Module 4: Water in soils (part 3)

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Spring 2022

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COURSE CONTENTS AND SCHEDULE

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Tentative schedule

Day	Date	Topic	Lab.
W	1/19/2022	Class introduction, syllabus, policies	Soil
F	1/21/2022	Invited speaker: Topic TBD	components
M	1/24/2022	Introduction: The geological cycle, soil origin	Grain size
W	1/26/2022	Introduction: Site investigation	dist.
F	1/28/2022	Index properties: Phase relationships	
M	1/31/2022	Index properties: Grain size distribution, Atterberg limits	Atterberg
W	2/2/2022	Index properties: Soil classification	limits
F	2/4/2022	Compaction	
M	2/7/2022	Quiz 1: Introduction, index properties, compaction, in-situ testing	Visual
W	2/9/2022	Water in soils: Groundawater table, pore pressure, total and effective stresses	classification
F	2/11/2022	Water in soils: Darcy's law	
M	2/14/2022	Water in soils: Permeability and hydraulic conductivity	Compaction
W	2/16/2022	Water in soils: One-dimensional seepage	
F	2/18/2022	Water in soils: 2D-3D seepage, flow nets, pore pressure, uplift force, seepage force	
M	2/21/2022	President's day: no class	In-situ
W	2/23/2022	Water in soils: piping	density
F	2/24/2022	Quiz 2: Water in soils	
M	2/28/2022	Induced stress: Approximations, Bousinesq's elastic solution	Permeability
W	3/2/2022	Induced stress: Bousinesq's elastic solution, superposition	
F	3/4/2022	Induced stress: Stress tensor, elastic deformations	
M	3/7/2022	Consolidation: Oedometer test, primary and secondary consolidation	Site
W	3/9/2022	Consolidation: Preconsolidation pressure, OCR	investigation
F	3/11/2022	Consolidation: Primary consolidation parameters	
M	3/14/2022	Spring break: no class	
W	3/16/2022	Spring break: no class	
F	3/18/2022	Spring break: no class	
M	3/21/2022	Consolidation: rate of consolidation	Bonus
W	3/23/2022	Consolidation: preloading, radial consolidation	
F	3/25/2022	Quiz 3: Induced stress and consolidaiton	
M	3/28/2022	State of stress: 2D stresses and Mohr's circle	Consolidation
W	3/30/2022	State of stress: principal stresses, stress invariants, rotations	
F	4/1/2022	State of stress:: Usage of Mohr's circle	
M	4/4/2022	State of stress: stress paths, simple shear, triaxial compression	Settlement
W	4/6/2022	Quiz 4: State of stress	estimates
F	4/8/2022	Shear strength: Mohr-Coulomb failure criteria	
M	4/11/2022	Shear strength: drained and undrained behavior	Unconfined
W	4/13/2022	Shear strength: Shear strength of clays	compression
F	4/15/2022	Shear strength: Shear strength of sands	test
M	4/18/2022	Quiz 5: Shear strength	Direct
W	4/20/2022	Lateral earth pressure: at-rest, passive, and active conditions [2]	shear
F	4/22/2022	Intro to slope stability [2]	
M	4/25/2022	Intro to bearing capacity [2]	Direct
W	4/27/2022	Maine's day: no class	shear
F	4/29/2022	Classes end: Q&A session	
M	5/2/2022	Final exam (1:30 PM- 3:30 PM) Williams Hall 110	

M: Monday - W: Wednesday - F: Friday

[2]This items may or may not be covered. It will be determined by how far the course has progressed.

RECAP

- We learned about 1D flow in porous media.
- We learned about Darcy's law and the permeability of soils.
- We learned about measuring the permeability of soils.
- We learned how to determine the equivalent permeability of soils.
- Today we will learn about 2D and 3D flow trough soils.

CONTENTS

- Mass balance and Laplace equation.
- Flow nets.
- Uplift pressure.
- Seepage erosion and piping
- Solutions if erosion is a potential problem.

More in chapter 7 of Holtz et al. (2013)

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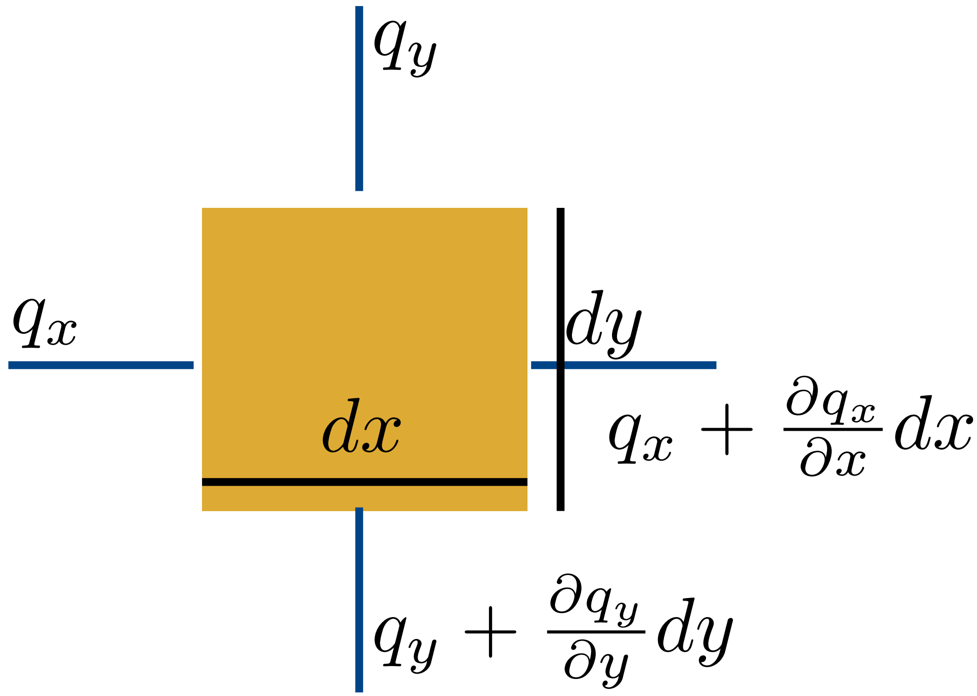
MASS BALANCE AND LAPLACE EQUATION



