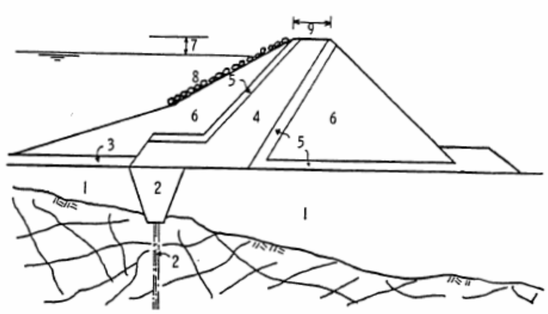
# Design of Earth Dams

## Earth Dam Components




| No | Component name | Purpose of component |
|---|---|---|
| 1 | Foundation | support dam and restrict underseepage |
| 2 | Cutoffs | reduce seepage through foundation |
| 3 | Blanket | alternative to cutoff for deep foundation |
| 4 | Core | prevent leakage through the dam |
| 5 | Filters | prevent particle migration and piping |
| 6 | Shells | provide gravity fill and structural support |
| 7 | Freeboard | prevent overtopping and provide storage |
| 8 | Rip-rap | prevent wave and water erosion |
| 9 | Crest | provide access and increase stability |

# Design Requirements

Basic design requirements for earth dams may be listed, following the U.S. Corps of Engineers (1968) as:

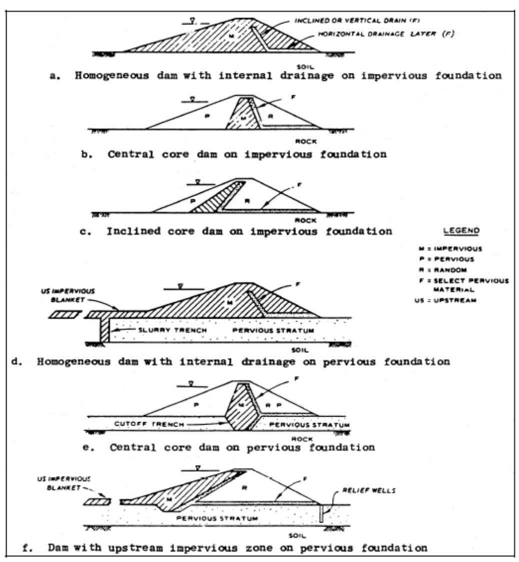
(a) Embankment slopes must be stable under all construction and operating conditions, including reservoir drawdown.

(b) The embankment must not impose excessive stresses on the foundation or abutments.

(c) Seepage flow through the embankment, foundation and abutments must be controlled so that piping, sloughing, or removal of material by solution does not occur. Seepage flow quantities may also be limited by storage considerations.

(d) Spillways, outlet capacities and freeboard must be sufficient to prevent overtopping, Freeboard must include allowances for post construction embankment and foundation settlements.

# Types of Earth Dams



## Other Types of Dams

- Concrete
- Roller Compacted concrete
- Debris flows

## Choice of Type Depends on

Availability of materials
  - Trucking increases cost
- Homogeneous Earth Dam
  - Lots of low K material – Till
- Zoned
  - Limited core material
  - Rock available
- Upstream construction
  - Use mine tailings as a construction material

## Foundation Requirements

1. Strong foundation
   - Minimal differential settlement
   - No bearing capacity shear failure
   - Sand/Gravel or rock
2. Low hydraulic conductivity
   - Silt and/or Clay, non-fractured rock

Since 1 and 2 are often incompatible we need to do foundation treatment

## Foundation Treatment

- Soil
  - Cut-offs walls
  - Sheet pile walls
  - Slurry trench
  - Impervious upstream blanket
  - Removal and replacement
  - Densification
  - Zone grouting
- Rock
  - Removal and replacement of upper fractured rock
  - Grouting
  - Impervious upstream blanket

# Hydraulic Efficiency

- Install upstream and down stream peizometers

$$E_H = \frac{Head\ loss\ across\ barrier}{Total\ head\ loss} = \frac{\Delta h}{h}$$

