BACKGROUND ON

FAILURE OF TETON DAM

Near Rexburg, Idaho

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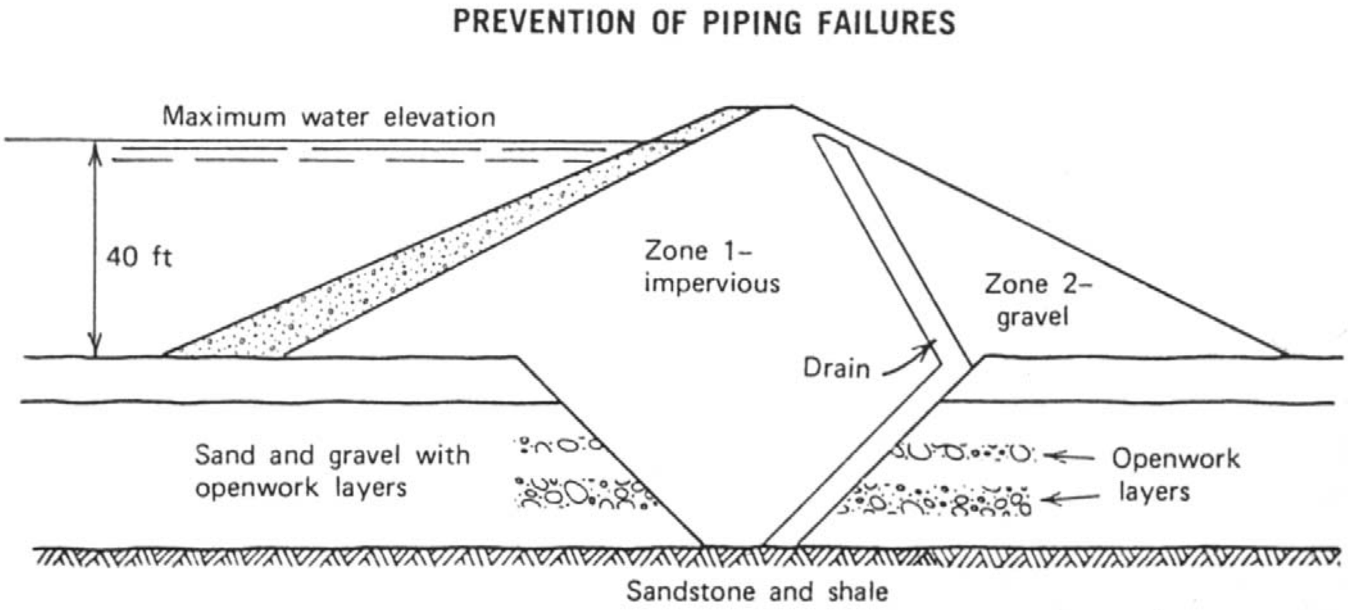
Part 1

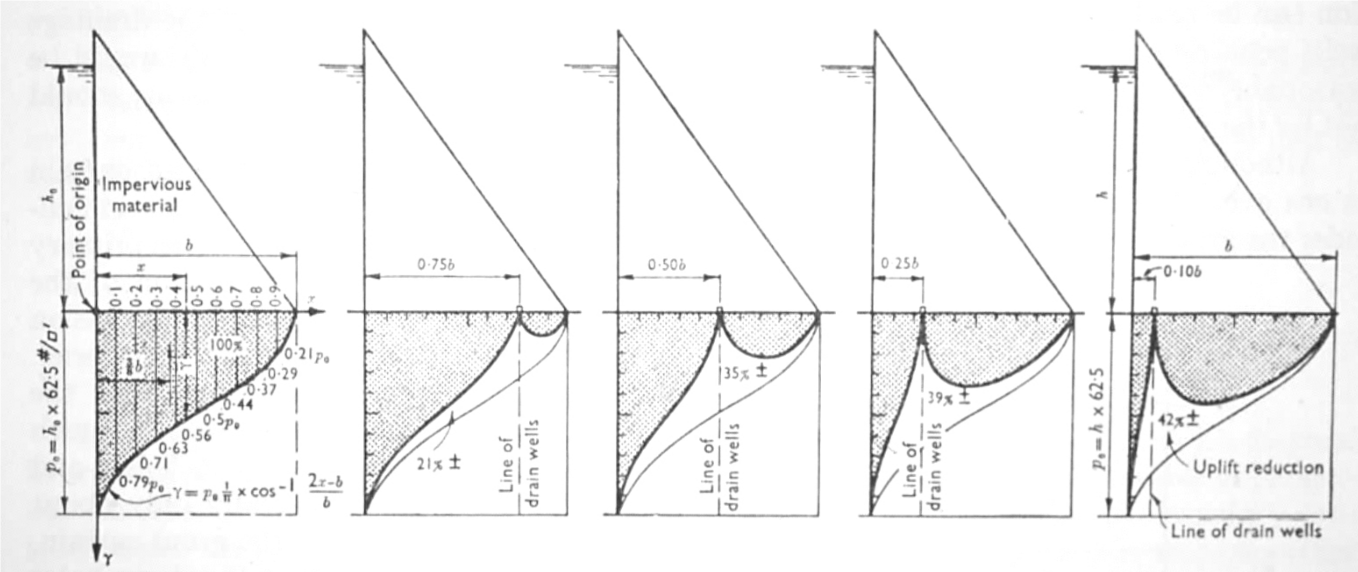
EVOLUTION OF THOUGHT ON HYDRAULIC PIPING POSING A THREAT TO DAM STABILITY

1922-65

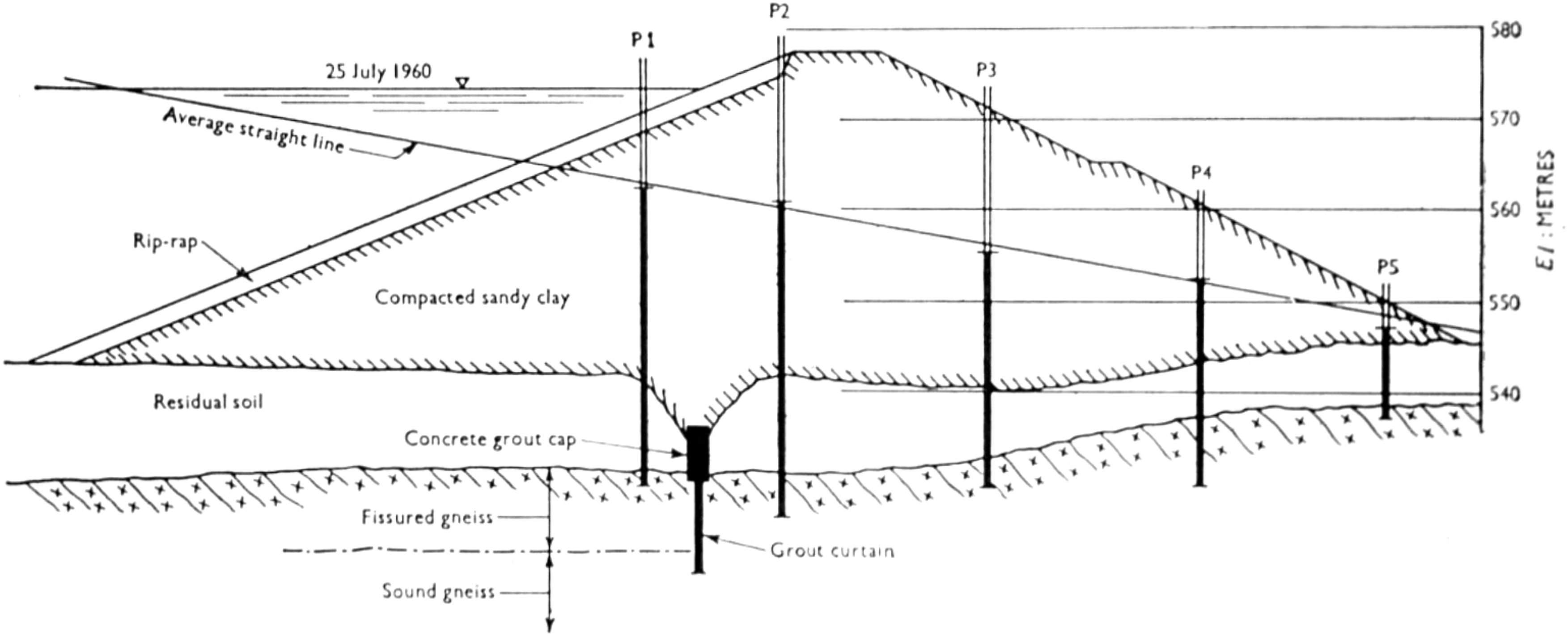
- **Between 1930 and 1945 Karl Terzaghi reversed his opinion on the development of pore pressures in concrete and dam foundations.**
- **After testing jacket specimens of concrete he conceded that pore pressures conduct almost instantaneously through seemingly low permeability media such as concrete or granite**