- Laplace equation:

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

- Assumptions:
  1. Incompressible fluid
  2. Incompressible soil particles and skeleton
  3. Isotropic permeability
  4. Soil is homogenious
  5. Darcy's law is valid

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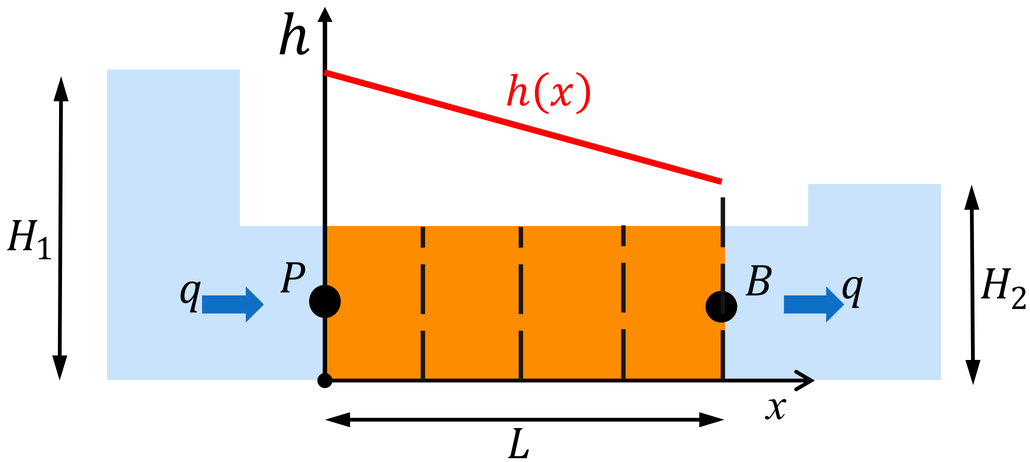
LAPLACE EQUATION

Solution of the Laplace equation: $$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \longrightarrow h(x,y)$$

- For 1D flow: $$\frac{\partial^2 h}{\partial x^2} = 0 \longrightarrow h(x) = ax + b$$



Boundary conditions:

$x = 0 \ \rightarrow h_P = H_1$

$x = L \ \rightarrow h_B = H_2$

$$\boxed{h(x) = \frac{H_2 - H_1}{L} x + H_1}$$

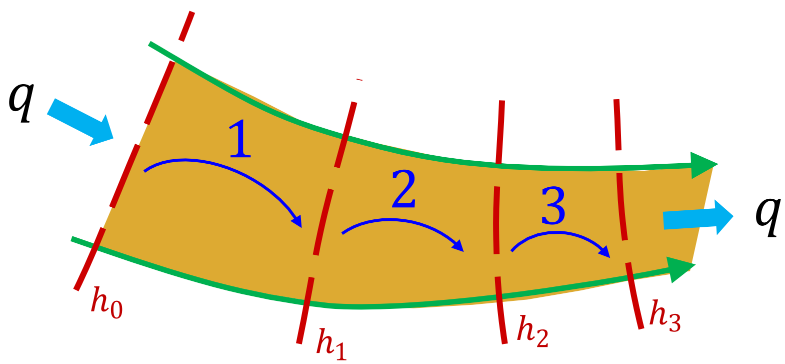
- For 2D/3D flow solve numerically or using FLOW NETS

FLOW NETS

- Graphical solution to the Laplace equation.
- Real advantage in 2D flow (in 1D we already have analytical solution).
- Reminder : what we really want is to know the total head (h) at any point of the domain (x, y).

Definitions:

- Equipotential lines: contours of constant total head (h=$constant$).
- Flow lines: indicate the direction of the water flow.
- Flow tube: area defined between two any adjacent flow lines.
- Total head drop: decrease in total head between two adjacent equipotential lines.



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RULES FOR DRAWING A FLOW NET

- Intersections of flow lines with equipotential lines are perpendicular , hence each cell in a flow net should be "as squared as possible ."
- "Entrance " and "exit " boundaries are (usually) equipotential lines.
- Impervious boundaries are flow lines.
- Flow nets are drawn only in porous media, never in "free" water.
- You will need many iterations , so use a pencil (never a pen!).
- Flow lines can never cross .

