In [1]:
```
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
import panel as pn
pn.extension("katex", "mathjax")
```

Tutorial 3

- **tutorial problems on Darcy's law and intrinsic permeability**
- **homework problems on Darcy's law and intrinsic permeability**

Tutorial Problems on

- Darcy's Law and
- Intrinsic Permeability

Tutorial Problem 7: Flow Direction and Hydraulic Gradient

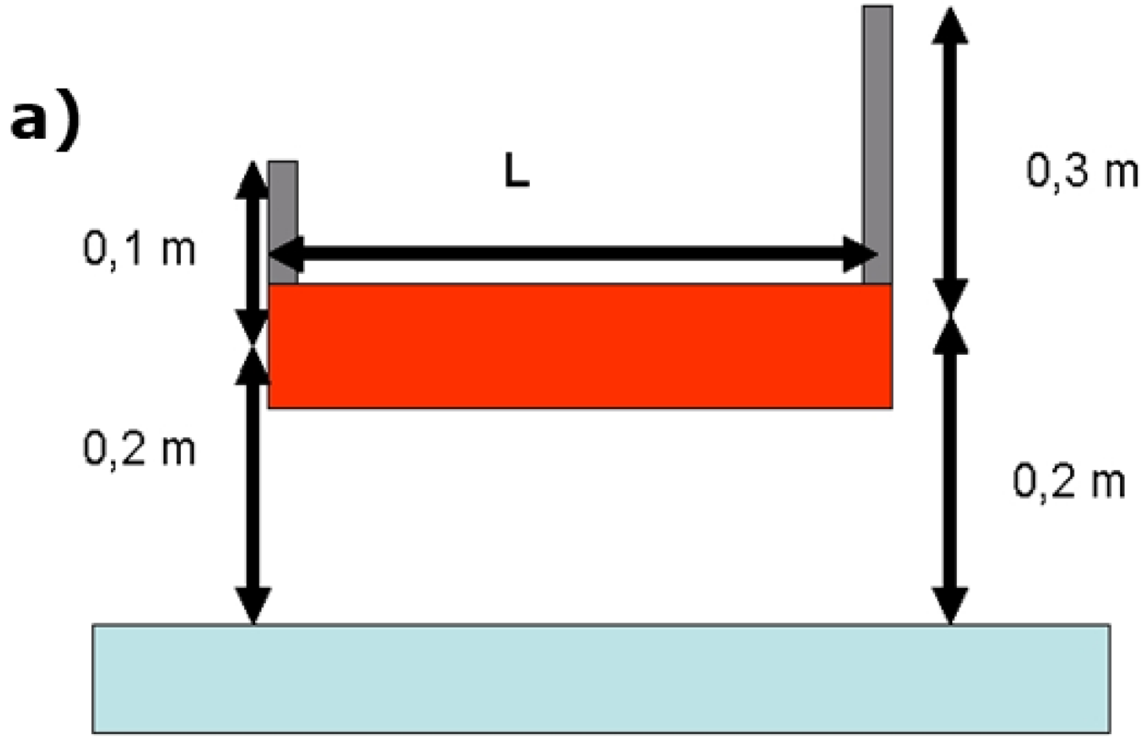
Indicate the direction of flow shown in the figure in next slides, and determine the hydraulic gradient for a Darcy column with length L = 50 cm! (Figures not to scale.)

Tutorial Problem 7 – Solution

The relevant topic is covered in Lecture 04, slide 8

In [2]:
```
png_pane = pn.pane.PNG("images/T03_TP7_a1.png", width=600)
png_pane
```

Out[2]:

