - Based on geologic mapping
  - Line bottom with concrete slab
- What is the potential problem with lining reservoir?

Fiberglass Rock Bolts with WWF/Rebar and Shotcrete on Sidewalls and Concrete Slab

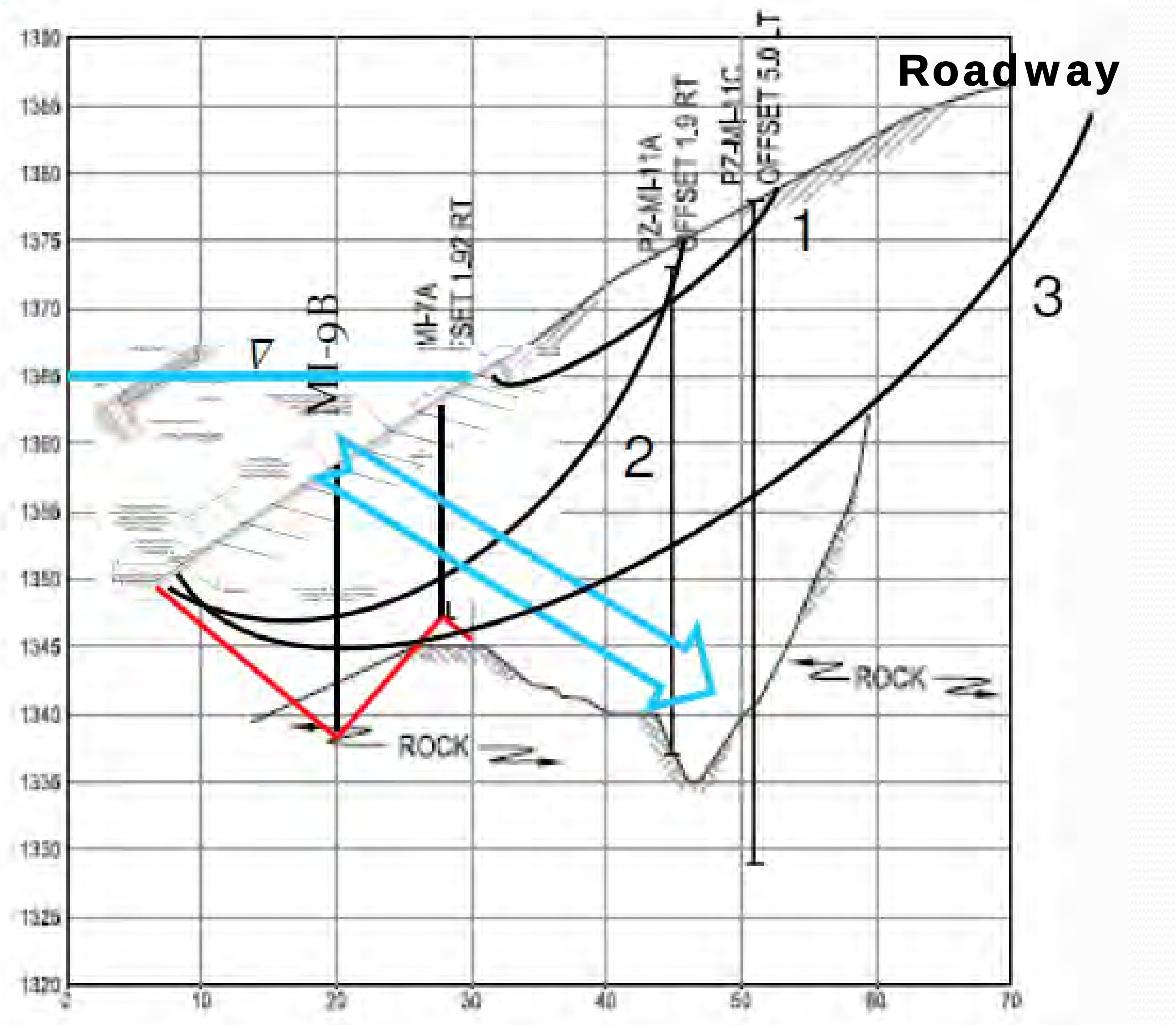
Landslide Looking Upstream from Spillway

- Temporary Solution - design and construct a soil nailed slab over base of landslide to operating level of reservoir

Slope Protection Issues

- <u>What concerns would you have with this soil nailed slope protection?</u>

- 1 - Shallow above soil nailed slope protection
- 2 - Deep seated downslope from roadway
- 3- Deep seated under roadway