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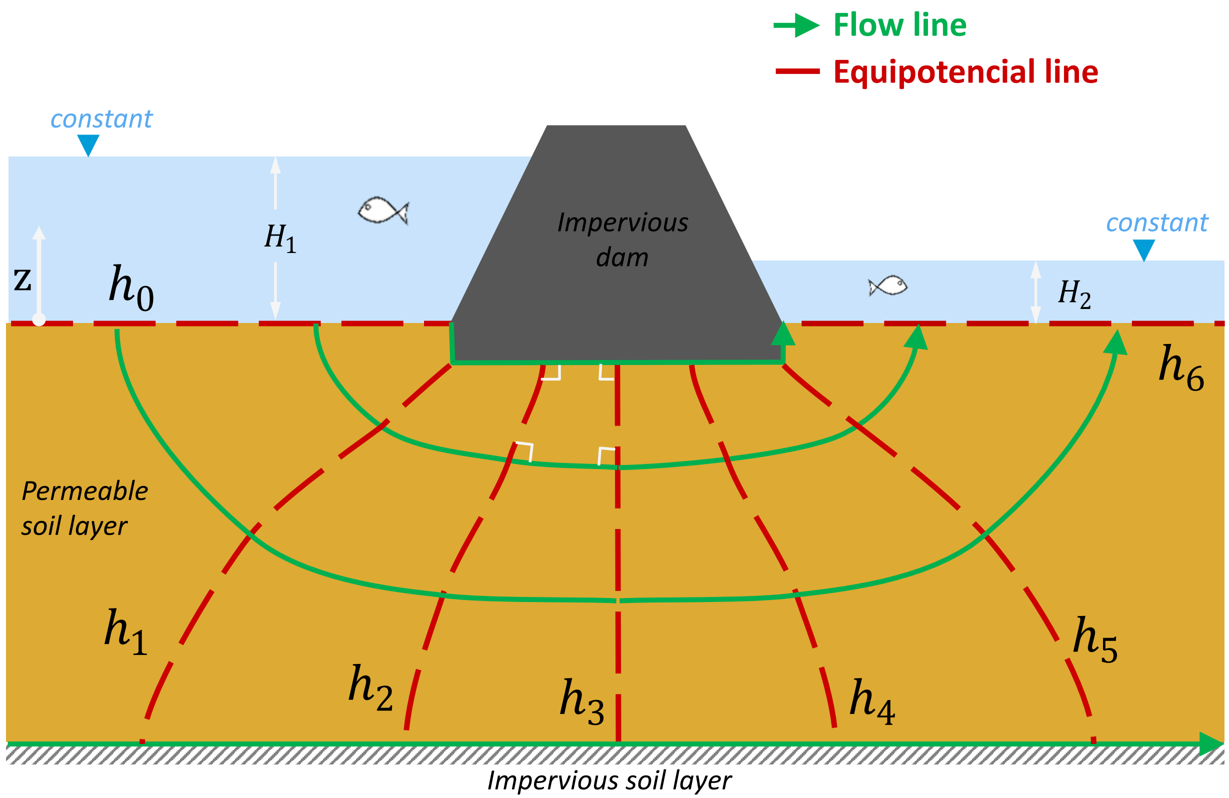
FLOW NET



$$h_{entrance} = h_0 = H_1$$
$$h_{exit} = h_6 = H_2$$

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FLOW NET

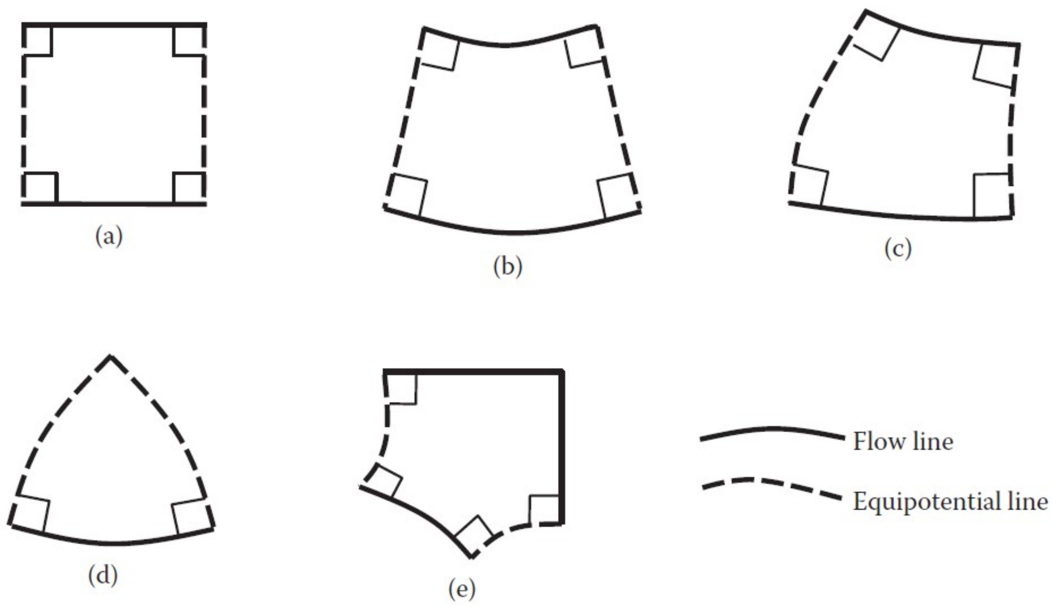
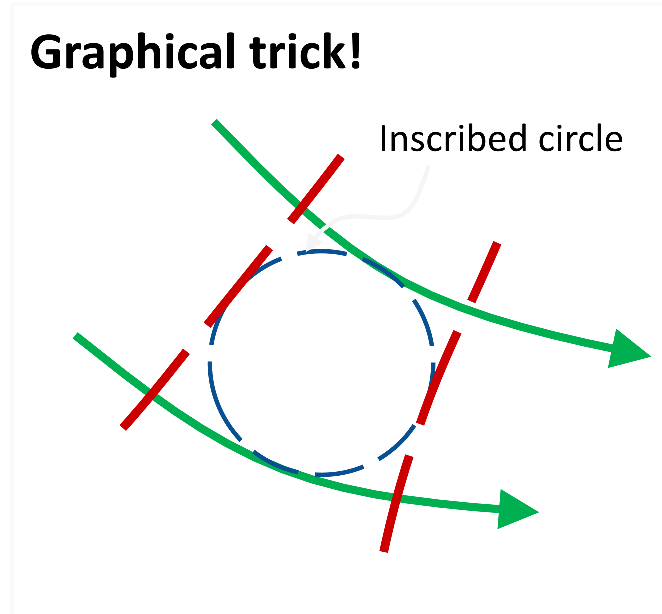


FIGURE 6.11 Acceptable near-squares in flow net construction.