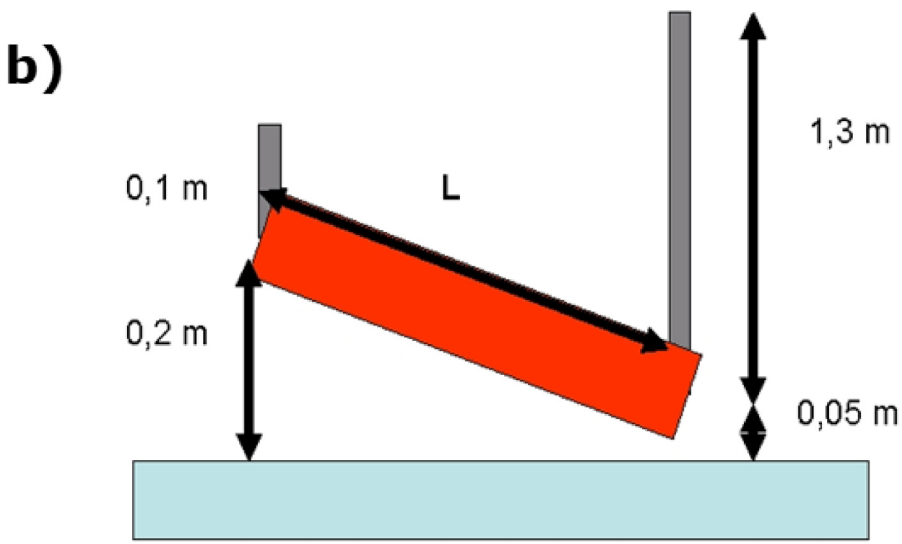


In [3]:
```
# Image (a)
L = 0.5 # m, length of the column
Ea_hl = 0.2 #, m, elevation head, left
Pa_hl = 0.1 #, m  pressure head, left
Ea_hr = 0.2 #, m, elevation head, right
Pa_hr = 0.3 #, m  pressure head, right
Ha_hl = Ea_hl + Pa_hl # m, hydraulic head, left
Ha_hr = Ea_hr + Pa_hr # m, hydraulic head, right
DH_a = Ha_hr - Ha_hl
H_ga = DH_a/L#, no unit, hydraulic gradient

print("Hydraulic head LEFT: {0:1.3e}".format(Ha_hl),"m"); print("Hydraulic head RIGHT:: {0:1.1f}".format(Ha_h
r),"m")
print("Hydraulic Head Difference: {0:1.1f}".format(DH_a),"m");print("Hydraulic gradient: {0:1.1f}".format(H_g
a))
png_pane.object = "images/T03_TP7_a2.png"
```

```
Hydraulic head LEFT: 3.000e-01 m
Hydraulic head RIGHT:: 0.5 m
Hydraulic Head Difference: 0.2 m
Hydraulic gradient: 0.4
```

In [4]:
```
png_pane2 = pn.pane.PNG("images/T03_TP7_b1.png", width=500)
png_pane2
```

Out[4]:

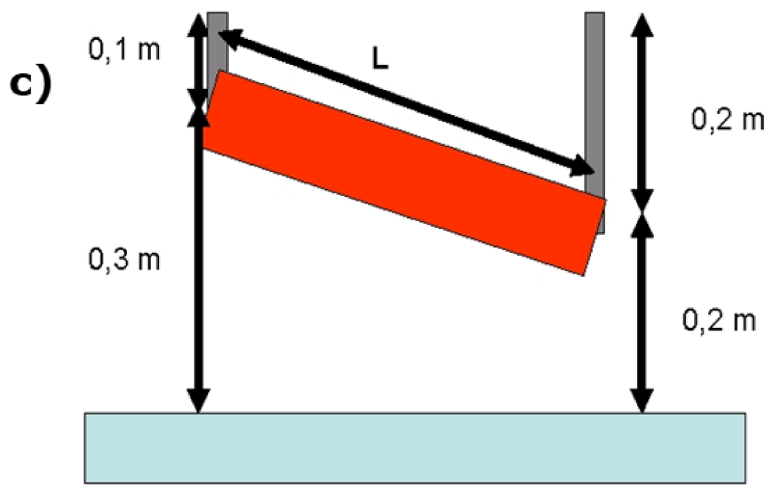


In [5]:
```
# Image (b)
L = 0.5 # m, length of the column
Eb_hl = 0.2 #, m, elevation head, left
Pb_hl = 0.1 #, m  pressure head, left
Eb_hr = 0.05 #, m, elevation head, right
Pb_hr = 1.3 #, m  pressure head, right
Hb_hl = Eb_hl + Pb_hl # m, hydraulic head, left
Hb_hr = Eb_hr + Pb_hr # m, hydraulic head, right
DH_b = Hb_hr - Hb_hl
H_gb = DH_b/L#, no unit, hydraulic gradient
print("Hydraulic head LEFT: {0:1.1f}".format(Hb_hl),"m");print("Hydraulic head RIGHT:: {0:1.1f}".format(Hb_hr
),"m")
print("Hydraulic Head Difference: {0:1.1f}".format(DH_b),"m");print("Hydraulic gradient: {0:1.1f}".format(H_g
b))
png_pane2.object = "images/T03_TP7_b2.png"
```

```
Hydraulic head LEFT: 0.3 m
Hydraulic head RIGHT:: 1.4 m
Hydraulic Head Difference: 1.1 m
Hydraulic gradient: 2.1
```

In [6]:
```
png_pane3 = pn.pane.PNG("images/T03_TP7_c1.png", width=400)
png_pane3
```

Out[6]:

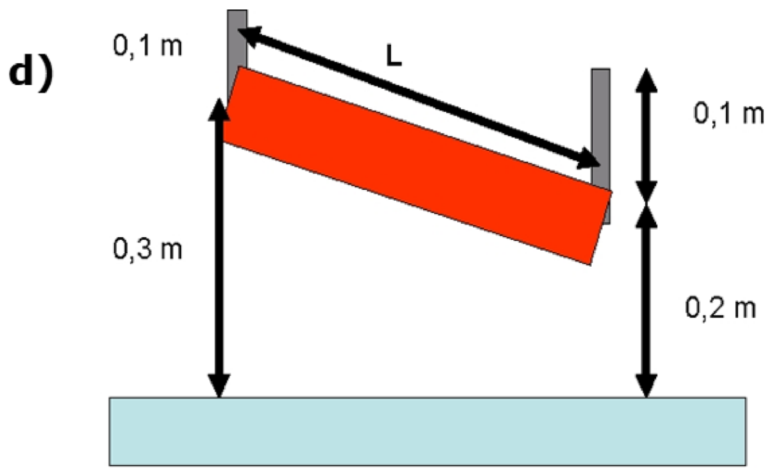


In [7]:
```
# Image (c)
L = 0.5 # m, length of the column
Ec_hl = 0.3 #, m, elevation head, left
Pc_hl = 0.1 #, m  pressure head, left
Ec_hr = 0.2 #, m, elevation head, right
Pc_hr = 0.2 #, m  pressure head, right
Hc_hl = Ec_hl + Pc_hl # m, hydraulic head, left
Hc_hr = Ec_hr + Pc_hr # m, hydraulic head, right
DH_c = Hc_hr - Hc_hl
H_gc = DH_c/L#, no unit, hydraulic gradient
print("Hydraulic head LEFT: {0:1.1f}".format(Hc_hl),"m");print("Hydraulic head RIGHT:: {0:1.1f}".format(Hc_hr
),"m")
print("Hydraulic Head Difference: {0:1.1f}".format(DH_c),"m");print("Hydraulic gradient: {0:1.1f}".format(H_g
c))
png_pane3.object = "images/T03_TP7_c2.png"
```

```
Hydraulic head LEFT: 0.4 m
Hydraulic head RIGHT:: 0.4 m
Hydraulic Head Difference: 0.0 m
Hydraulic gradient: 0.0
```

In [8]:
```
png_pane4 = pn.pane.PNG("images/T03_TP7_d1.png", width=400)
png_pane4
```

Out[8]:



In [9]:
```
# Image (d)
L = 0.5 # m, length of the column
Ed_hl = 0.3 #, m, elevation head, left
Pd_hl = 0.1 #, m  pressure head, left
Ed_hr = 0.2 #, m, elevation head, right
Pd_hr = 0.1 #, m  pressure head, right
Hd_hl = Ed_hl + Pd_hl # m, hydraulic head, left
Hd_hr = Ed_hr + Pd_hr # m, hydraulic head, right
DH_d = Hd_hr - Hd_hl
H_gd = DH_d/L#, no unit, hydraulic gradient
#output
print("Hydraulic head LEFT: {0:1.1f}".format(Hd_hl),"m");print("Hydraulic head Right:: {0:1.1f}".format(Hd_hr
),"m")
print("Hydraulic Head Difference: {0:1.1f}".format(DH_d),"m");print("Hydraulic gradient: {0:1.1f}".format(H_g
d))
png_pane4.object = "images/T03_TP7_d2.png"
```

```
Hydraulic head LEFT: 0.4 m
Hydraulic head Right:: 0.3 m
Hydraulic Head Difference: -0.1 m
Hydraulic gradient: -0.2
```

Tutorial Problem 8

The hydraulic conductivity of a fine sand sample was found to be equal to 1.36×10^{-5} m/s in a Darcy experiment using water at a temperature of 20°C. What is the intrinsic permeability of this sample? Give results in cm^2 and D. (density of water at 20°C: 998.2 kg/m^3; dynamic viscosity of water at 20°C: 1.0087×10^{-3} Pa·s; 1 D = 0.987×10^{-12} m^2)

Tutorial Problem 8 - Solution

Relevant topics are covered in Lecture 04 slides 18-20.

Relationship between hydraulic conductivity K and intrinsic permeability k from lecture notes:

$$K_{water} = k \cdot \frac{\rho_{water} \cdot g}{\eta_{water}}$$

Solve for , k

$$k = \frac{\eta_{water} \cdot K_{water}}{\rho_{water} \cdot g}$$

In [10]:
```
#Given
Darcy = 0.987 * 10**-12 # m^2, 1D = 0.987*10^-12 m^2
nu_w = 1.00087*10**-3 # Pa-S dynamic viscosity of water
K_w = 1.36*10**-5 # m/s Conductivity of water
g = 9.81 # m/s^2 accln due to gravity
rho_w = 998.2 # kg/m^3, density of water

# Solution
k = (nu_w*K_w)/(rho_w*g)#, m^2, permeability of water
k_D = k/Darcy


print("The permeability is {0:1.1E}".format(k),"m\u00b2")
print("The permeability in Darcy unite is: {0:1.2f}".format(k_D),"D")
```

```
The permeability is 1.4E-12 m²
The permeability in Darcy unite is: 1.41 D
```

In [11]:
```
## Tutorial Problem 9: Constant-Head Permeameter

r1 = pn.pane.LaTeX(r"""
(a). Derive the expression for $K$ given below.
$$
K = \frac{QL}{A(h_{in}-h_{out})}
$$

(b). The hydraulic conductivity of a medium sand sample (length 15 cm,
cross-sectional area 25 cm$^2$) is to be determined. The hydraulic head
difference is 5 cm and a water volume of 100 cm³ pas-sed the sample during
an experimental period of 12 min.
<br><br>

(c). How long would 100 cm$^3$ diesel (density: 0.85 g/cm$^3$, dynamic viscosity: 3.5$\cdot 10^{-3}$
Pa$\cdot$s at 20$^\circ$C) need to pass the sample under a head difference of 5 cm (density and
dynamic viscosity of water at 20$^\circ$C: 998.2 kg/m$^3$ and 1.0087$\cdot 10^{-3}$ Pa$\cdot$s, resp.)?
""", width=400, style={'font-size': '13pt'})
spacer = pn.Spacer(width=100)

r2 =pn.pane.PNG("images/T03_TP9.png", width=400)

pn.Row(r1,spacer, r2)
```