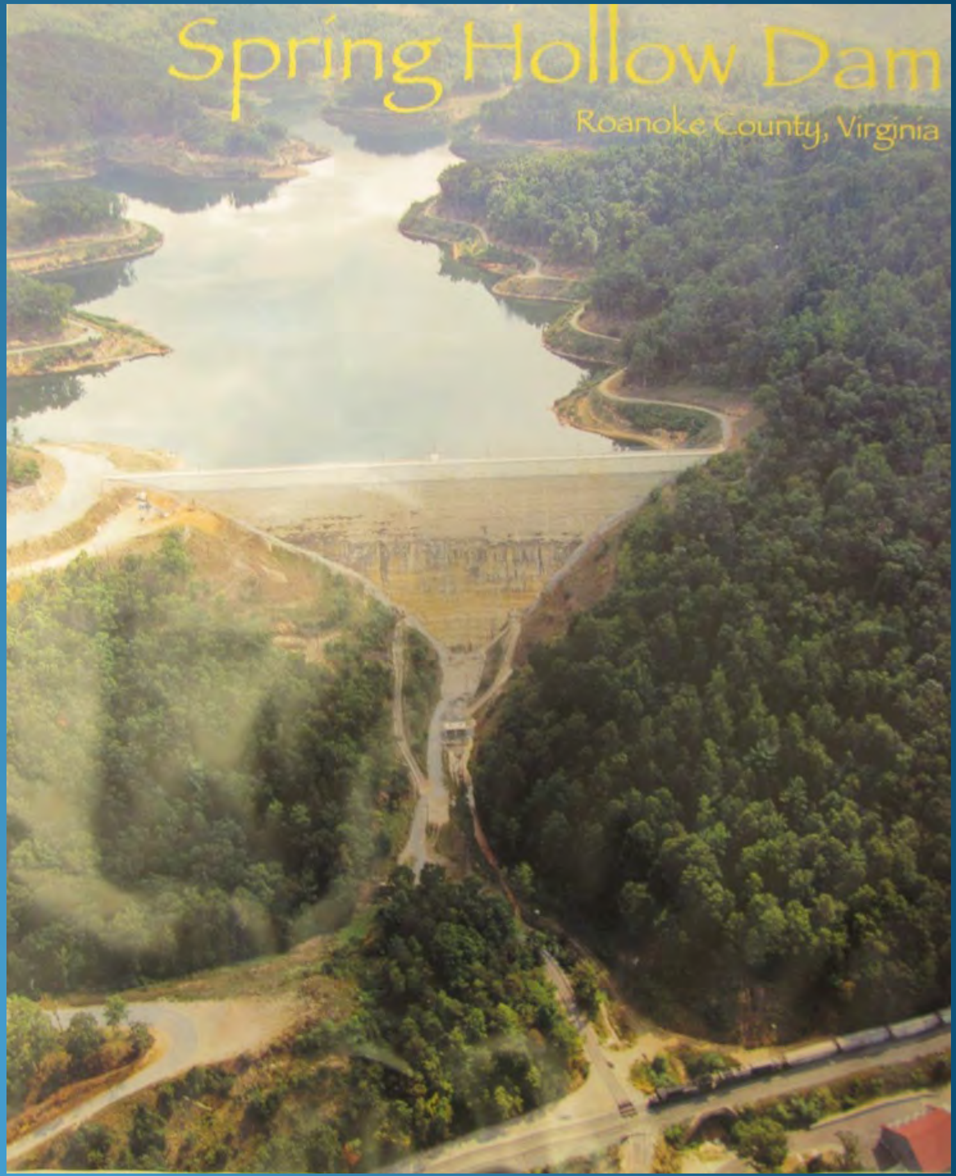


Summary

- Estimated cost of project – about $100M
- Actual cost pre-repairs – about $80M
- Remedial repairs to reservoir - $10M
- Remedial repairs in the tunnel and penstock thrust blocks - $10M
- Cost after remedial repairs – about $100M
- The reservoir holds water
- The slope has not failed, yet (2016)

