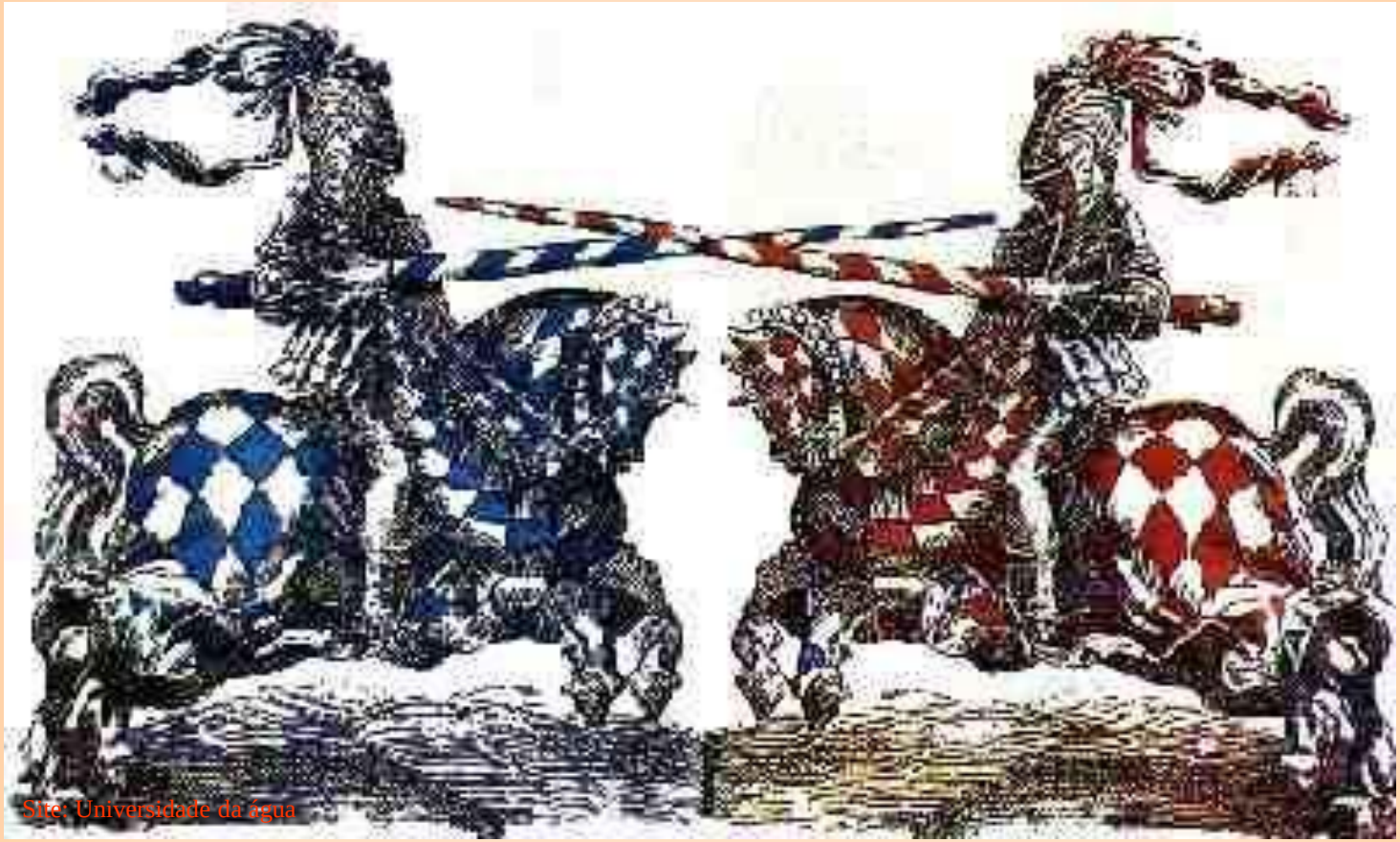
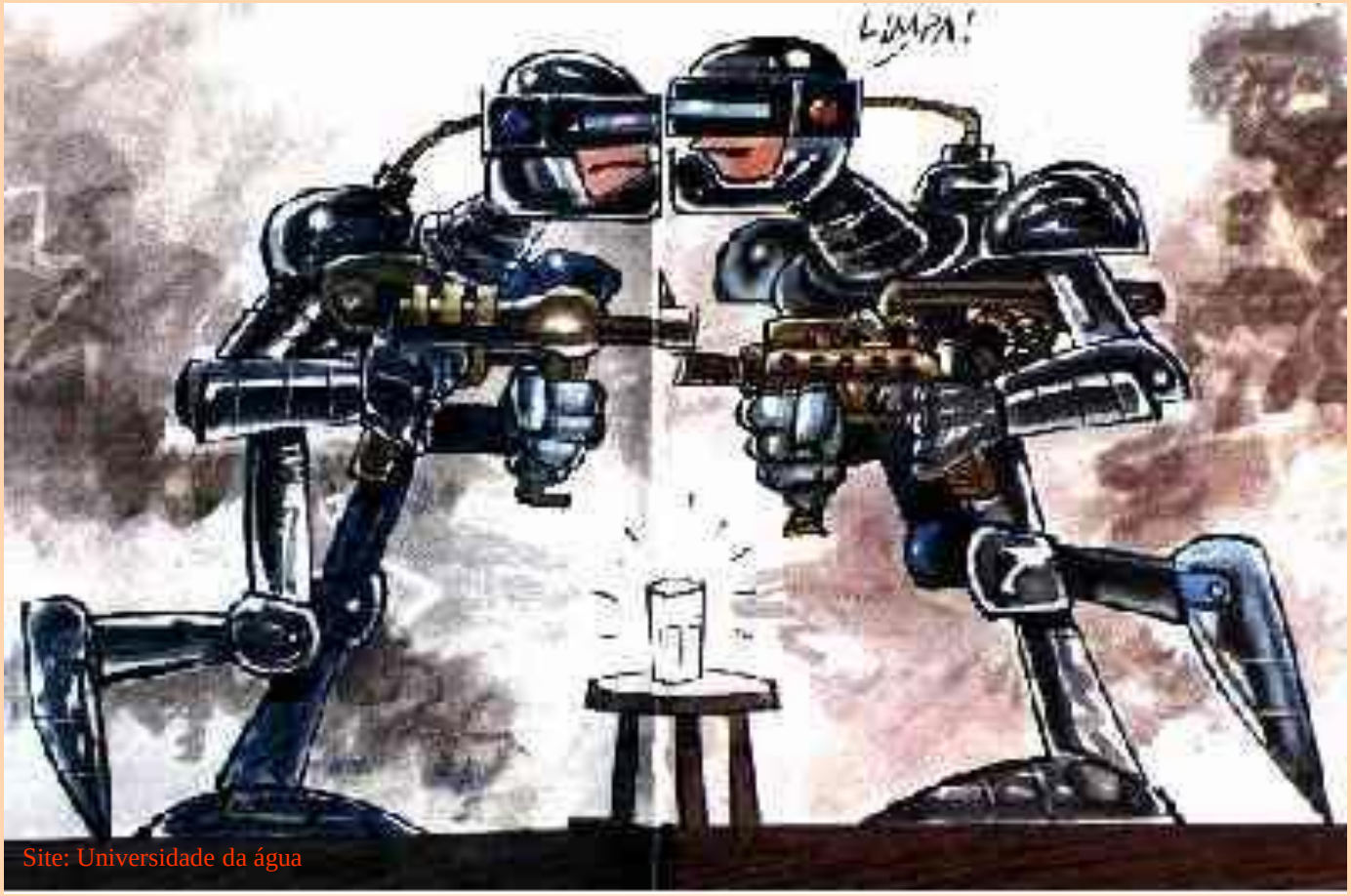
Fluxo em meios porosos



Fernando A. M. Marinho



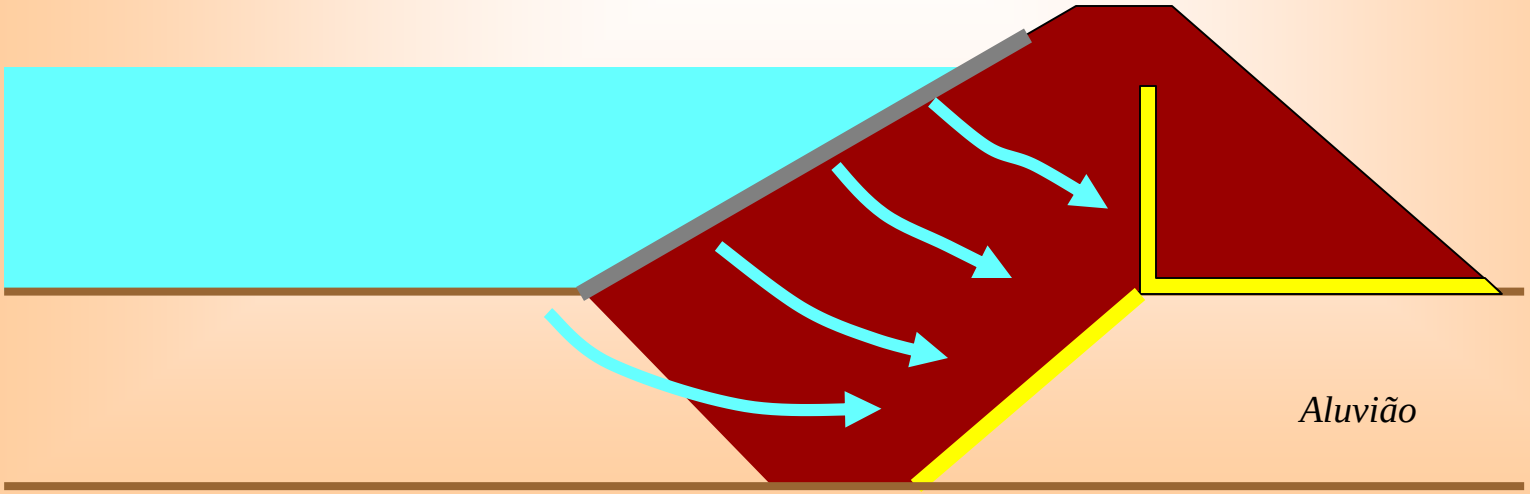
Antigamente faziam-se guerras para conquistar terras



Em breve vamos guerrear por um pouquinho de água... LIMPA



Barragem de Paraitinga



Esquemático



Barragem do Funil - RJ









Objetivos dos Estudos de Fluxo

- Estimar a vazão
- Determinar os gradientes
- Determinar a distribuição de pressão neutra
- Avaliar estabilidade de taludes
- Entender as variações de tensão efetiva

A equação de balanço de massa pode ser expressa da seguinte forma:

$$\sum E + \sum G - \sum S - \sum P = \sum A$$

Onde:
E = Entrada
G = Geração
S = Saída
P = Perdas
A = Acumulação

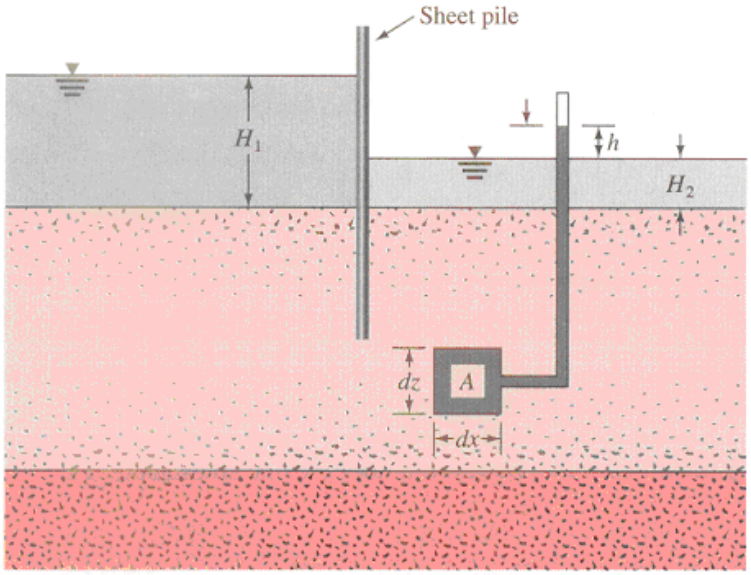
Expressão semelhante à do estudo dos permeâmetros, que impunha que a vazão de entrada fosse igual à vazão de saída

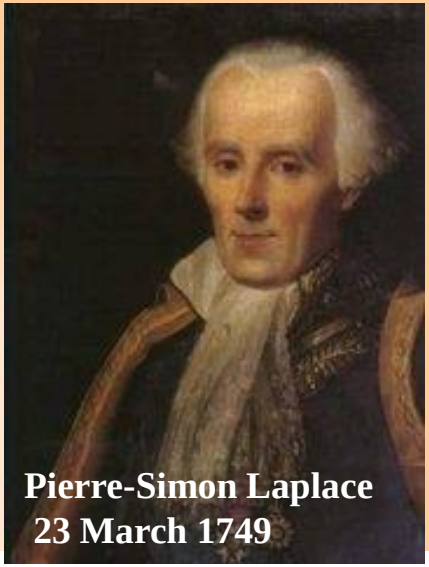
Quando o regime é permanente temos que:

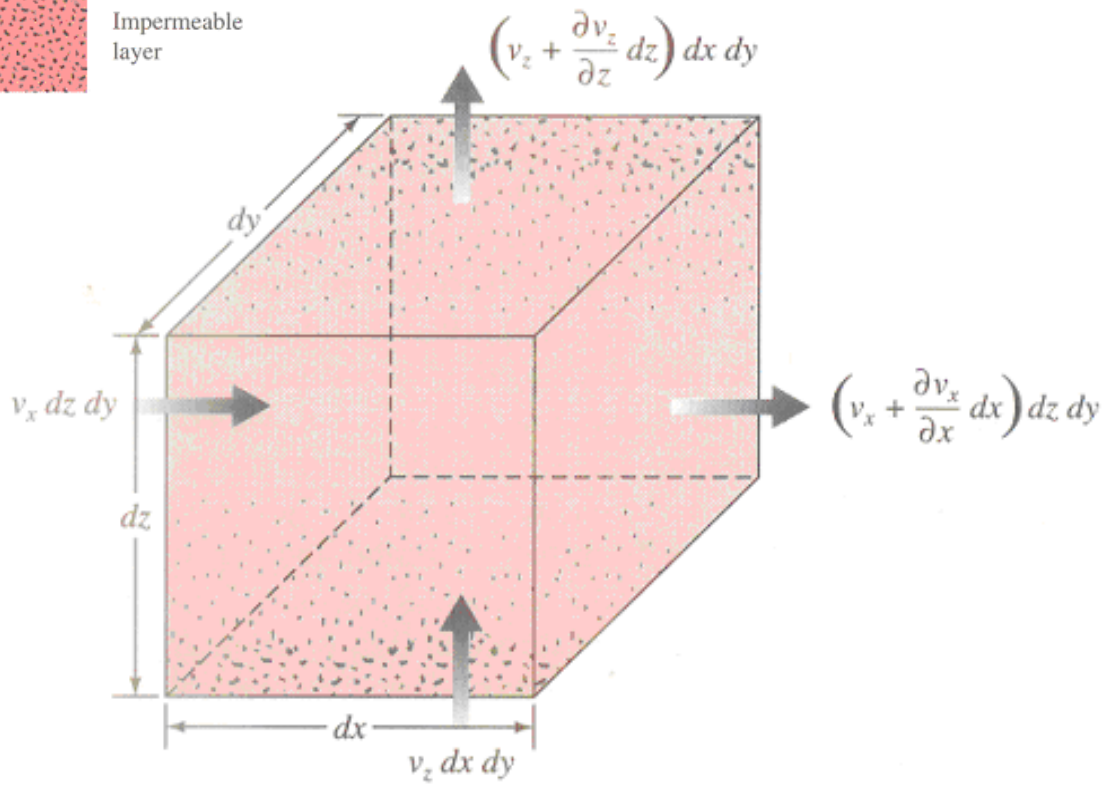
$$\sum A = 0$$
$$\sum G = 0$$
$$\sum P = 0$$

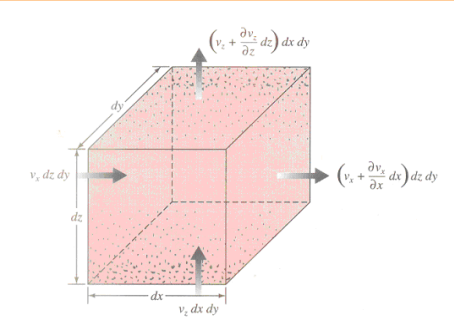
Logo: $\sum E + \sum S = 0$

Equação de Laplace




Pierre-Simon Laplace
23 March 1749





$$\left[\left(v_x+\frac{\partial v_x}{\partial x}\right)dzdy+\left(v_z+\frac{\partial v_z}{\partial z}\right)dxdy\right]=\left[v_x dzdy+v_z dxdy\right]$$

$$OU$$

$$\left[\frac{\partial v_x}{\partial x}+\frac{\partial v_z}{\partial z}\right]=0$$

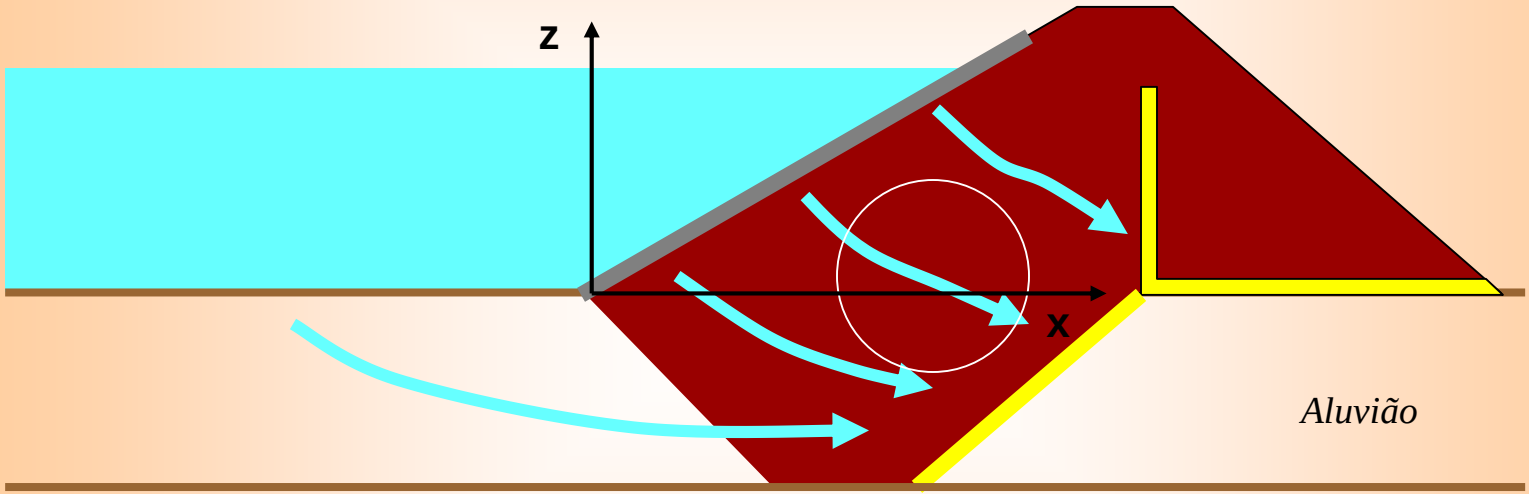
Aplicando a Lei de Darcy temos que:

$$v_x=-k_x i_x=-k_x\frac{\partial h}{\partial x}$$

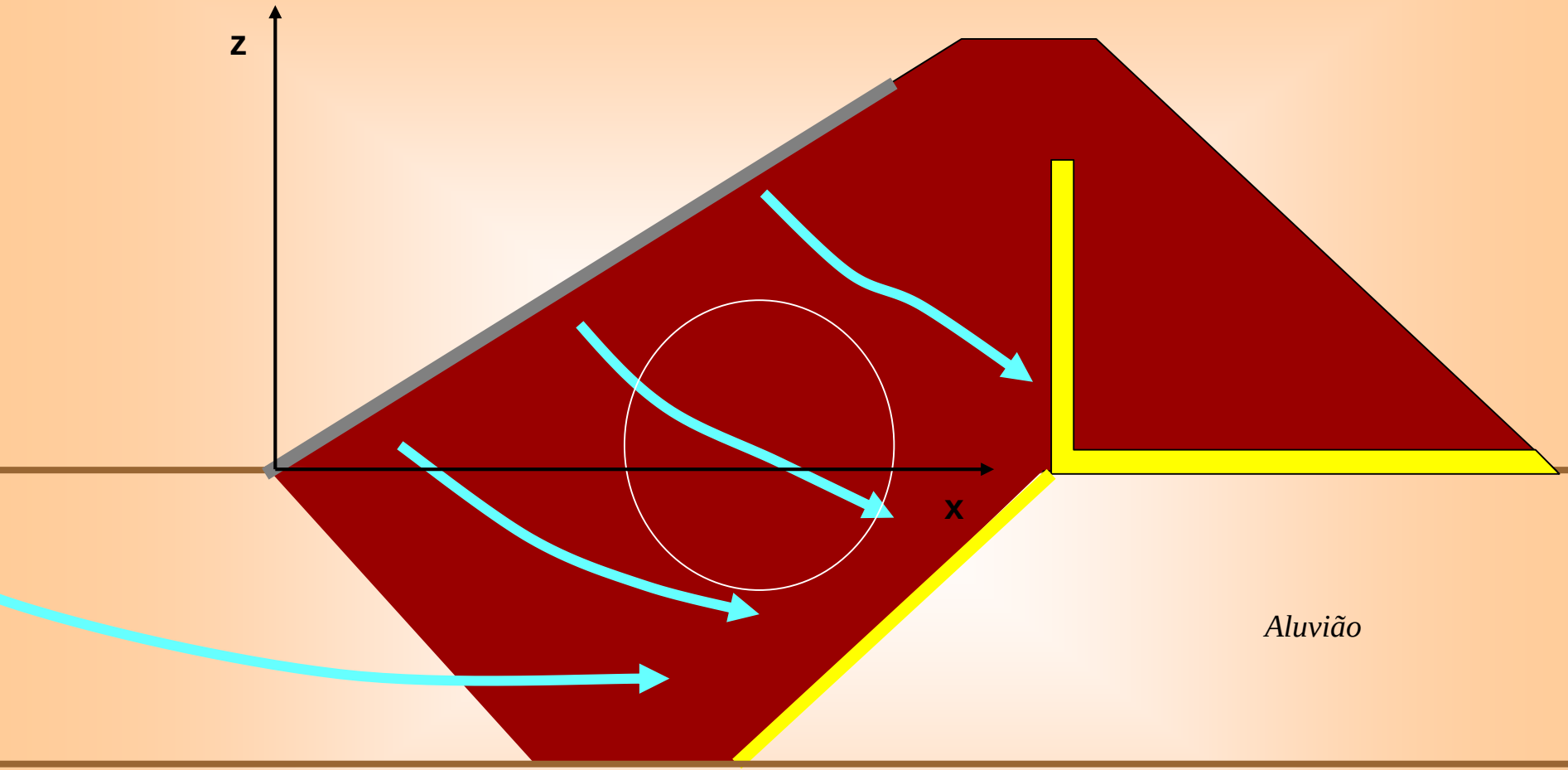
$$v_z=-k_z i_z=-k_z\frac{\partial h}{\partial z}$$

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

Se o solo é isotrópico em termos de condutividade hidráulica $k_x = k_z$



Esquemático


z
x
Aluvião

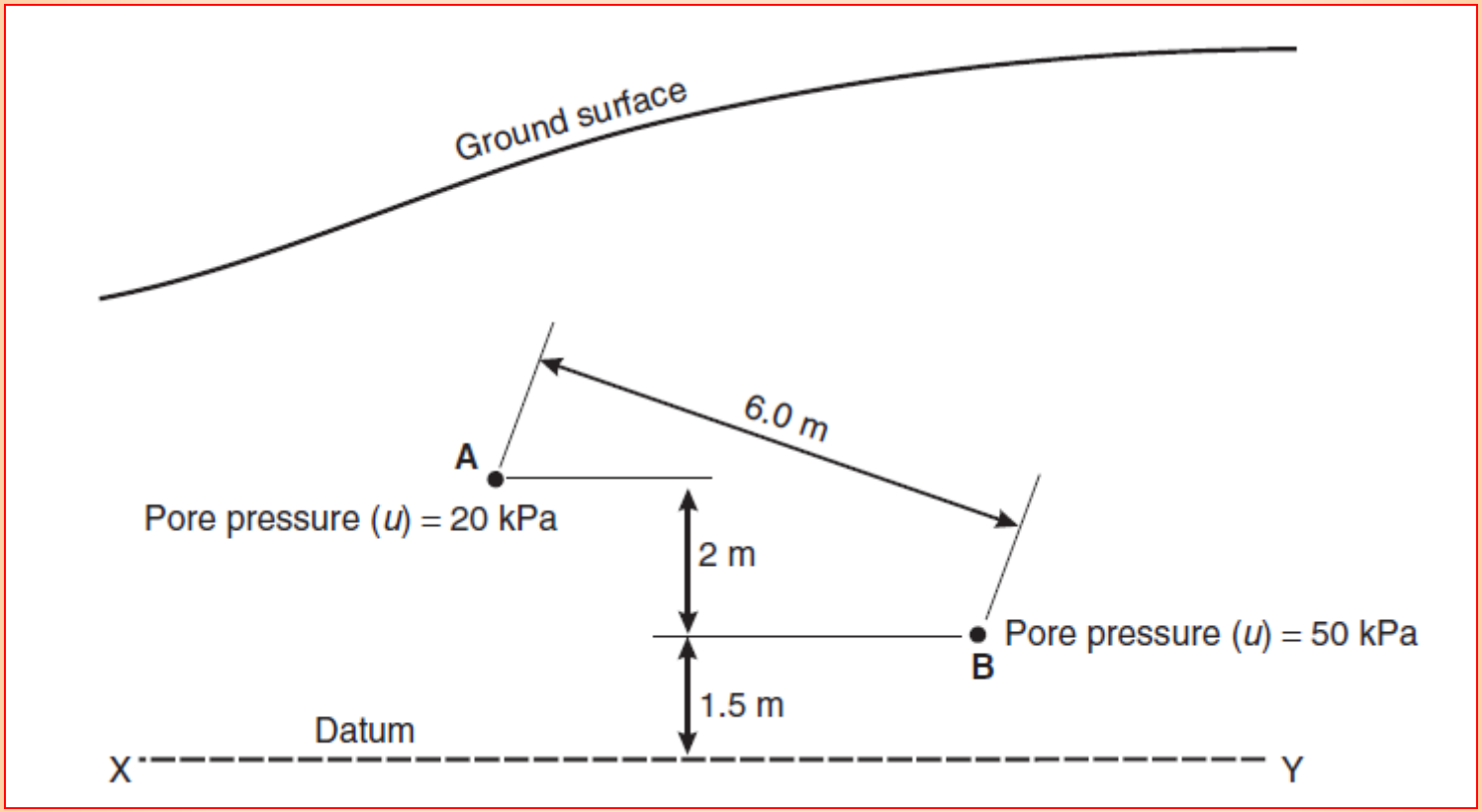
Em meio isotrópico a solução, em termos de cargas hidráulicas, não depende da condutividade hidráulica!

