11th PURDUE GEOTECHNICAL SOCIETY WORKSHOP

Important Role of Filters in Hydraulic Soil Structures

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Apr. 19, 2013

Outline

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Introduction – **Importance of Piping Erosion**

Overall failure statistics for large embankment dams up to 1986, excluding dams constructed in Japan pre-1930 and in China (Foster et al., 2000)

Mode of failure	No. of cases: All failures	No. of cases: Failures in operation	% failures (where known): All failures	% failures (where known): Failures in operation	Average frequency of failure ($\times 10^{-3}$): All failures	Average frequency of failure ($\times 10^{-3}$): Failures in operation
Overtopping and appurtenant						
Overtopping	46	40	35.9	34.2	4.1	3.6
Spillway–gate	16	15	12.5	12.8	1.4	1.3
Subtotal	62	55	48.4	47.0	5.5	4.9
Piping						
Through embankment	39	38	30.5	32.5	3.5	3.4
Through foundation	19	18	14.8	15.4	1.7	1.6
From embankment into foundation	2	2	1.6	1.7	0.18	0.18
Subtotal	59	57	46.1	48.7	5.3	5.1
Slides						
Downstream	6	4	4.7	3.4	0.54	0.36
Upstream	1	1	0.8	0.9	0.09	0.09
Subtotal	7	5	5.5	4.3	0.63	0.45
Earthquake–liquefaction	2	2	1.6	1.7	0.18	0.18
Unknown mode	8	7				
Total no. of failures	136	124			12.2 (1.2%)	11.1 (1.1%)
Total no. of failures where mode of failure known	128	117				
No. of embankment dams	11 192	11 192				

Brief History – **Filter Design Criteria**

- As the first recommendation on grain size distribution of the filters, in a consulting report for the proposed Granville storage dam at Westfield, Mass, Terzaghi (1926) states that:

  "*To prevent the finer particles of the downstream section of the dam from being washed out through the downstream toe, a filter should be provided between the dam proper and the toe. The effective size of the filter should not exceed ten times the average grain size of the dam construction material.*", or:

$$D_{10f} < 10D_{50b}$$

Photo from NGI, Norway

Brief History - **Filter Design Criteria**

- Later, during the design of Bou-Hanifia rockfill dam in Algeria, Terzaghi (1935) established the well-known empirical filter rules, which was the base for all the later filter design regulations:

$$D_{15f} < 4D_{85b}\text{ , retention}$$

$$D_{15f} > 4D_{15b}\text{ , permeability}$$

- Sherard and Dunnigan (1985) carried out extensive laboratory testing in United States Soil Conservation Service (USSCS) to check filter criteria. Based on these tests, they recommended a comprehensive filter design criterion which became the main basis for design and construction of filters in practice.

Brief History - **Filter Design Criteria**

- The Sherard and Dunnigan (1985) criterion was also accepted and recommended by US Army Corps of Engineers and International Commission of Large Dams – ICOLD (Bulletin 95, 1994), as the main filter design criterion.
- There are other filter design methods such as Kenney and Lau (1985), Vaughan and Soares (1982), Lafleur et al. (1993), and Foster and Fell (1999).
- There are other factors affecting filter design, including permeability, segregation, and grain size distribution properties.

