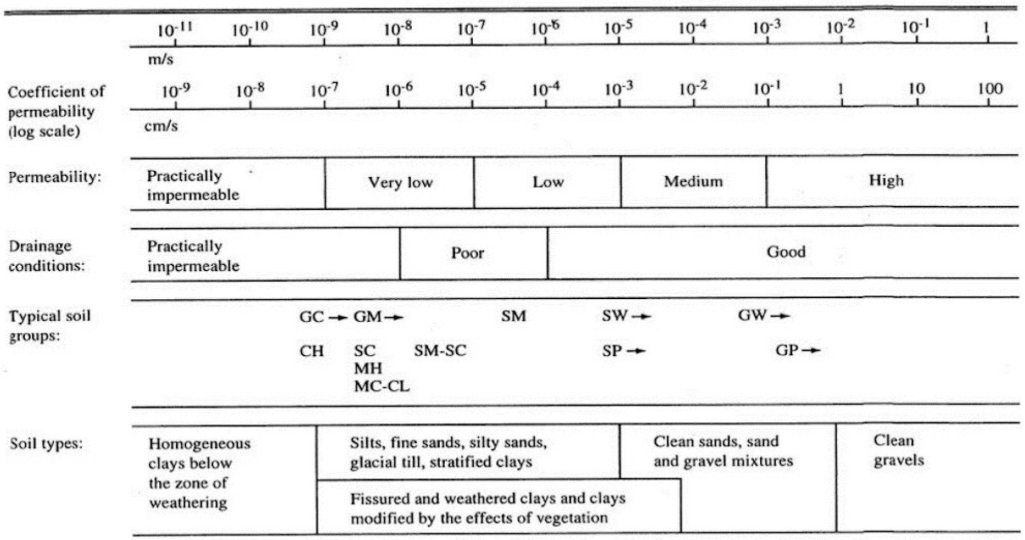
# ENCE 3610
# Soil Mechanics

Lecture 7
Groundwater II
Empirical and Field Tests for Hydraulic Conductivity, Dewatering and Flow Nets, Soil Boiling and Filters

# More Typical Permeability Values

**Table 5-10**

**Typical permeability values in soils (after Carter and Bentley, 1991)**




Note: The arrow adjacent to group classes indicates that permeability values can be greater than the typical value shown.

**Table 5-11**

**Typical permeability values for highway materials (after Krebs and Walker, 1971)**

| **Materials** | **Permeability (cm/sec)** |
|---|---|
| Uniformly graded coarse aggregate | 40 - $4\times10^{-1}$ |
| Well-graded aggregate without fines | $4\times10^{-1}$ - $4\times10^{-3}$ |
| Concrete sand, low dust content | $7\times10^{-2}$ - $7\times10^{-4}$ |
| Concrete sand, high dust content | $7\times10^{-4}$ - $7\times10^{-6}$ |
| Silty and clayey sands | $10^{-5}$ - $10^{-7}$ |
| Compacted silt | $7\times10^{-6}$ - $7\times10^{-8}$ |
| Compacted clay | Less than $10^{-7}$ |
| Bituminous concrete (new pavements)* | $4\times10^{-3}$ - $4\times10^{-6}$ |
| Portland cement concrete | less than $10^{-8}$ |

* Values as low as $10^{-8}$ have been reported for sealed, traffic compacted highway pavement.

# Empirical Formula to Estimate Hydraulic Conductivity in Cohesionless Soils

$$k = \beta_\alpha D_\alpha^x$$

Where

- $k$ = hydraulic conductivity, cm/sec
- $\beta_\alpha$ = empirical or semi-empirical constant
- $D_\alpha$ = effective grain size
- $\alpha$ = percent passing according to effective grain size
- $x$ = exponent, theoretically $x = 2$, empirically slightly above that
- All assume laminar flow in soils

# Empirical Correlations

**Table 6-5 Estimating Hydraulic Conductivity based on Effective Grain Size**

| Source | Reported Application | $\alpha$ | $\beta_\alpha$ (cm/sec/mm²) | $x$ |
|---|---|---|---|---|
| Kenney et al. (1984) | Sand and fine gravel, $C_u$ = 1 to 12 | 5 | 1 | 2 |
| Hazen (1892, 1911) | Loose Sands with $D_{10}$ between 0.01 and 0.3 cm | 10 | Varies by source from 0.01 to 10<br>Often taken to equal to 1 | 2 |
| Slichter (1905) and (McCook 2010) | Sands with $D_{10}$ between 0.01 and 0.5 cm | 10 | $0.01047\exp\left(\frac{9.3071e}{1+e}\right)$ | 2 |
| Chapuis (2004) | Sand | 10 | $2.4622\left(\frac{e^3}{1+e}\right)^{0.7825}$ | 1.565 |
| Carrier (2003) | Sand, assuming uniform spheres | 10 | $5.52\left(\frac{e^3}{1+e}\right)$ | 2 |
| Sherard et al. (1984) | Sand and gravel with low fines content | 15 | Average = 0.35, range = 0.2 to 0.6 | 2 |

Notes: $k$ is estimated in cm/sec, $C_u$ = coefficient of uniformity = $D_{60}/D_{10}$ , $e$ = void ratio

# Example of Conductivity Estimate

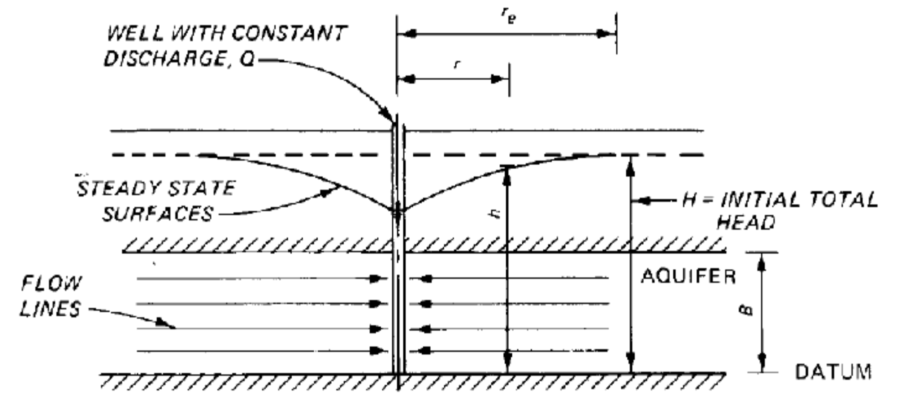
- Given: Soil as Shown Below
  - $D_{10} = 0.15$
  - $D_5 = 0.08$
  - Uniformity Coefficient $C_u = 8$
  - Void Ratio e = 0.6
- Find
  - Hydraulic Conductivity, using a variety of methods

| Correlation | $\alpha$ | $\beta_\alpha$ | x | k, cm/sec |
|---|---|---|---|---|
| Kenney | 5 | 1.000 | 2 | 0.0064 |
| Hazen | 10 | 1.000 | 2 | 0.0225 |
| Slichter & McCook | 10 | 0.565 | 2 | 0.0127 |
| Chapuis | 10 | 0.368 | 1.565 | 0.0189 |
| Carrier | 10 | 0.745 | 2 | 0.0168 |
| Sherard et.al. | 15 | 0.350 | 2 | Not enough information |

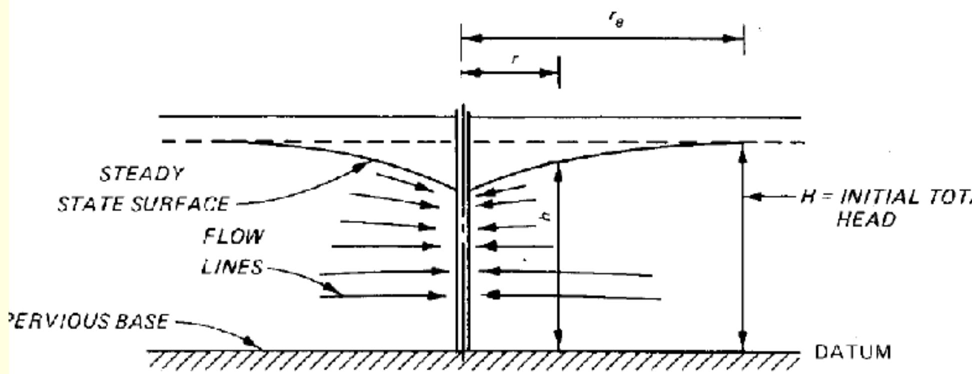
# Field Permeability Tests and Dewatering Wells

| Type of Test | Description | Advantages and Disadvantages |
|---|---|---|
| Constant Head Test | Water is added to an open-ended pipe (cased borehole) at a constant rate. Water level in hole maintained at a constant level. | Can be performed in saturated and partially saturated soils. Difficult to perform on soils with a very high or very low k. Only a small zone of soil is tested (if unscreened). |
| Variable Head Rising Head and Falling Head Tests (ASTM D4044) | An interval of a borehole is screened. A "slug" of water removed from or added to the borehole. Elevation of the water level recorded over time. | Construction and development of the well is more difficult than constant head test. Data reduction can be complex. |
| Pressure Tests | Borehole section isolated by or sealed off with "packers." Elevated pressure can be applied to achieve increased flow. | Best for deep explorations. Can be conducted above or below the water table. Can be used to measure the hydraulic conductivity of fractured rock. |
| Pumping Tests | Install pumped well and observations wells radially from the pumped well. Record the amount of water pumped and the elevation of water in the wells is over time. Use analytical or numerical analysis to determine the hydraulic parameters of the soil deposit. | More expensive than other methods. Hard to justify increased cost for common geotechnical projects. Provides addition information regarding aquifer transmissivity and storativity. Tests a larger volume of soil than other methods. Long testing times. |