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

Observação importante

Em meio anisotrópico a solução, em termos de cargas hidráulicas, depende apenas dos valores relativos das condutividades hidráulicas!

Existe fluxo de A para B ou vice-versa?

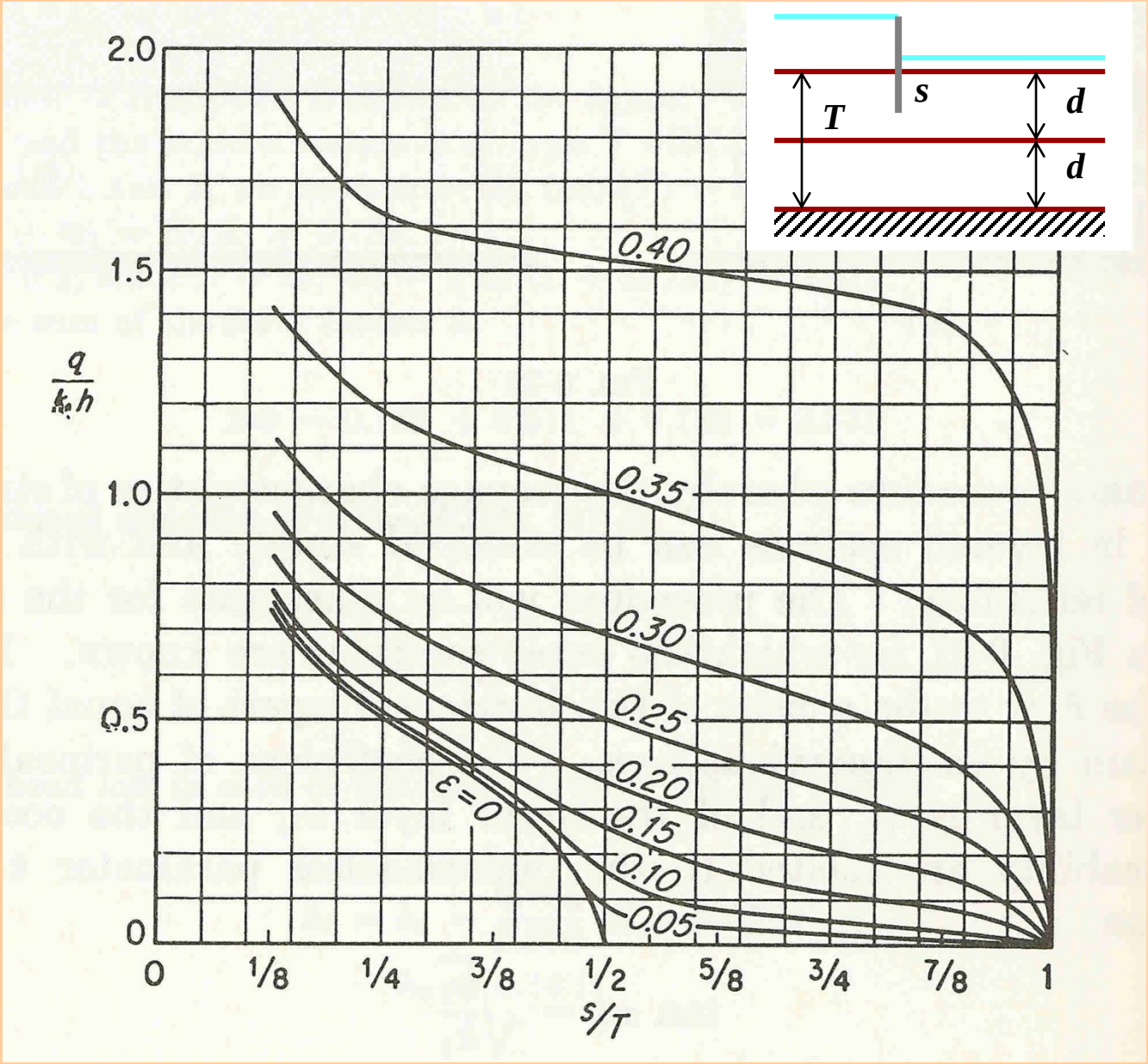


Wesley (2009)

Métodos para Resolver a Equação de Laplace

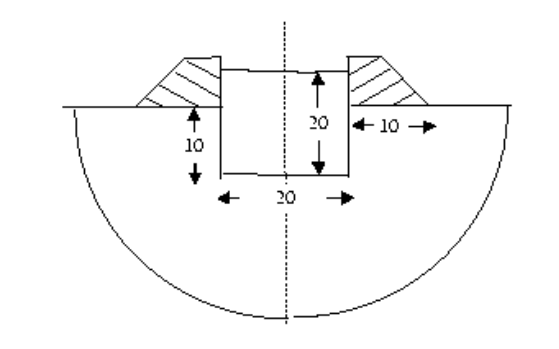
- **Solução exata: h = h(x,y,z)**
  - **integração da equação diferencial: problema matemático (não de Engenharia) com soluções disponíveis apenas para geometrias, distribuições de condutividades hidráulicas e condições de contorno simples**
- **Soluções aproximadas: h obtida em diversos pontos do domínio de fluxo**
  - **soluções analógicas: fenômenos similares em outras disciplinas (eletricidade, transferência de calor, magnetismo) obedecem à mesma equação de Laplace**
  - **soluções numéricas**
    - **diferenças finitas**
    - **elementos finitos**
    - **elementos de contorno**
  - **solução gráfica: rede de fluxo**

Solução matemática

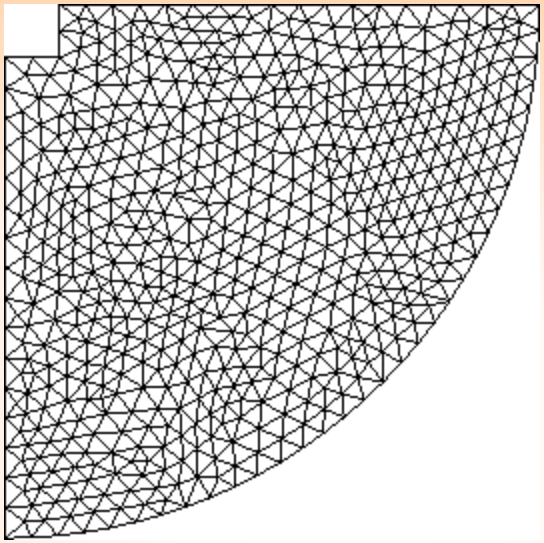


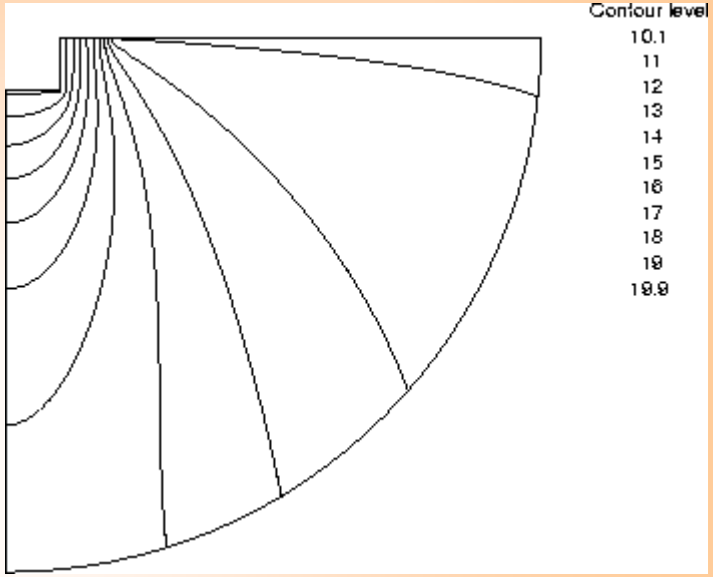
$$\tan \pi\varepsilon = \sqrt{\frac{k_2}{k_1}}$$