From: *Soil Mechanics Fundamentals and Applications by Ishibashi and Hazarika*



EXAMPLES

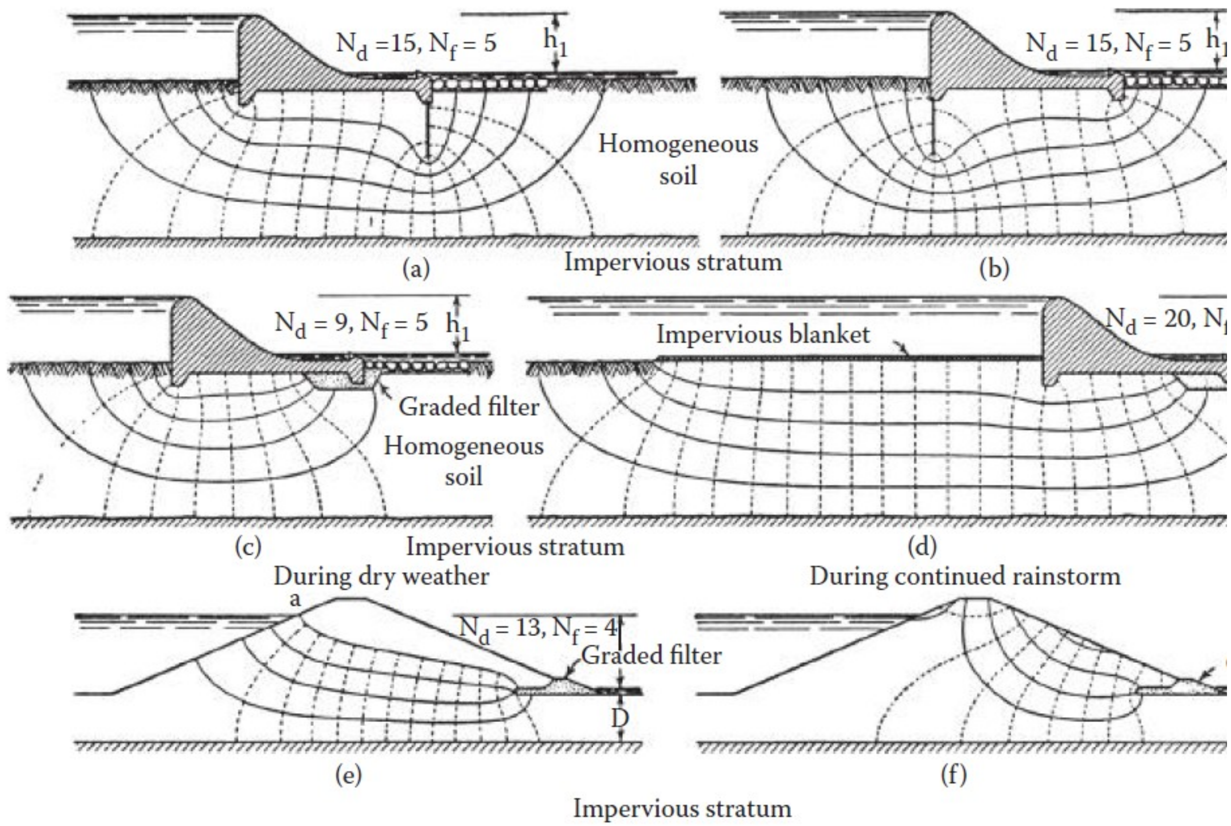
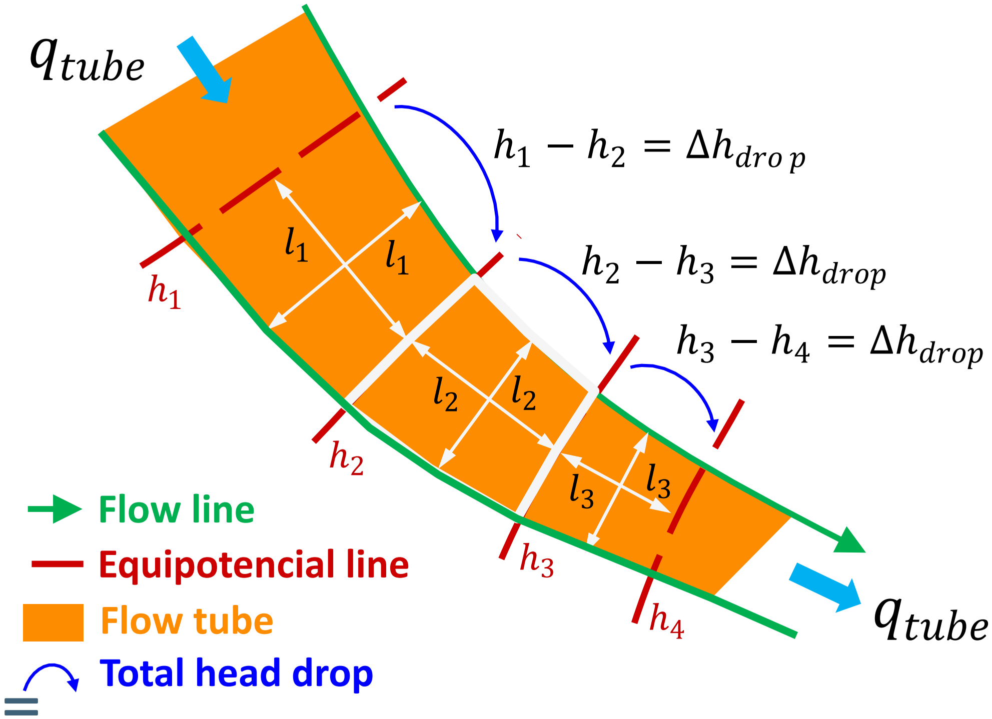


FIGURE 6.13 Examples of flow net for dams. (From ***Terzaghi, K., 1943,*** *Theor*
Mechanics. John Wiley & Sons. New York.)

FLOW NETS

If the flow net is sketched properly, the following rules will apply:

- The flow within a flow tube is constant ($q =$ constant).
- The decrease in total head in each drop is constant ($\Delta h_d =$ constant).



$$q = k\Delta H \frac{N_f}{N_d}$$

- $\Delta H =$ Total head loss between entrance and exit of problem.
- $N_f =$ number of flow channels.
- $N_d =$ number of drop heads.