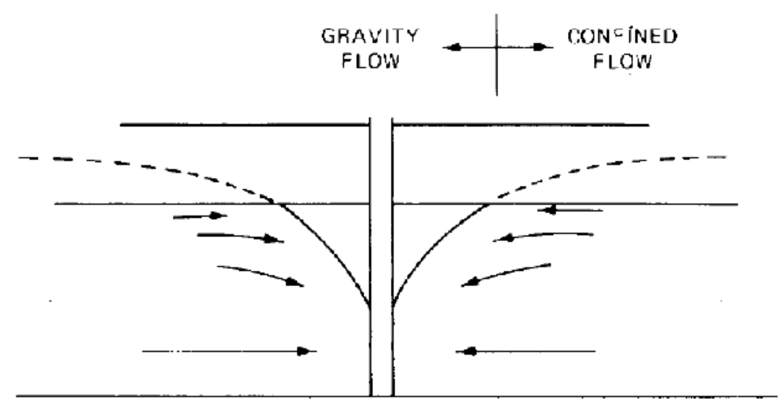
# Confined and Unconfined Aquifers




a. HORIZONTAL AQUIFER CONFINED BETWEEN IMPERVIOUS STRATA (ARTESIAN FLOW)




b. HORIZONTAL UNCONFINED AQUIFER (GRAVITY FLOW)




c. COMBINED AND CONFINED AND GRAVITY FLOW

# Confined Aquifer: Determination of Height

- Governing Equation:
  - *h*=height from bottom of well to water level at well
  - $h_0$=water table height from bottom of well to water table
  - $Q_0$=flow from well
  - *k*=coefficient of permeability
  - *H*=thickness of permeable layer
  - *r*=radius of well or wherever h is measured
  - *R*=outer boundary of influence of well, or wherever $h_0$ is measured

$$h = h_0 + \frac{Q_0}{2\pi kH} \ln\left(\frac{r}{R}\right)$$

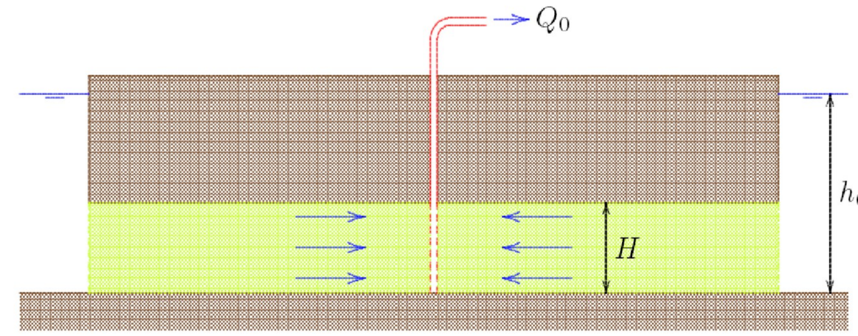



Figure 11.1: Single well in aquifer.

$$Q_0 = \frac{2\pi kH}{\ln\left(\frac{r}{R}\right)} \; h - h_0$$

$$k = \frac{Q_0 \ln \; \frac{r}{R}}{2\pi H \;\; h - h_0}$$

# Unconfined Aquifer

- Only difference is that upper layer is the same (pervious) as lower layer
- Equations have same variables, but expression is different:

$$h^2 = h_0^2 + \frac{Q_0}{\pi k}\ln\left(\frac{r}{R}\right)$$

$$Q_0 = \frac{\pi k}{\ln\left(\frac{r}{R}\right)}\left(h^2 - h_0^2\right)$$

$$k = \frac{Q_0 \ln\left(\frac{r}{R}\right)}{\pi\left(h^2 - h_0^2\right)}$$

# Dewatering

# Layered Soils

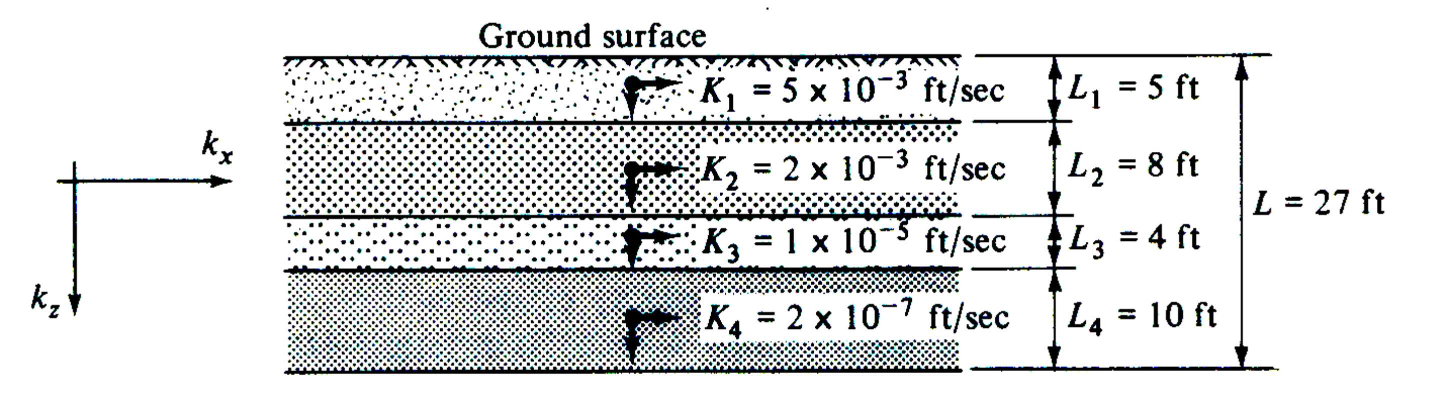
- "Resistor Model" except that we're dealing in conductivities, not resistances
- For horizontal layers:
  - Vertical flow is a single flow through several hydraulic resistances in series

$$k_{V_{eq}} = \frac{H}{\sum_{i=1}^{n} \frac{H_n}{k_{V_n}}}$$

  - Horizontal flow is several flows through several hydraulic resistance in parallel

$$k_{H_{eq}} = \frac{1}{H}\sum_{i=1}^{n} H_n k_{H_n}$$

# Example of Layered Soils




- Given soil profile above near a dam
- Find equivalent horizontal and vertical permeabilities
- Solution: from formulae previously given:
  - Horizontal: $k_{eq} = (5*5x10^{-3}+8*2x10^{-3}+4*1x10^{-3}+10*2x10^{-7})/27 = 1.52x10^{-3}$ ft/sec
  - Vertical: $k_{eq} = 27/(5/5x10^{-3}+8/2x10^{-3}+4/1x10^{-3}+10/2x10^{-7}) = 5.36x10^{-7}$ ft/sec

# Anisotropy in Permeability

$$k_H \neq k_V \, (Anisotropic \, Soil)$$

$$k_H > k_v \, (in \, general)$$

- Can be significant, esp. with some types of clays, esp. varved clays
  - Varved clay: “alternating seams or layers of sand, silt and clay” (SFH Table 4.7)
  - Result of sediment deposits with vary in nature due to seasonal fluctuations, etc.

# Two-Dimensional Flow Analysis

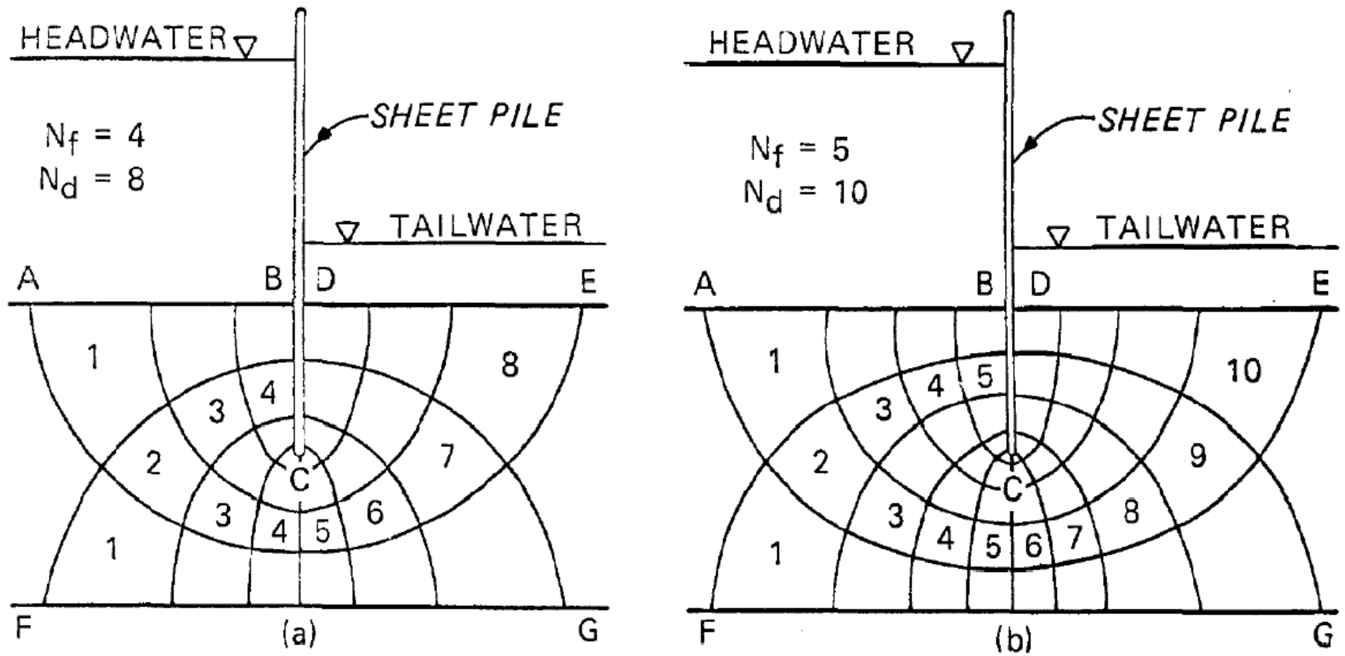
- Methods
  - Theoretical equations from complex analysis
  - Flow nets
    - Traditionally, most common method in use
  - Electro-hydraulic analogy
  - Finite Element Methods
- Theory: Laplace's Equation
  - Equation in two dimensions:

$$k_1 \frac{\partial^2 h}{\partial x^2} + k_2 \frac{\partial^2 h}{\partial y^2} = 0$$

  - Also applicable to electrical and stress problems as well
  - Analogy can be applied to one-dimensional case as well
  - $k_1$ and $k_2$ apply to the anisotropic condition

# Flow Nets

- Allow application of Darcy's Law and Laplace's Equation in two dimensions
- Enables calculation of flow in complex geometries without a complex hand solution; a good estimate even when computer (finite element analysis) is employed
- Can be used with isotropic or non-isotropic soils




a. Net drawn for four flow channels.

b. Net drawn for five flow channels.