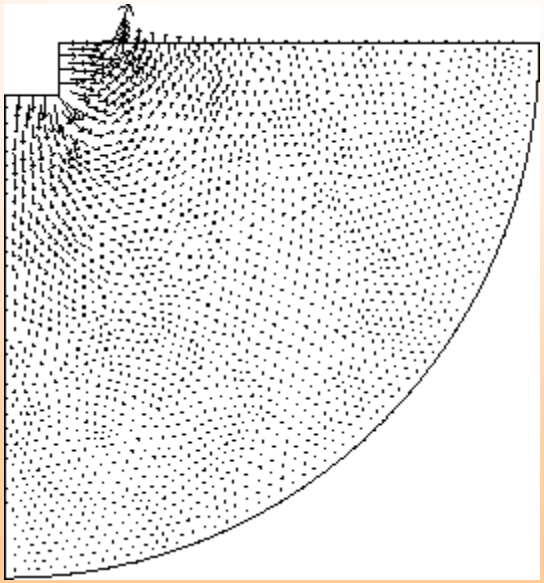
Solução numérica

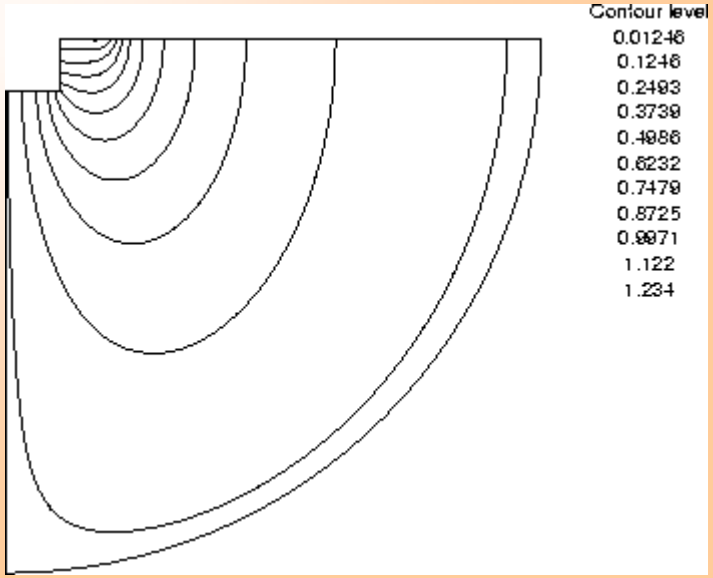


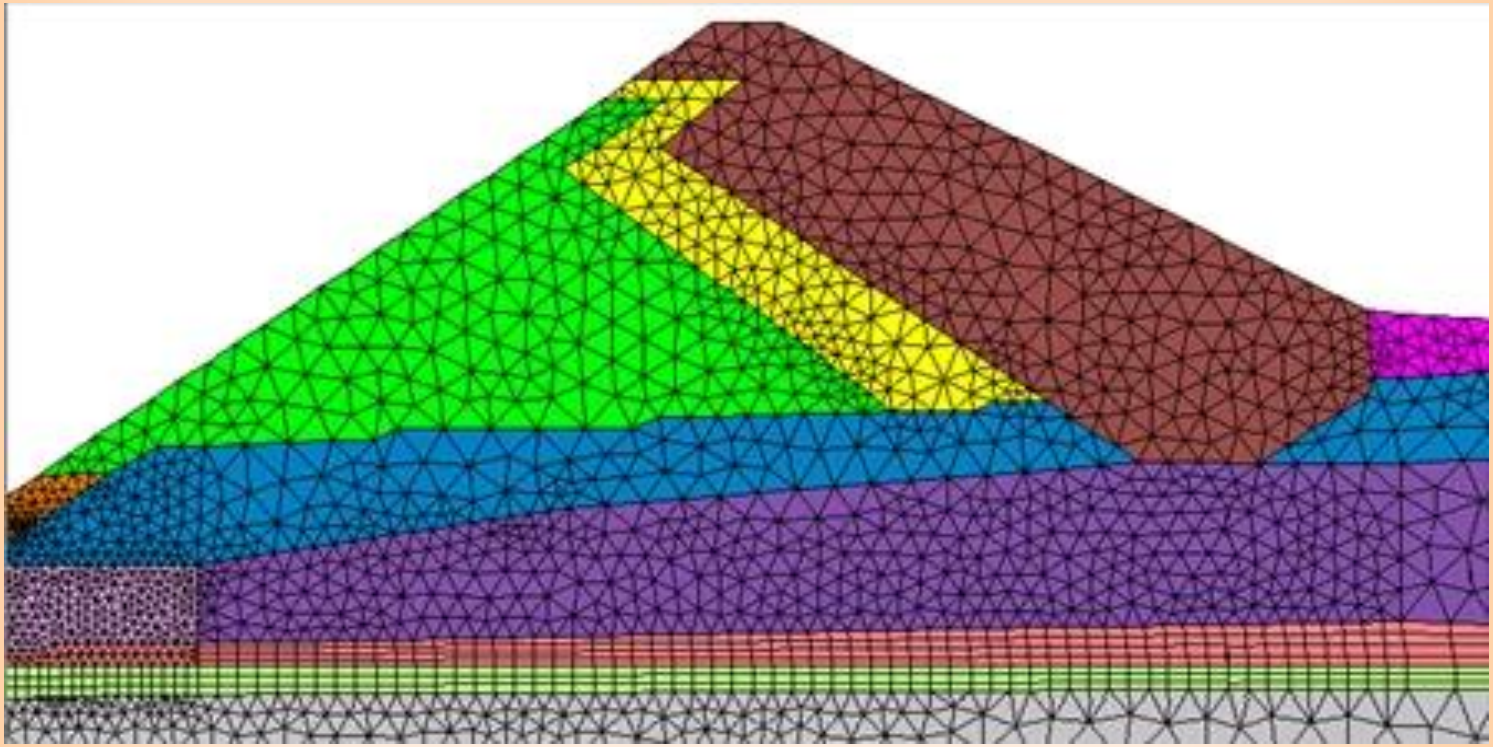
$k_y = 3k_x$

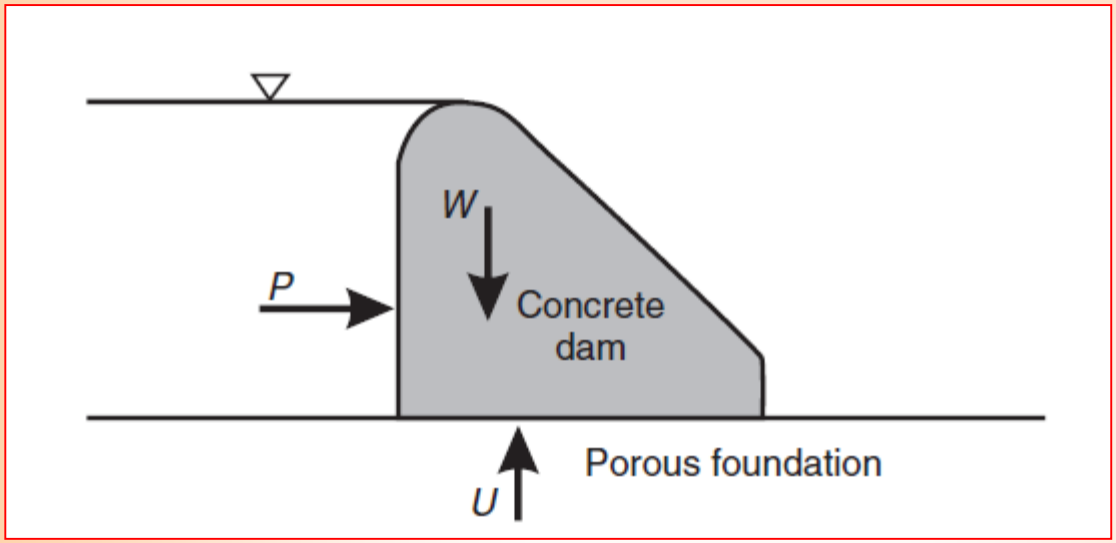










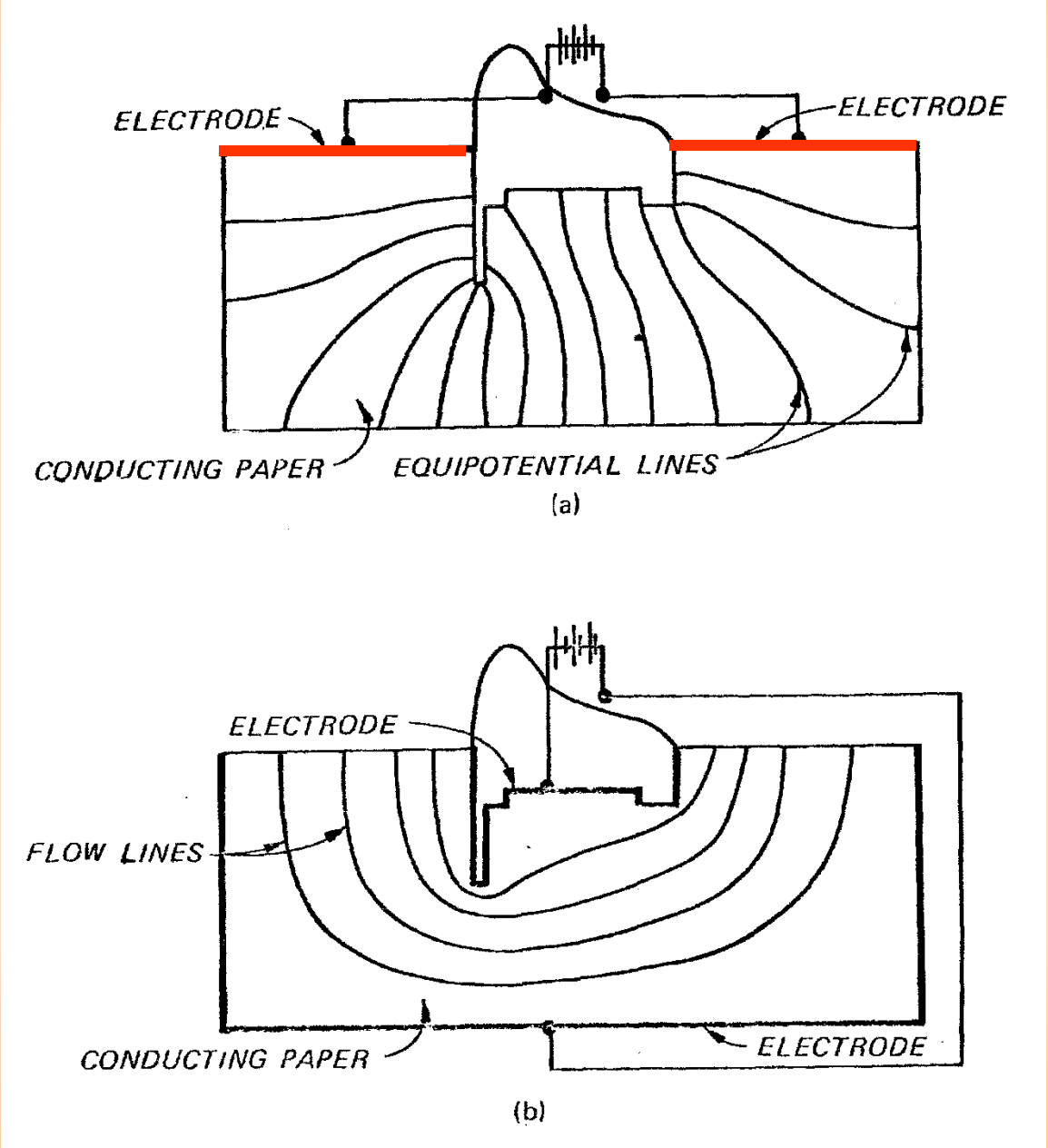


Wesley (2009)

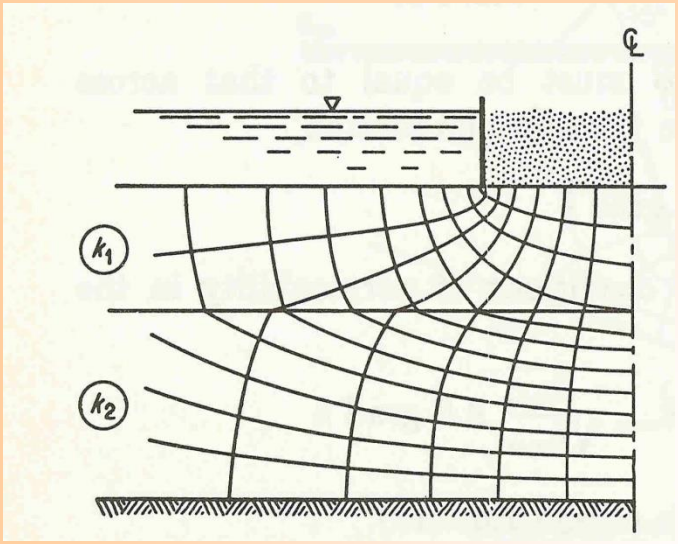
Fator de segurança contra deslizamento

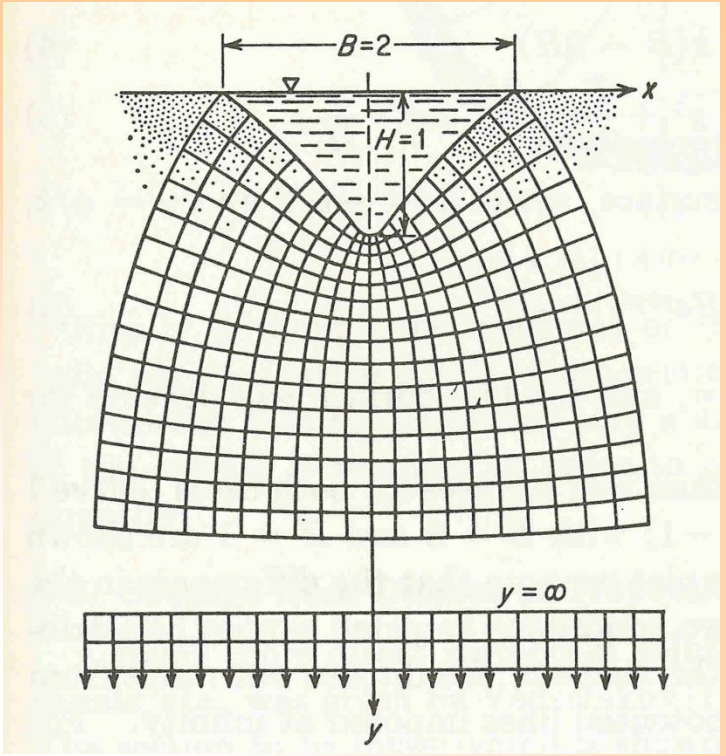
$$F = \frac{(W - U)\,\mu}{P} = \frac{(W - U)\tan\sigma'}{P}$$

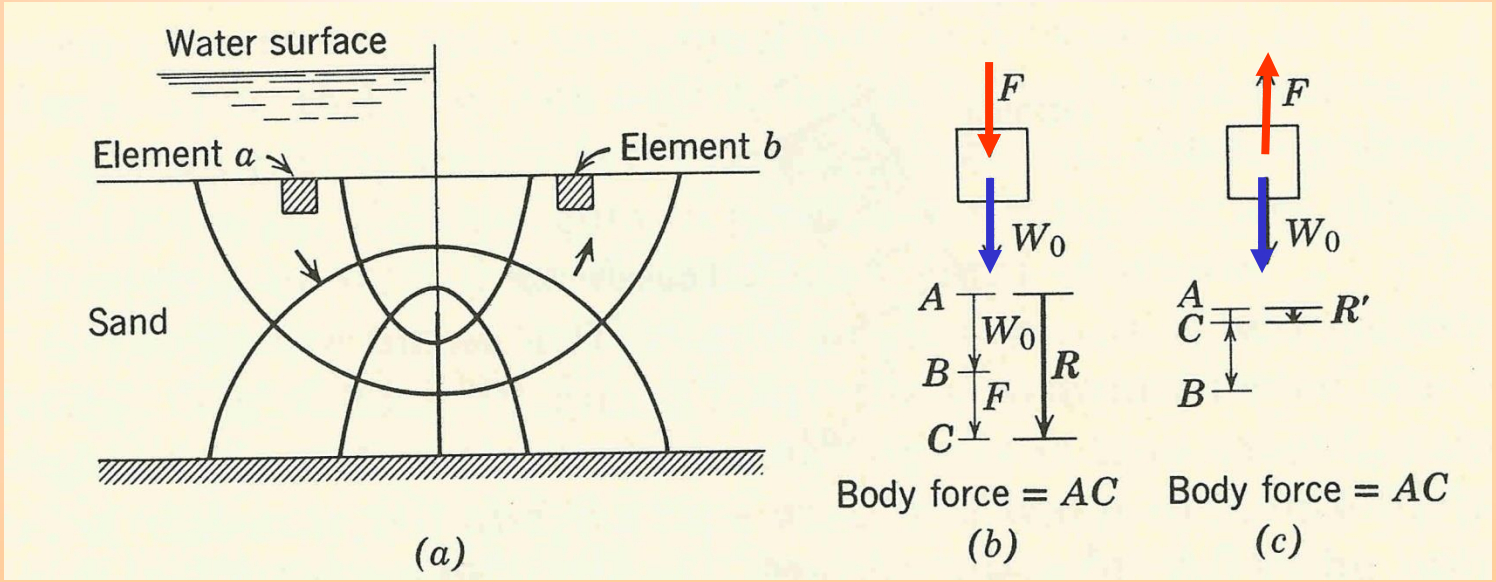
Análogia elétrica

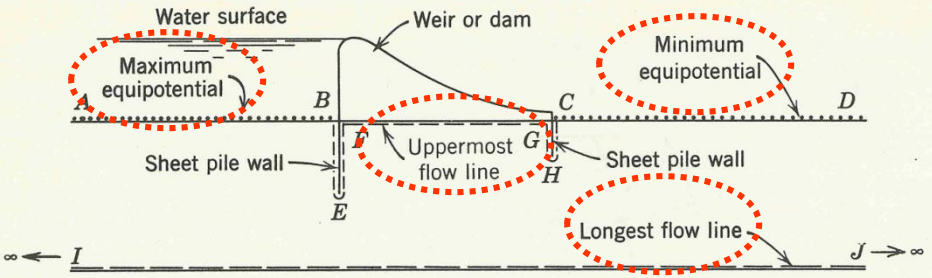


Solução gráfica

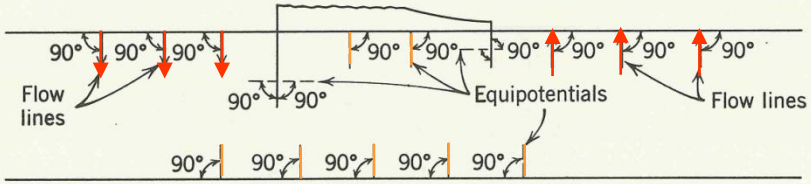




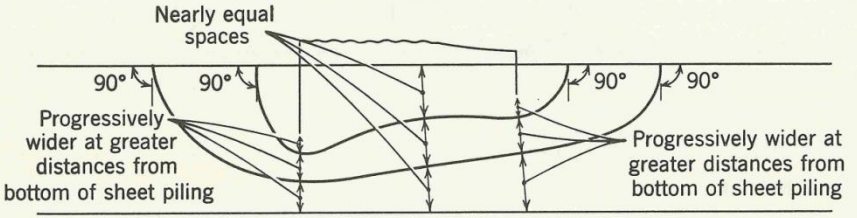




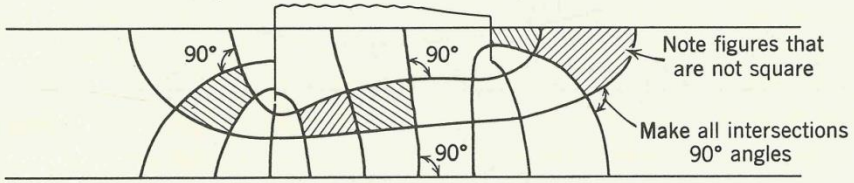
(a)