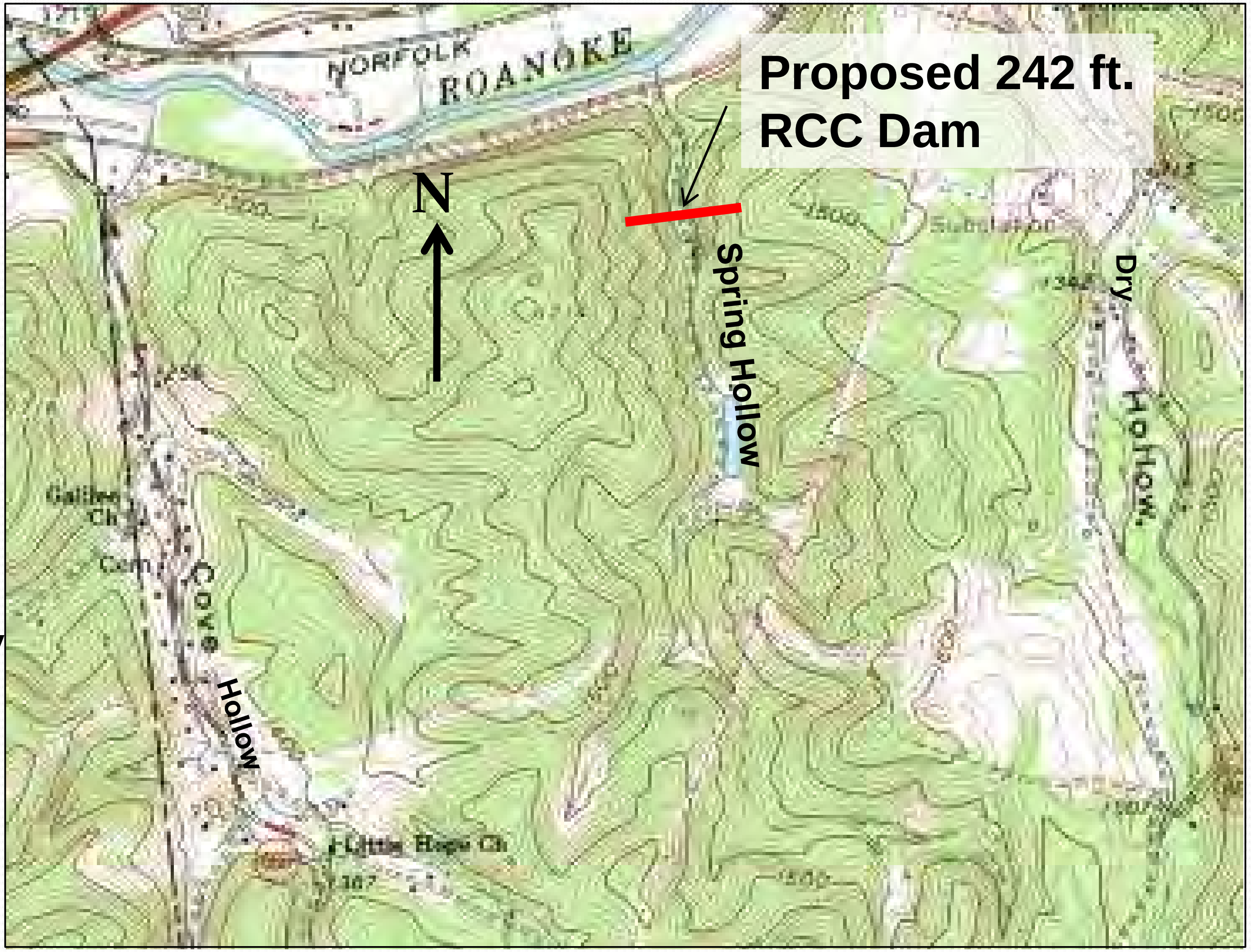
Dam/Reservoir in Karst

Clifford Craig Dam/Reservoir, Roanoke Co, VA (1986-1996)



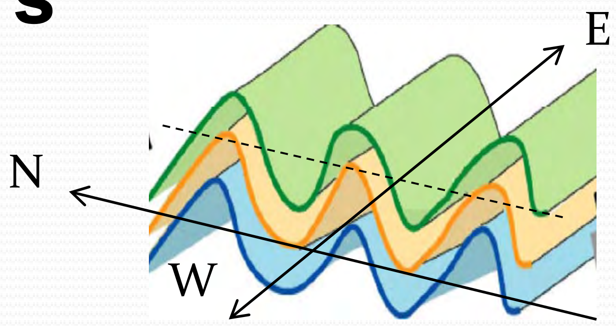
Geomorphology

- Dry Hollow, large sinkholes, disappearing stream
- Spring Hollow, steep slopes, caves & springs
- Cove Hollow, dry tributary valley