Figure 4-5. Flow net for a sheetpile wall in a permeable foundation (from U. S. Army Engineer District, Little Rock[92])

# Flow Net Equation

Once drawn, flow nets can be used to calculate a number of properties including: seepage quantities, pore pressures, uplift forces, and hydraulic gradients. The volumetric flow rate through a flow net section can be calculated as:

$$q = k \cdot h_L \cdot \left( \frac{N_f}{N_d} \right) \cdot W \qquad \textbf{(6-9)}$$

where:

$h_L$ = the total differential head or head loss across the flow net,

$k$ = the isotropic hydraulic conductivity (use $\sqrt{k_{max} k_{min}}$ for transformed flow nets),

$N_f$ = the number of flow channels in the flow net,

$N_d$ = the total number of equipotential (head) drops in the flow net, and

$W$ = the width of the system perpendicular to the page, often taken as a unit width.

The ratio $N_f / N_d$ from the flow net is sometimes referred to as the *shape factor* ($SF$). The shape factor incorporates the influence of geometry into the calculation of flow. Two flow nets with a different number of flow lines but the same value of $SF$ will predict the same flow rates, total heads, and pore pressures.

# Flow Net Rules and Example

RULES FOR FLOW NET CONSTRUCTION

1. WHEN MATERIALS ARE ISOTROPIC WITH RESPECT TO PERMEABILITY, THE PATTERN OF FLOW LINES AND EQUIPOTENTIALS INTERSECT AT RIGHT ANGLES. DRAW A PATTERN IN WHICH SQUARE FIGURES ARE FORMED BETWEEN FLOW LINES AND EQUIPOTENTIALS.

2. USUALLY IT IS EXPEDIENT TO START WITH AN INTEGER NUMBER OF EQUIPOTENTIAL DROPS, DIVIDING TOTAL HEAD BY A WHOLE NUMBER, AND DRAWING FLOW LINES TO CONFORM TO THESE EQUIPOTENTIALS. IN THE GENERAL CASE, THE OUTER FLOW PATH WILL FORM RECTANGULAR RATHER THEN SQUARE FIGURES. THE SHAPE OF THESE RECTANGLES (RATIO B/L) MUST BE CONSTANT.

3. THE UPPER BOUNDARY OF A FLOW NET THAT IS AT ATMOSPHERIC PRESSURE IS A "FREE WATER SURFACE". INTEGER EQUIPOTENTIALS INTERSECT THE FREE WATER SURFACE AT POINTS SPACED AT EQUAL VERTICAL INTERVALS.

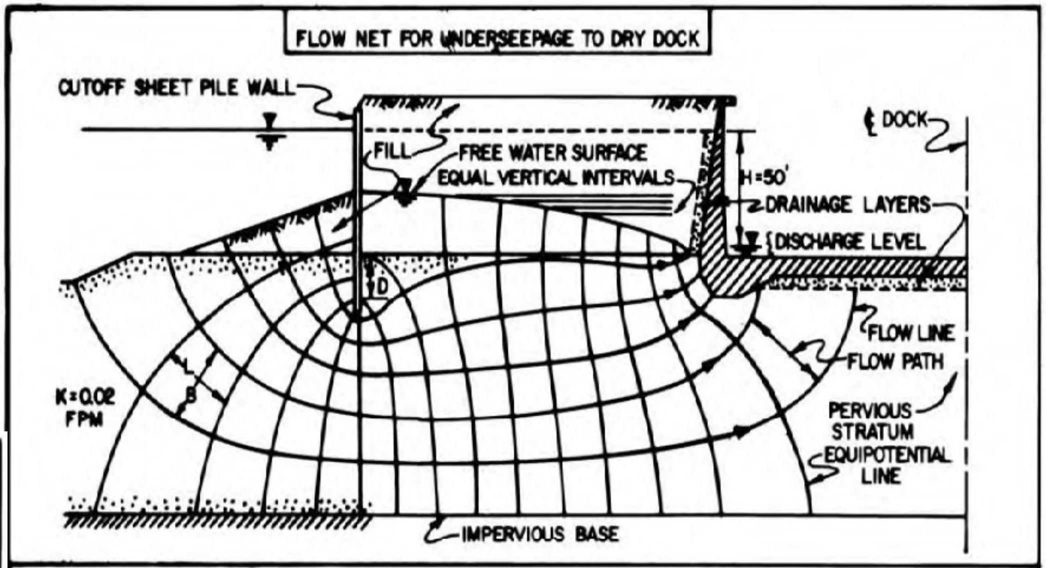
4. A DISCHARGE FACE THROUGH WHICH SEEPAGE PASSES IS AN EQUIPOTENTIAL LINE IF THE DISCHARGE IS SUBMERGED, OR A FREE WATER SURFACE IF THE DISCHARGE IS NOT SUBMERGED. IF IT IS A FREE WATER SURFACE, THE FLOW NET FIGURES ADJOINING THE DISCHARGE FACE WILL NOT BE SQUARES.

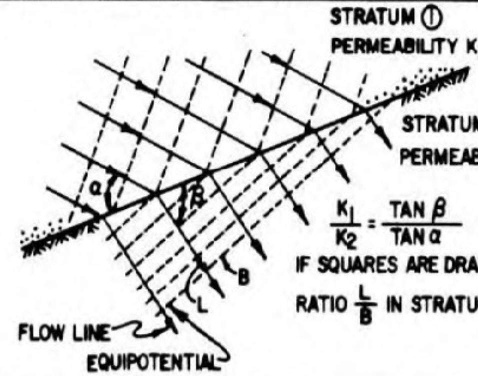
5. IN A STRATIFIED SOIL PROFILE WHERE RATIO OF PERMEABILITY OF LAYERS EXCEEDS 10, THE FLOW IN THE MORE PERMEABLE LAYER CONTROLS. THAT IS, THE FLOW NET MAY BE DRAWN FOR MORE PERMEABLE LAYER ASSUMING THE LESS PERMEABLE LAYER TO BE IMPERVIOUS. THE HEAD ON THE INTERFACE THUS OBTAINED IS IMPOSED ON THE LESS PERVIOUS LAYER FOR CONSTRUCTION OF THE FLOW NET WITHIN IT.

6. IN A STRATIFIED SOIL PROFILE WHERE RATIO OF PERMEABILITY OF LAYERS IS LESS THAN 10, FLOW IS DEFLECTED AT THE INTERFACE IN ACCORDANCE WITH THE DIAGRAM SHOWN ABOVE.

7. WHEN MATERIALS ARE ANISOTROPIC WITH RESPECT TO PERMEABILITY, THE CROSS SECTION MAY BE TRANSFORMED BY CHANGING SCALE AS SHOWN ABOVE AND FLOW NET DRAWN AS FOR ISOTROPIC MATERIALS. IN COMPUTING QUANTITY OF SEEPAGE, THE DIFFERENTIAL HEAD IS NOT ALTERED FOR THE TRANSFORMATION.

8. WHERE ONLY THE QUANTITY OF SEEPAGE IS TO BE DETERMINED, AN APPROXIMATE FLOW NET SUFFICES. IF PORE PRESSURES ARE TO BE DETERMINED, THE FLOW NET MUST BE ACCURATE.




$$\frac{K_1}{K_2} = \frac{\tan\beta}{\tan\alpha}$$

IF SQUARES ARE DRAWN IN STRATUM ①:

RATIO $\frac{L}{B}$ IN STRATUM ② $= \frac{K_2}{K_1}$

FROM FLOW NET:

NUMBER OF FLOW PATHS $= n_f = 6$

NUMBER OF EQUIPOTENTIAL DROPS $= n_d = 15$

UNDERSEEPAGE PER RUNNING FOOT OF DOCK WALL,

$$q = K\frac{n_f}{n_d}H = 0.02\left(\frac{6}{15}\right)50 = 0.4 \text{ CFM}$$

SEEPAGE PRESSURE IN A DISTANCE $D = \frac{H}{n_d D}\gamma_w$

FOR ANISOTROPIC SOIL:

TRANSFORM CROSS SECTION BY DIVIDING DIMENSIONS IN THE DIRECTION OF $K_{MAX}$ BY THE FACTOR $\sqrt{\frac{K_{MAX}}{K_{MIN}}}$

# Other Information That Can be Obtained from a Flow Net

The flow net divides the total head loss across the system into $N_d$ equal head drops. The head loss associated with each head drop is:

$$\Delta h_L = \frac{h_L}{N_d} \qquad \textbf{(6-10)}$$

where:
$\Delta h_L$ = the total differential head or head loss across one head drop,
$h_L$ = the total differential head or head loss across the flow net, and
$N_d$ = the total number of head drops in the flow net.

The total head at any point within the flow net can be calculated by reference to the known total head at either the upstream or downstream boundary. The change in head from the boundary for any point is equal to the number of head drops from the boundary multiplied by $\Delta h_L$. By knowing the total head and elevation at a point of interest, the pore water pressure at any point can be calculated from the flow net as:

$$u = h_p \gamma_w = \left(h_t - h_z\right)\gamma_w \qquad \textbf{(6-11)}$$

where:
$h_p$ = the pressure head at the point in question,
$h_t$ = the total head at the point in question,
$h_z$ = the elevation head at the point in question, and
$\gamma_w$ = the unit weight of water.