- **Terzaghi’s protégé Arthur Casagrande taught at Harvard University from 1932-71.**
- **Casagrande was a fierce proponent of deep seepage cutoff beneath embankments dams, as shown here.**
- **His ideas influenced the designs of the US Corps of Engineers**



- **The First Rankine Lecture delivered by Professor Arthur Casagrande in 1961, titled "*Control of Seepage Through Foundations and Abutments of Dams*". Casagrande criticized the conventional view (shown above) that surface drains emplaced for uplift relief should be positioned as close to the upstream face as possible. He argued that seepage relief wells should extend down into the underlying foundation rock.**

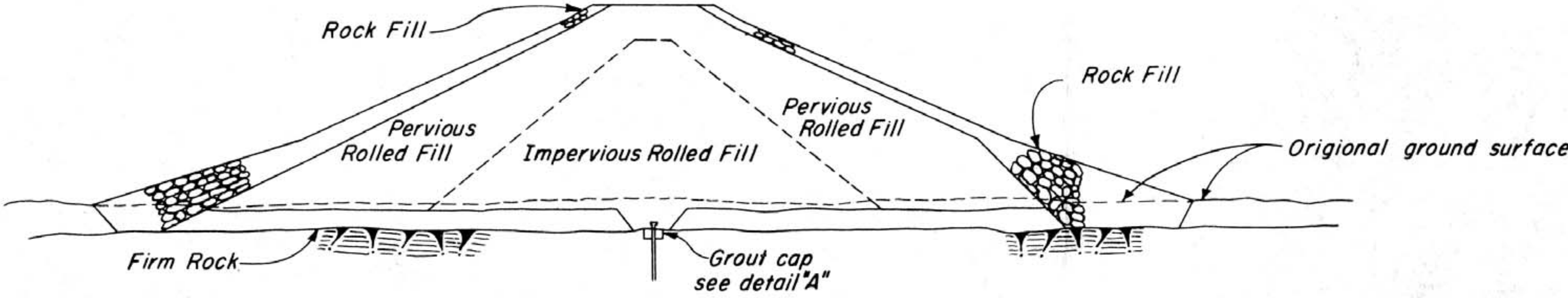


- Casagrande then asserted that the most damaging seepage pressures tend to develop within the foundation rock, the character and fracturing intensity of which is highly variable. This example from his Rankine Lecture shows that seepage through fissured gneiss was able to “bypass” the grout curtain placed beneath the dam’s core and seepage cutoff keyway.

MULTIPLE LINES OF DEFENSE

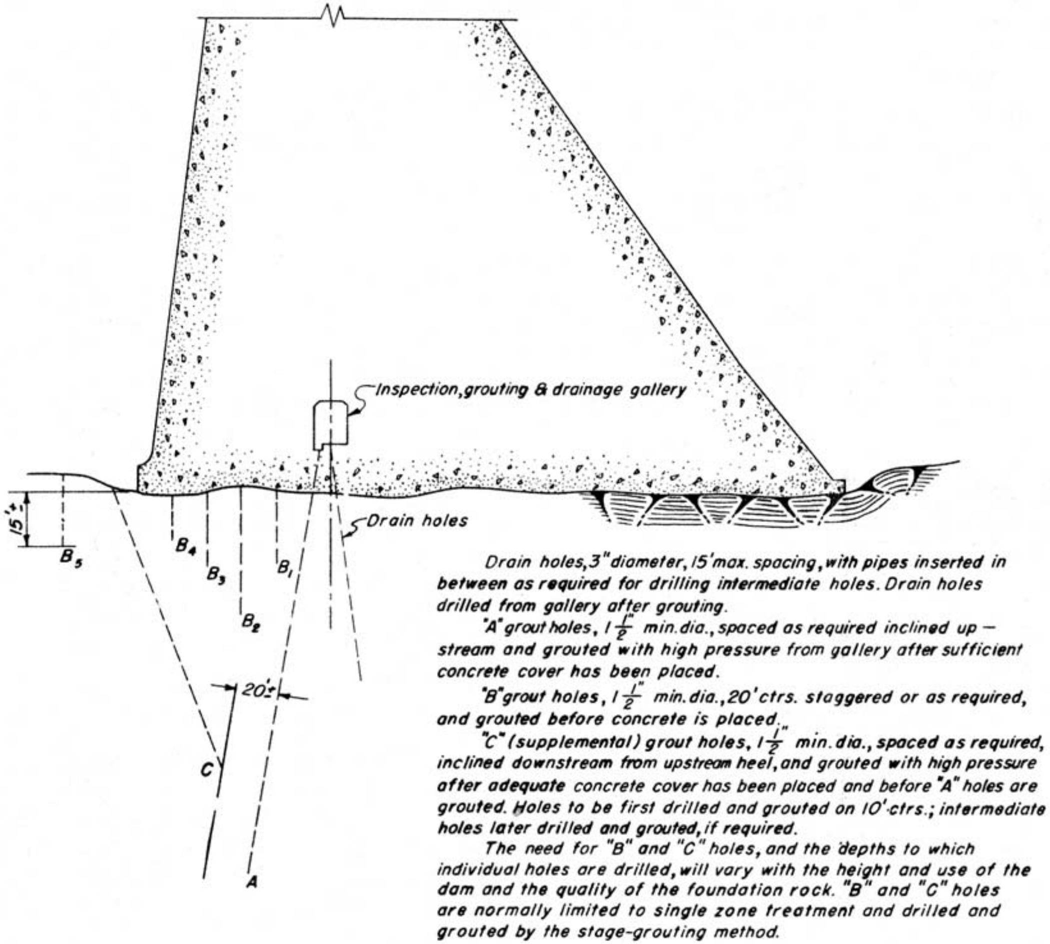
- **Casagrande went onto to assert that grout curtains may not have a significant influence on the seepage conditions, i.e. they cannot be implicitly trusted to eliminate seepage flow beneath or around a dam. Karl Terzaghi responded to the lecture, writing: "if a grout curtain fails to serve its purpose *<u>the second line of defense, drainage, becomes the only line of defense</u>*" (underling his quote of Casagrande's words)**

CUTOFFS AND GROUT CURTAINS



TYPICAL EMBANKMENT SECTION

- **By the late 1940s it was standard practice to equip embankment dams with a seepage cutoff trench and a grout curtain**
- **This shows example from Corps of Engineers *Manual on Foundation Grouting*, released in April 1949 (EM 135-1-4)**



Drain holes, 3" diameter, 15' max. spacing, with pipes inserted in between as required for drilling intermediate holes. Drain holes drilled from gallery after grouting.