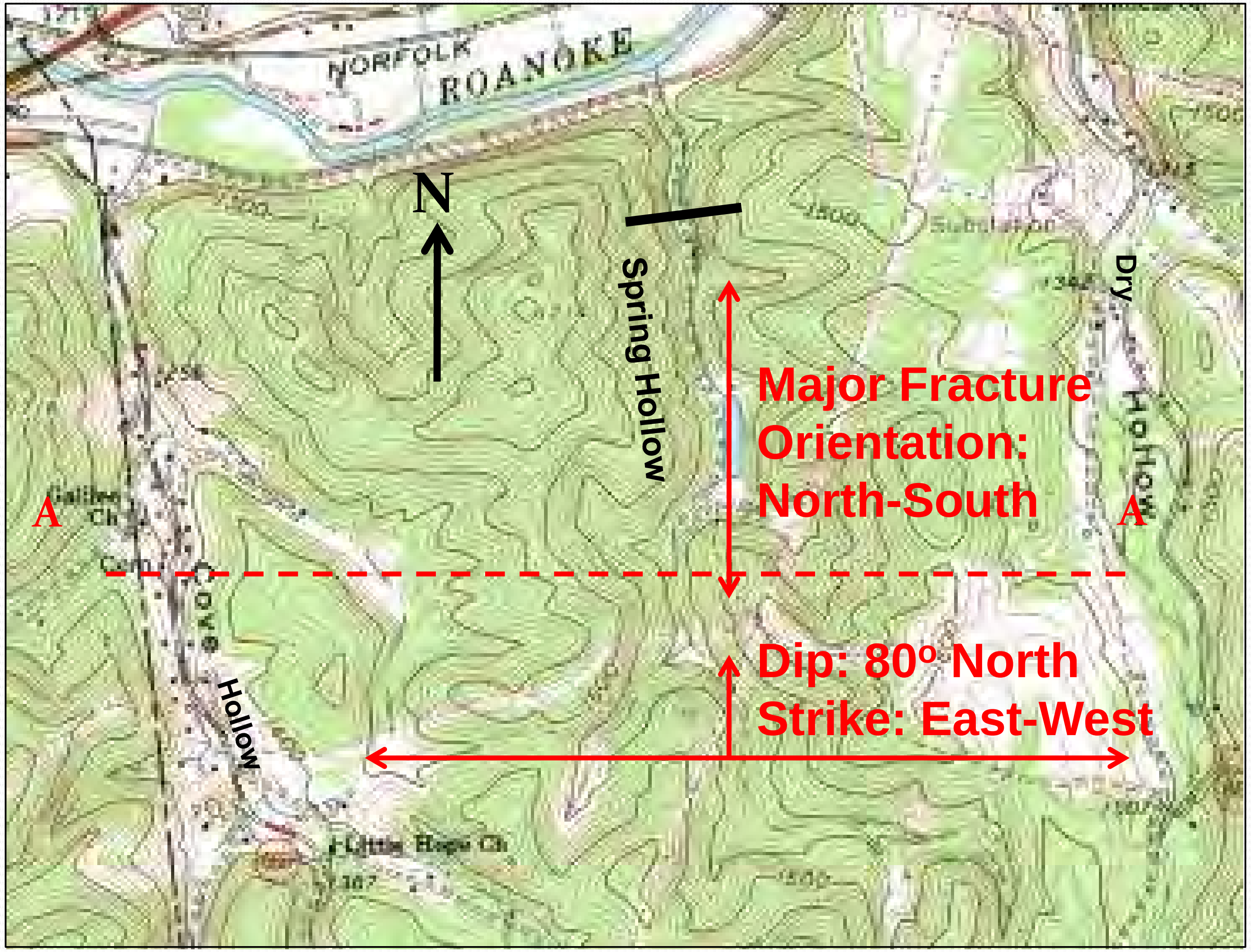
Geologic Setting

- Rome Formation shale interbedded with **limestone and dolomite layers**
- Successive large tight folds
  - Top half of folds had been eroded in past geologic history
  - Bedding dips steeply to north towards Roanoke River
  - Formation strike is east-west perpendicular to valleys
  - Major fractures oriented north-south, perpendicular to strike