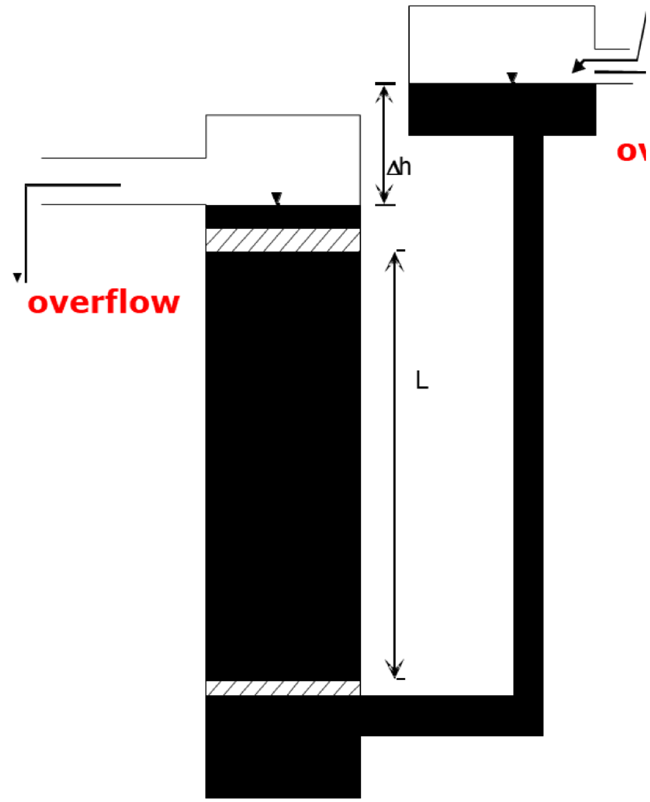
Out[11]:

(a). Derive the expression for K given below.

$$K = \frac{QL}{A(h_{in} - h_{out})}$$

(b). The hydraulic conductivity of a medium sand sample (length 15 cm, cross-sectional area 25 cm^2) is to be determined. The hydraulic head difference is 5 cm and a water volume of 100 cm³ pas-sed the sample during an experimental period of 12 min.

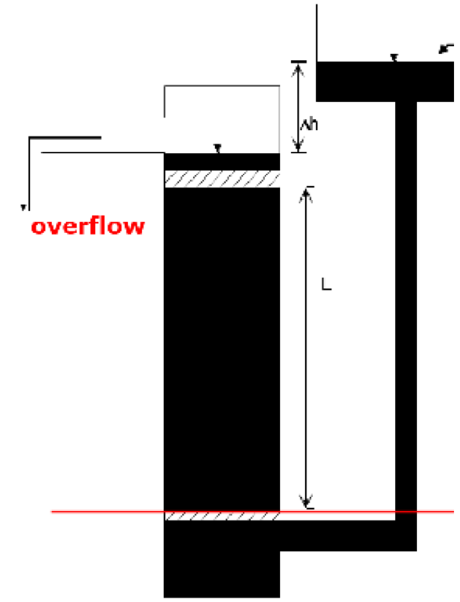
(c). How long would 100 cm^3 diesel (density: 0.85 g/cm^3, dynamic viscosity: 3.5$\cdot 10^{-3}$ Pa·s at 20°C) need to pass the sample under a head difference of 5 cm (density and dynamic viscosity of water at 20 $^\circ$C: 998.2 kg/m^3 and 1.0087$\cdot 10^{-3}$ Pa·s, resp.)?



In [12]:
```
### Tutorial Problem 9 - Solution ###

r1 = pn.pane.LaTeX(r"""

The relevant topic can be found in lecture 04, slides 15, 18-20
<br><br>

Let the reference datum be at the bottom. Then from Darcy's Law:
$$Q= -A\cdot K\frac{h_{out}-h_{in}}{L}$$
With,


Q = discharge [L$^3$/T]<br>
L =column length [L]<br>
A = cross-sectional area of column [L$^2$]<br>
K = hydraulic conductivity [L/T]<br>
h$_{in}$ =hydraulic head at column inlet [L]<br>
h$_{out}$ = hydraulic head at column outlet [L]<br>
<br>
Solve for $K$:
$$
K= \frac{Q\cdot L}{A\cdot(h_{in}-h_{out})}
$$

If the reference level $(z = 0)$ is located at the downgradient overflow, then set $h_{out} = 0$.
""", width= 500, style={'font-size': '13pt'} )
spacer = pn.Spacer(width=100)

r2 =pn.pane.PNG("images/T03_TP9a.png", width=300)

pn.Row(r1,spacer, r2, width=1000)
```

Out[12]:

The relevant topic can be found in lecture 04, slides 15, 18-20



Let the reference datum be at the bottom. Then from Darcy's Law:

$$Q = -A \cdot K \frac{h_{out} - h_{in}}{L}$$

With, Q = discharge [L^3/T]
L =column length [L]
A = cross-sectional area of column [L^2]
K = hydraulic conductivity [L/T]
h_{in} =hydraulic head at column inlet [L]
h_{out} = hydraulic head at column outlet [L]

Solve for K:

$$K = \frac{Q \cdot L}{A \cdot (h_{in} - h_{out})}$$

If the reference level $(z = 0)$ is located at the downgradient overflow, then set $h_{out} = 0$.