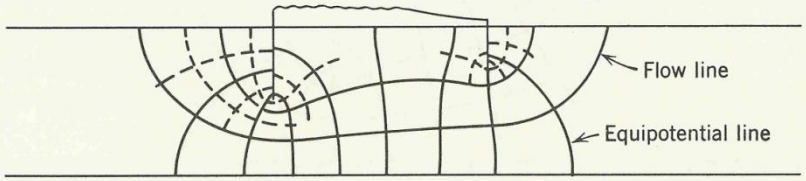
(b)



(c)



(d)



(e)

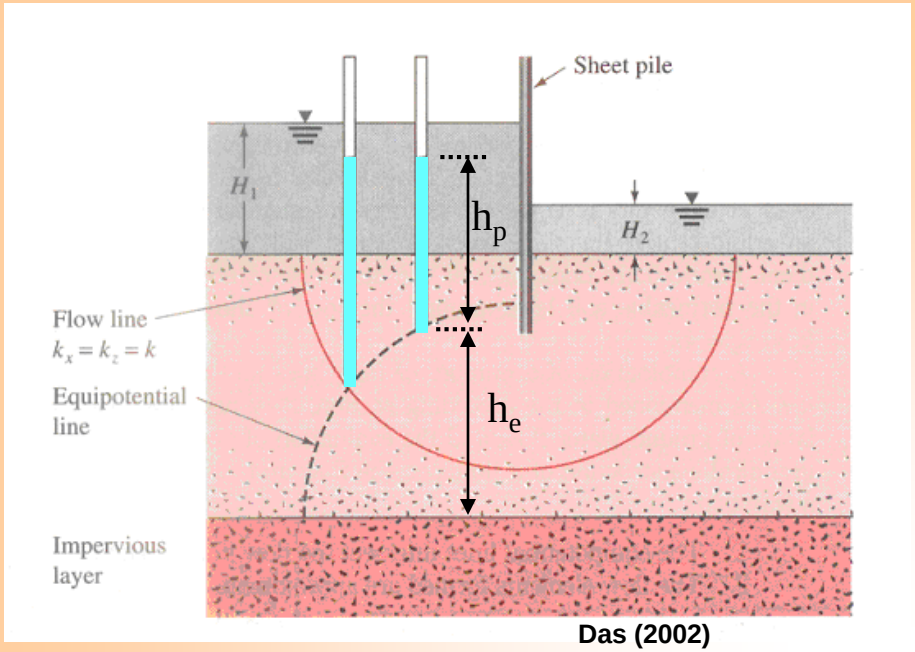
Condições de contorno

início das linhas de fluxo e equipotenciais

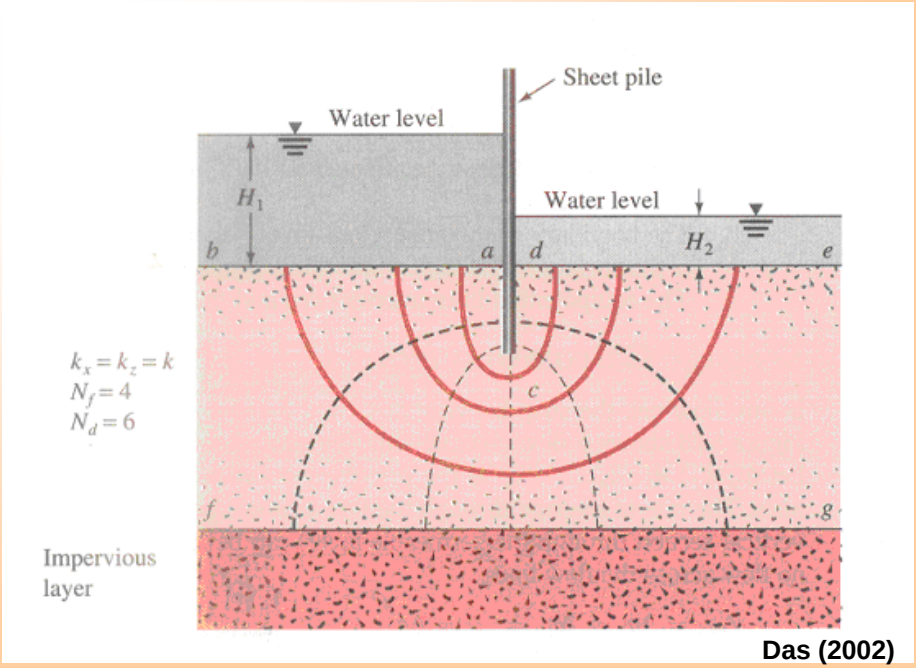
Primeira tentativa de traçado da linhas de fluxo

Tentativa de traçado

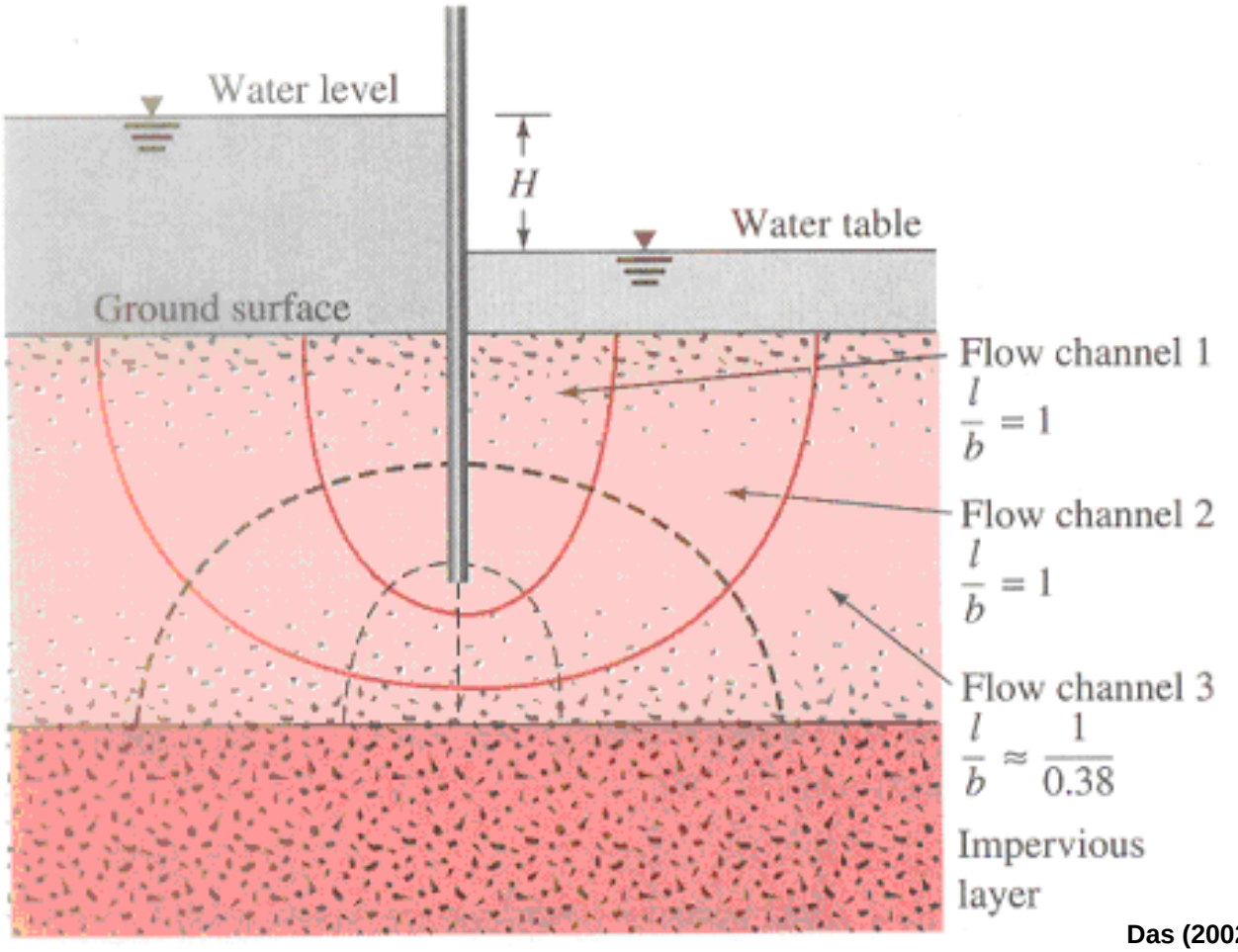
Final



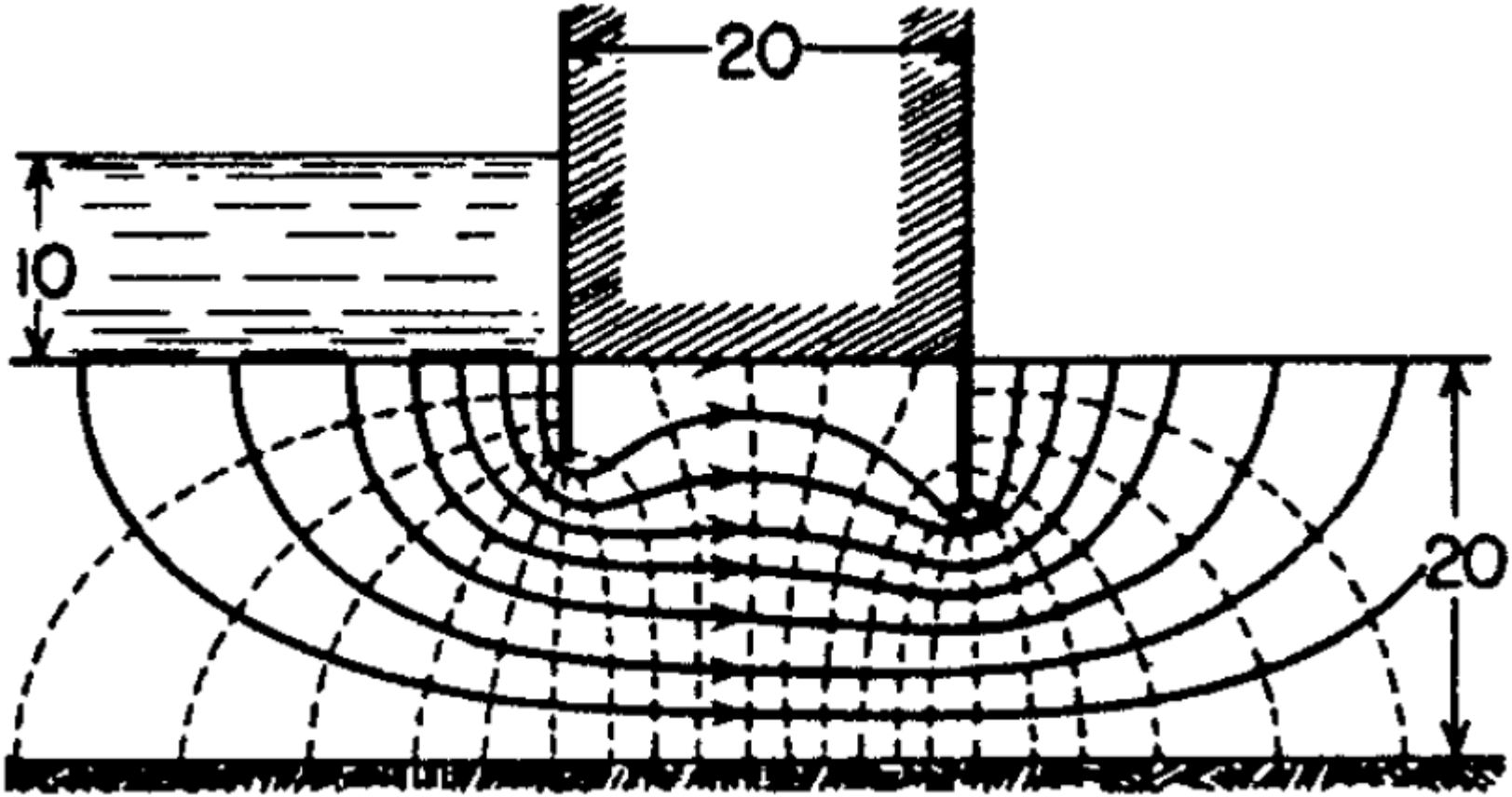
Das (2002)