FLOW NETS

How to solve a flow net exercise:

1. Plot the flow net following all the rues.
2. Determine the number of flow lines and tubes , number of equipotential lines and drops .
3. Label all equipotential lines and determine the total head at the entrance and exit quipotential lines .
4. Determine $\Delta H = h_{entrance} - h_{exit}$ and $\Delta h_d = \Delta H / N_d$
5. You are now able to determine h at any point of your geometry base on its position in the flow net.
6. You can now determine the pore pressure at any point using the total head equation $u = (h - z)\gamma_w$.
7. You can also determine the flow rate for any tube or the entire problem.

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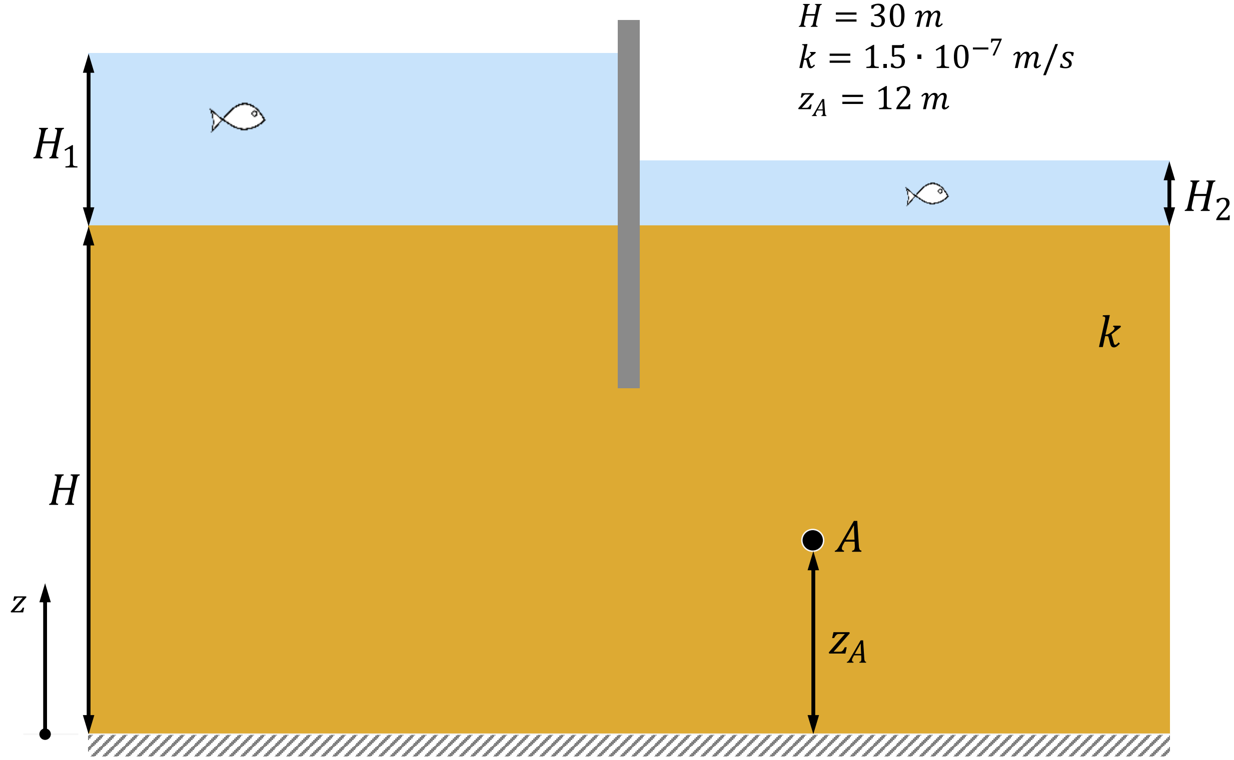
EXAMPLE 4.5

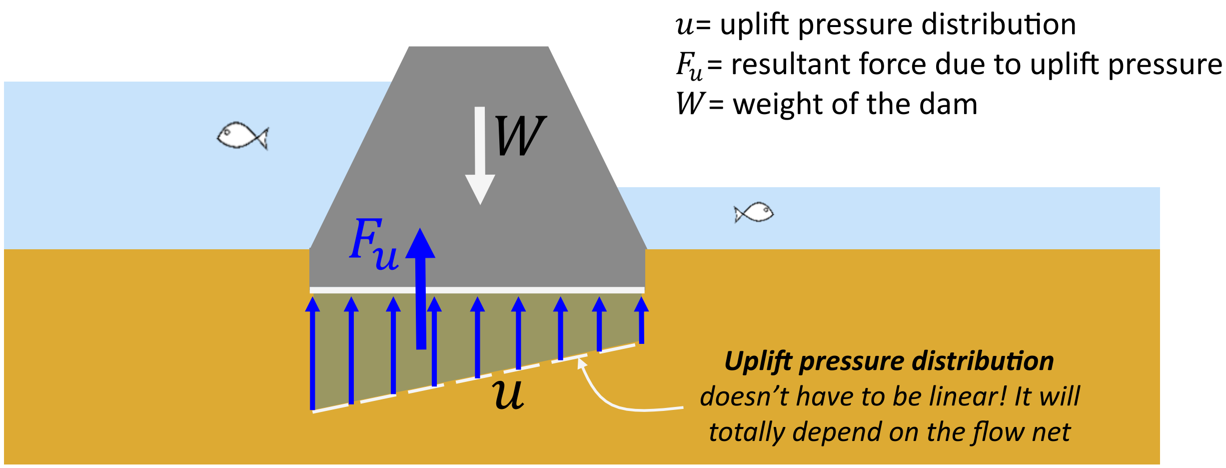
Example: Flow around sheet pile wall

Data:
$H_1 = 10\ m$
$H_2 = 3\ m$
$H = 30\ m$
$k = 1.5 \cdot 10^{-7}\ m/s$
$z_A = 12\ m$



UPLIFT PRESSURE

- Water pressure (u) along the base of a dam is referred to as uplift pressure .
- Uplift pressure can make the dam unstable ! $\longrightarrow$ Important to ensure the stability of the structure.
- Recall that water pressure acts in all directions. In practice we use the perpendicular component to the surface.