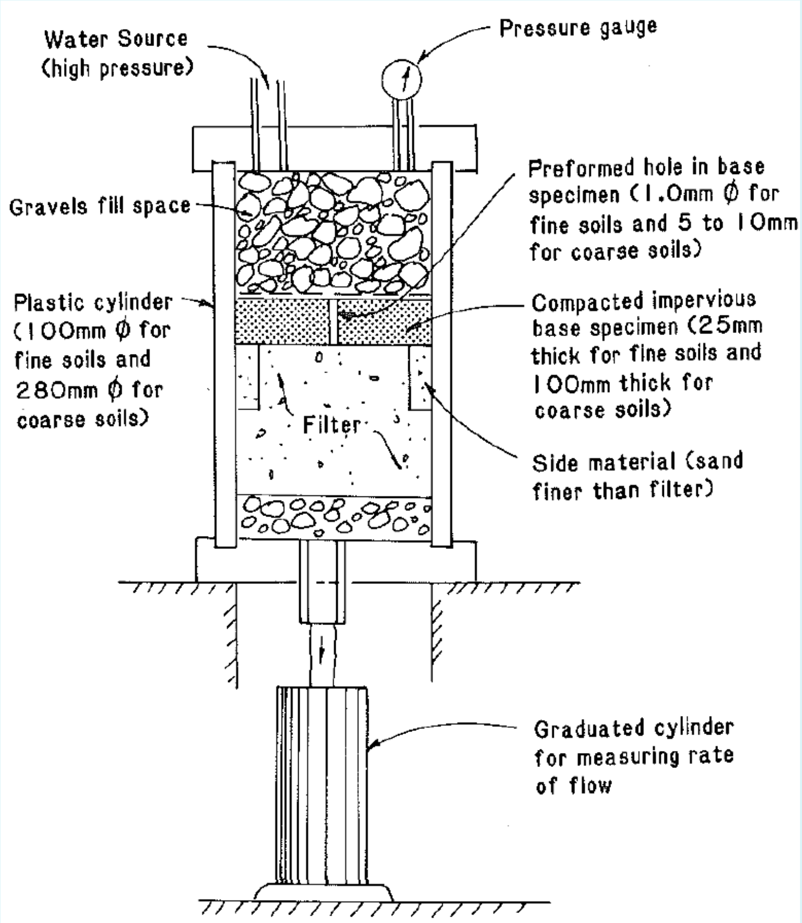
Design Considerations

- In practice, the Sherard and Dunnigan (1985) criterion is usually considered conservative enough for design of filter in major hydraulic structures such as zoned embankment dams.
- In case that the available filter material does not meet this criterion, or for exceptionally important structures, suitability of the filter material is checked by special tests, such as No Erosion Filter (NEF) test (Sherard and Dunnigan, 1989).

Filter retention criteria (Sherard and Dunnigan, 1985)

Base soil category	Base soil description, and percent finer than No. 200 (0.075 mm) sieve[1]	Filter criteria in terms of maximum D_{15} size[2]	Note
1	Fine silts and clays; more than 85% finer	$D_{15} \leq 9 \times d_{85}$	(1)
2	Sands, silts, clays, and silty and clayey sands; 40 to 85% finer.	$D_{15} \leq 0.7$ mm	
3	Silty and clayey sands and gravels; 15 to 39% finer	$D_{15} \leq \frac{40-A}{40-15}$ {((4 x d_{85})- 0.7 mm} + 0.7 mm	(2),(3)
4	Sands and gravels; less than 15% finer.	$D_{15} \leq 4$ to $5 \times d_{85}$	(4)

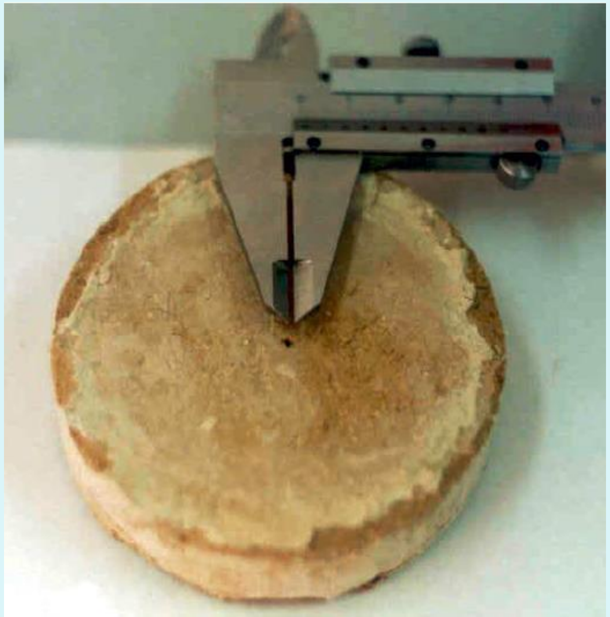
Design Considerations – **NEF Test**



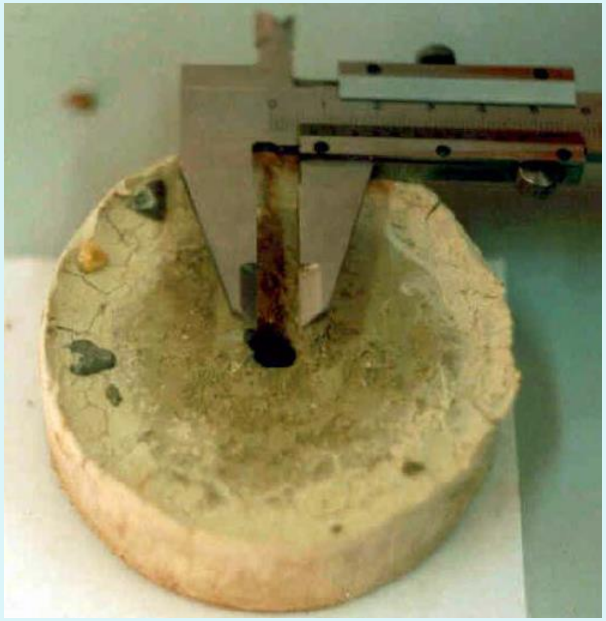
NEF test (Sherard and Dunnigan, 1989)