The hydraulic gradient can be calculated between any two points in the flow region by dividing the change in total head that occurs between two points by the distance over which the head loss occurs. When calculating gradients, it may be useful to subdivide flow net sections for more precision.

# Seepage Forces in Soils

- Water flowing through soil also exerts force on the soil itself
- That force (see Verruijt Eq.7.15) is, in simple terms

$$f = \gamma_w i$$

- For our purposes, the most important consideration of seepage forces is in soil boiling, which takes place when water flows upward

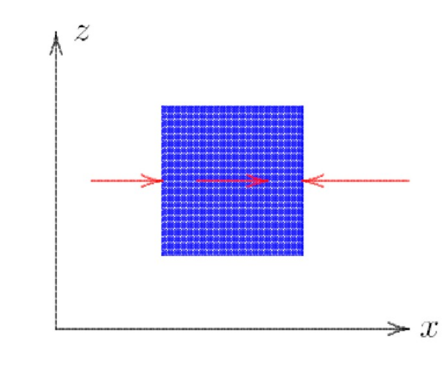


Figure 6.3: Forces.

# Soil Boiling and Critical Gradient

- A consequence of an excessive hydraulic gradient (and thus water force on soil) in upward flow
- Must watch for it with underground water flow
- Start with equation for flow and hydraulic gradient:

$$\Delta p = \gamma z (1 - i)$$

- Now equate change in pressure to total stress from soil weight:

$$\Delta p = \sigma_t = \gamma_s z$$

Combining the two equations, we can solve for the critical gradient, the point at which the upward water force on the soil is equal to the soil's own total stress:

$$i_{cr} = 1 - \frac{\gamma_s}{\gamma_w} = -\frac{\gamma_{sub}}{\gamma_w}$$

# Example: Upward Flow Example from SL 6

- Given
  - Hydraulic gradient as computed in problem = -2.333 (upward)
  - Assume soil saturated unit weight = 20 kN/m$^3$
- Find
  - Whether soil boiling might take place

$$i_{cr} = 1 - \frac{\gamma_s}{\gamma_w} = -\frac{\gamma_{sub}}{\gamma_w}$$

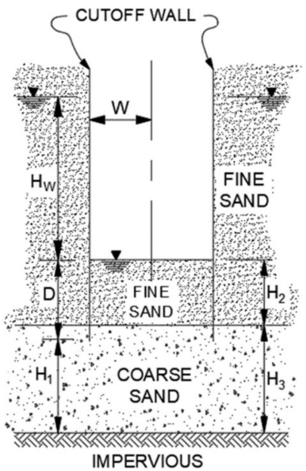
- Solution
  - Compute submerged unit weight = 20 -9.8 = 10.2 kN/m$^3$
  - Compute critical hydraulic gradient =$\gamma_{sub}/\gamma_w$ = 10.2/9.8=1.04
  - Compute factor of safety = 1.04/2.333 = 0.45
    - You can also use the formula directly, thus $i_{critical}$ = 1 - 20/9.8 = -1.04 (same result)
  - This is obviously unacceptable; however, some mitigation will take place due to the 3m water head above the surface of the soil

# Example: Upward Flow Example from SL 6

- Accounting for effect of water above the sample
  - There are four forces:
    - Downward force of still water (3m) on sample
    - Weight of 3m thick sample
    - Upward force of seepage
    - Upward force of buoyant weight of water

- Calculations
  - Downward force of water above sample = (3)(9.8) = 29.4 kPa
  - Downward force of weight of sample = (3)(20) = 60 kPa
  - Upward force of seepage = -(3)(9.8)(2.333) = 68.6 kPa
  - Upward force of buoyant weight of water = (3)(9.8) = 29.4 kPa
  - Net force per unit area = 29.4 + 60 – 68.6 – 29.4 = -8.6 kPa (this is also the effective stress at the base of the sample)
  - Net force is still upward, sample is unstable w/o other restraint

# Example: Sheet Pile Cut-off

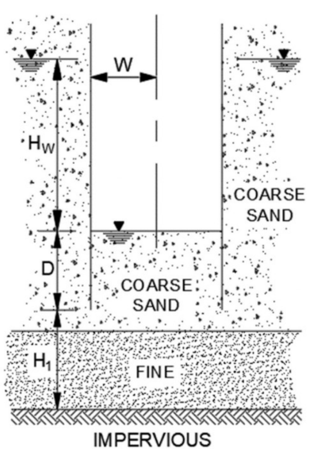



Coarse Sand Underlying Fine Sand

The presence of the coarse sand layer makes flow in the fine sand nearly vertical and generally increases hydraulic gradients in the fine sand layer when compared with the homogenous case.

If the top of the coarse sand layer is at a depth greater than the excavation width below the depth of the cutoff, the safety factors for the homogenous case apply.

If the top of the coarse sand layer is at a depth less than the excavation width below the depth of the cutoff, the uplift pressures will be greater than for the homogenous case. If the permeability of the coarse layer is more than 10 times the permeability of the fine layer, the failure head ($H_w$ in Figure 6-9) will equal the thickness of the fine layer, $H_2$.



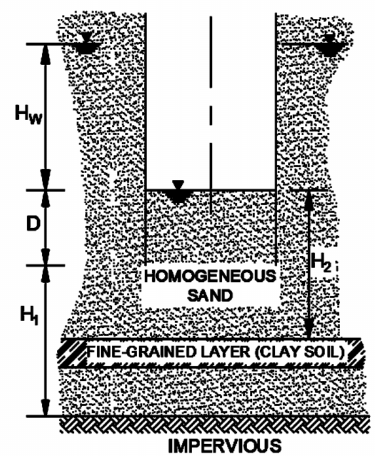

Fine Sand Underlying Coarse Sand

The presence of the fine sand constricts the flow beneath the cutoff wall and generally decreases hydraulic gradients at the base of the excavation when compared with the homogenous case.

If the top of the fine sand layer is below the depth of the cutoff, the safety factors are intermediate between those for the homogenous case (calculated using Figure 6-9) for an impermeable boundary located between the top and bottom the fine layer.

If the top of the fine sand layer is at a depth less than the depth of the cutoff, the factors of safey for the homogenous case (calculated using Figure 6-9) will be somewhat conservative.

**Figure 6-12 Corrections to Required Depth of Penetration of Cutoff Wall-Supported Excavations for Stratified Sand (after Marsland 1953)**

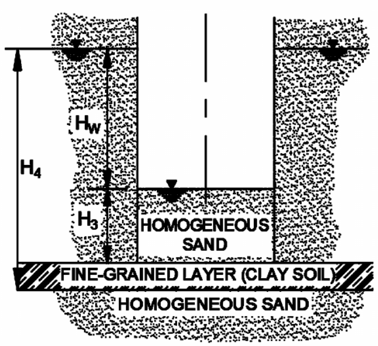



Fine-Grained Layer Within Homogenous Sand Stratum

If the top of the fine layer is at a depth greater than the excavation width below the depth of the cutoff wall, the safety factors for the homogenous case (in Figure 6-13) apply, assuming the impervious base is at the top of the fine layer.

If the top of the fine-grained layer is at a depth less than the excavation width below the depth of the cutoff, pressure relief is required so that the differential head ($H_w$) does not exceed the height of soil above the fine layer ($H_2$).

If the fine-grained layer lies above the final base of the excavation, the final condition is safer than the homogenous case. However, dangerous conditions may arise during excavation above the base of the fine layer and pressure relief may be required as outlined above.




To avoid bottom heave, the weight of the soil above the base of the fine layer ($\gamma_t \cdot H_3$) should be greater than the water pressure acting at the base of the fine-grained layer ($\gamma_w \cdot H_4$),

where:

$\gamma_t$ = the total unit weight of the soil

$\gamma_w$ = unit weight of water

**Figure 6-13 Corrections to Required Depth of Penetration of Cutoff Wall-Supported Excavations in Sand Containing Fine-Grained Layers (after Marsland 1953)**

# Sheet Piling

- A type of retaining wall that is:
  - Driven into the ground by driving or pushing
  - Has a relatively thin cross section
- Sheet piling first developed in late 1800's
- First major use in the raising of the *USS Maine* from Havana harbour

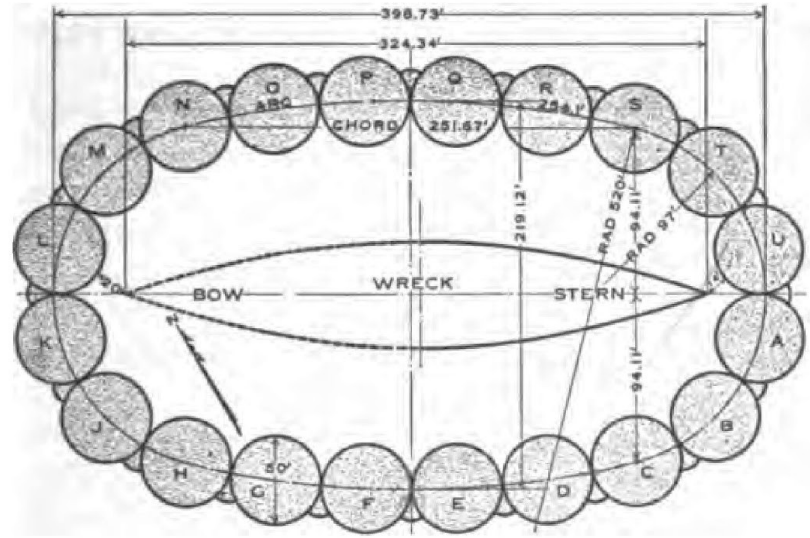



FIG 71e.—Plan of Cofferdam for Raising the "Maine."

