Placement of earthen clay core, up and downstream filters, and rockfill shells at Fena Dam on Guam by Navy Seabees in 1951. Upstream is to the right.
Hydraulic piping/soil erosion can be prevented by the placement of filter layers of intermediate size material between the soil and the drain rock, if their particle sizes are dramatically different. This is a common precaution when constructing earth dams, like that shown here (Sabena Yegua Dam in the Dominican Republic).
Inclined chimney drain comprised of coarse gravel at Teton Dam, between the loess core and the loess shell
The “Crackstopper Theory” was advanced in by the Corps of Engineers in the early 1940s; it assumes that progressively larger particles will infill a adjoining fissure and plug it, preventing hydraulic piping.
- The Bureau of Reclamation limits filter aggregate to 3 inches diameter and demands:
- The ratio $D_{15}(\text{filter})/D_{85}(\text{soil})$ must always be less than 5
The basic filter criteria are given as:

- \( D_{15} \) (filter)/\( D_{85} \) (soil) < 4 to 5 < \( D_{15} \) (filter)/\( D_{15} \) (soil)
- \( D_{15} \) (filter) must not be more than 4 or 5 X \( D_{85} \) (soil)
- The ratio \( D_{15} \) (filter)/\( D_{85} \) (soil) is the piping ratio
- The \( D_{15} \) (filter) must be 4 to 5X the \( D_{15} \) (soil being protected)
Abutment seepage at Starvation Dam and Reservoir near Duchesne, Utah, as viewed in 1977. This dam had recently been built by the Bureau of Reclamation, between 1967-70. The Bureau of Reclamation undertook a thorough study of the seepage problems and corrected them in the 1980s.
Most seepage-related failures of dams have occurred via percolation through fractured bedrock abutments, or along outlet conduits. This concrete-faced earthfill dam near Lima, Peru failed upon its initial filling because of inadequate seepage collars along the outlet works conduit on the right abutment.
The **Baldwin Hills Reservoir** in Los Angeles failed in Dec. 1963 by hydraulic piping through the rock abutment, along an active fault that had shifted about 1.5 feet over the previous decade.

Piping occurred along a branch of the Newport-Inglewood fault, shown below.

Water streaming from the reservoir’s abutment, shortly before breach of the embankment.
Fontinelle Dam was constructed by the US Bureau of Reclamation on the Green River in Wyoming in 1961-65, with a single line grout curtain.

In September 1965 a serious piping failure occurred on the right abutment where reservoir water passed through valley-side stress relief joints in the sandstone (with only 46 feet of head). The dam came dangerously close to failing, as shown here.

8 rows of grout curtains were installed on the right abutment and the entire dam was subsequently retrofitted with a vertical diaphragm seepage cutoff wall.
The **Teton Dam** near Rexburg, Idaho failed by hydraulic piping through the fractured rhyolitic ignimbrite in the right abutment keyway on June 5, 1976, during its initial filling.

This could have been prevented by installing a filter between the fill and the fractured rhyolite exposed in the right abutment keyway.
One of the problems with $D_{15}$ and $D_{85}$ filter criteria is “gap gradation”, caused by well sorted (river run) material. Filters should always be comprised of well-graded mixtures, with a graduated range of particle sizes.
Filter criteria should be compared between the aquifers producing seepage and the soil being protected. In this case, the sandstone (B) is producing seepage and the subdrain is comprised of Material C. Material A (shale) may not be a factor if it does not produce moisture.
Filter criteria for riprap slope protection of earthen embankments, from Cedergren (1989). Intermediate Filter Curve 2 prevents soil of Curve 1 from washing through the rock cushion (Curve 3) or through the armor rock (Curve 4).
Filters essential for breakwaters

Note size of coral boulders comprising the core of the breakwater fill.

Fines are easily expunged from a heterogenous rockfill by the pumping action of waves pounding against the breakwater, as seen at right.

50 ft wide bench on crest of the breakwater was eroded down to 3 feet, only one month after placement!

Two months after placement the seaward end of the Apra Harbor breakwater was completely washed away because of lack of filters between massive armor rock and the interstitial fill.

The Apra Harbor breakwater on Guam constructed by the Navy’s 76th NCB in July 1945 – lasted just one month.
Riprap face protection

- **Upper left:** If riprap is to protect against near-constant wave action, it should be carefully placed, stacked to interlock.

- **Lower left:** Rip rap is often loose dumped and spread over the downstream face of embankment dams and levees where it is assumed the it retard face erosion, if and when the structure is overtopped.

- **Lower right:** Vegetated boulder revetments, like this one in Madison, Wisconsin, can be constructed to provide adequate protection and be aesthetically pleasing, important in an urban environment.
Filter criteria for pavements, from Cedergren (1989). Fine filter (Curve 2) prevents native soils (Curve 1) from pumping into open-graded drainrock (Curve 3). This sort of protection is essential in areas with high groundwater.
Pavement Distress is almost always related to a lack of subdrainage.

When we see water seeping up out of the pavement, this indicates an inadequate pavement design. This is particularly problematic in shales and clayey soils.
Segregated filter materials are very common if the material is excavated from a river or stream bed. Segregated materials can also cause problems. The $D_{15}$ of the unsegregated filter aggregate (Curve 2) should be no more than $5D_{85}$ of the soil (Curve 1), but the $D_{15}$ of segregated pockets of coarse filter material (curve 3) is actually $50D_{85}$ of the soil! This problem occurs more often than most engineers realize, and leads to poor pavement performance.
Pervious pavement subgrade

Pervious pavement subgrade beneath paving stones by Vermont DOT

Porous pavements

Pervious basecourse over geotextile Port of Portland Terminal 6

Pervious subgrade layer laid over black geotextile (at right), prior to placement of Continuous Reinforced Concrete Pavement of Interstate 40 in Oklahoma City