NEF test facility

Design Considerations – **NEF Test**



(a)



(b)

(c)

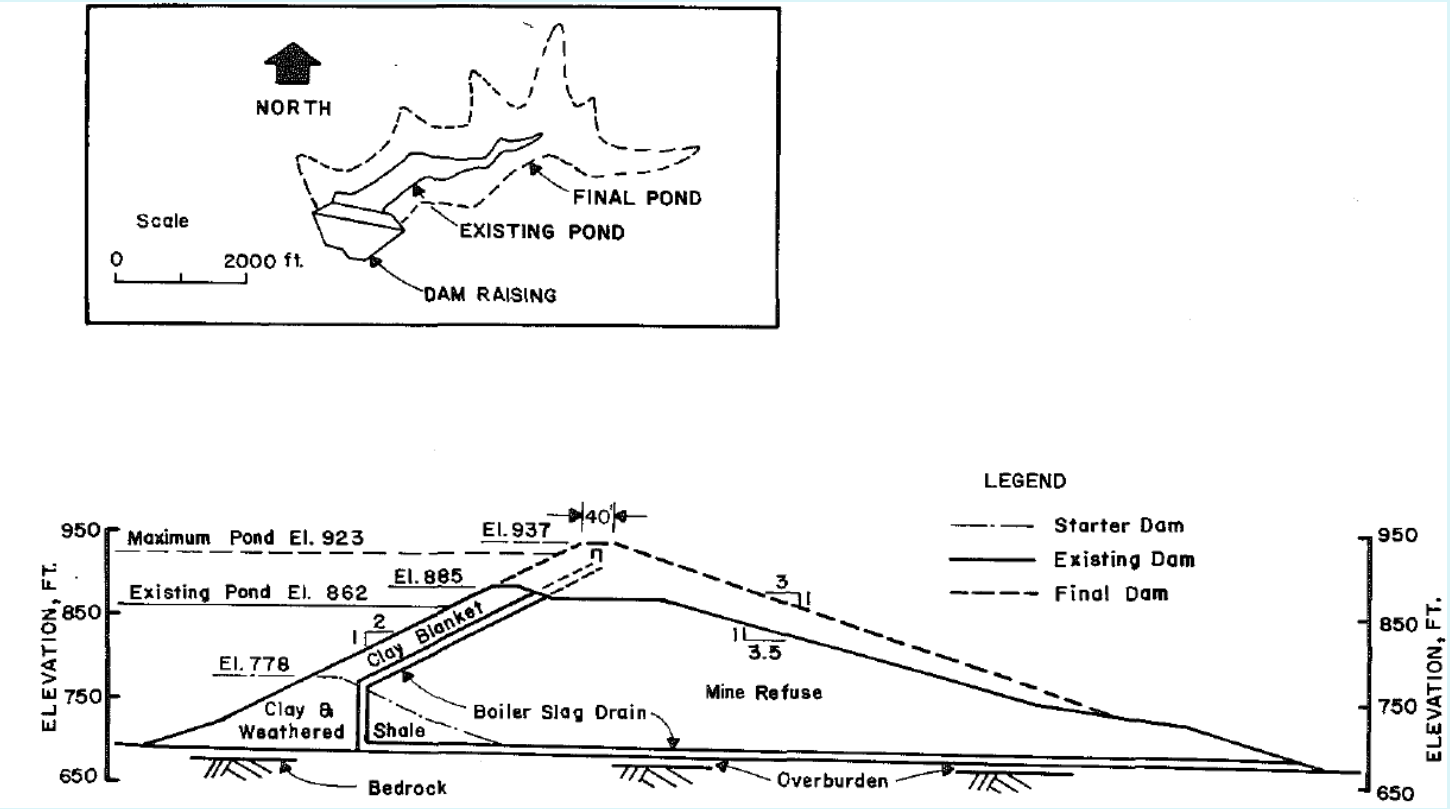
NEF test results (Yasrobi and azad, 2006):