"A" grout holes, $1\frac{1}{2}''$ min. dia., spaced as required inclined upstream and grouted with high pressure from gallery after sufficient concrete cover has been placed.

"B" grout holes, $1\frac{1}{2}''$ min. dia., 20' ctrs. staggered or as required, and grouted before concrete is placed.

"C" (supplemental) grout holes, $1\frac{1}{2}''$ min. dia., spaced as required, inclined downstream from upstream heel, and grouted with high pressure after adequate concrete cover has been placed and before "A" holes are grouted. Holes to be first drilled and grouted on 10' ctrs.; intermediate holes later drilled and grouted, if required.

The need for "B" and "C" holes, and the depths to which individual holes are drilled, will vary with the height and use of the dam and the quality of the foundation rock. "B" and "C" holes are normally limited to single zone treatment and drilled and grouted by the stage-grouting method.

DETAIL OF MULTIPLE LINE CUT-OFF

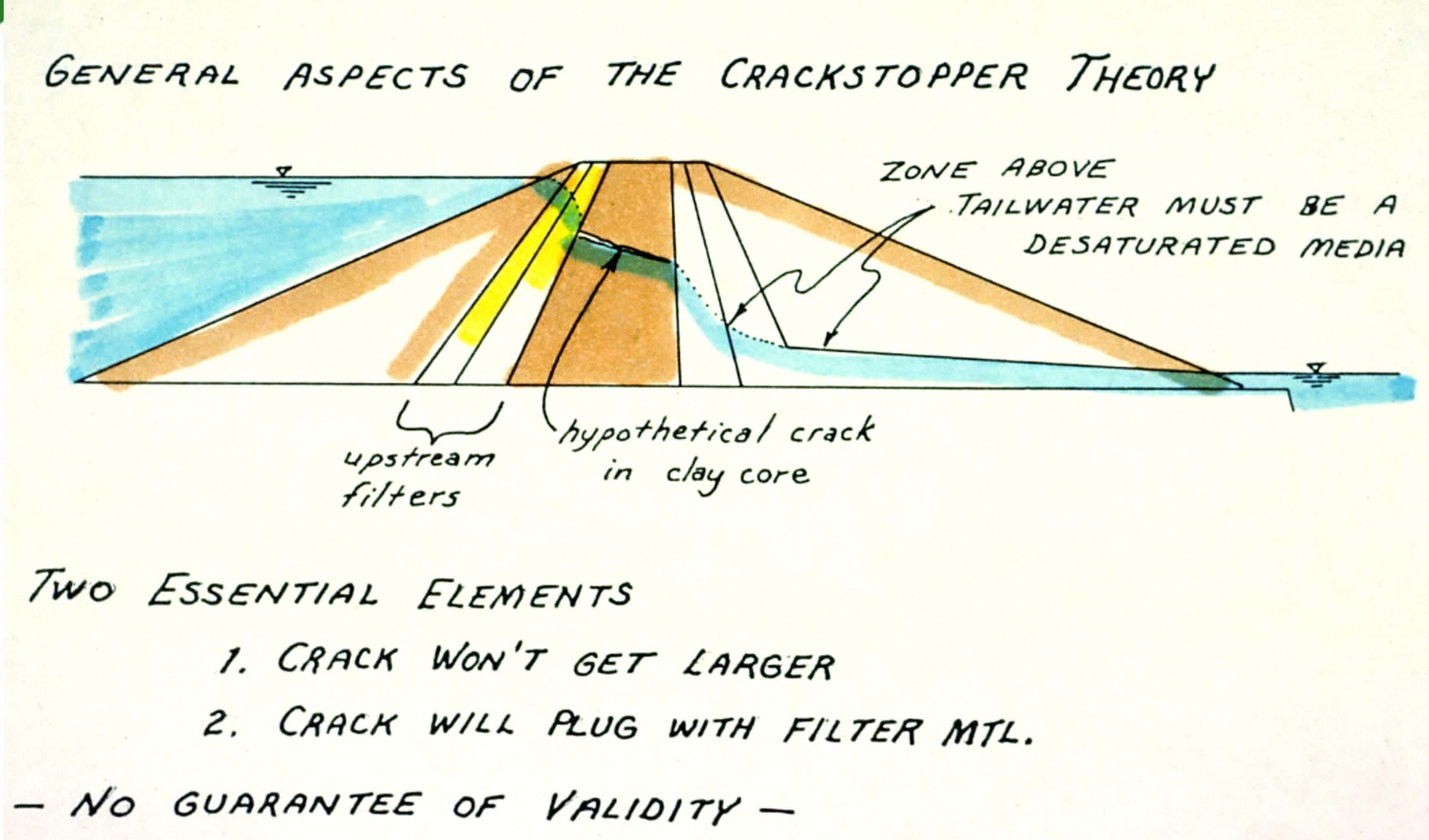
- **One of Casagrande's conclusions in his Rankine Lecture was: "Excessively pervious zones for which grouting will be considered necessary or desirable, may require three rows of closely spaced grout holes, or equivalent clusters of grout holes, in order to create the necessary width of the grouted rock mass.**
- **Drawing at left shows three rows of grout holes from Corps of Engineers standards released in 1949**

HYDRAULIC PIPING

- Darcy’s Law predicts that under normal conditions, the volume of water that flows through a porous medium increases in direct proportion to the hydraulic head
- Terzaghi (1929) asserted that the moment that the seepage pressure becomes equal to the force of gravity (effective stress), the discharge increases abruptly, because soil particles begin to be lifted apart and dispersed.