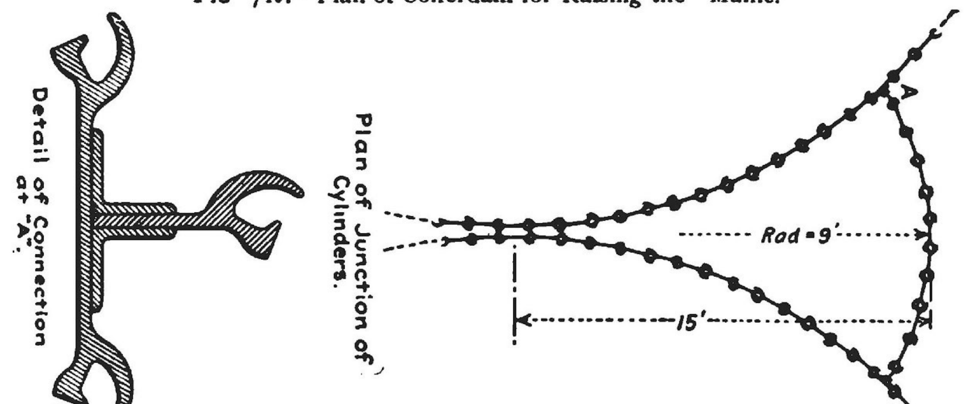



FIG. 71f.—Connection of Cofferdam Cylinders.

15

FIG. 71g.—Filling Clay into Cylinder *A*. Part of *B* in Foreground.

# Materials for Sheet Piling

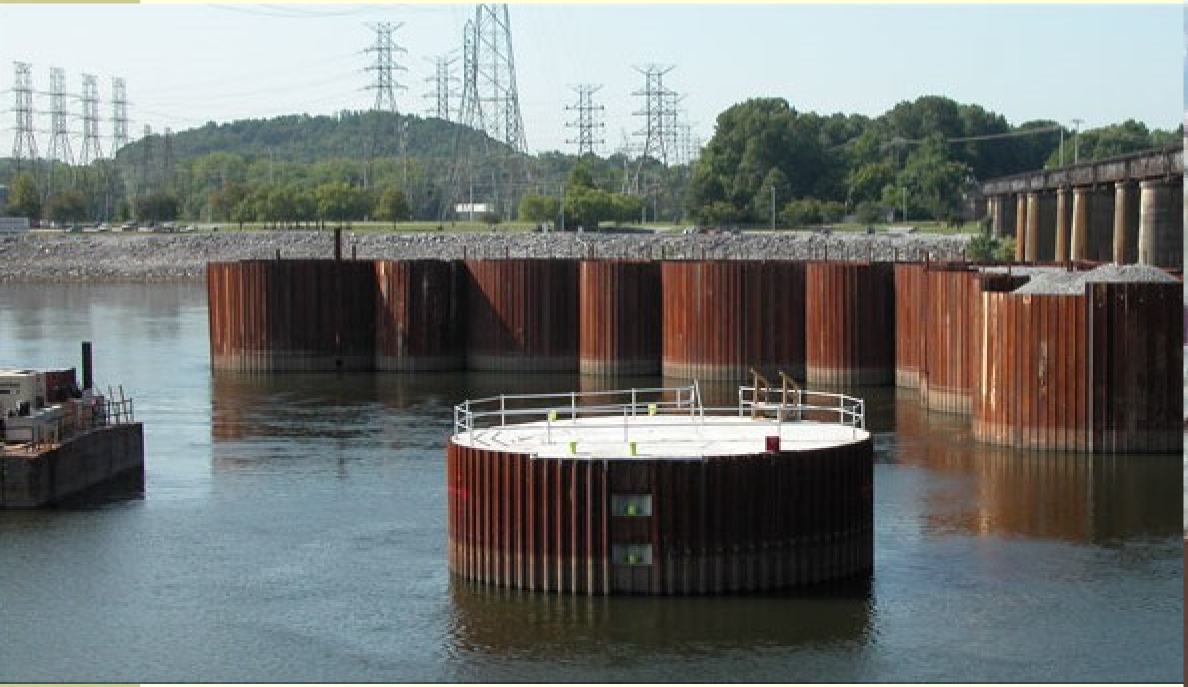
- Steel
  - Cold formed
  - Hot rolled
- Aluminium
  - Extruded
- Vinyl
  - Extruded
- Fibreglass
  - Pultruded
- Concrete
- Wood

# Sections of Sheet Piling

- Z-shaped sheeting
  - Popular in north America
  - Usually drive two at a time with split clamp
  - Wall stiffness developed with each sheet without assumed assistance from the interlocks
- U-shaped (similar to deep arch) sheeting (Larssen, etc.)
  - Very popular in Europe
  - Usually driven one at a time
  - Wall stiffness developed with two sheets and load transferred using the interlocks


Figure 9-16. Steel sheetpiling installation (from U. S. Army Engineer Waterways Experiment Station[57])

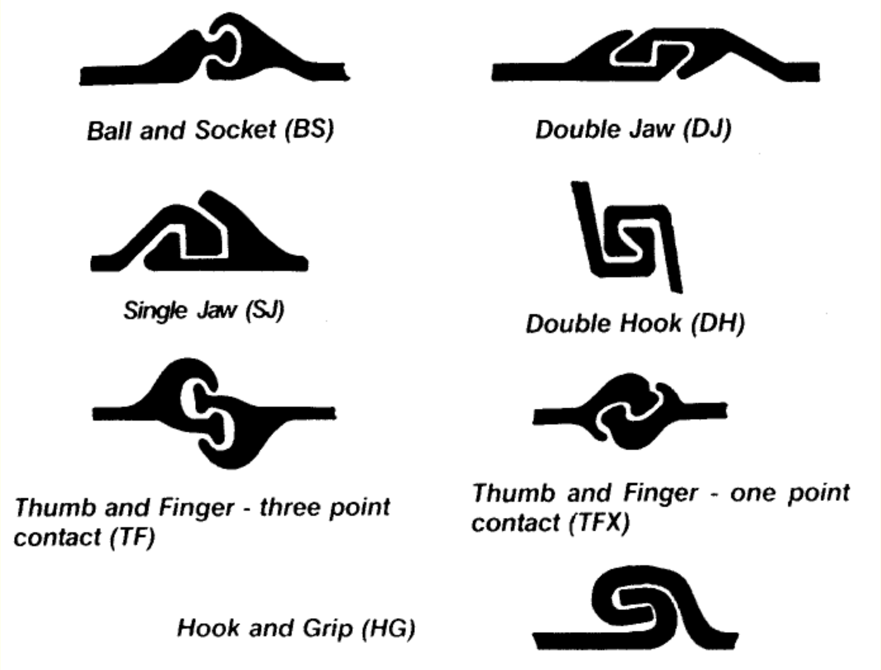
# Sections of Sheet Piling



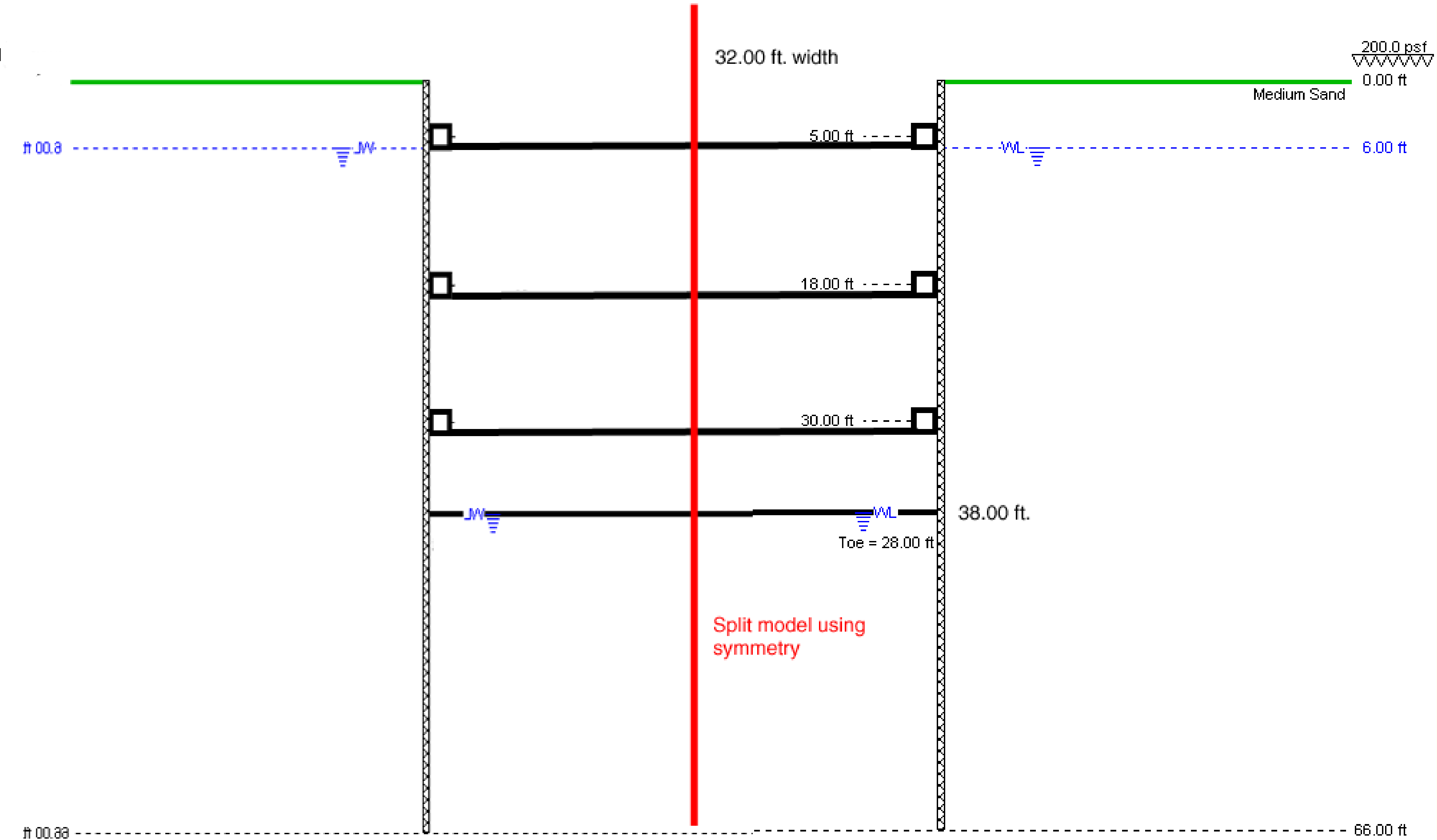
- Flat-web sheeting
  - Almost exclusively used for cellular cofferdams
  - Can be driven singly or two at a time
- Arched shaped
  - Used for shallower wall construction
  - Used in cold form steel and aluminium sheeting