(a) Base soil after successful test,

(b) Base soil after unsuccessful test,

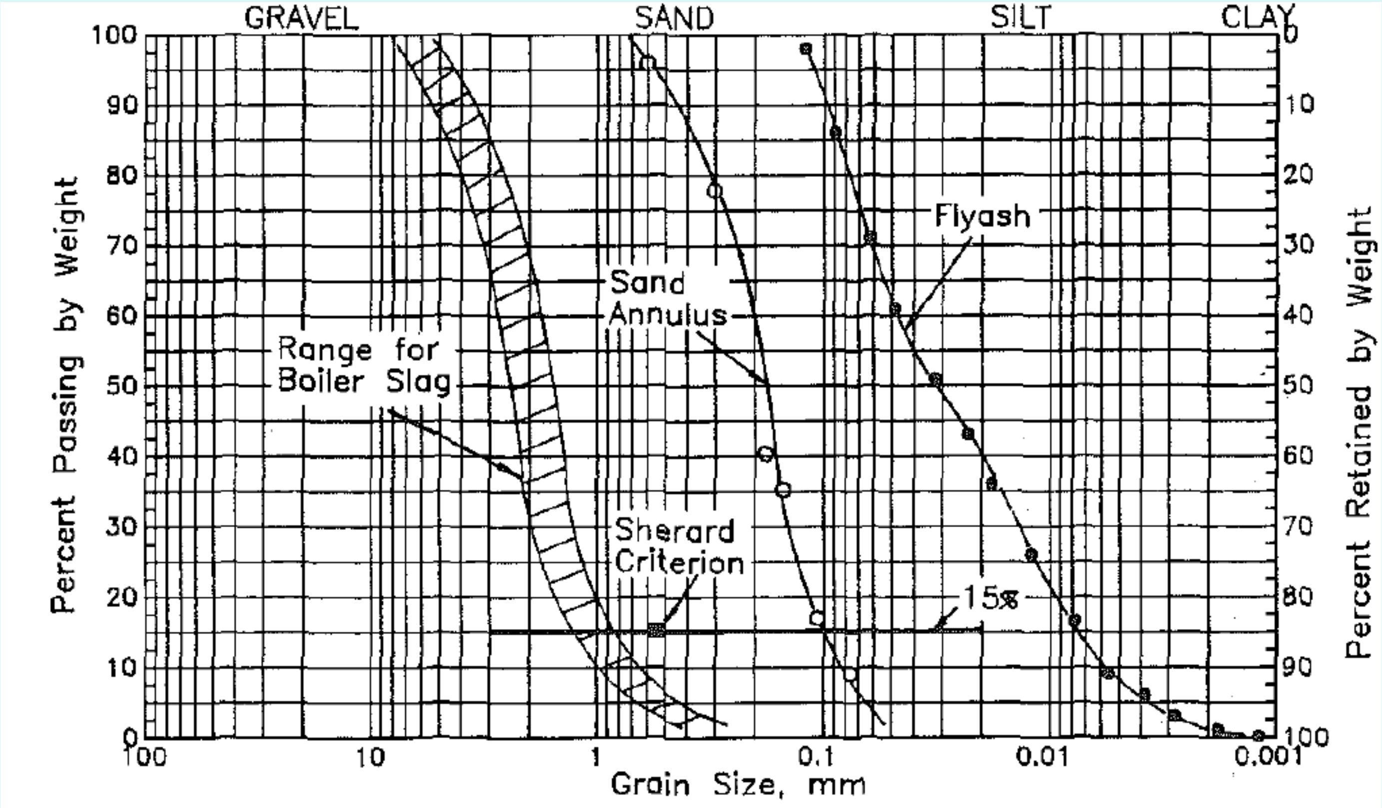
(c) The output water for 4 minutes.

Case History: **Conner Run Dam (Leonards et al., 1991)**



- A storage dam 190 ft high in West Virginia, to impound fly ash waste slurry
- During design studies for raising the dam, it was discovered that the existing chimney drain (made by boiler slag) did not meet the requirements of current filter criteria (Sherard and Dunnigan, 1985).

Case History: **Conner Run Dam**



- According to Sherard and Dunnigan (1985), the D_{15} of the filter should be less than about 0.5-0.6 mm to prevent internal erosion.
- The boiler slag drain did not meet this requirement with the D_{15} of 0.85 to 3.0 mm.