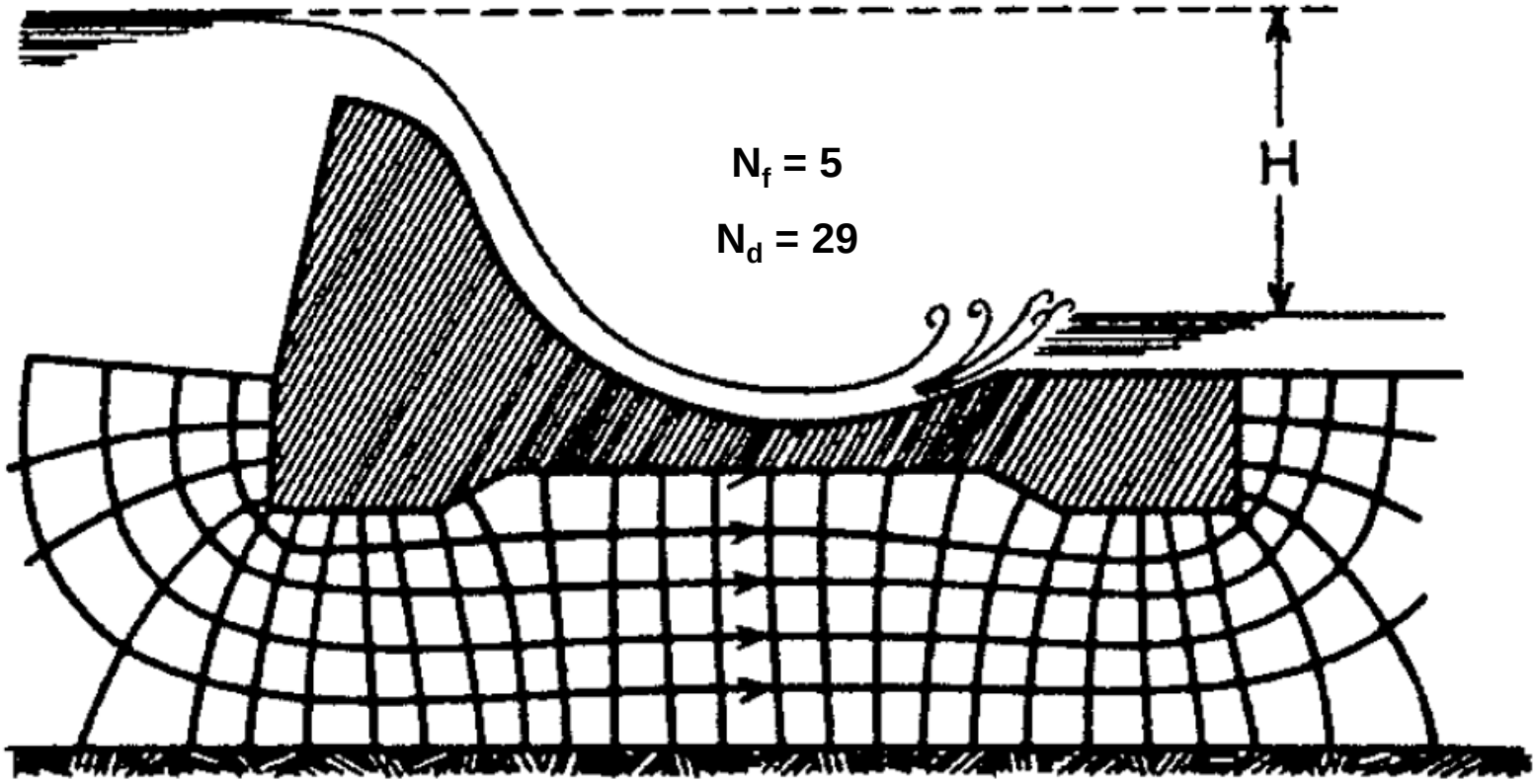
Das (2002)


Water level
H
Water table
Ground surface
Flow channel 1
$\frac{l}{b} = 1$
Flow channel 2
$\frac{l}{b} = 1$
Flow channel 3
$\frac{l}{b} \approx \frac{1}{0.38}$
Impervious layer

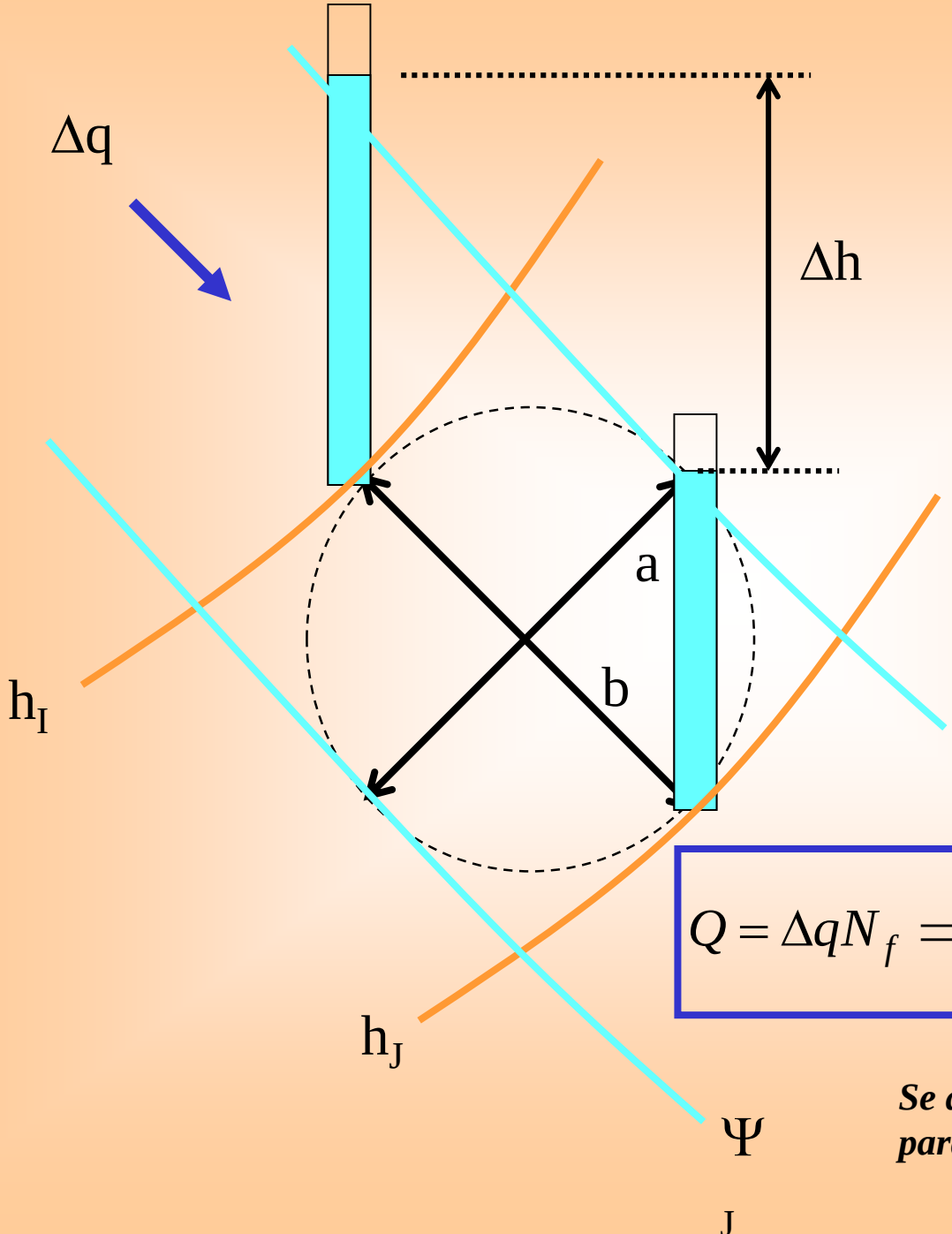
Das (2002)



Terzaghi



Terzaghi



$$\Delta q = \frac{Q}{N_f}$$

N_f – Número de canais de fluxo

$$\Delta h = \frac{h}{N_d}$$

N_d – Número de perdas de carga

Lei de Darcy

$$\Delta q = k \frac{\Delta h}{b} a1$$

i

A

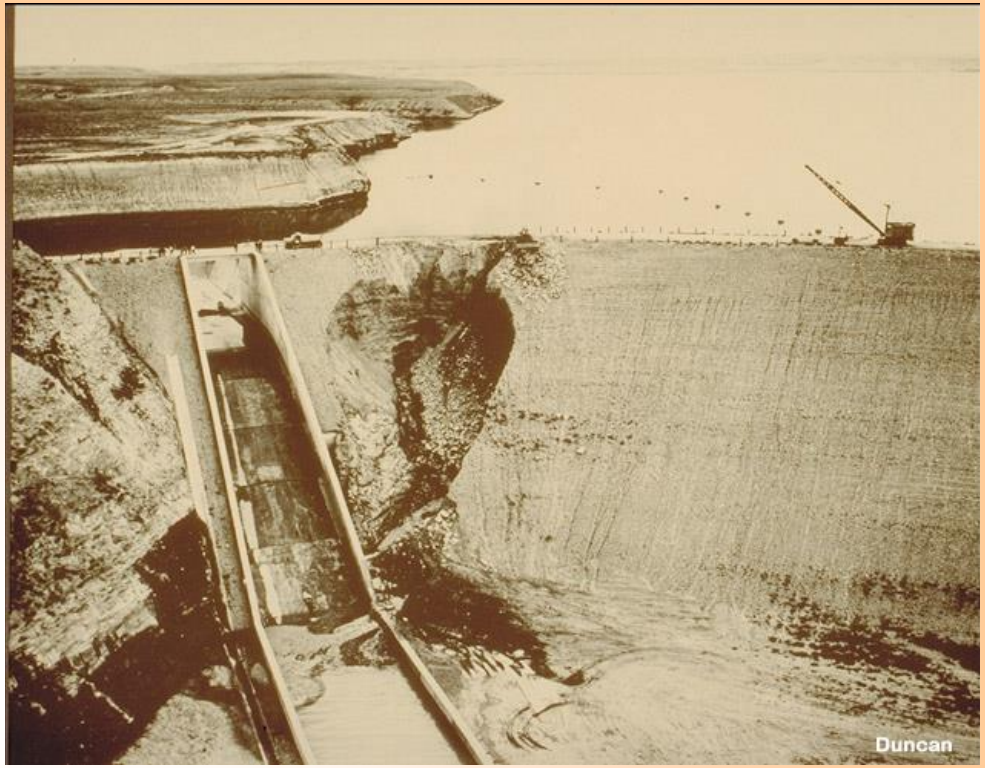
$$Q = \Delta q N_f \Rightarrow Q = k \frac{\Delta h}{b} a1 N_f = kh \frac{a}{b} \frac{N_f}{N_d}$$

Se a = b (mais simples para o traçado)

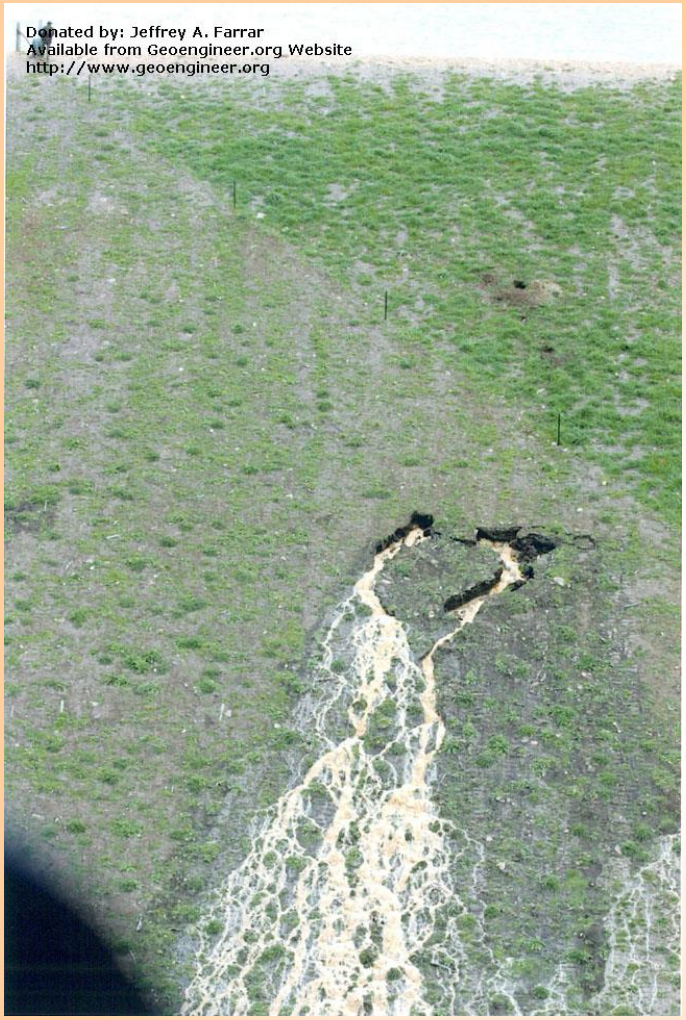
$$Q = kh \frac{N_f}{N_d}$$



Barragem Baldwin Hills (rompeu em 1963 por “piping”)