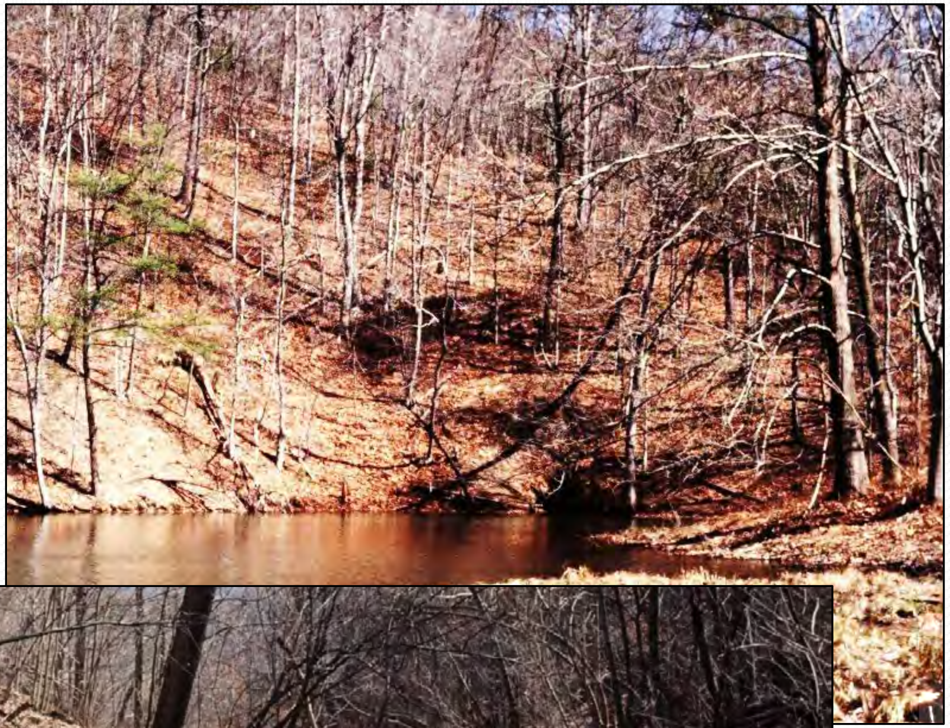
Structural Geology

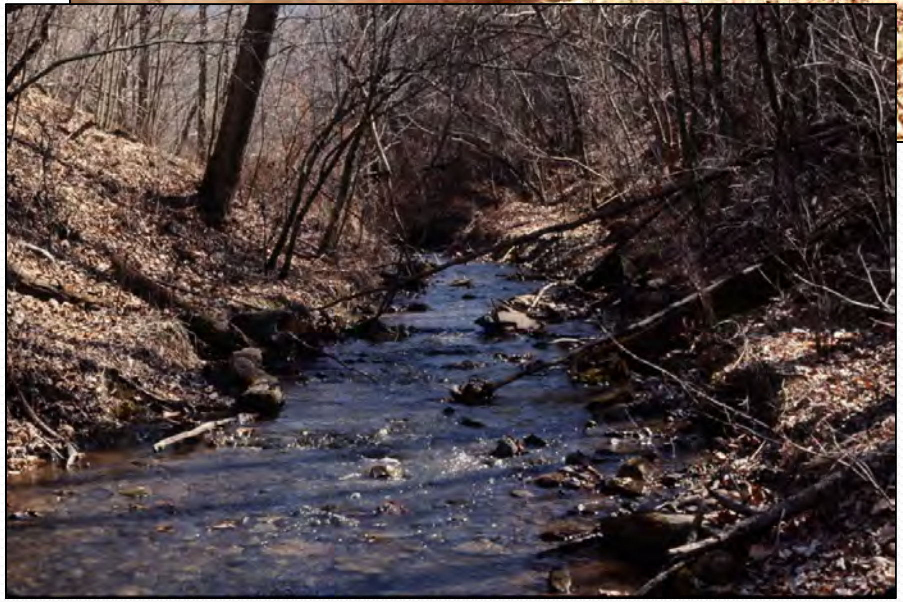
- Creeks aligned along major fracture orientation
- Section A-A - Dry Hollow 130 feet higher than Spring Hollow and Cove Hollow