Case History: **Conner Run Dam**

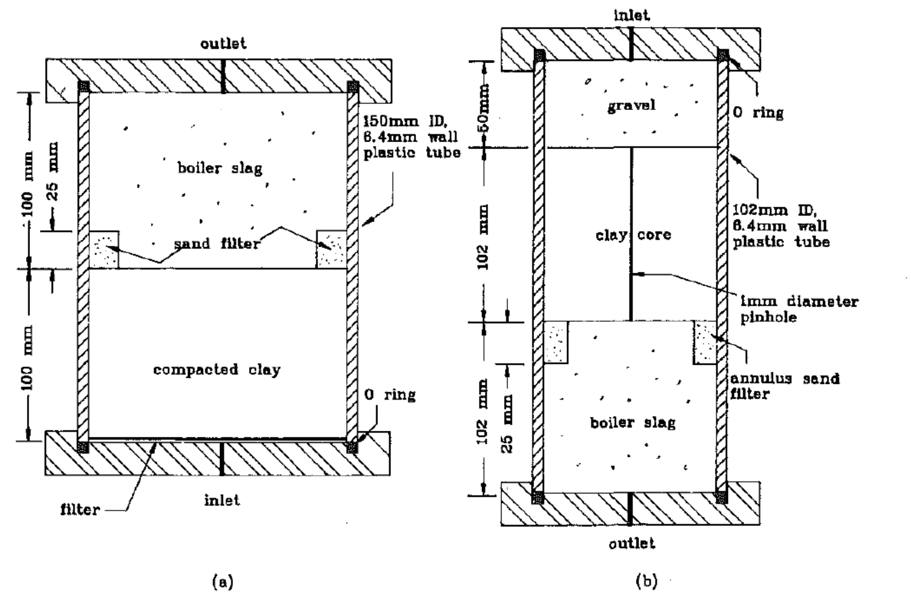
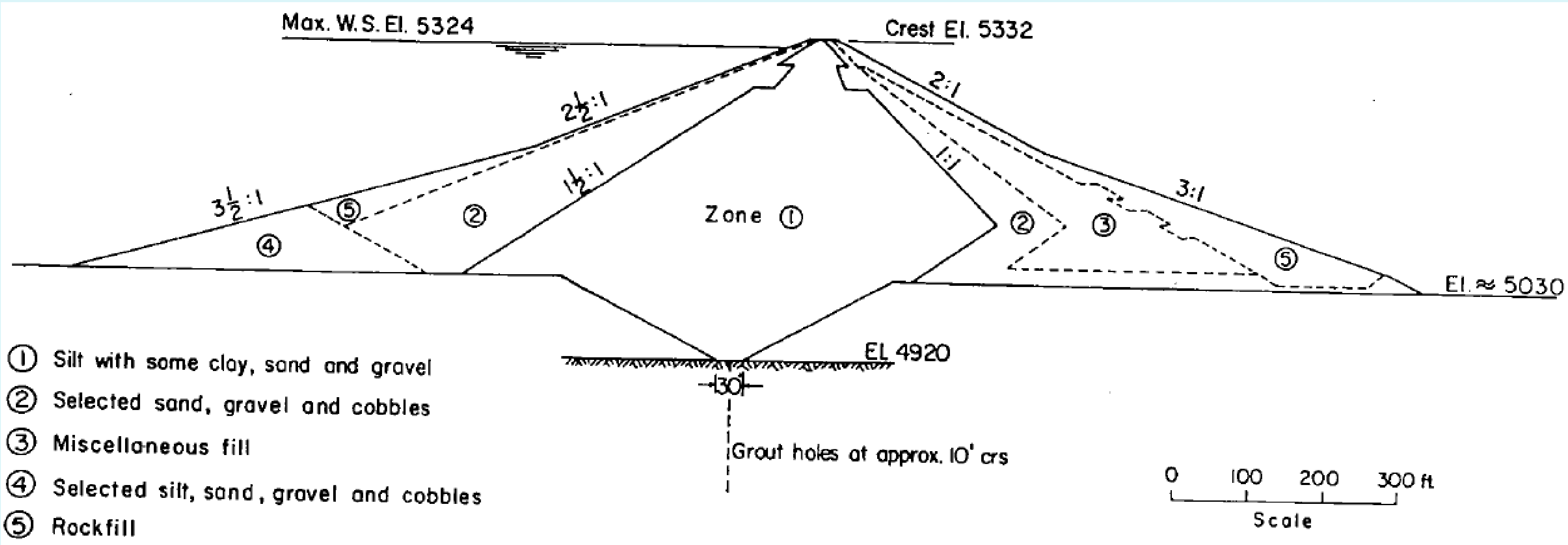


FIG. 4. Schematic Diagrams of Apparatus Used for: (*a*) Piping Tests; (*b*) Pinhole Tests

- In the pinhole tests, internal erosion commenced immediately and the boiler slag filter failed to retain that at upstream water pressures corresponding to 55 m head of water (maximum reservoir level), as expected by the filter criteria.
- No internal erosion was observed in the pinhole tests when fly ash was placed upstream of the clay core, to replicate the fly ash slurry in the reservoir. Therefore, it was concluded that there is no risk of internal erosion with the present reservoir condition.