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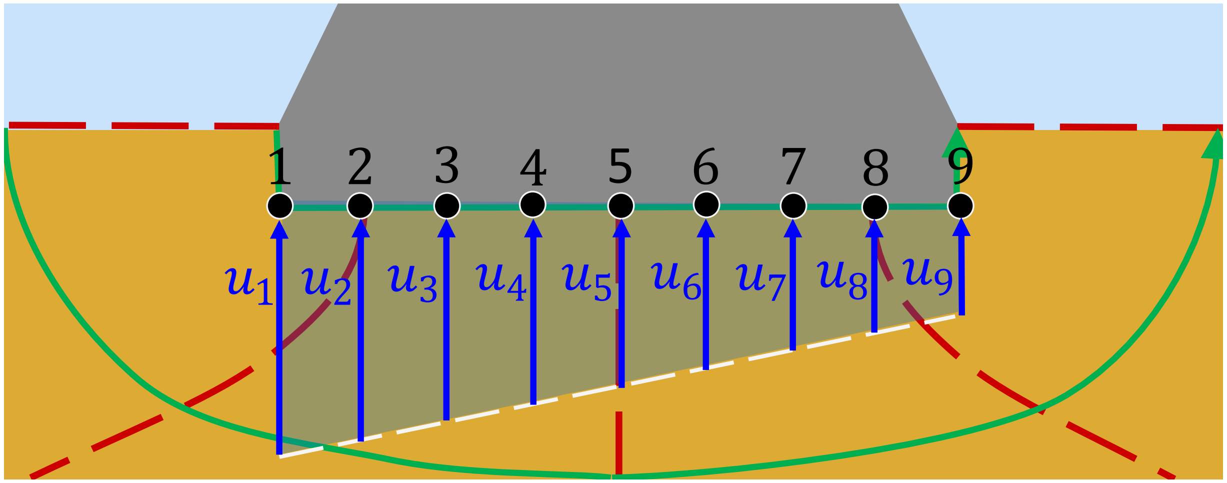
UPLIFT PRESSURE

Steps to determine uplift pressure distribution: (also applicable to any surface type)

1. Plot the flow net.
2. Distribute a certain number of points along the surface of interest.
3. Determine the pore water pressure at each selected point.
4. Plot the pore pressure distribution.
5. Finally, compute the area of the pressure distribution.



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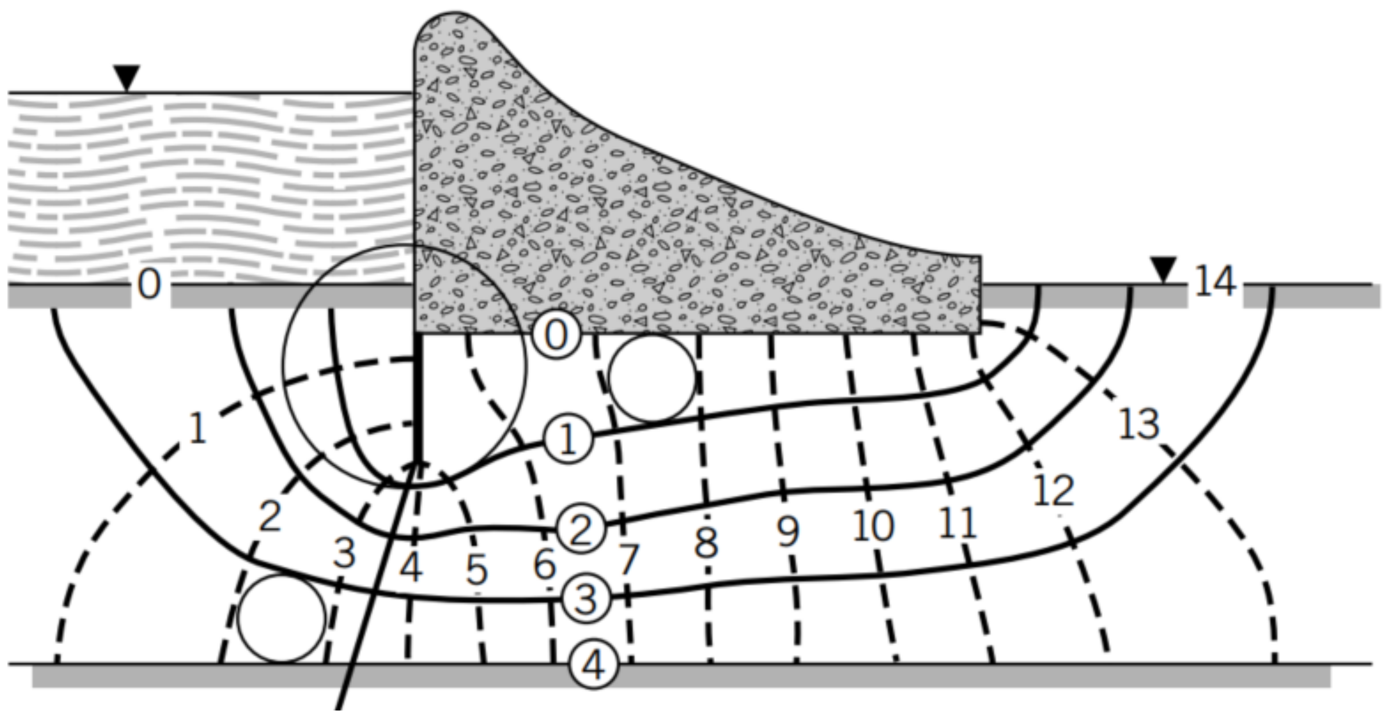
EXAMPLE 4.6

For the example in the figure, find the uplift force and the factor of safety against uplift if the dam weights 2500 kN



EORSION DUE TO SEEPAGE

Erosion: mobilization of solid grains due to watr flow (seepage forces).