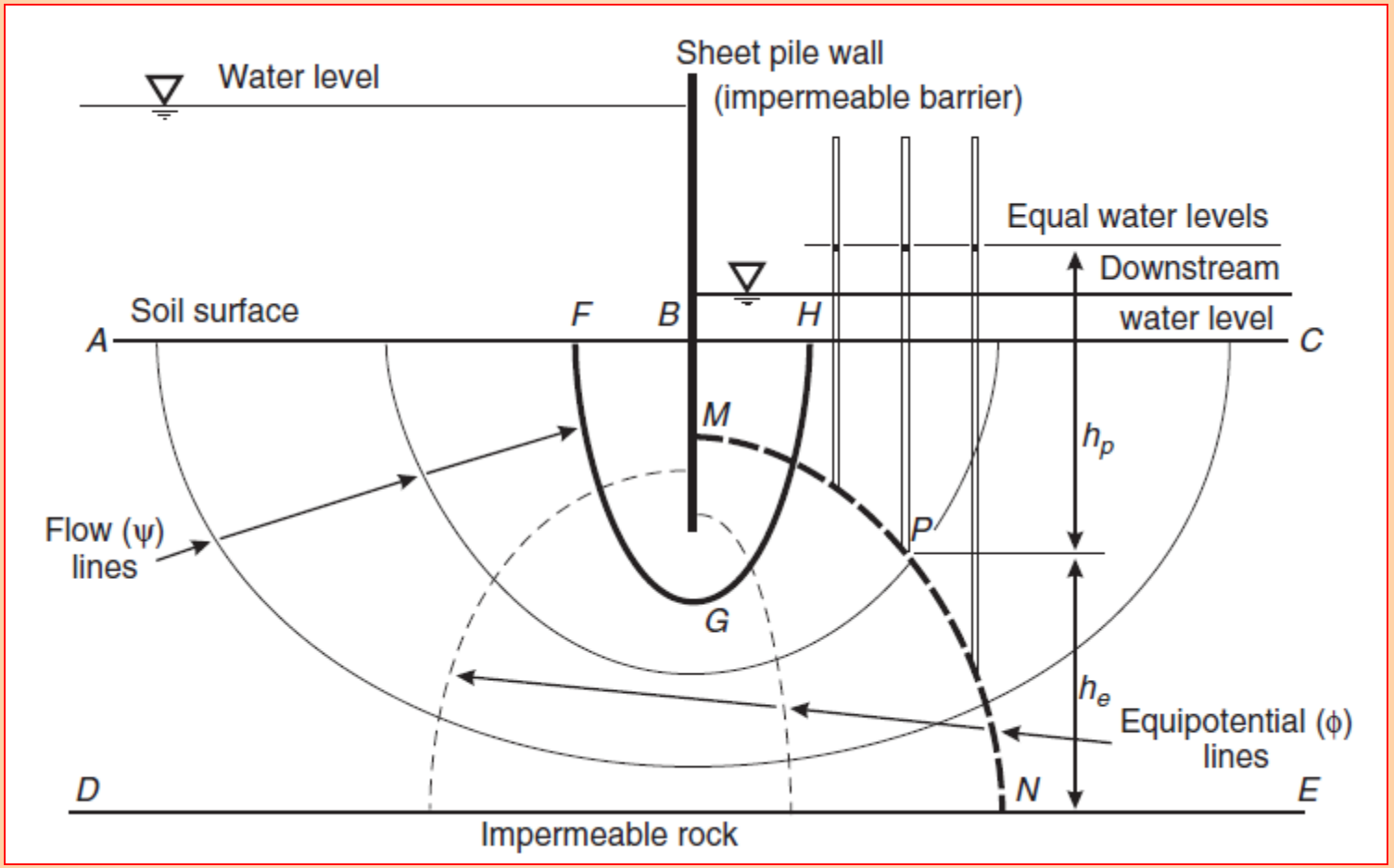
Barragem Fontenelle, USA (1965)



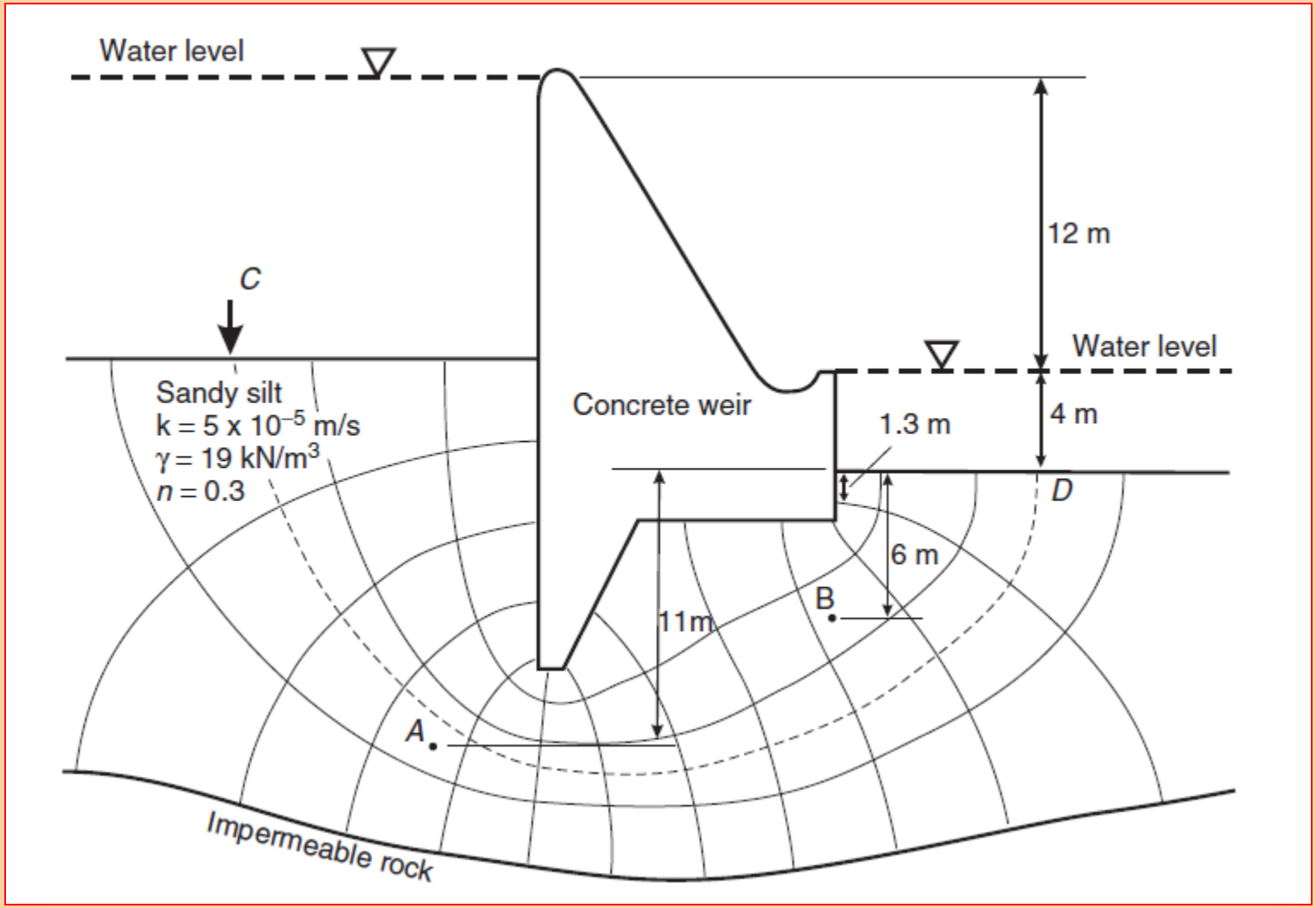


Piping

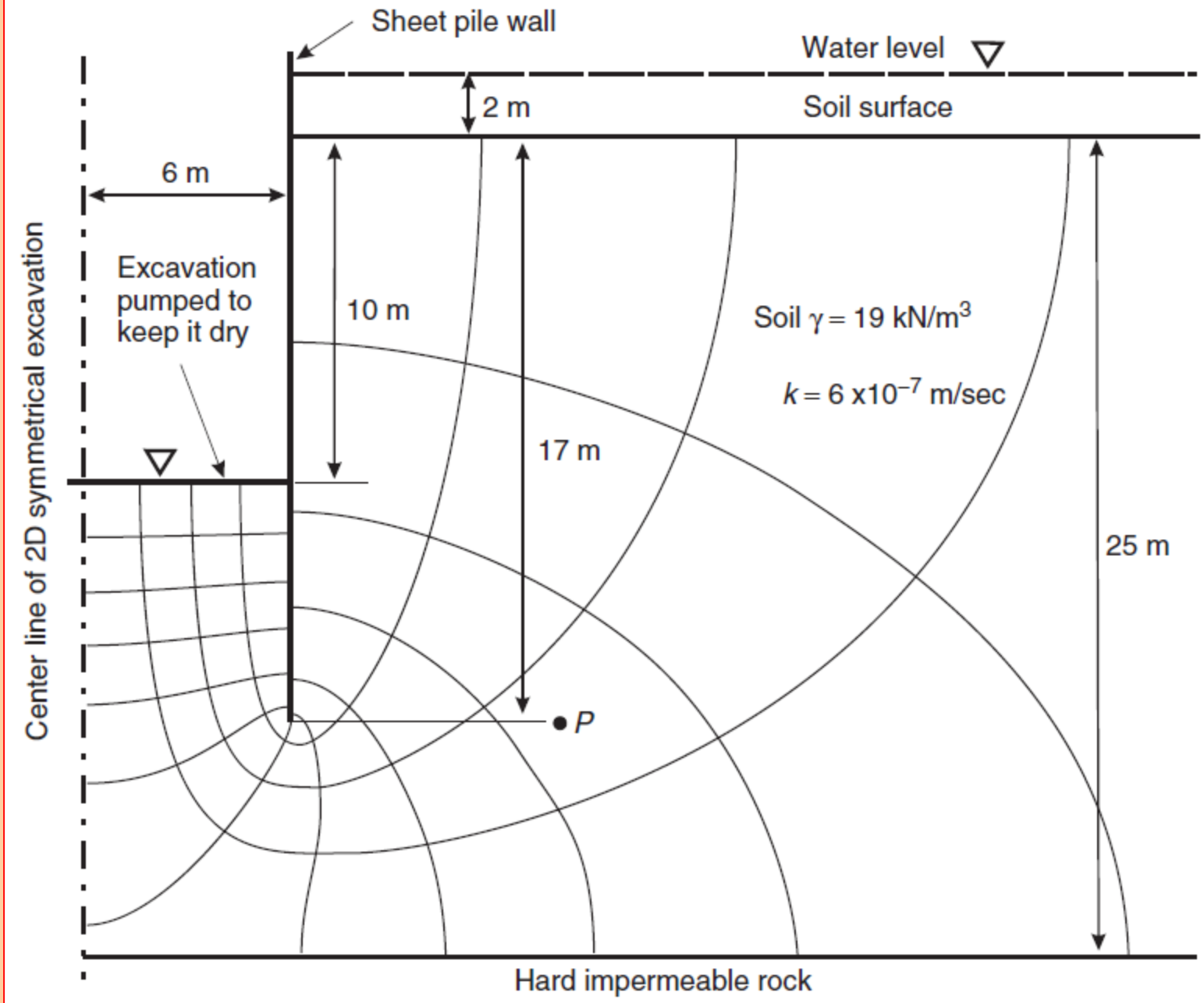
Tunbridge Dam, Tasmania, Australia


Water level
Sheet pile wall
(impermeable barrier)
Equal water levels
Downstream
water level
Soil surface
A
F
B
H
C
M
h_p
P
Flow (ψ)
lines
G
h_e
Equipotential (ϕ)
lines
D
N
E
Impermeable rock

Wesley (2009)


Water level
12 m
C
Water level
Sandy silt
k = 5 x 10⁻⁵ m/s
γ = 19 kN/m³
n = 0.3
Concrete weir
1.3 m
4 m
D
6 m
B
11m
A
Impermeable rock

Wesley (2009)


Sheet pile wall
Water level
2 m
Soil surface
6 m
Excavation
pumped to
keep it dry
10 m
17 m
25 m
Soil γ = 19 kN/m3
k = 6 x10−7 m/sec
P
Center line of 2D symmetrical excavation
Hard impermeable rock

Filtros

Usados com o objetivo de:

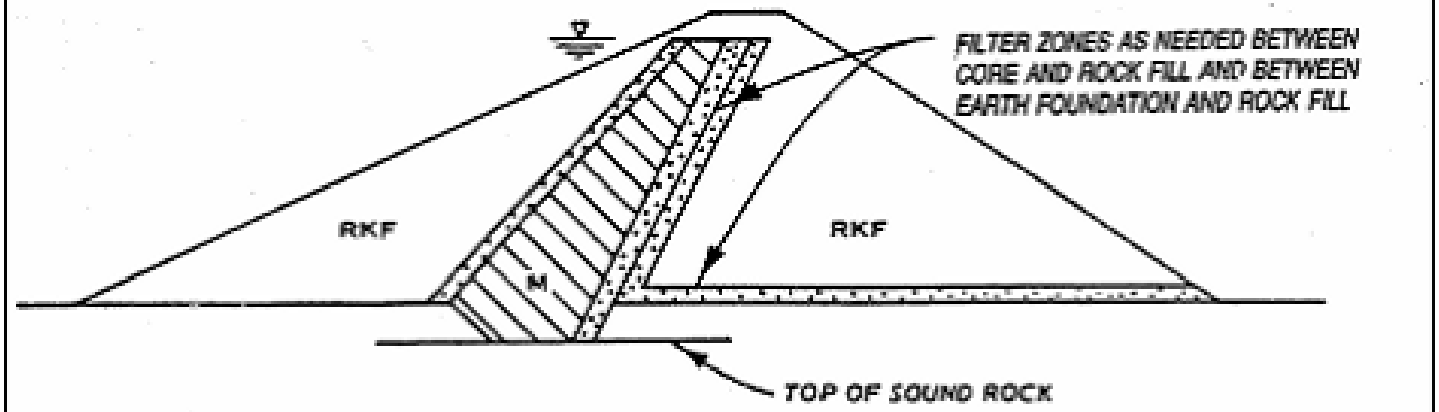
- ✓ ***facilitar a drenagem***
- ✓ ***impedir os finos de serem carreados***