Case History: **Teton Dam**



- 300 ft high earth dam, construction completed on 1976
- Founded on welded tuff, highly jointed, with joint widths varying typically between ¼ to 3 in., and occasionally up to 12 in. (highly permeable)
- Dam core (Zone 1) constructed with wind-blown silt deposit (available at site)
- Foundation watertight by a key trench and a grout curtain (one line of holes)

Case History: **Teton Dam**

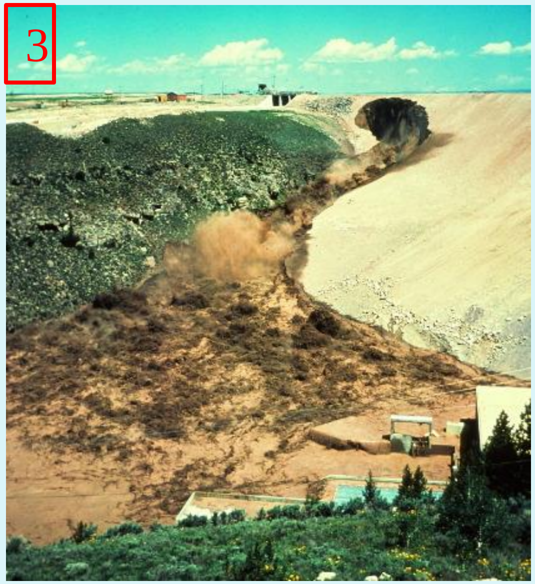
On the failure day (June 05, 1976):

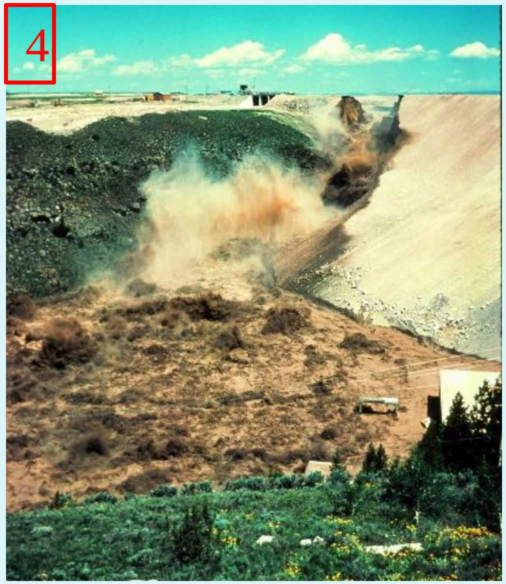
- 7:00 – Water was flowing from d/s face, 130 ft below the crest (about 2 ft^3/s)
- 10:30 – Flow rate increased to 15 ft^3/s, with a loud burst
- 11:20 – The eroded hole was so large that bulldozers sank into the flow.
- 11:55 – Dam crest was breached and complete failure occurred.
- Failure caused 14 losses of life plus ~$1 billion in damage

Main causes of failure (Seed and Duncan, 1981):

- Seepage under the grout cap in unsealed bedrock joints (not covered with filter), leading to erosion and piping failure through the key trench fill
- Piping through cracks caused by hydraulic fracturing or differential settlement