- Efficiencies greater than 90% have been attained

# Foundation Treatment (Mitchell)

| Cutoff type | Brief Description | Suitable Soil Type and Depths | References and Comments on Performance |
|---|---|---|---|
| sheet piling diaphragm wall | drive plane or zeta piling with vibratory hammer and water jets moderate costs | alluvium, no large boulders, to 30 m | efficiency often low unless upstream side grouted with bentonite slurry. Lane and Wohlt (1961) Middlebrooks (1942) |
| grout curtains | several rows of 2 to 3 m spaced holes grouted at high pressure with cement soil grouts. Medium to high costs | fractured rock and coarse grained soils to 150 m $k < 10^{-8}$ m/s | fair to good efficiency reduces k by a factor 50 to 100. Also used in abutments to control leakage Wafa and Labib (1967) Marsal and Resendiz (1971) |
| concrete piles and panels (also precast concrete walls) | excavate bentonite slurry stabilized slot between piles and insert panels with grouted joints or tremie concrete panels medium costs | weak rocks alluvium to depths of 50 m excavate with Kelly bar | good efficiency but requires special construction control and design. Calbiati (1963) Dascal (1979) Marsal and Resendiz (1971) |
| slurry trench | dragline excavation of slurry stabilized trench. Displacement backfilled with sand, gravel, clay, bentonite (well graded with 50 mm max size) low costs | alluvium or coarse grained soils to 30 m or greater | good efficiency, flexible and compressible. Possible loss of slurry if soils are coarse. Jones (1967) |
| impervious blanket | impervious soil compacted over reservoir bottom and connected to internal core or extended as upstream core on dam face costs variable | very deep foundation soil of suitably low permeability and good grading characteristics | effective if abutment conditions are good downstream filter drains or relief wells may be required Casagrande (1969) |
| Removal and replacement | excavate above or below water level at stable slopes dry excavation allows inspection and treatment of underlying material costs variable | soils which can be economically excavated to required depth with or without seepage control (20 m common) | good efficiency if replacement soil compacted in dry excavation fair to good efficiency if placed under water |

## Foundation Treatment (Mitchell)

| Treatment Method | Brief Description | Suitable Soil Type and Effective Depth | References and Comments on Performance |
|---|---|---|---|
| Densification by blasting | blast vibrations liquefaction and settlement | loose saturated silts and sands to 20 m | 70-80% relative density obtained Dupont (1958) |
| Compaction piles, sand piles | hollow pile vibrations densify soil, sand piles formed on removal | saturated or dry sand to 20 m | relatively high densities obtained Wallways (1964) James (1973) |
| vibro-probes with replacement vibro-floatation with water jets on probe | vibratory probe densifies soil by displacement and compacts selected replacement material | cohesionless soils and sandy tills or alluvium to 30 m | relatively high densit and good uniformity obtained Baumann & Bauer (1974) Basore & Boitano (1969) |
| vibratory rollers (to 50 tonne) | roller mass compacts with aid of vibration | cohesionless soils to 3 m | high density obtained Moorhouse and Baker (1968) |
| dynamic consolidation (to 40 tonne) | repeated dropping of large mass on soil surface | cohesionless soils and insensitive cohesive soils to 15 m | relatively high densities obtained Menard and Broise (1975) |
| grouting with slurries or chemicals | injected from bore holes, with limewater (for expansive soils), chemical grouts | soils with groutability ratio $\frac{D_{15}\text{ (soil)}}{D_{85}\text{ (grout)}} > 25$ $k > 5 \times 10^{-6}$ m/s unlimited depths | significant reductions in permeability and compressibility obtained , high cost.ASCE soil improvement report (1978) |
| consolidation by preloading | embankment preload or constructed in stages | soft compressible clays and silty clays | improves bearing capacity by consolidation over extended time period, time reduced by sand or wick drains Ladd et al (1976) |
| displacement construction | granular or rock fill advanced to displace soil, excavation of forward mud wave | very soft clays, organic soils to 20 m blasting may be required in fibrous peats | controlled failure to avoid entrapment of soft soils. Not recommended for impoundment structures Weber (1962) |

## Foundation Preparation

Want smooth transition to minimize negative skin friction and soil arching as that can led to hydraulic fracturing as well as core cracking