CRITICAL HYDRAULIC GRADIENT

- **Terzaghi defined the critical hydraulic gradient as that value of pressure head which equals the ratio between effective normal stress acting on the soil and the pore water pressure. When these values become equal, the effective stress becomes zero because the seepage pressure equals the submerged weight of the soil.**
- **The percolating water can then lift particles of soil into suspension and transport them.**
- **This process is known as hydraulic piping**



GENERAL ASPECTS OF THE CRACKSTOPPER THEORY

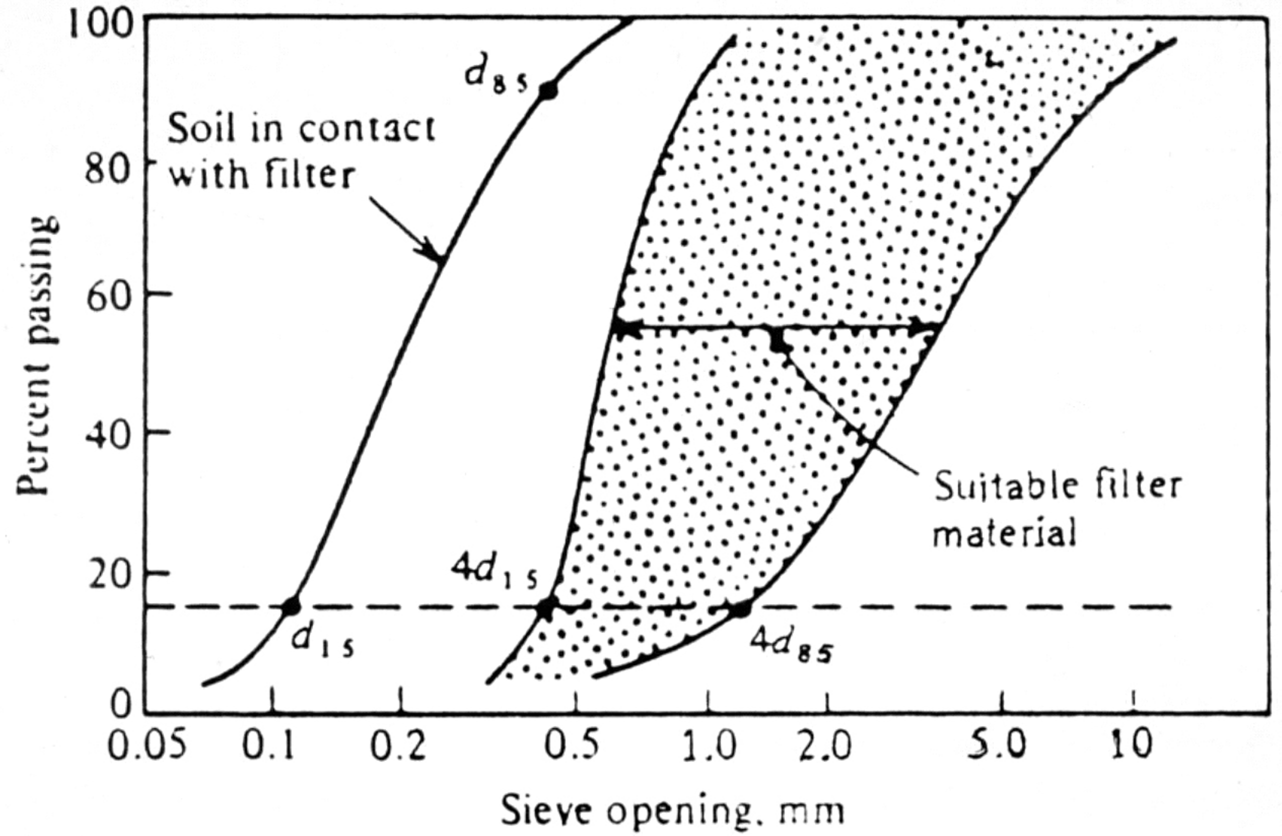
TWO ESSENTIAL ELEMENTS

1. CRACK WON'T GET LARGER
2. CRACK WILL PLUG WITH FILTER MTL.

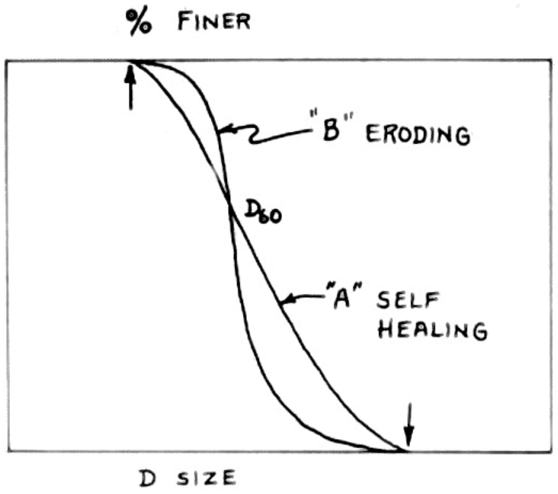
— NO GUARANTEE OF VALIDITY —

- **Graded filters** are intended to restrict the migration of fines on either side of the impervious clay core of an embankment dam

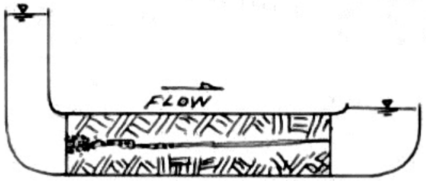
GRADED FILTER CRITERIA



- **Filtration criteria were initially explored by Terzaghi in 1922, then refined by experiments of the Bureau of Reclamation, published in 1947 (shown here). The purpose of filters is to prevent migration of soil particles under a positive hydraulic gradient; a process referred to as ‘hydraulic piping”.**



COULD SIMPLY BE DUE TO PARTICLE SEGREGATION DURING HANDLING AND EMPLACEMENT



TYPE "A"
- enough of the coarser range

TYPE "B"
- not enough of the coarser range

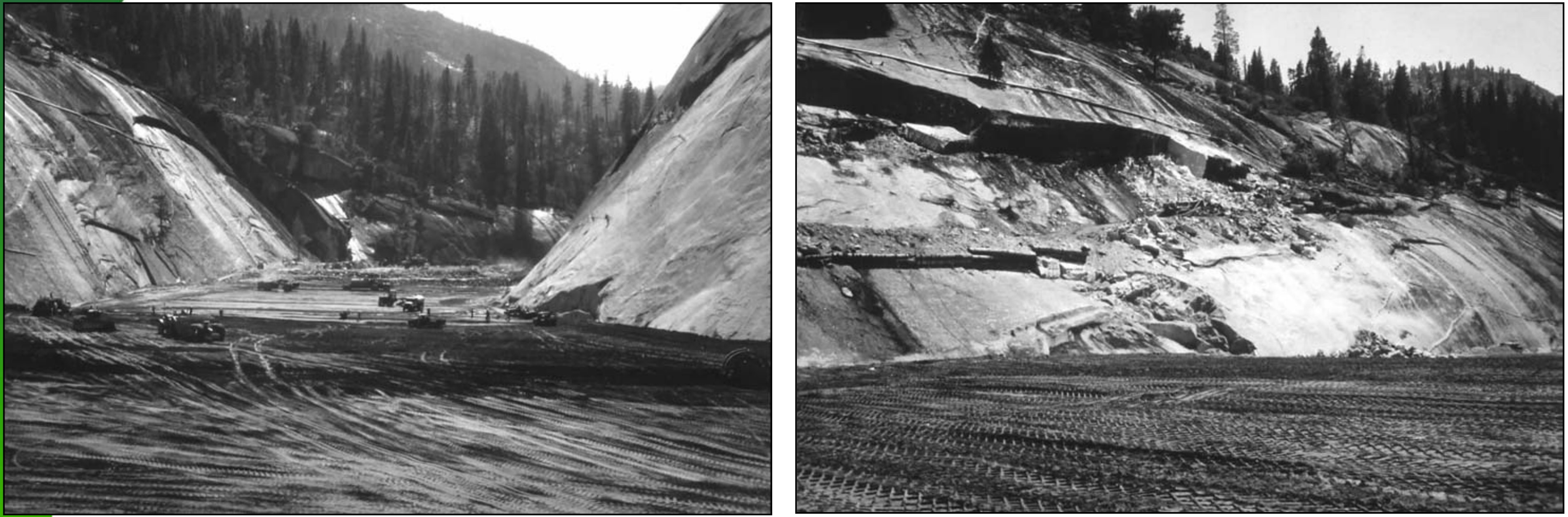
- model after PYLES and ROGERS

Long term seepage questions
- Types of adsorbed ions in pore water of core
- chemistry of reservoir water