In [13]:

```
#Given (solution on 9b)
L = 15 #cm, length of column
A = 25 # cm^2, surface area of column
h_diff = 5 # cm, h_in-h_out
Q = 100/12 # cm^3/min discharge per min

# Solution using derived equation in first part of the problem
# K = QL/A(h_in- h_out)

K = (Q*L)/(A*h_diff)# cm/min, required conductivity
K_1 = K*10**-2/60 #, m/s, conductivity in m/s

#output
print("The conductivity in column is {0:1.2E}".format(K),"cm/min")
print("The conductivity in column is {0:1.2E}".format(K_1),"m/s \n")

if K_1 <= 1.67*10**-4:
    print("Fine to medium sand")
else:
    print("to check further") # to be completed later.
```

```
The conductivity in column is 1.00E+00 cm/min
The conductivity in column is 1.67E-04 m/s

Fine to medium sand
```

Continue solution on 9c

Discharge and Darcy's law: $Q_{water} = \frac{V}{t_{water}} = -A \cdot K_{water} \cdot \frac{\Delta h}{L}$

Solve for t_{water}: $t_{water} = \frac{V}{Q_{water}} = -\frac{V}{A \cdot K_{water} \cdot \Delta h / L} = -\frac{V \cdot L}{A \cdot K_{water} \cdot \Delta h}$

Same step for t_{diesel}: $t_{diesel} = -\frac{V \cdot L}{A \cdot K_{diesel} \cdot \Delta h}$

time ratio: $\frac{t_{diesel}}{t_{water}} = \frac{-\frac{V \cdot L}{A \cdot K_{diesel} \cdot \Delta h}}{-\frac{V \cdot L}{A \cdot K_{water} \cdot \Delta h}} = \frac{K_{water}}{K_{diesel}}$

Use relationship between conductivity K and permeability k from lecture notes (slides 18)

$$\frac{K_{water}}{K_{diesel}} = \frac{k \cdot \frac{\rho_{water} \cdot g}{\eta_{water}}}{k \cdot \frac{\rho_{diesel} \cdot g}{\eta_{diesel}}} = \frac{\rho_{water} \cdot \eta_{diesel}}{\rho_{diesel} \cdot \eta_{water}}$$

Solve for t_{diesel}

In [14]:

```
# Given data

rho_w = 920.2 # kg/m^3, density of water at 20°C
eta_w = 1.0087*10**-3#, Pa-S dynamic viscosity of water
rho_d = 0.85 # g/cm^3, density of diesel at 20°C
eta_d = 3.5*10**-3#, Pa-S dynamic viscosity of diesel
V_d = 100 # cm^3 volume of diesel
t_w = 12 # min, time taken by water

# Calculations

t_d = (rho_w*eta_d)/(rho_d*1000*eta_w)*t_w

# multiplied by 1000 to convert unit g/cm^3 to kg/m^3

print("The time required for diesel will be: {0:0.2f}".format(t_d), "min")
```

```
The time required for diesel will be: 45.08 min
```