Usados em:

- *Barragens*
- *Muros de arrimo*

Materiais de Filtro:

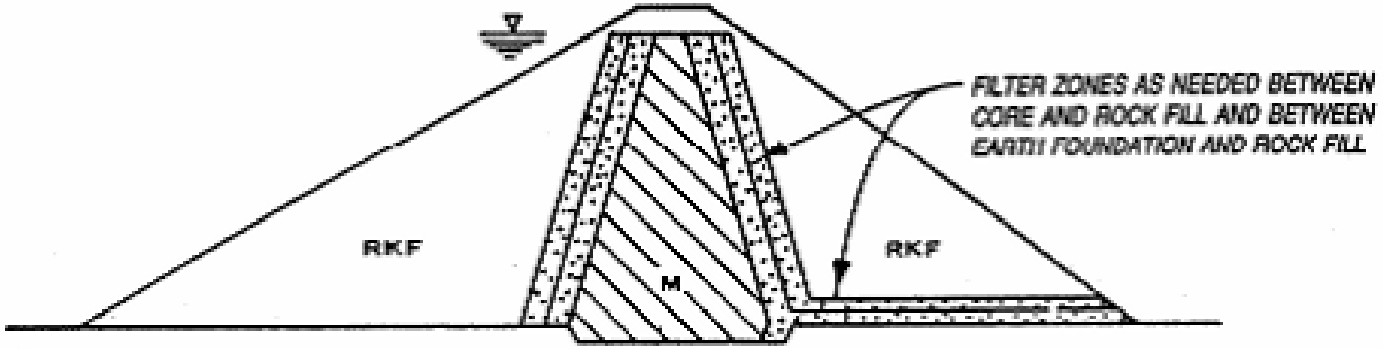
- *Solos granulares*
- *Geotêxteis*



a. DAM WITH INCLINED IMPERVIOUS ZONE

LEGEND

M = IMPERVIOUS
RKF = ROCK FILL



b. DAM WITH CENTRAL CORE

Projeto de Filtro com Material Granular

Dois Critérios:

Critério de **retenção de finos**

- impede os finos de serem “lavados”

O filtro não deve ser muito grosso

Critério de p**ermeabilidade**

- facilita a drenagem evitando o desenvolvimento de pressões neutras

O filtro não deve ser muito fino

Projeto de Filtro com Material Granular

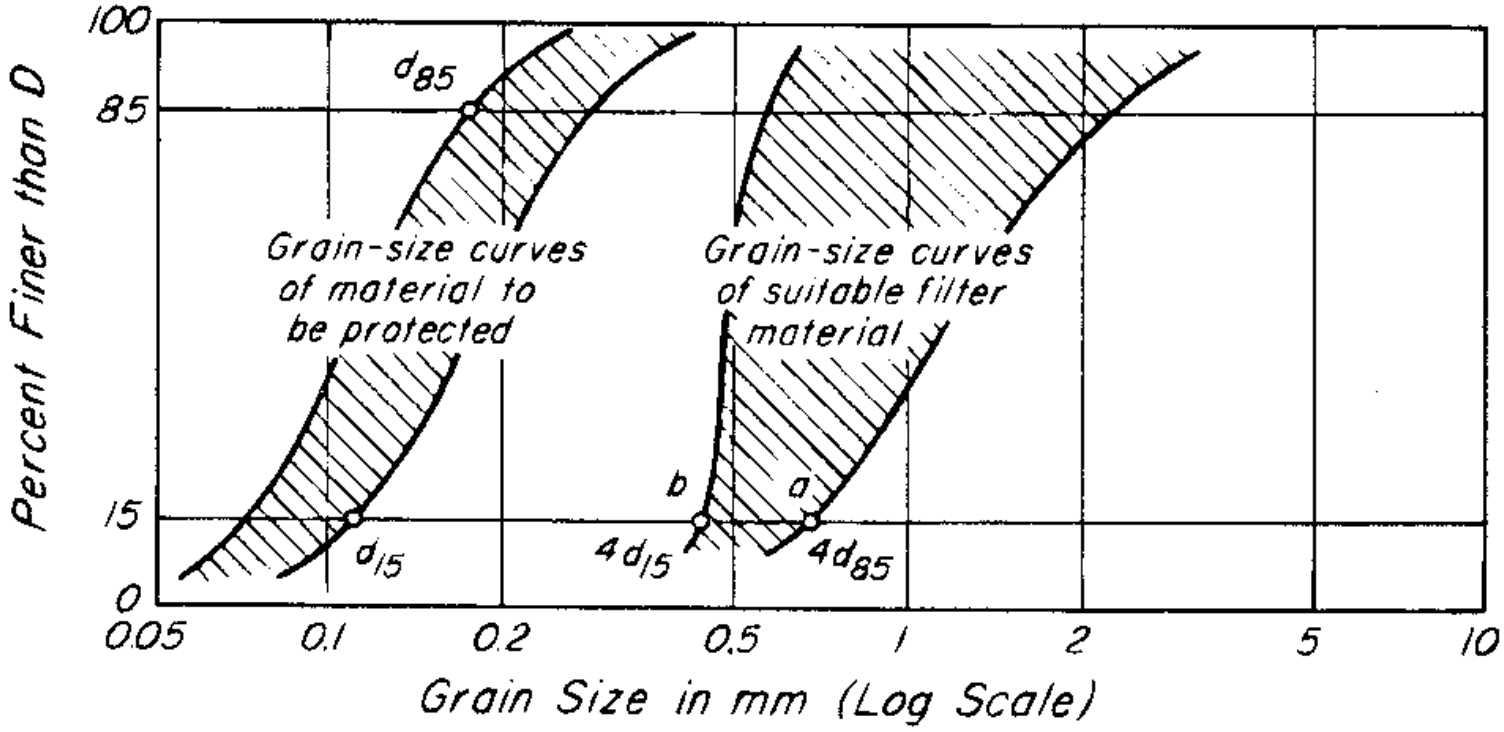
Critério de Retenção:

$D_{15,\ filtro} < 5\ D_{85,\ solo}$

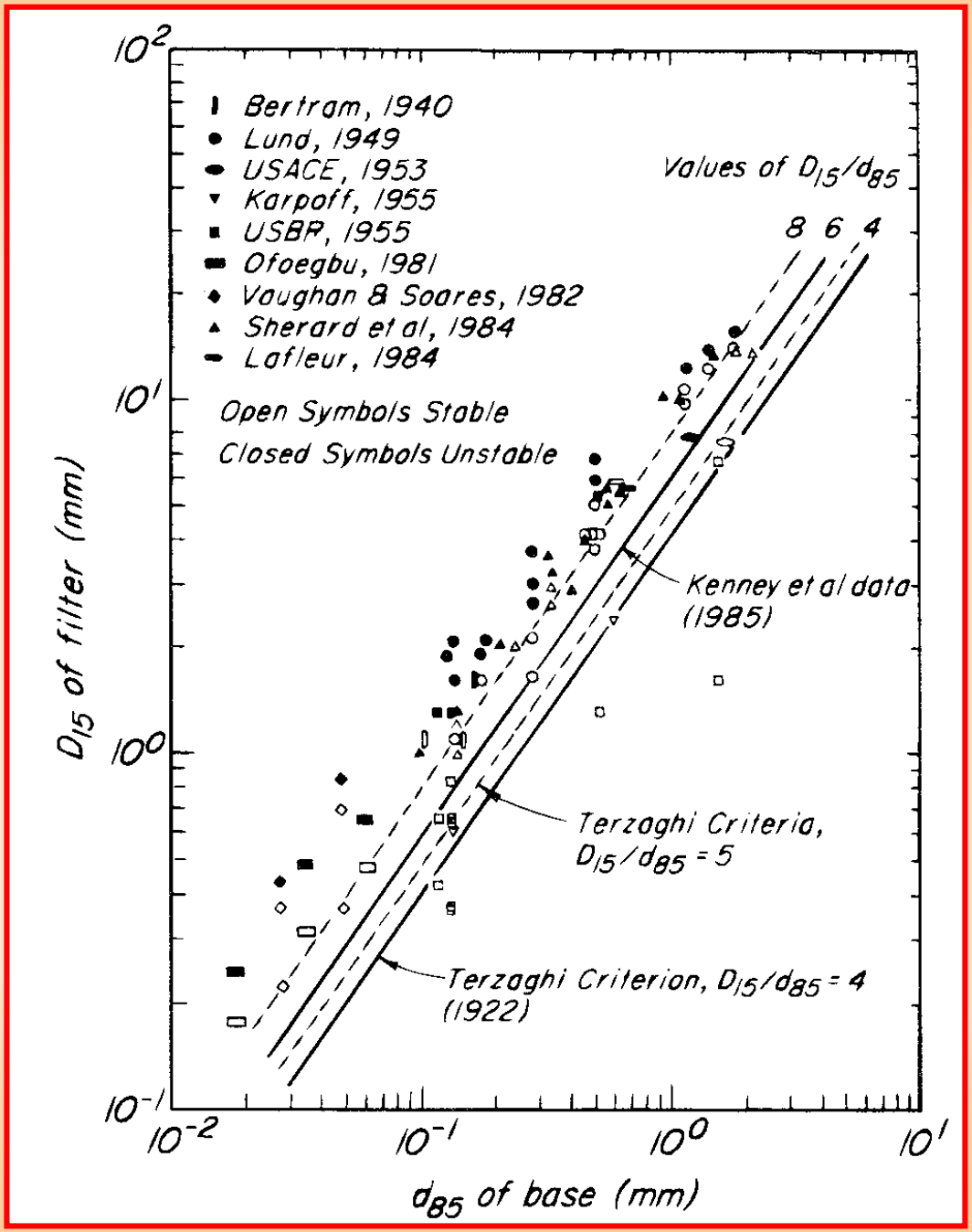
Critério de Permeabilidade:

$D_{15,\ filtro} > 4\ D_{15,\ solo}$

Terzaghi & Peck (1967)

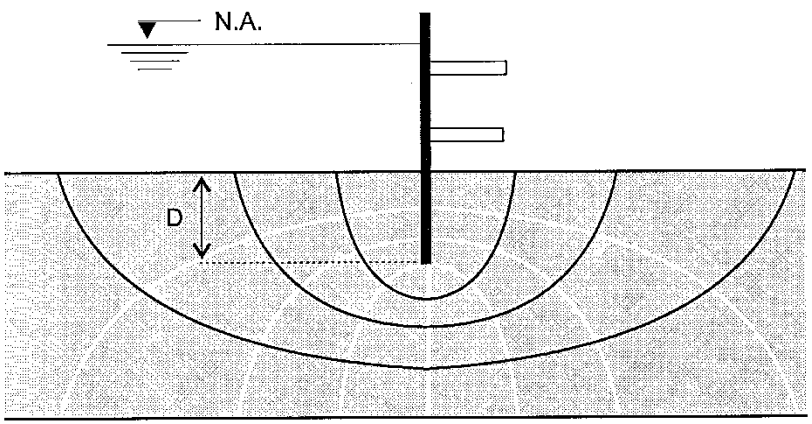


Terzaghi , Peck & Mesri (1996)

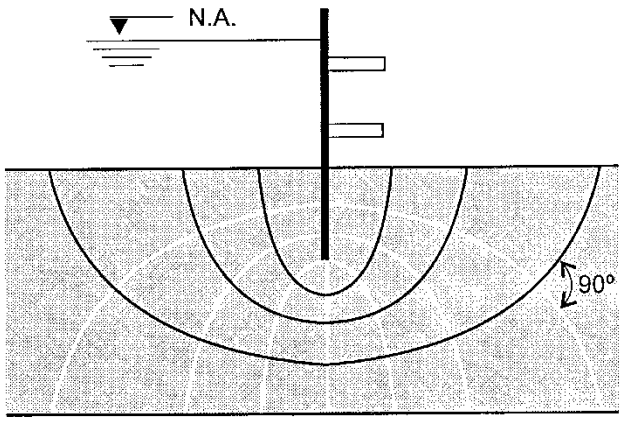


Terzaghi , Peck & Mesri (1996)

Anisotropia de Permeabilidade

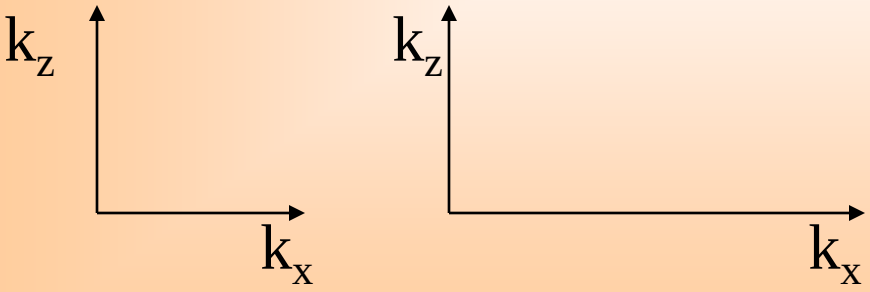


a) Seção verdadeira
(escala natural)



b) Seção transformada

Pinto (2000)



isotrópico **anisotrópico**

$$x_T = x\sqrt{\frac{k_z}{k_x}}$$

$$k_E = \sqrt{k_x k_z}$$