# Interlock Styles

- Hot rolled and extruded sections
  - Ball and socket
  - Single or double jaw
  - Double hook
  - Thumb and finger
    - One point contact
    - Three point contact
- Cold formed sections
  - Hook and grip



# Flow Net and Soil Boiling Example



# Flow Net and Soil Boiling Example

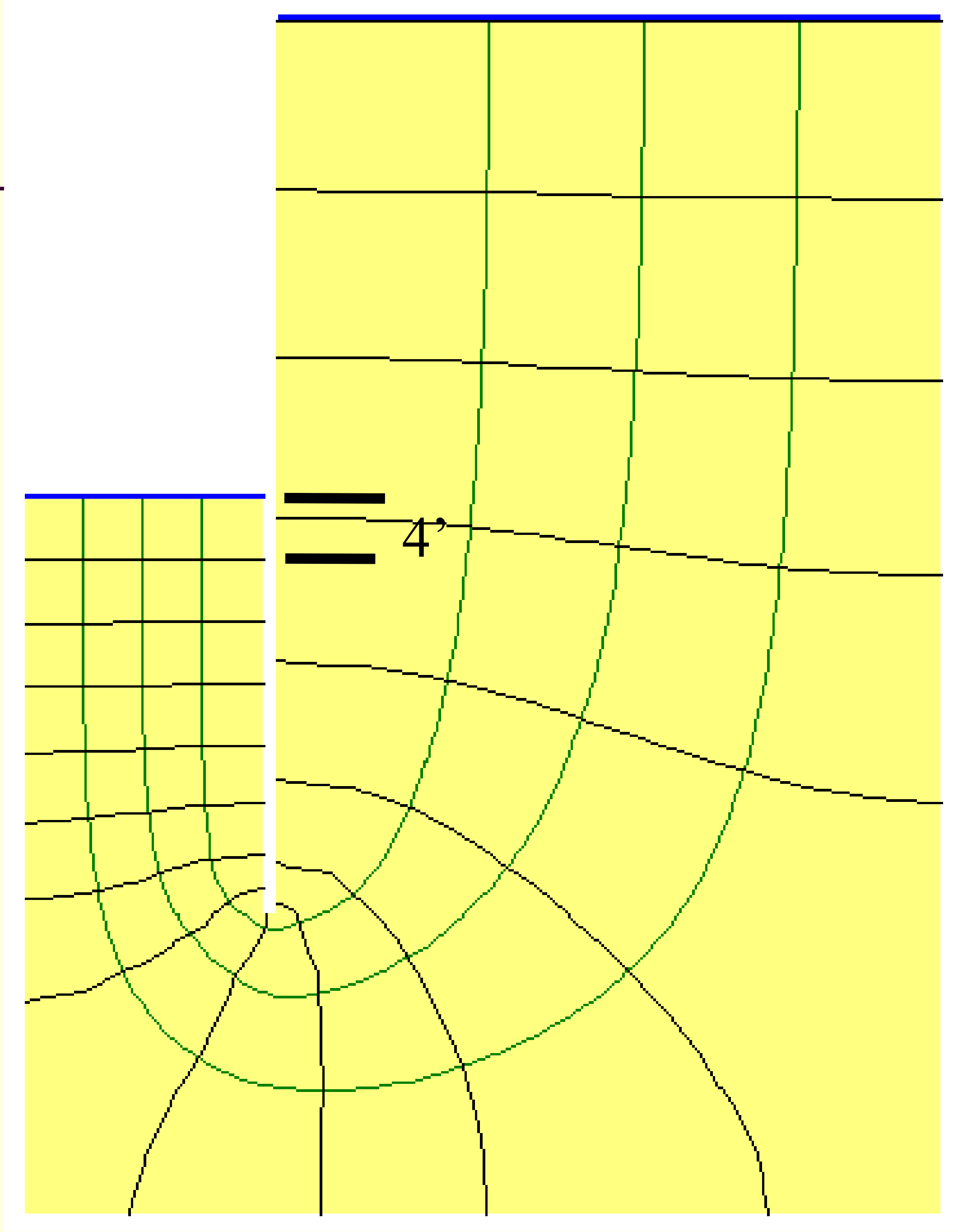
- Given
  - Braced Sheet Piling Excavation
    - Depth of excavation = 38'
    - Width of excavation = 32'
    - Impervious layer 20' below the toe of the sheeting
    - Length of Sheet Piling = 46'
    - Water table at the excavation level on the excavation side
    - Water table 6' below the top of the sheeting on the soil side
  - Soil Conditions
    - Uniform medium sand, k = 0.0003 ft/sec
    - Saturated Unit Weight = 115 pcf
- Find
  - Factor of safety against soil boiling

# Flow Net

- Flow net extends from one water table to another
- Number of equipotential drops = 16
- Number of flow tubes = 4
- "Aspect ratio" is essentially unity
- Flow Net Equation

$$q = k \cdot h_L \cdot \left( \frac{N_f}{N_d} \right) \cdot W$$

- Substitution of variables for flow
  - q = (0.0003)(32)(4/16)(1) = 0.0024 ft$^3$/sec/ft of wall = 1.08 gpm/ft of wall



# Hydraulic Gradient from Flow Net

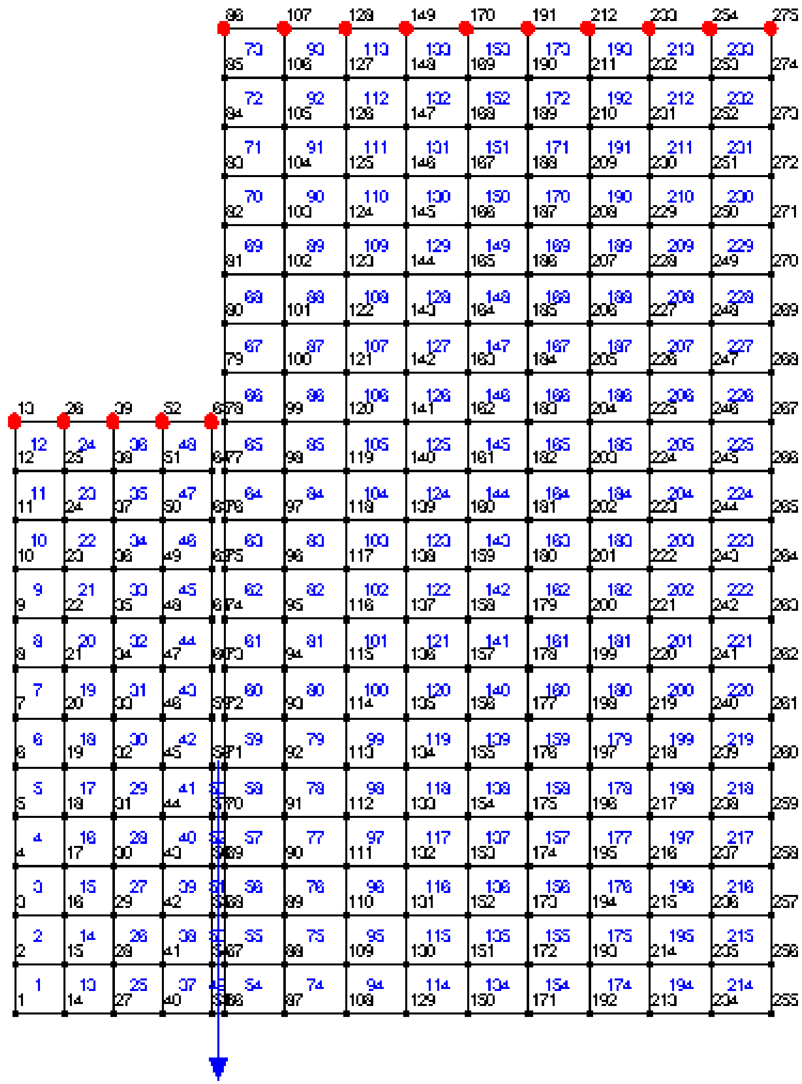
- Computation of Gradient
  - Total head change = 32’
  - Number of equipotential drops = 16
  - Head change per drop = 32’/16 = 2’
  - Length of the drops at the bottom of the excavation = 4’
  - Hydraulic gradient at the bottom of the excavation = 2’/4’ = 0.5
  - Critical hydraulic gradient = (115-62.4)/62.4 = 0.85
  - Factor of safety = 0.85/0.5 = 1.7