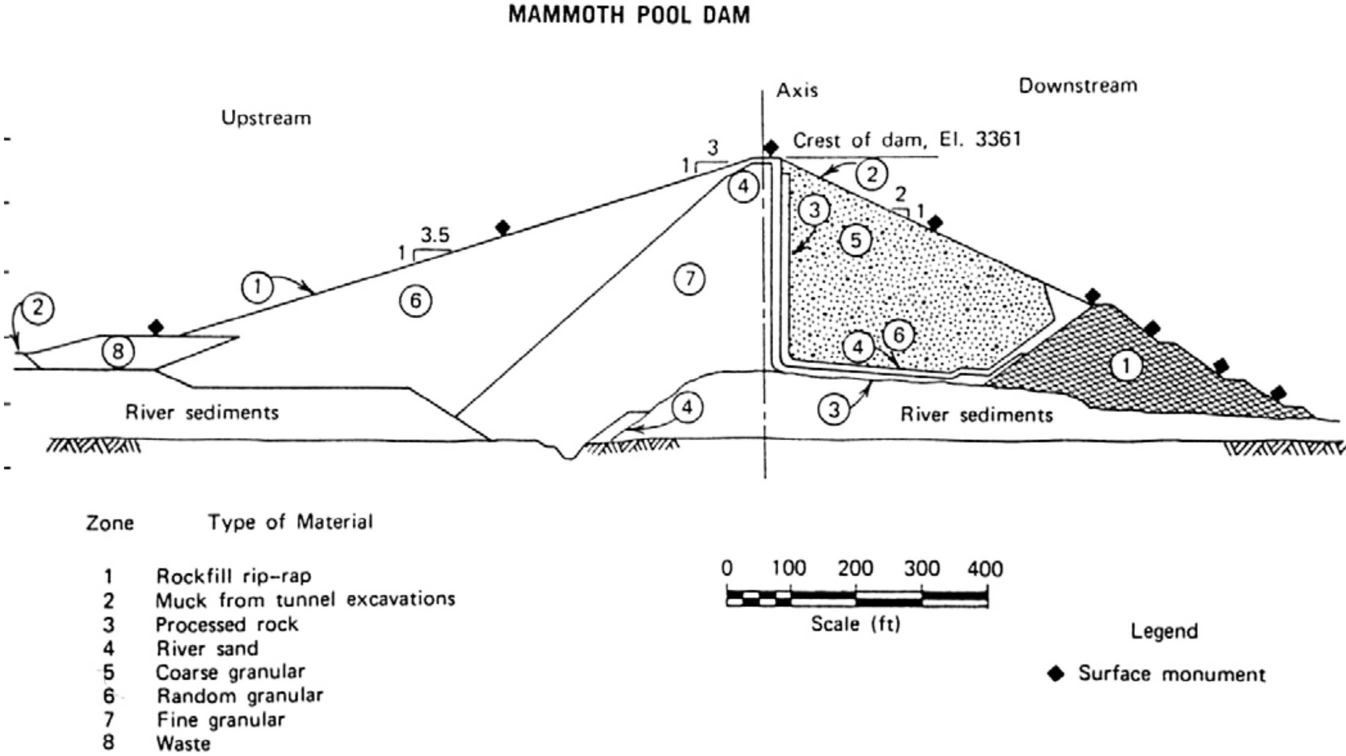
osmotic gradients ⇒ increased erosion & dispersion

- Hydraulic piping sometimes occurs because filter materials are "gap graded" (most of the material being of one particle size), instead of being well graded (an assortment of particle sizes)

A FEW CASE STUDIES of HYDRAULIC PIPING



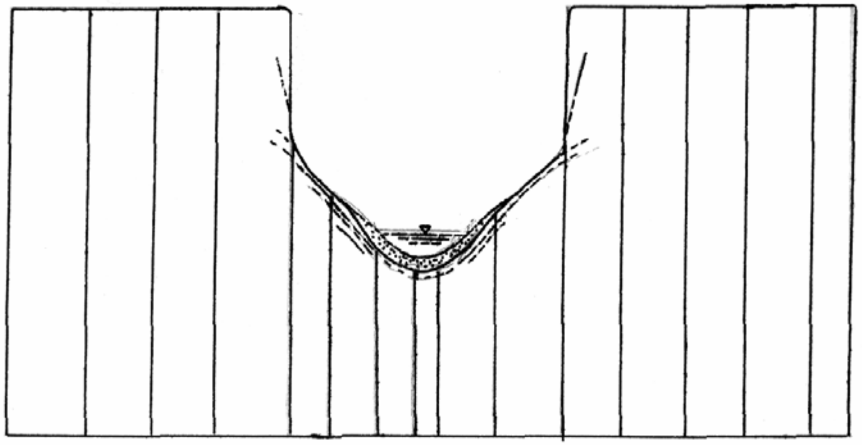
- When **Mammoth Pool Dam** was being constructed in the late 1950s along the San Joaquin River in California’s Sierra Nevada Mountains, the builders encountered valley-side sheet joints which kept opening up as the abutments were excavated, through-going creating voids in the abutments.
- As these blocks were excavated, new sheet joints formed beneath the abutments. Reservoir seepage could pass through these open joints without significant head loss.



Zone	Type of Material
1	Rockfill rip-rap
2	Muck from tunnel excavations
3	Processed rock
4	River sand
5	Coarse granular
6	Random granular
7	Fine granular
8	Waste

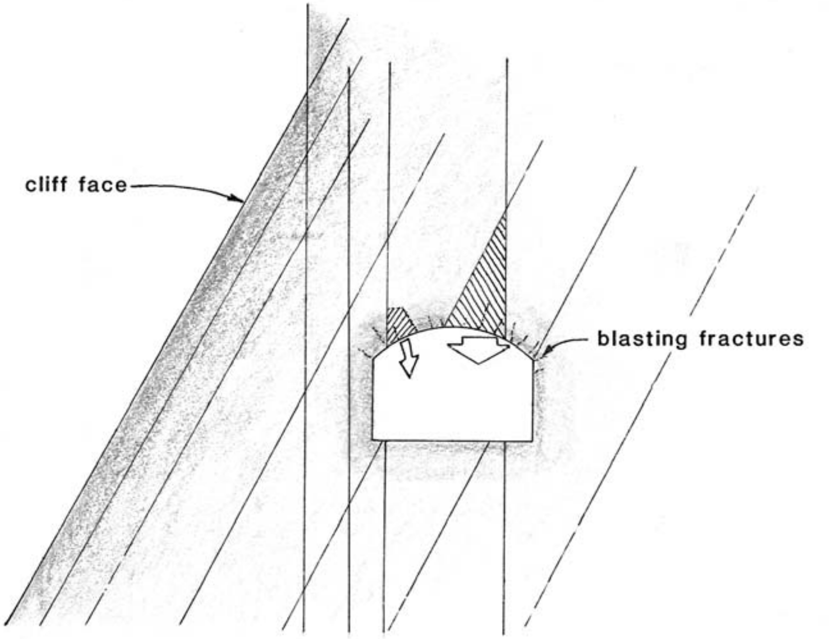
- **Terzaghi was brought in as a consultant on Mammoth Pool Dam. He recommended grouting the open sheet joints in the abutments after the dam was complete and added a massive rockfill rip rap toe to the embankment, as well as zoned chimney and blanket drains downstream of the core. These were intended to decant any excess seepage through the abutments.**