# Foundation Preparation

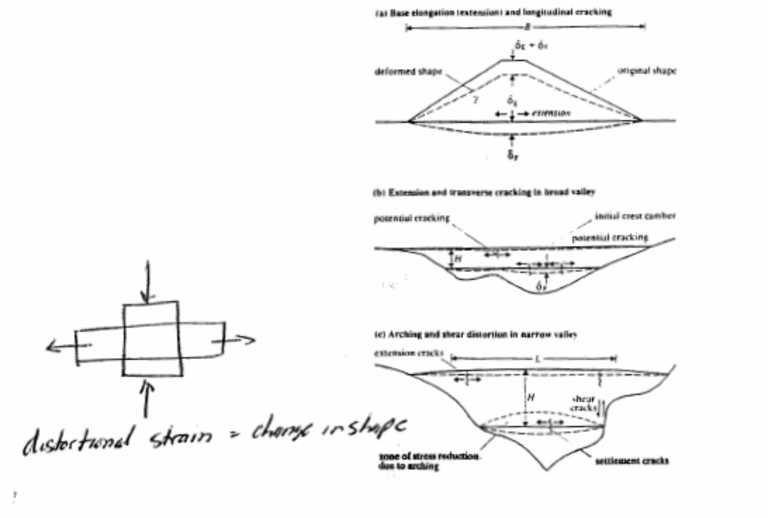



FIGURE 3.4 DAM DISTORTION AND CRACKING

# Foundation Distortion

$$\varepsilon_h = \frac{-2\left[\left(\frac{B}{2}\right)^2 + \partial_F{}^2\right]^{0.5}}{B} + 1 = \frac{\Delta L_h}{L_h}$$

$$\varepsilon_v = m_v \gamma H$$

Shear Strain ($\tau$) = $\varepsilon_v$-$\varepsilon_h \leq 1\%$

# Hydraulic Fracturing

Occurs when the porewater pressure is equal to the minimum embankment effective stress

$$\sigma_h = K\sigma_v = K\gamma H - E_h\varepsilon_h > \mu = H\gamma_w$$

where

K~0.5 for compacted materials

$E_h$ is the tensile modulus obtained from a triaxial extension test

$\varepsilon_h$ = horizontal strain

# Linear and Plastic Deformations

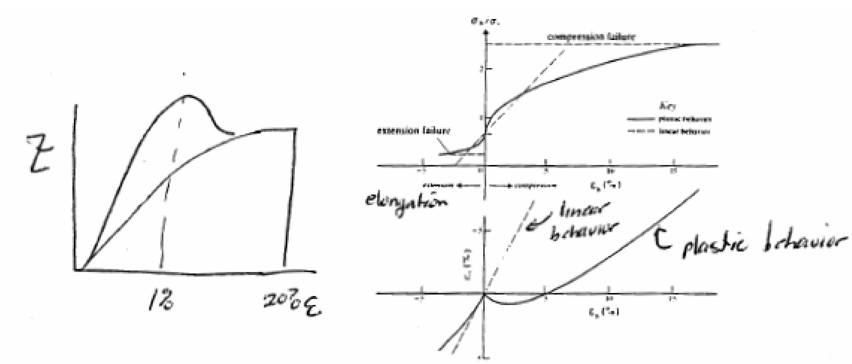



FIGURE 3.5 LINEAR AND PLASTIC DEFORMATIONS

# Soil Arching

- Terzaghi 1943

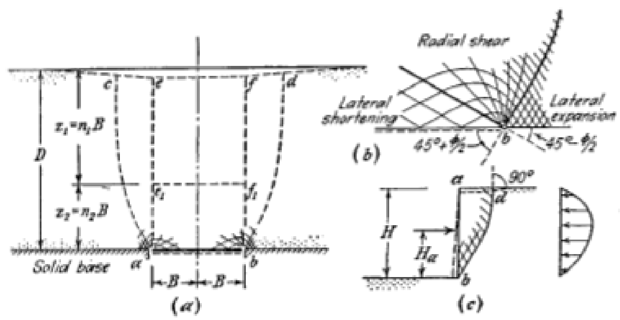



FIG. 17. Failure in cohesionless sand preceded by arching. (a) Failure caused by downward movement of a long narrow section of the base of a layer of sand; (b) enlarged detail of diagram (a); (c) shear failure in sand due to yield of lateral support by tilting about its upper edge.