$$i = \Delta h/\Delta l$$

$$i_{critical} = 1 - \boldsymbol{\gamma}_{sat}/\boldsymbol{\gamma}_{w}$$

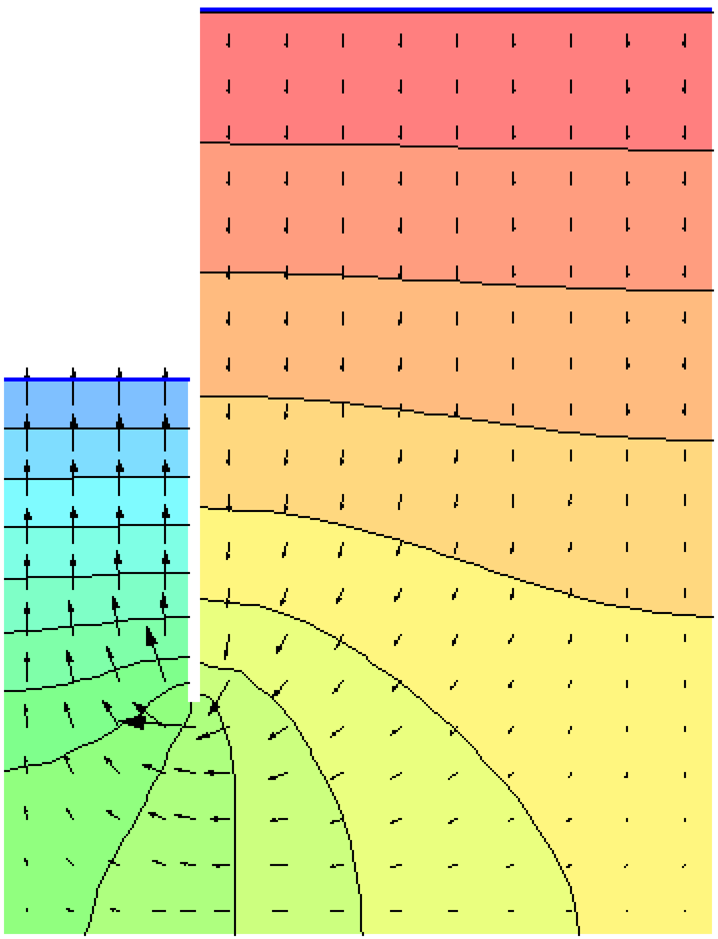
$$FS = i_{critical}/i_{imax}$$

# SEEP-W Model



# SEEP-W Model Results

Variation of Head



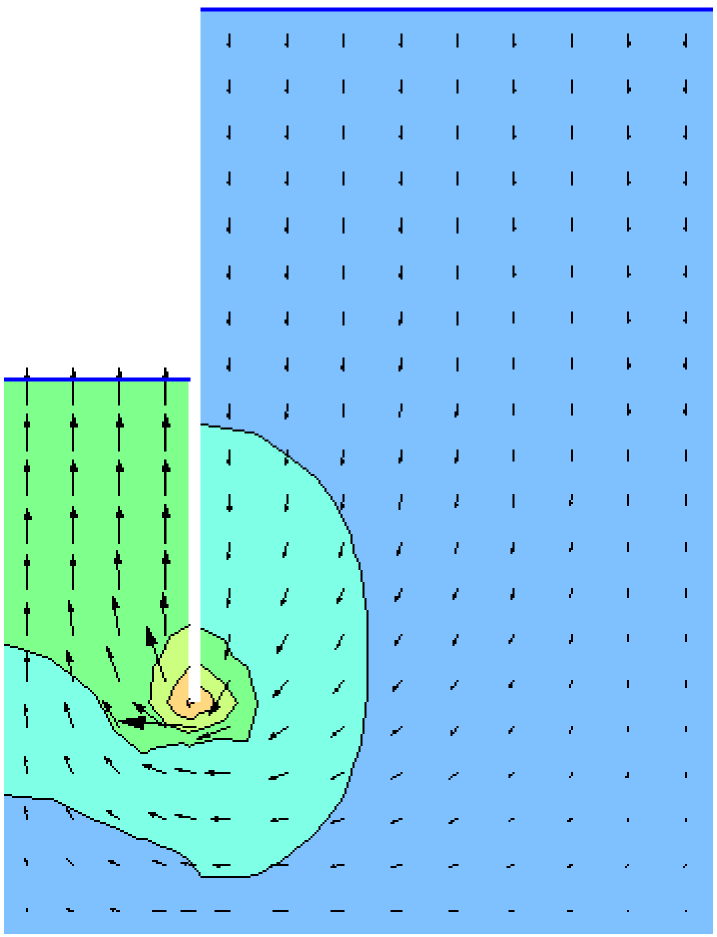
SEEP-W Results:

Gradient at bottom of excavation = 0.48

Factor of safety = 1.77

Total flow = 1.02 gpm/ft of wall

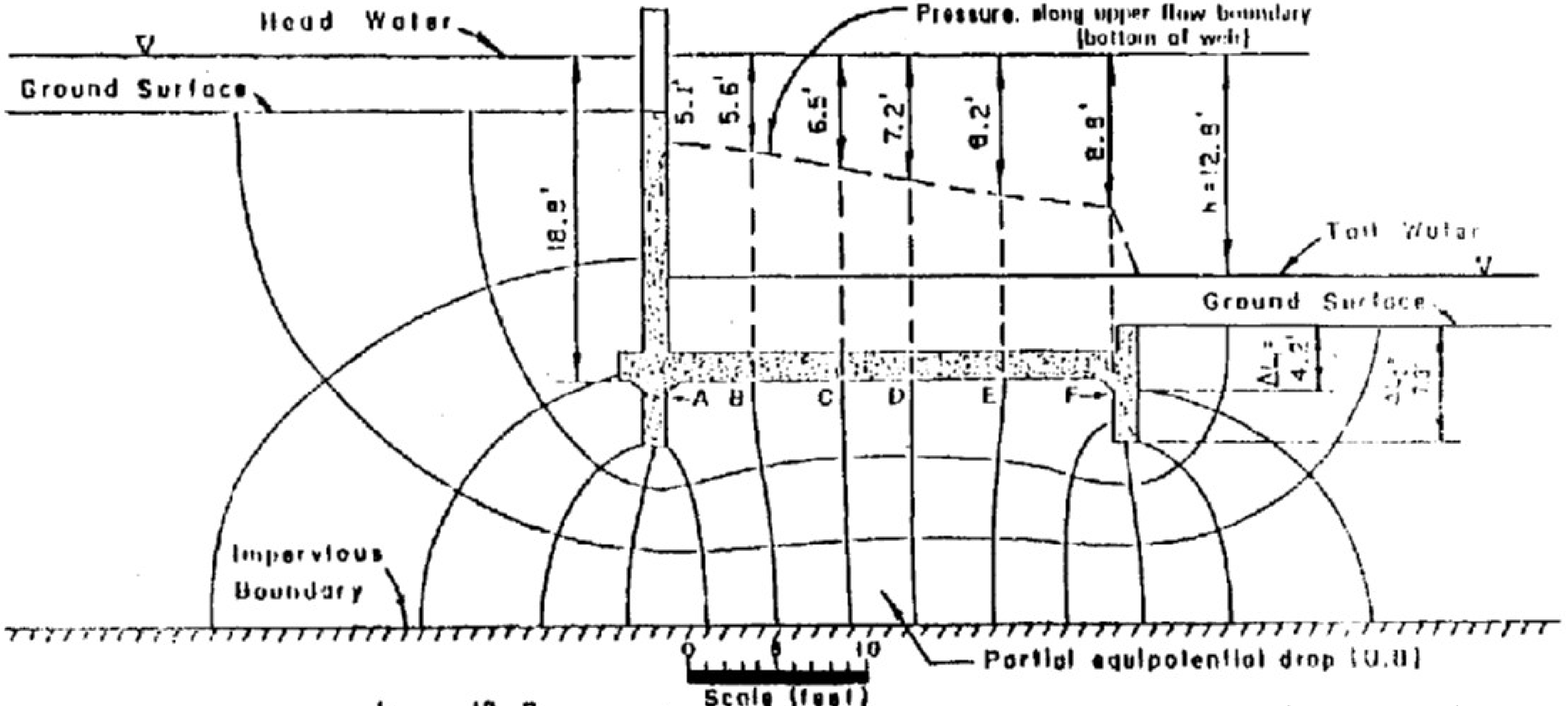
Gradient



# Additional Problem: Compute Effective Stress at Bottom of Element

- For Hydrostatic Case (comparison purposes)
  - $z = 4'$
  - $\sigma = (4)(115) = 460$ psf
  - $u = (4)(62.4) = 249.6$ psf
  - $\sigma' = 460 – 249.6 = 210.4$ psf
- Actual Case
  - $z = 4'$
  - $\sigma = (4)(115) = 460$ psf
  - $u = (4 + 2)(62.4) = 374.4$ psf
  - $\sigma' = 460 – 374.4 = 85.6$ psf
  - Difference due to additional head at base of element due to upward seepage

# Uplift Pressures and Flow Nets




$N_d = 13.8;\ \Delta h = \frac{h}{N_d} = \frac{12.8}{13.8} = 0.93'$

$$u = h_p \gamma_w = \left(h_t - h_z\right)\gamma_w$$

| Point designation | No. of drops to point | Head loss = ($\Delta h$ x No. drops) (ft.) | Uplift pressure (18.8' - hd. loss) $\gamma_w$ (p.s.f.) |
|---|---|---|---|
| A | 5.5 | 5.1 | 855 |
| B | 6 | 5.6 | 824 |
| C | 7 | 6.5 | 768 |
| D | 7.8 | 7.2 | 724 |
| E | 8.8 | 8.2 | 661 |
| F | 9.5 | 8.8 | 624 |