BATTLING VALLEY-SIDE JOINTS AT GLEN CANYON DAM

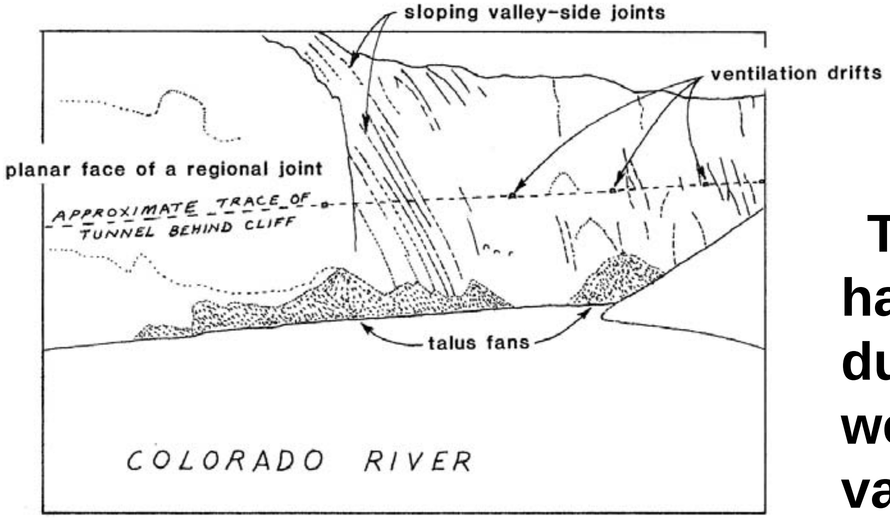


- The Glen Canyon damsite has prominent haunches formed by curvalinear valley- side joints.
- The upper vertical walls are controlled by regional systematic joints in the massive Navajo Sandstone.

GLEN CANYON TUNNEL FAILURE

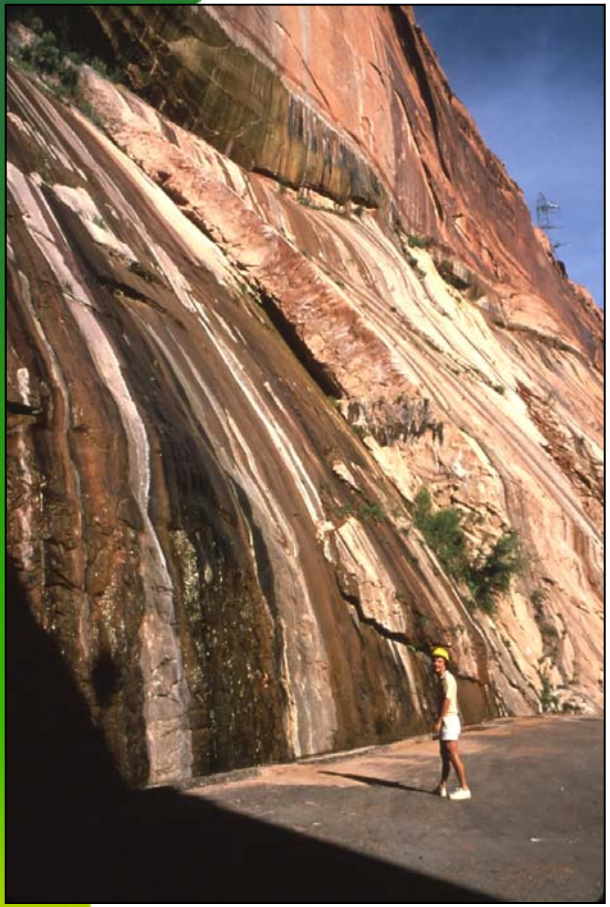


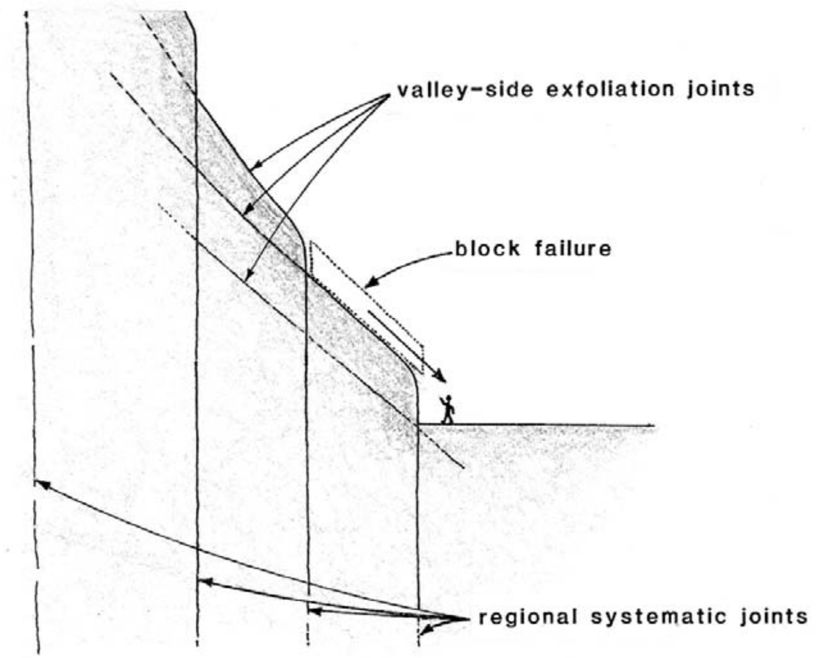
Roof cave-ins in the Glen Canyon Powerplant Service Tunnel during construction in 1958.



The Glen Canyon Powerplant Tunnel had a series of deadly block failures during excavation in 1958 because of wedges formed between inclined valley side and systematic joints, as sketched above.

BLOCK FAILURES at GLEN CANYON DAM





Valley side joints are usually inclined. Where these intercept near vertical systematic joints, massive blocks are formed on steep inclines. When these are undercut the blocks slide off. A little bit of water hastens the process by decreasing the friction markedly.

Rockbolts Used at Glen Canyon Dam

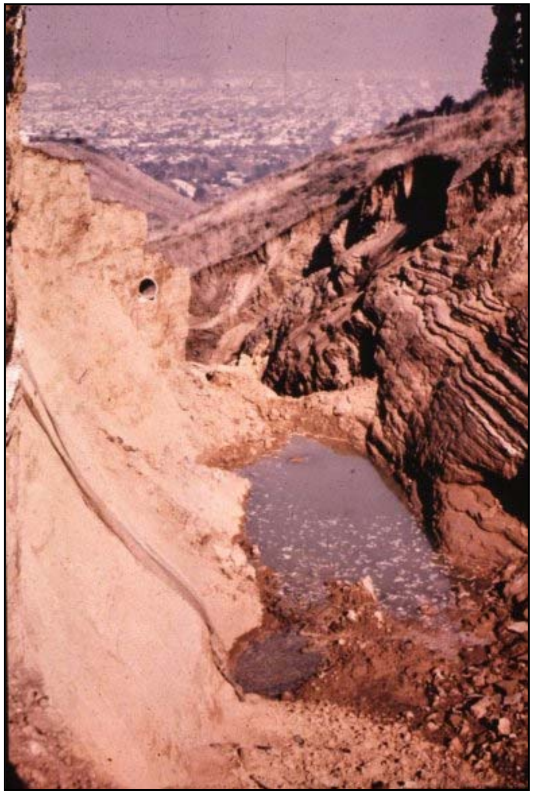
- 1500 post-tensioned rockbolts were employed at Glen Canyon Dam in 1960-61 to secure valley-side sheet joints. Seepage averaged over 5500 gpm on each abutment.