Recall: In this course we have seen that the soil strength depends directly on the contacts beyween solid grains. The effective stress quantifies contact forces. If solid particles are not in contact, soil becomes a fluid with no shear resistance.

If $\sigma' = 0$, there is no contact between solid grains, soil becomes internally unstable , and grains can be dragged away.

Stable: $\sigma' > 0$ Unstable: $\sigma' = 0$

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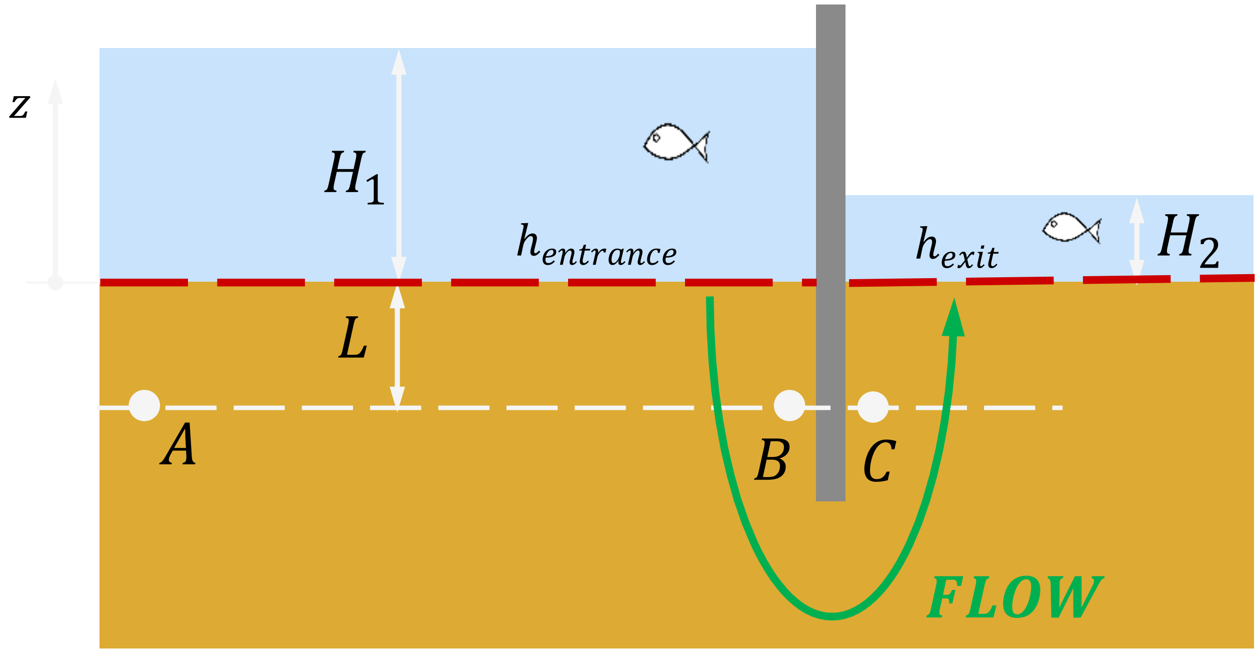
EROSION DUE TO SEEPAGE

- Scenario A: No flow
- Scenario B: Downward flow
- Scenario C: Upward flow

Assumptions:

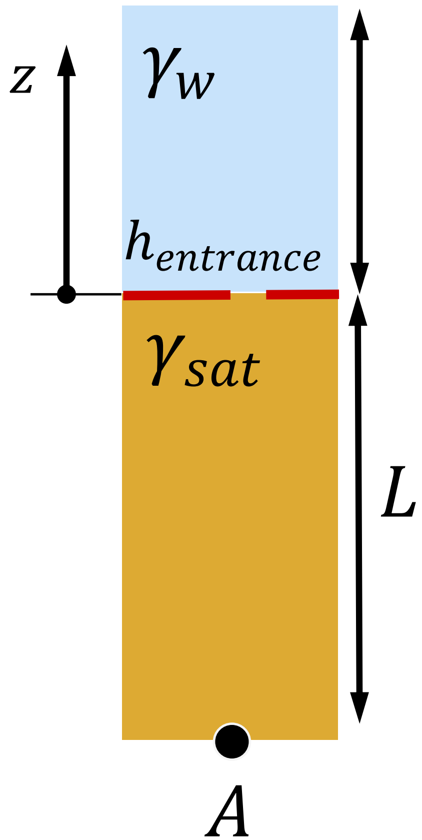
- 1D vertical flow
- Horizontal direction is stable