Escape gradient at toewall and transverse sill:

$$i_{e_1} = \frac{\Delta h}{\Delta L_1} = \frac{0.93}{4.2} = 0.22$$

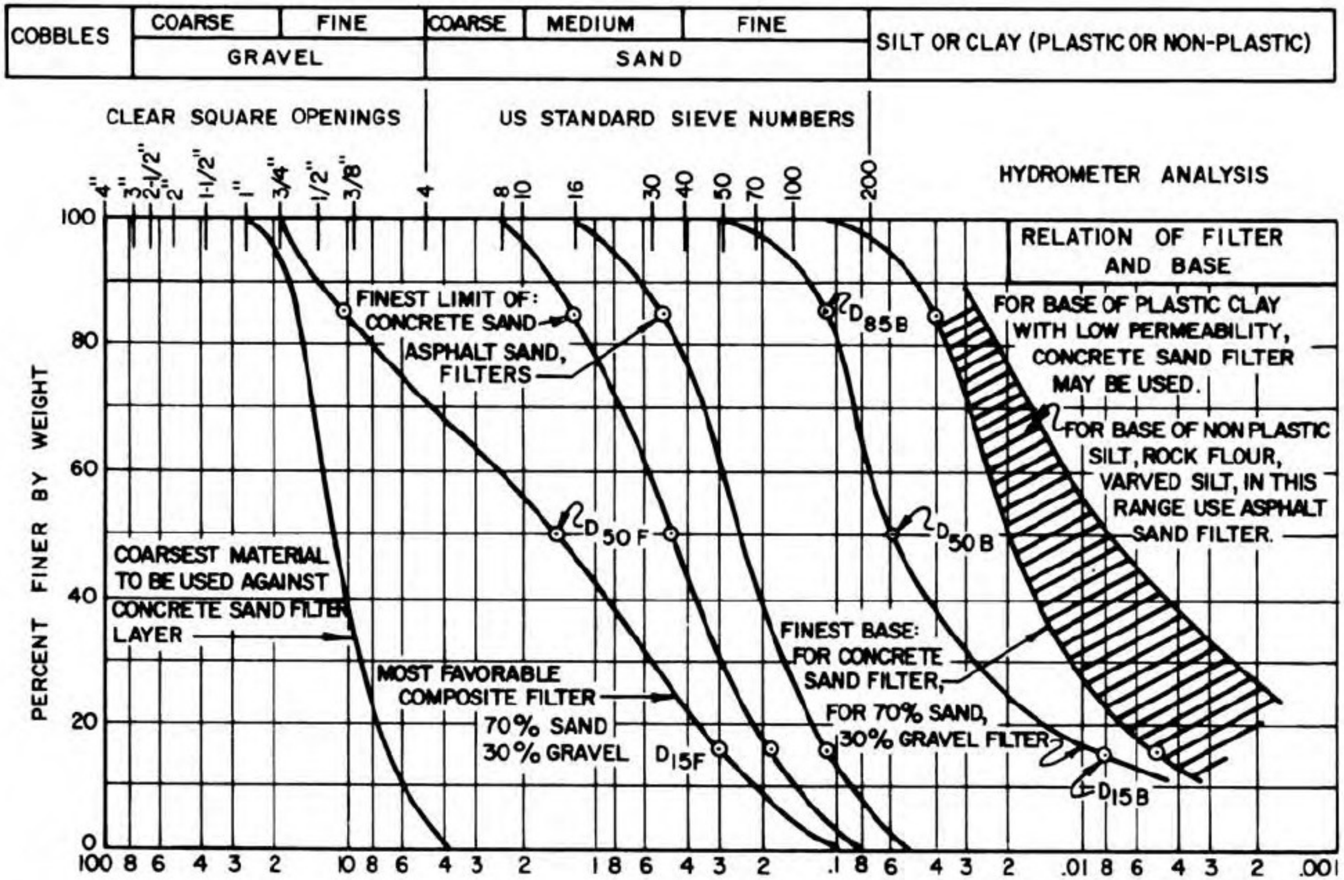
$$i_{e_2} = \frac{2\Delta h}{\Delta L_2} = \frac{1.86}{7.3} = 0.25$$

Figure 4-15. Base uplift and escape gradient for concrete drop spillway (from U. S. Department of Agriculture[123])

# Filters

- If water flows from a silt to a gravel, the silt will wash into the interstices of the gravel. This could lead to the following, which must be avoided:
  - The loss of silt may continue, causing creation of a cavity.
  - The silt may clog the gravel, stopping flow, and causing hydrostatic pressure buildup.
- The purpose of filters is to allow water to pass freely across the interface (filter must be coarse enough to avoid head loss ) but still be sufficiently fine to prevent the migration of fines.
- The filter particles must be durable, e.g., certain crushed limestones may dissolve.
- In addition to soil filters, geotextiles are commonly used

# Filter Material Requirements



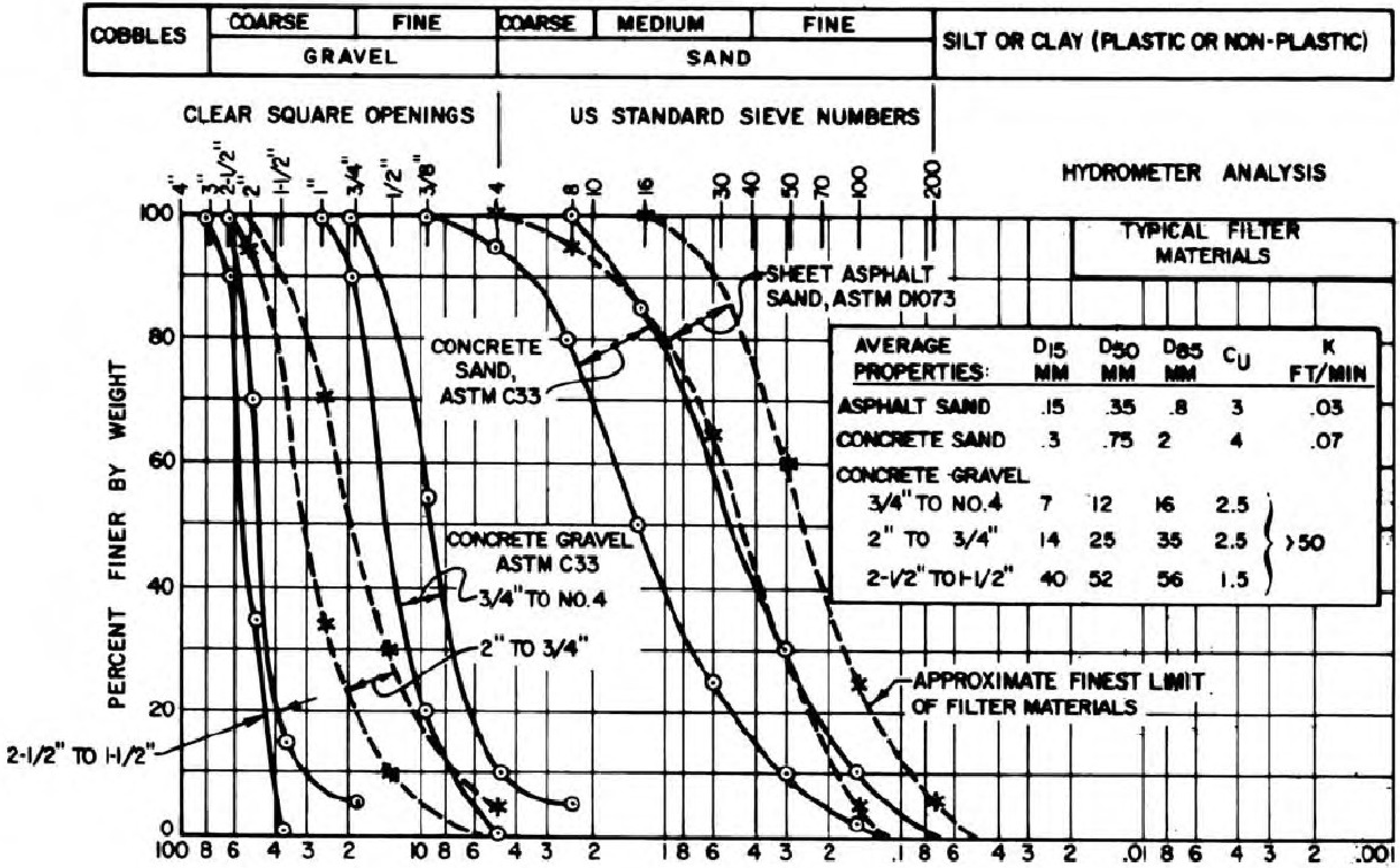

GENERAL REQUIREMENTS:

1. TO AVOID HEAD LOSS IN FILTER: $\frac{D_{15F}}{D_{15B}} > 4$, AND PERMEABILITY OF FILTER MUST BE LARGE ENOUGH TO SUFFICE FOR PARTICULAR DRAINAGE SYSTEM
2. TO AVOID MOVEMENT OF PARTICLES FROM BASE: $\frac{D_{15F}}{D_{85B}} < 5$, $\frac{D_{50F}}{D_{50B}} < 25$, $\frac{D_{15F}}{D_{15B}} < 20$

   FOR VERY UNIFORM BASE MATERIAL ($C_u < 1.5$): $D_{15F}/D_{85B}$ MAY BE INCREASED TO 6

   FOR BROADLY GRADED BASE MATERIAL ($C_u > 4$): $D_{15F}/D_{15B}$ MAY BE INCREASED TO 40
3. TO AVOID MOVEMENT OF FILTER IN DRAIN PIPE PERFORATIONS OR JOINTS: $D_{85F}$/SLOT WIDTH > (1.2 TO 1.4), $D_{85F}$/HOLE DIAMETER > (1.0 TO 1.2)
4. TO AVOID SEGREGATION, FILTER SHOULD CONTAIN NO SIZES LARGE THAN 3".
5. TO AVOID INTERNAL MOVEMENT OF FINES, FILTER SHOULD HAVE NO MORE THAN 5% PASSING No. 200 SIEVE.

# Filter Materials




| AVERAGE PROPERTIES: | $D_{15}$ MM | $D_{50}$ MM | $D_{85}$ MM | $C_U$ | K FT/MIN |
|---|---|---|---|---|---|
| ASPHALT SAND | .15 | .35 | .8 | 3 | .03 |
| CONCRETE SAND | .3 | .75 | 2 | 4 | .07 |
| CONCRETE GRAVEL | | | | | |
| 3/4" TO NO. 4 | 7 | 12 | 16 | 2.5 | >50 |
| 2" TO 3/4" | 14 | 25 | 35 | 2.5 | |
| 2-1/2" TO 1-1/2" | 40 | 52 | 56 | 1.5 | |

# Questions?