Case History: **Teton Dam**



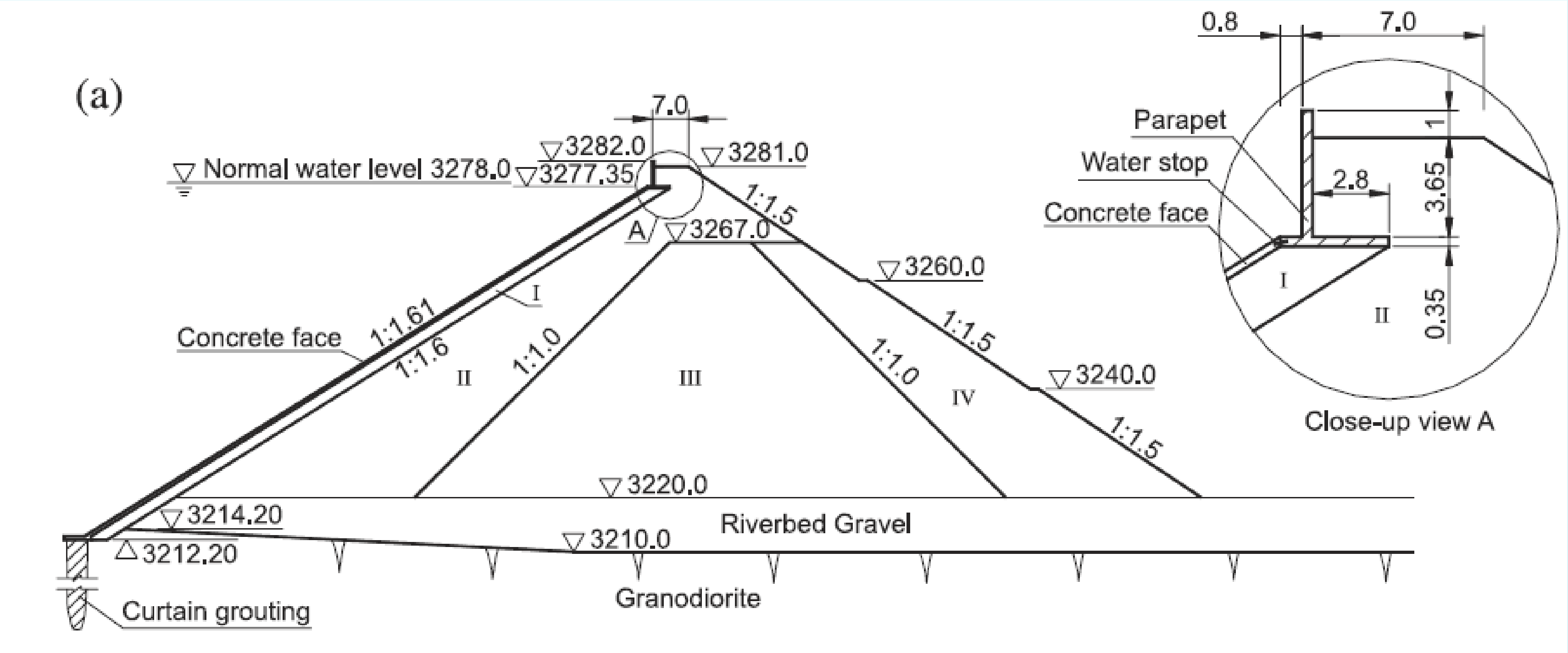


Photos by Mrs. Eunice Olson, 5 June 1976

Case History: **Teton Dam – Lessons Learned**

- Treatment of jointed bedrock underneath high rockfill dams is one of the most critical aspects of safe dam construction.
- Even with a perfect bedrock treatment, a filter cover is essential in case of placing fine core material on a highly jointed bedrock, to prevent movement of the core material into any voids. This is specially important when the core material is potentially erodible, similar to Teton dam.
- Cracks are always likely to occur in the dam core, because of different reasons such as differential settlement. However, role of filter zones is critical in retaining the core particles and avoiding progressive piping erosion leading to dam failure.

Case History: **Gouhou Dam - China**



- Type: concrete face rockfill dam (CFRD)
- Height: 71 m
- Construction completed on 1990
- Zone I: cushion, II: transition, III and IV: rockfill

Case History: **Gouhou Dam**

On the failure day (Aug. 27, 1993):