Dry Hollow/Spring Hollow

Broad valley





Steep sided valley

Hydraulic Connection

Legend

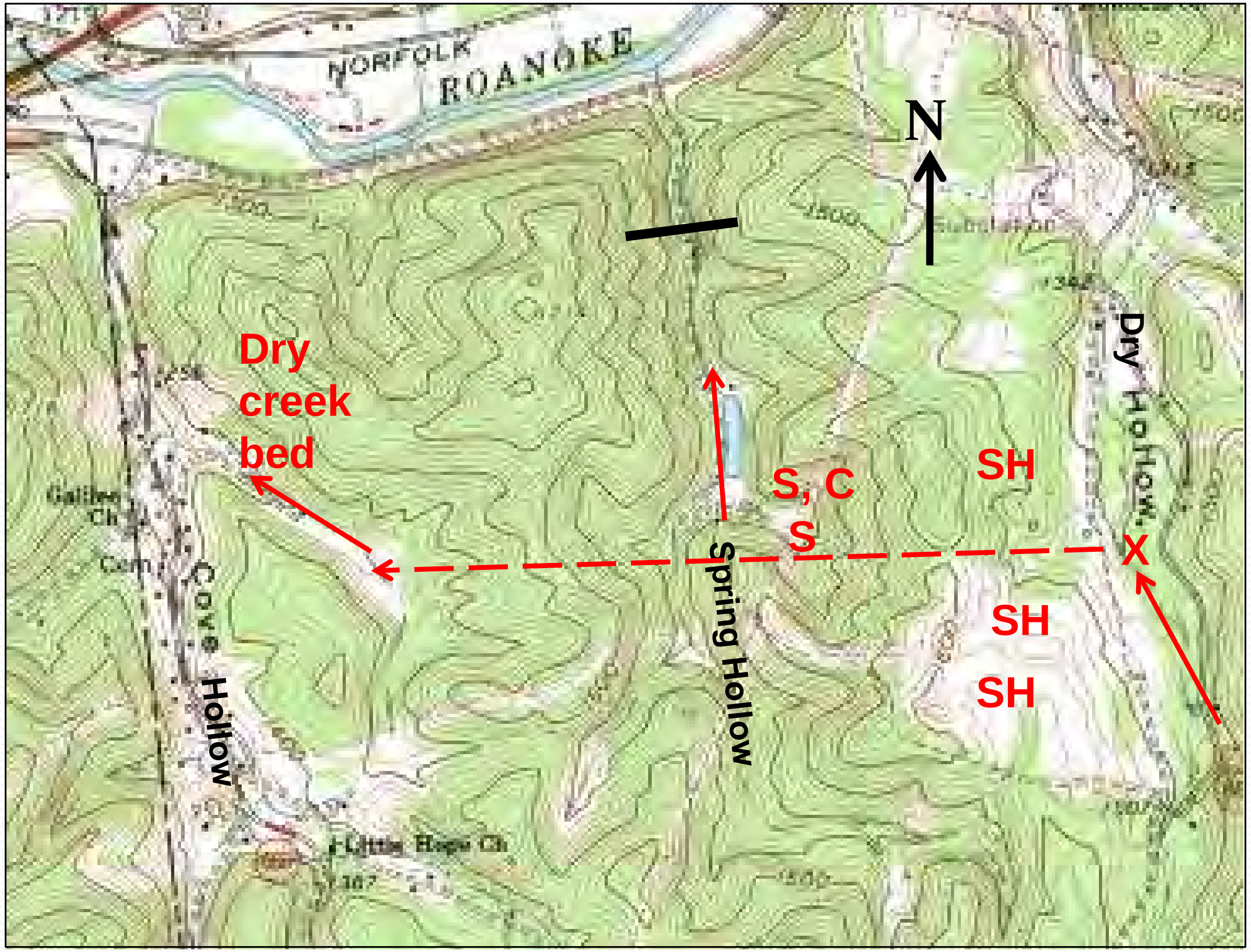
SH - Sinkholes

X - Disappearing stream

C - Cave

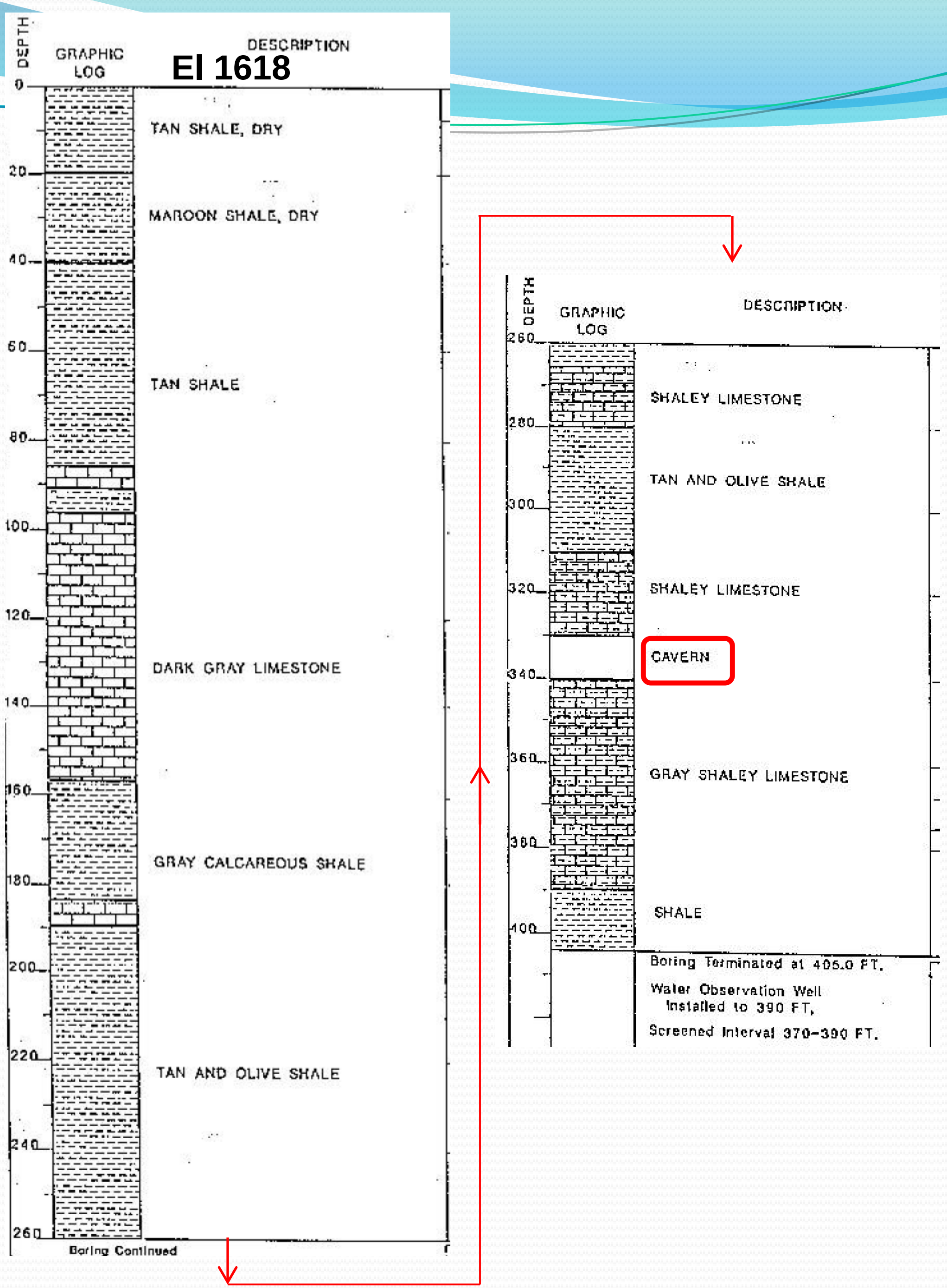
S - Springs

- What occurred at this site in past geologic history?