# Soil Arching

- Terzaghi Trap Door
  - Note significant reduction is vertical stress

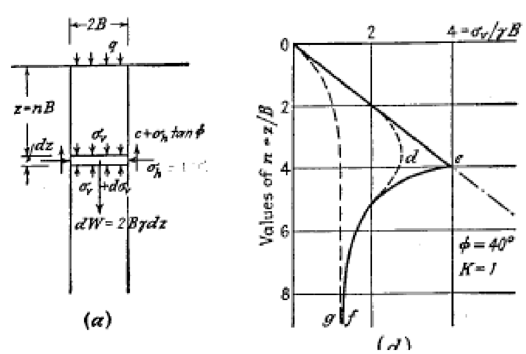



FIG. 18. (a) Diagram illustrating assumptions on which computation of pressure in sand between two vertical surfaces of sliding is based; (c and d) representations of the results of the computations.

# Soil Arching

- Terzaghi Trap Door

$$\sigma_v = \gamma a B \quad [6a]$$

wherein

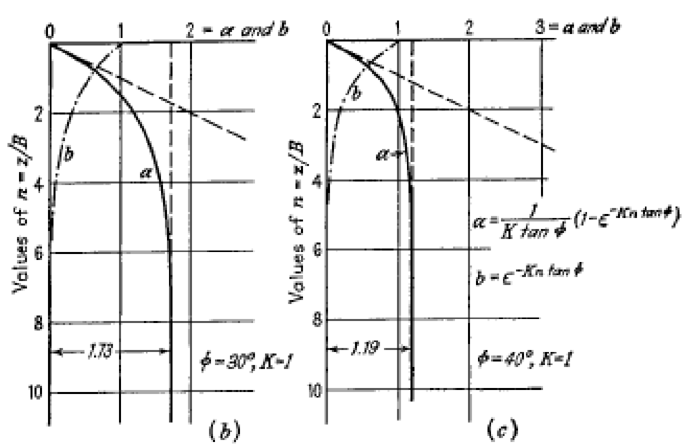
$$a = \frac{1}{K \tan \phi}\left(1 - \epsilon^{-K \tan \phi \, z/B}\right) = \frac{1}{K \tan \phi}\left(1 - \epsilon^{-Kn \tan \phi}\right) \quad [6b]$$

For $z = \infty$ we obtain $a = 1/K \tan \phi$ and

$$\sigma_v = \sigma_{v\infty} = \frac{\gamma B}{K \tan \phi} \quad [7]$$

FIG. 18. (a) Diagram illustrating assumptions on which computation of pressure in sand between two vertical surfaces of sliding is based; (c and d) representations of the results of the computations.

# Soil Arching



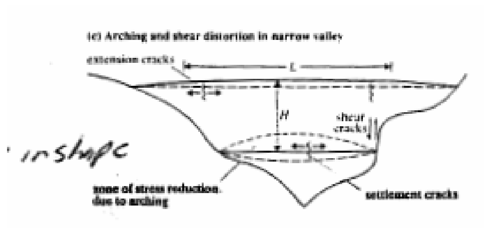
# Approximation of Vertical Stress in DAMS

$$\sigma_v = \frac{L\gamma}{2K\tan\phi}\left[1 - e^{-2K(\tan\phi)\frac{Z}{L}}\right]$$

Where L is the width of the valley

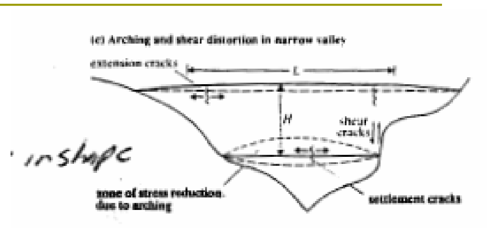
K=constant ~1

Z is depth from dam crest




# Approximation of Vertical Stress in DAMS

If H>L then z/L >1 and K=1




$$\sigma_v = \frac{L\gamma}{2\tan\phi}$$

## Hydraulic Fracturing

if

$$\mu \approx H\gamma_w \text{ for full reservoir}$$

$$\sigma_h \approx K\sigma_v \quad \text{where K} \sim \tan\phi$$

$$\sigma_h \approx \frac{L\gamma}{2}$$

## Hydraulic Fracturing

then

$$\sigma'_h = 0 \;\; \text{when} \frac{L\gamma}{2} = \gamma_w H$$

$$note \quad \frac{\gamma}{2} \approx \gamma_w \text{ there } \sigma'_{\mathrm{h}} \approx 0 \text{ when L} = \text{H}$$