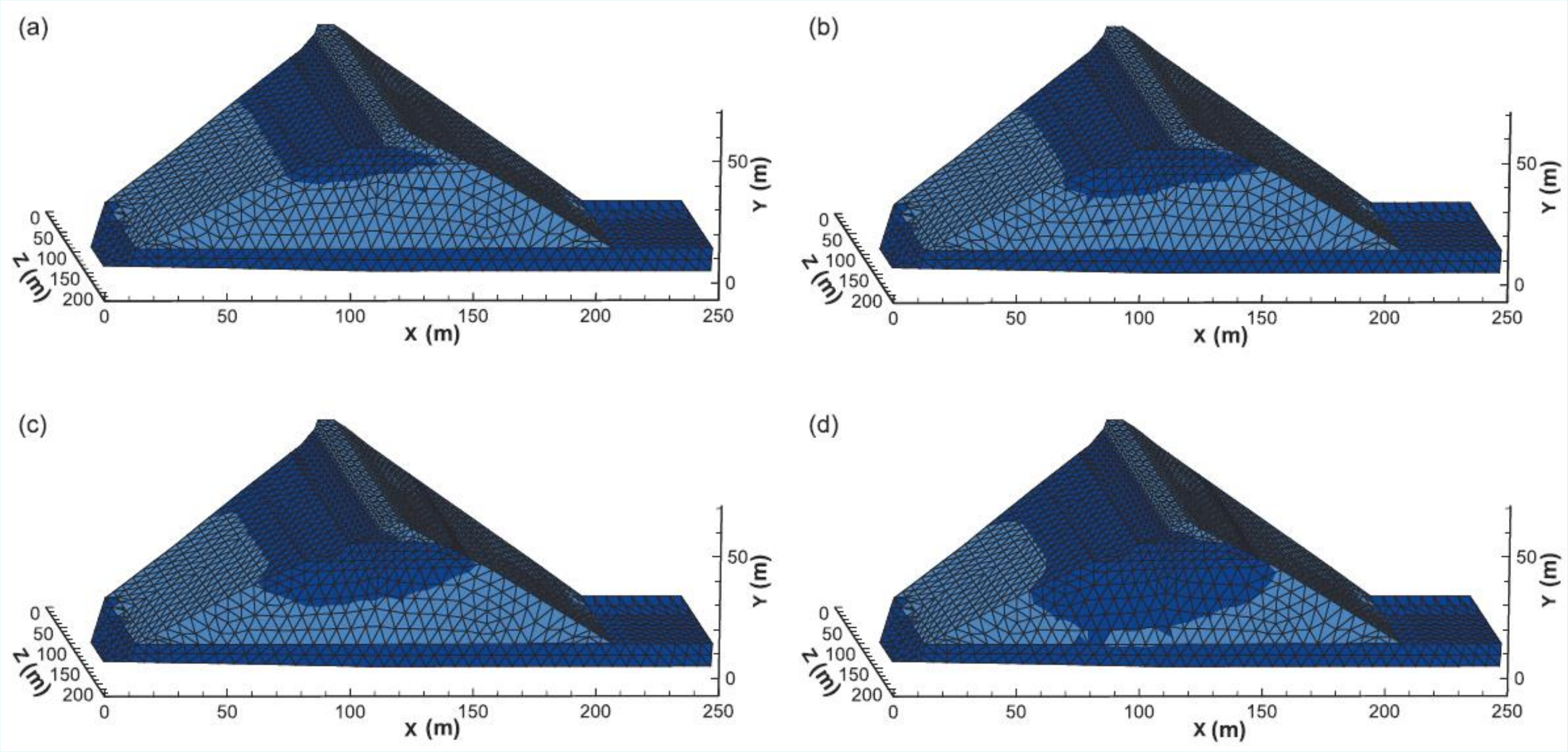
- 12:00 – water level reached to El. 3277.30 m (0.7 m below NWL) for the first time – water started flowing into the dam, from the parapet wall-concrete face joint.
- 20:00 – seeped water was observed on d/s slope, El. 3260.00
- 21:00 – protection stones started rolling down.
- 22:40 – dam breached
- Loss of life: 288

Zhang and Chen (2006)

Main causes of failure:

- Defective parapet wall-concrete face connection
- Separation of concrete face from cushion
- Seepage channels through stratified rockfill
- Lack of proper drainage and filter action

Case History: **Gouhou Dam**



Evolution of the phreatic surface in the dam: (a) t = 0.04 days; (b) t = 0.1 days; (c) t = 0.2 days; (d) t = 0.4 days (Chen and Zhang, 2006)

Case History: **Gouhou Dam – Lessons Learned**

- Seepage control is essential for a CFRD d/s of the concrete face, in case of face crack or rupture.
- Clean crushed rock drainage layer is necessary at bottom of dam body, to safely convey the seeped water to downstream.
- filter criterion (retention) is required to be satisfied between successive zones: cushion, transition, and shell materials.

Conclusion

- Filter zones have a critically important role in stability and proper functioning of hydraulic soil structures, i.e. earth dams.
- In the US, there are approximately 85000 dams, with the average age of 53 years (Richards, 2012).
- New dams are designed and constructed with proper filters and drains, to control seepage and prevent piping erosion.
- Older dams, constructed before the development of the concept of zoned embankments, should be checked with the filter design criteria. If the present condition did not meet the criteria, retrofitting and remedial measures are needed.