$$h_{entrance} = H_1$$

$$h_{exit} = H_2$$

EROSION DUE TO SEEPAGE



No flow

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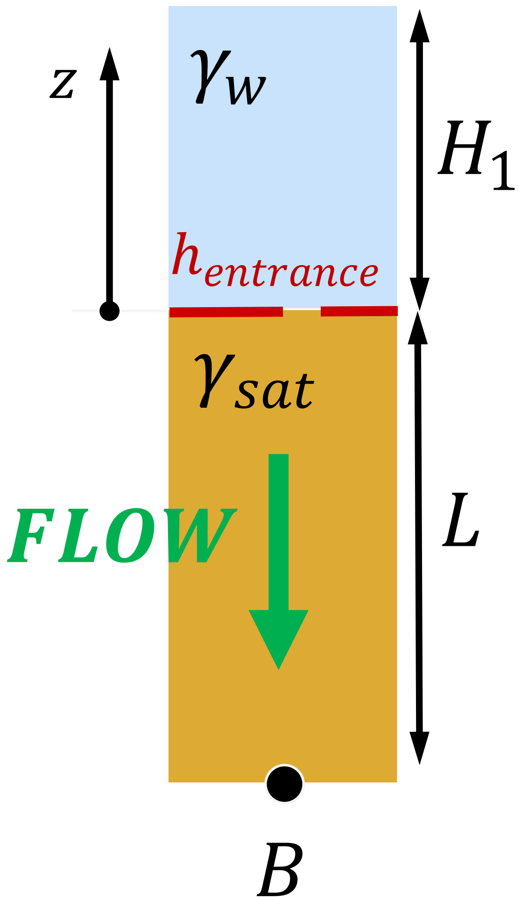
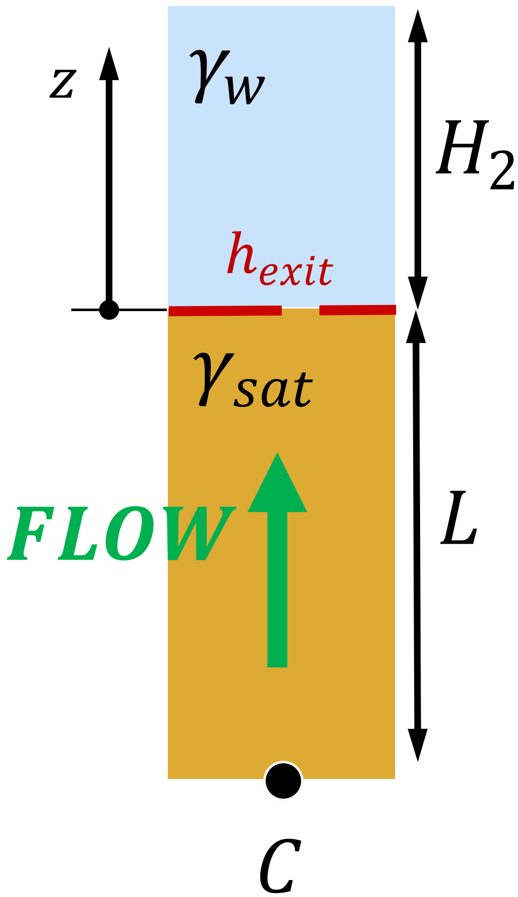
EROSION DUE TO SEEPAGE



Downward flow

EROSION DUE TO SEEPAGE



Upward flow

$$i_{crit} = \frac{\gamma'}{\gamma_w} = \frac{G_s - 1}{1 + e}$$

Factor of safety againts piping:

$$FS = \frac{i_{crit}}{i_{max}}$$

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EROSION DUE TO SEEPAGE

- Erosion will start if $FS \leq 1$.
- It is important to identify what "element" in a flow net has the maximun hydraulic gradient .
- Erosion (also called piping) usually begins at downstream side (upwardflow).
- Because the total head drop is constant between equipotentials, the size of elements control the hydraulic gradient $\longrightarrow$ Smaller elements will have larger hydraulic gradients .

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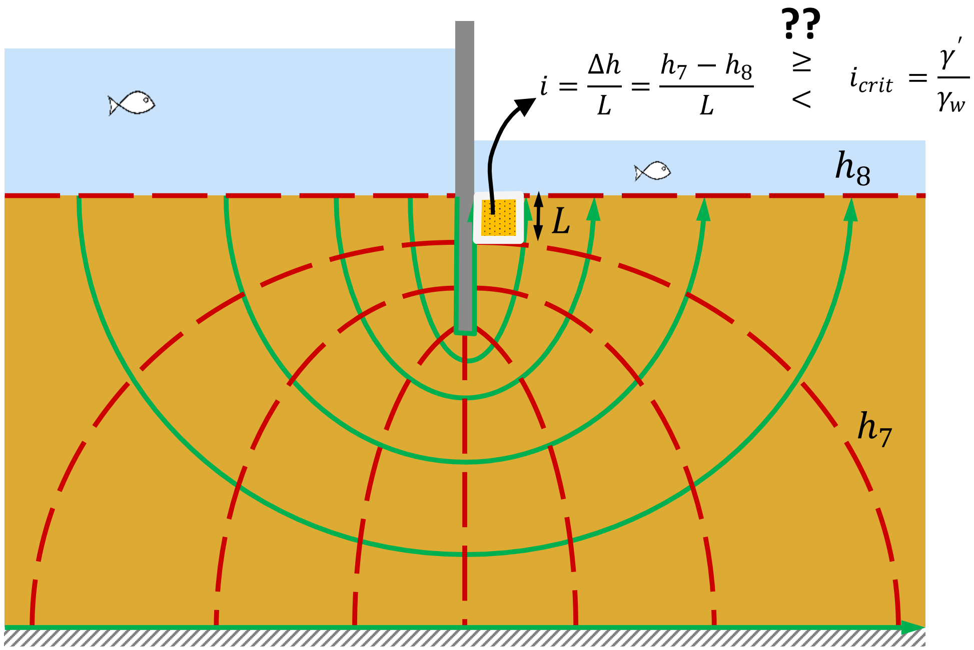
EXAMPLE 4.7

For the example in the figure, determine the factor of safety against piping knowing $G_s = 2.65$ and $\gamma_{sat} = 15.2\ \mathrm{kN/m^3}$



EROSION DUE TO SEEPAGE

1. Lower the upstream water level.

$$\downarrow H_1 \longrightarrow \downarrow \Delta h \longrightarrow \downarrow i$$

2. Place a filter material downstream (increase weight downstream).
3. Increase the length of the flow.

$$\uparrow L \longrightarrow \downarrow i$$

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