BALDWIN HILLS RESERVOIR

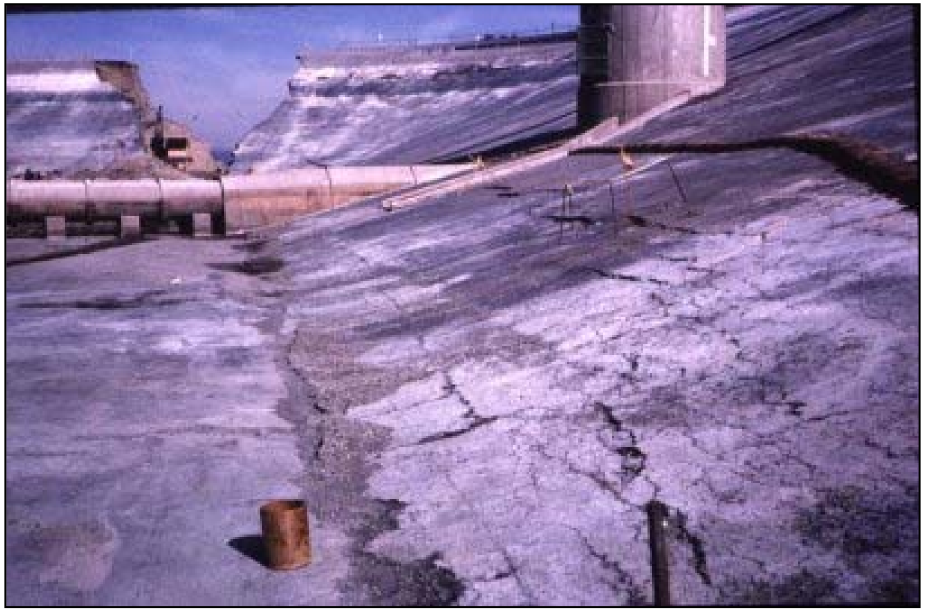
- Baldwin Hills Reservoir was an offstream municipal reservoir designed and built by the Los Angeles DWP in 1947-54. Its design capacity was 897 acre-feet. The grading volume was 859,000 yds^3
- On Saturday December 14, 1963 the caretaker noticed an unusual sound of water at the spillway intake, beginning around 11:15 AM
- By noon a DWP engineer was summoned and all outlets and inlets were opened to drain the reservoir of 738 ac-ft of water in storage. It would have taken 24 hrs to drain the entire reservoir

LIVE TELEVISION COVERAGE

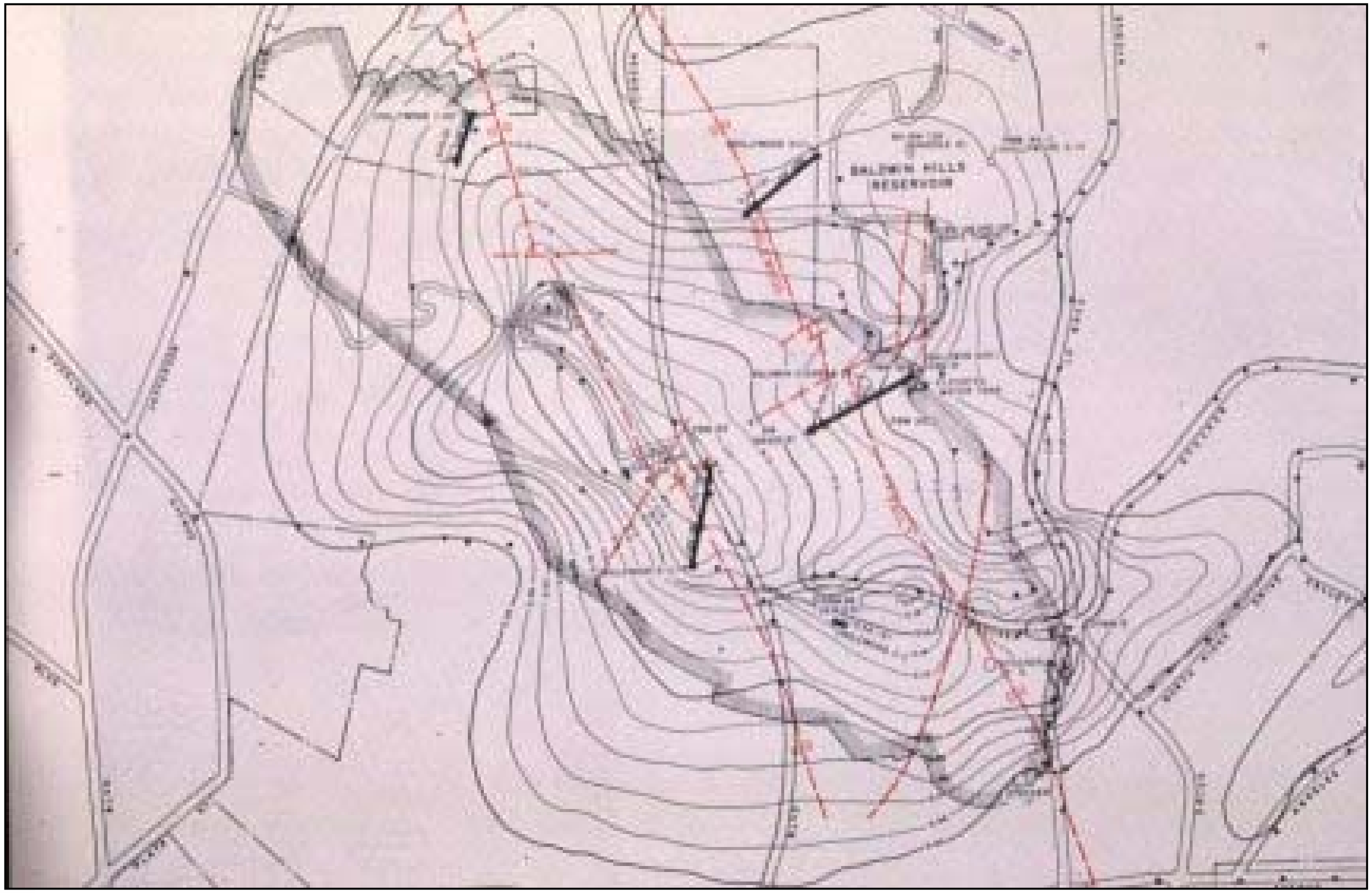
- Police and media were alerted shortly after noon that a failure was imminent and a full evacuation was ordered.
- At 3:38 PM a complete breach of the south embankment occurred, with increasing discharge spilling up to 4,300 cfs
- The flow spilled down a steep ravine towards Cloverdale Ave., destroying 41 and damaging 986 homes, and killing 6
- The failure was shown live on local television stations



- The outflow lasted 77 minutes, till 4:55 PM
- Afterwards, the eroded chasm was 90 feet deep and 70 feet wide, curiously dry in appearance afterwards (right)
- The water had leaked through joints in the abutment rock of the underlying Pico Formation (shown at right), first noted at the downstream face/abutment contact, 82 feet below crest.