Drilling Program

- Borings drilled along ridge lines on both sides above Spring Hollow
- Voids and caverns located along both sides of Spring Hollow at valley level
- Geomorphology sequence confirmed

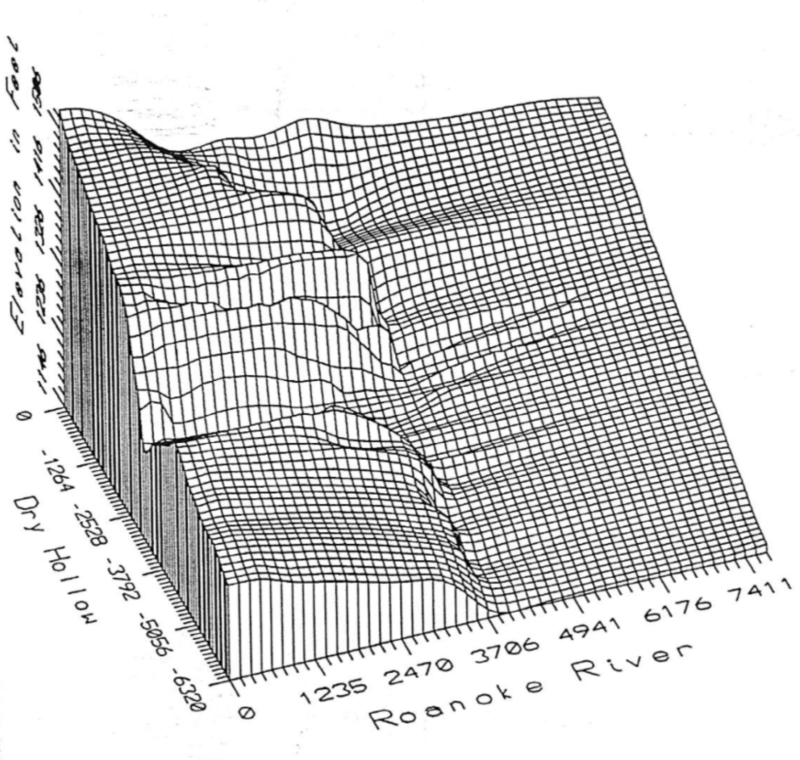


Possible Solutions

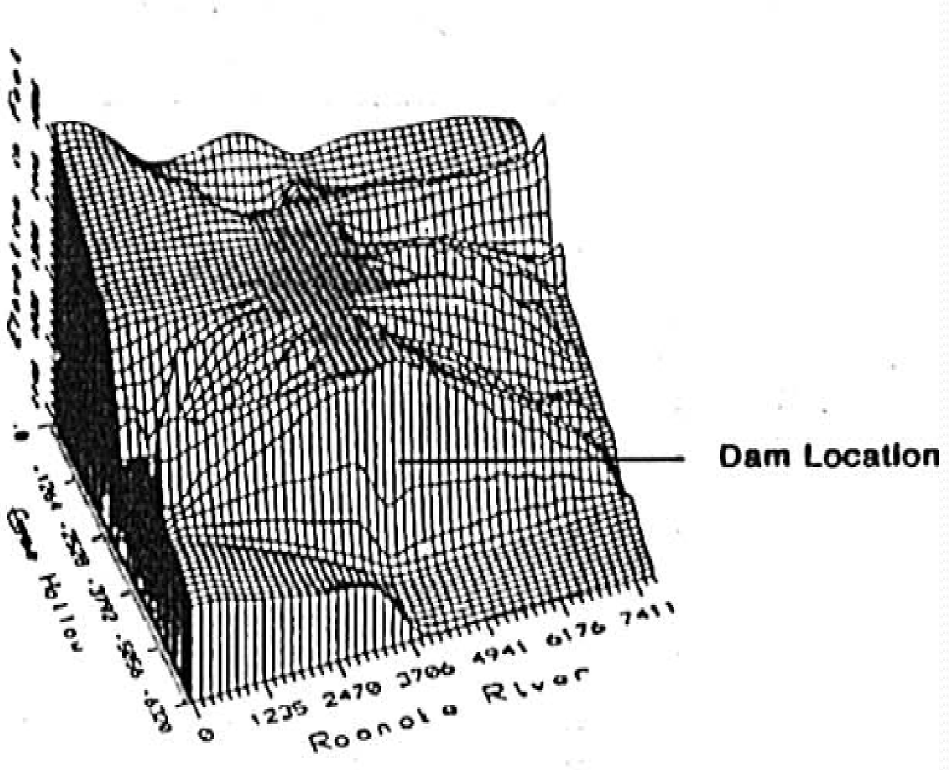
- Abandon site – too risky, reservoir may never fill
- Design a reservoir grouting program
  - Numerically model seepage conditions – pre-and post grout
- Evaluate risk - develop a test grouting program
  - Monitor spring flow, estimate production grouting cost
- Results of test grouting program
  - Spring flows not modified significantly – test section too short
  - Grout takes indicated production grouting costs acceptable if test section representative of remainder of grouting area