Note: hydraulic fracturing will occur when L is approximately equal to H

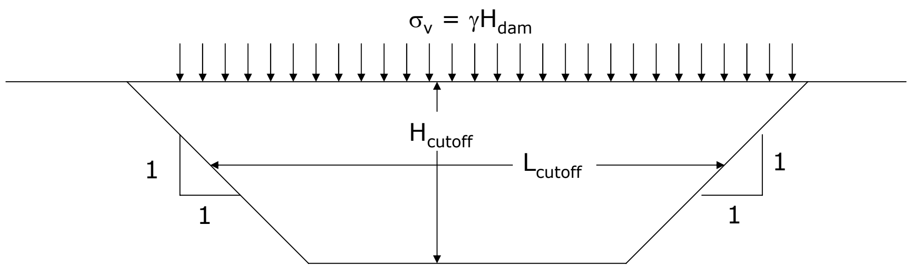
A few dams exists where average L < average H

## Design of Cutoffs

- Must prevent hydraulic fracturing

$\sigma'_h$>porewater pressure

Then $L_{cutoff} > H_{cutoff}$




## Foundation Preparation

1. To prevent hydraulic fracturing must:
   - Have no vertical shear boundaries that can create differential settlement
   - Smooth profile along base of dam
   - Cord Length greater than the height of dam
   - Cutoffs with cord lengths greater than cutoff height
2. Hydraulic conductivity that will allow water to pond behind the dam
3. Strong enough to minimize distortional strains to less than 1 percent

## Design of Zoned Dams

Rock fill will be much stiffer than core. As core settles arching will occur in the core.

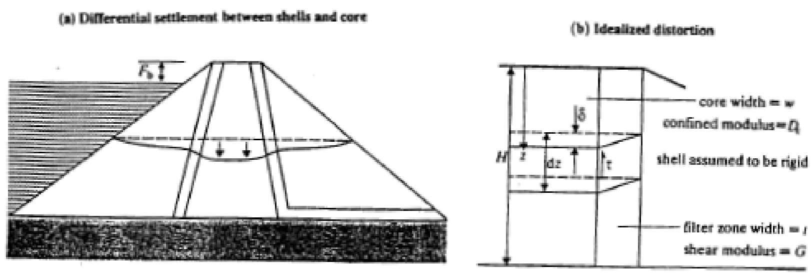



FIGURE 3.9 ARCHING IN COMPRESSIBLE CORE

## Design of Zoned Dams

To prevent core arching and hydraulic fracturing we need:

1. wide enough core
2. need shear layer between core and shell to prevent internal core cracking

## How wide of core do we need?

$$\sigma_v = \frac{Z\gamma_{core}}{1+\frac{GZ^2}{D_c tW}}$$

where:

W is the width of core

Z is depth below crest

$\gamma_{core}$ is unit weight of core

G is the shear modulus of filter material

t is width of filter material

$D_c$ is confined modulus of core = $1/m_v$

## Can Geotextiles Prevent Shear

Note t is very small for geotextiles this makes $\frac{GZ^2}{D_c tW}$ very large

Resulting is significant arching in core…creating core cracking and hydraulic fracturing.

To prevent hydraulic fracturing need

$$\frac{GZ^2}{D_c tW} < 0.35$$

## Methods to Prevent Core Cracking

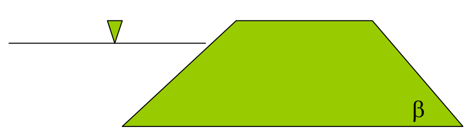
- Wider cores
- Greater filter width
- Greater core compaction
- Benched cores to increase vertical stress

## Transverse Core Cracking

- Develops when D/S shell material distorts to resist U/S water pressures transmitted by core
- Limit to less than 1% by having

$$G < \frac{200 H \gamma_w}{\cot \beta}$$

- Where G is modulus of shell material
- H is dam height
- β is down stream slope angle



## Tranverse Cracking

- Often dams designed with u/s arch. This keep d/s in compression

## Design Limits

| $\delta_v/H\cot\beta$ | Impact |
|---|---|
| 0.001 | No cracking |
| 0.002 | Thin reinforced concrete may crack |
| 0.003 | Longitudinal cracking in dry cores |
| 0.005 | Transverse cracks in cores and oblique core to shell cracks |
| 0.01 | Longitudinal cracks in wet cores & jointed concrete facing |
| 0.02 | Danger of transverse cracks and piping failures |