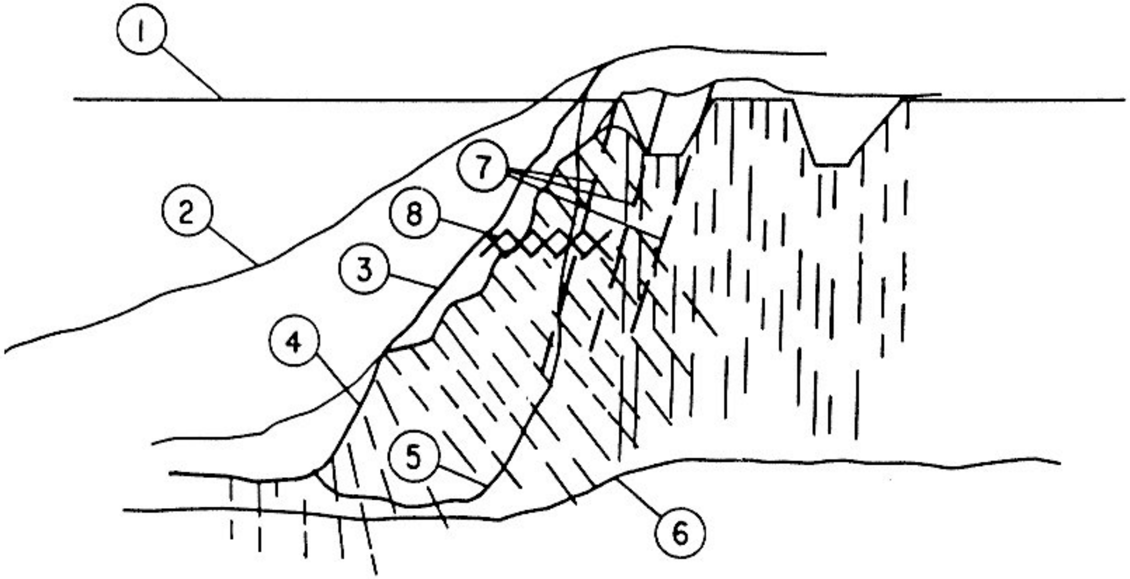
- **The eroded chasm extended into the reservoir floor along a linear north-south trend (left)**
- **Subsequent examination revealed an active fault scarp extending through the reservoir floor, shown in right view**
- **Up to 12 inches of vertical offset was noted along four strands of this fault exposed in the reservoir floor, diminishing towards the southerly side of the reservoir. The fault dipped 70 degrees west**



- A map showing faults and measured ground subsidence in the Inglewood Oil Field suggests that petroleum withdrawal over the previous 20+ years likely triggered movement along the short fault strand that extended through the reservoir area, precisely where the seepage ocurred. A little over 1.5 feet of subsidence was measured during the brief 9-year life of the reservoir!

- **Fontenelle Dam** was constructed by the US Bureau of Reclamation on the Green River in Wyoming in 1960-63, with a single line grout curtain. In September 1965 a serious piping failure occurred on the right abutment, with reservoir water percolating along valley-side sheet joints in the sandstone (with only 46 feet of head). The dam came dangerously close to failing.

Right Abutment of Fontinelle Dam



Right Abutment Detail.

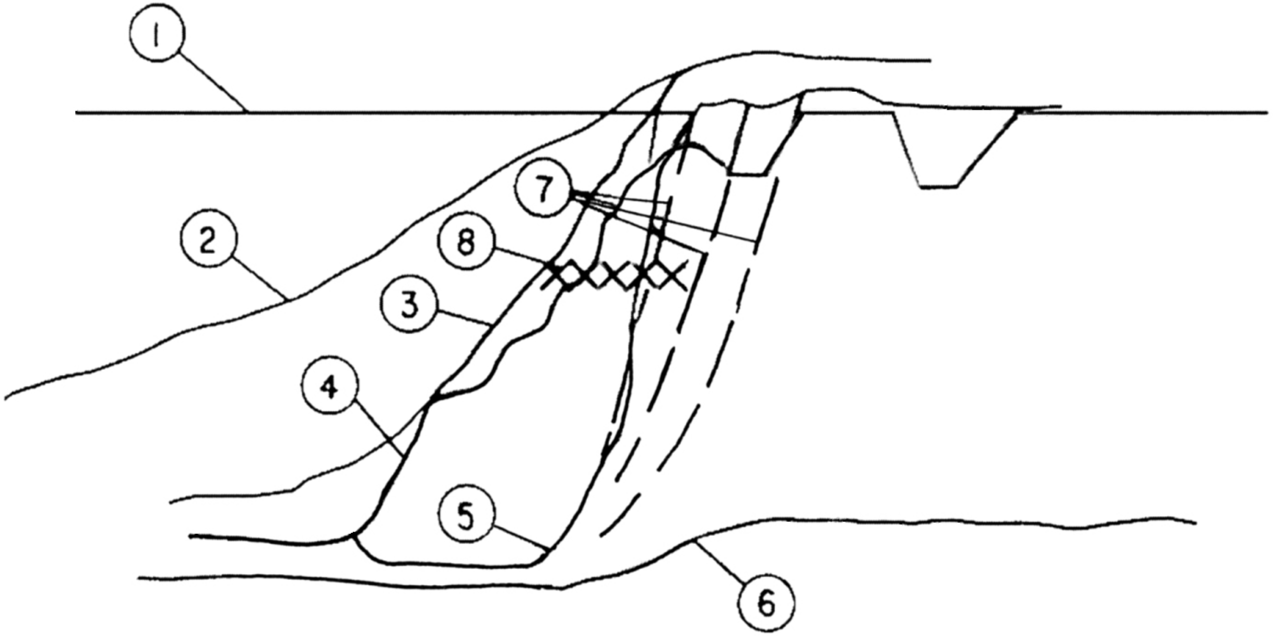
Plan :
(A) Embankment.
(B) Spillway.
(C) Canal outlet.
(D) Road.
(E) September 3, 1965, leakage and slough.
(F) Open cracks.

Section :
(1) Dam crest.
(2) Downstream abutment slope.
(3) Abutment slope at dam centerline.
(4) Bedrock surface at dam centerline.
(5) Upstream abutment slope.
(6) Lower limit of grout acceptance.
(7) Open cracks.
(8) Approximate location of leak.

- **After the piping failure the right abutment area was excavated, revealing a series of inclined valley-side joints**

- **Valley-side joints can occur in sedimentary rock!!**

FONTENELLE DAM REPAIRS



- **The seepage that almost caused the dam's failure percolated along undiscovered valley-side joints (#7) in bedded sedimentary rocks at position #8**
- **8 lines of grout holes were then drilled and filled with 203,500 sacks of cement**

- **Fontinelle Dam** performed admirably following the near catastrophe in 1965. A decade later, the same kind of hydraulic piping failure occurred in the right abutment of Teton Dam, also during initial filling.