Pre and Post Reservoir Groundwater Contours

- Seepage loss no grouting – 4MGD
- With grouting - reservoir leakage evaluated assuming fractured rock conditions



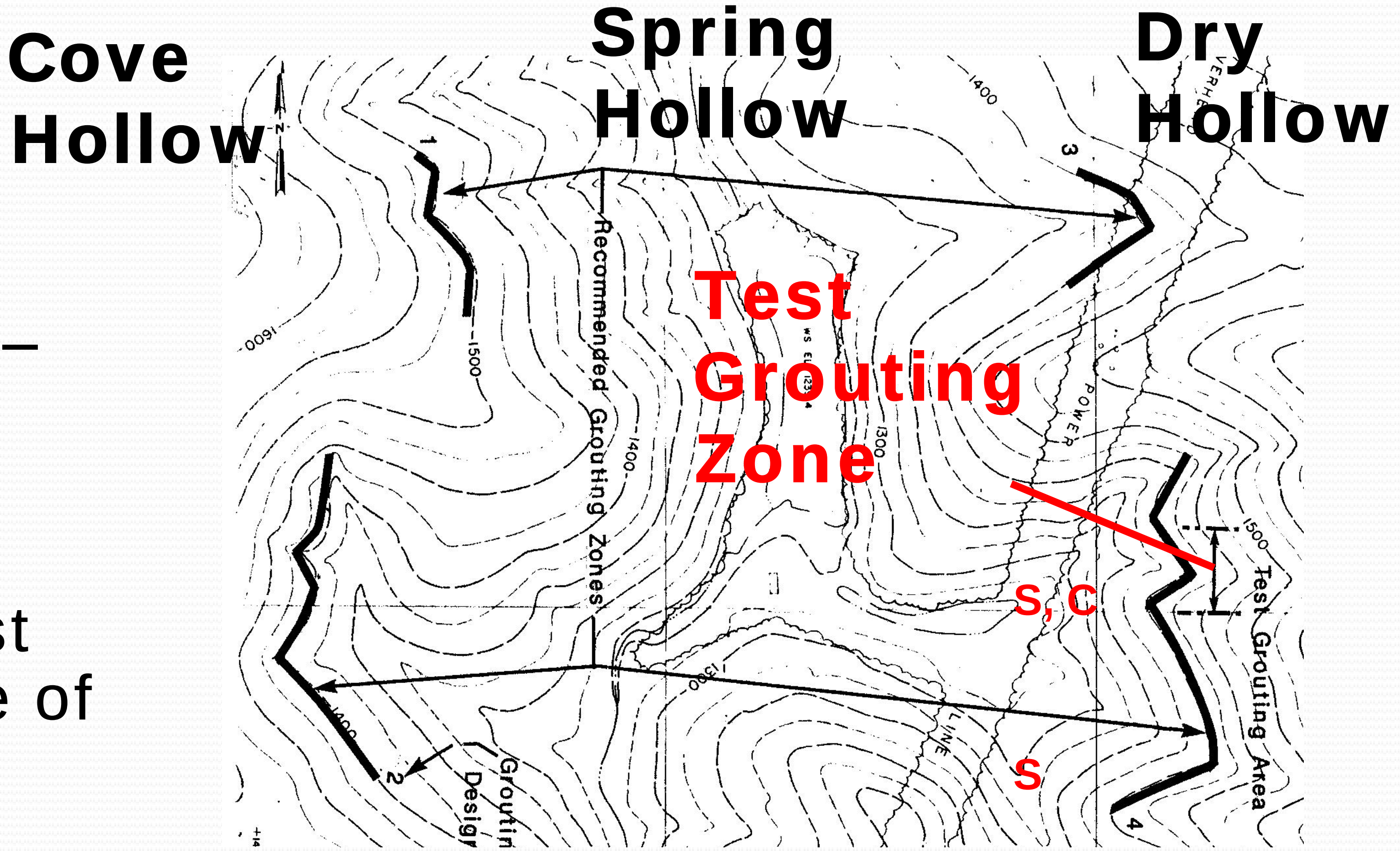
No reservoir



Reservoir Full

Test Grouting/Production Grouting Program

- Results of test grouting program
  - Spring flows not modified significantly – test section too short
  - Grout takes indicated production grouting costs acceptable if test section representative of remainder of grouting area



Performance

- Production grouting completed
  - Cost higher than estimated
- Reservoir holds water

Thank You

Questions?