In [15]:
```
#
r10_1a = pn.pane.Markdown("""
## Tutorial Problem 10: Falling-Head Permeameter
""", width= 500, style={'font-size': '13pt'})

r10_1 = pn.pane.LaTeX(r"""
$$
K = \frac{d_t^2 L}{d_c^2 L}\cdot \ln\frac{h_{in}(0)-h_{out}}{h_{in}(t)-h_{out}}
$$
""", width=400, style={'font-size': '13pt'})

r10_2 = pn.pane.Markdown("""
1. Derive the expression for K given above.
<br><br>
2. The hydraulic conductivity of a fine sand sample (length 15 cm, diameter 10 cm) is to be determined. The h
ydraulic head difference at the be-ginning and at the end of the experiment after 528 min is 5 cm and 0.5 cm,
resp. The inner tube diameter is 2 cm.

""", width= 500, style={'font-size': '13pt'})

r10_2a = pn.pane.Markdown("""
## Tutorial Problem 10: Solution##
<br>
**Relevant information can be found in Lecture 04, Slides 14 and 16**
""", width= 500, style={'font-size': '13pt'})

col1 = pn.Column(r10_1a, r10_1, r10_2, r10_2a)

r10_3 =pn.pane.PNG("images/T03_TP10.png", width=350)
spacer3 = pn.Spacer(width=50)
pn.Row(col1, spacer3, r10_3)
```

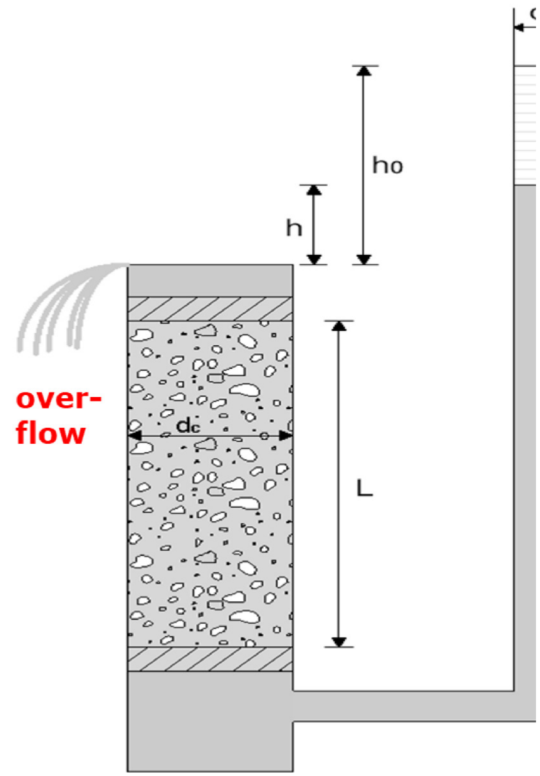
Out[15]:

Tutorial Problem 10: Falling-Head Permeameter

$$K = \frac{d_t^2 L}{d_c^2 L} \cdot \ln \frac{h_{in}(0) - h_{out}}{h_{in}(t) - h_{out}}$$

1. Derive the expression for K given above.

2. The hydraulic conductivity of a fine sand sample (length 15 cm, diameter 10 cm) is to be determined. The hydraulic head difference at the be-ginning and at the end of the experiment after 528 min is 5 cm and 0.5 cm, resp. The inner tube diameter is 2 cm.



Tutorial Problem 10: Solution

Relevant information can be found in Lecture 04, Slides 14 and 16

In [16]:

```
# Tutorial Problem 10: Solution

r10_a1 = pn.pane.LaTeX(r"""
Darcy's Law:
$$
Q(t) = -A_c \cdot K\cdot\frac{h_{out} - h_{in}(t)}{L}
$$

Volumetric budget for standpipe:
$$
Q(t) = -\frac{dV_t}{dt}(t) = -A_t \cdot \frac{dh_{in}}{dt}(t)
$$
with <br>
$A_t$ = cross-sectional area of standpipe [L$^2$]<br>
$V_t$ = water volume in standpipe [L$^3$]<br>
<br>
combine Darcy's law and the volumetric budget:
$$
-A_t \cdot \frac{dh_{in}}{dt}(t) =  -A_c \cdot K\cdot\frac{h_{out} - h_{in}(t)}{L}
$$

solve for $dh_{in}/dt$:
$$
\frac{dh_{in}}{dt} = \frac{K}{L}\frac{A_c}{A_t}(h_{out}-h_{in}) = \frac{K}{L}\bigg(\frac{d_c}{d_t}\bigg)^2(h_{out}-h_{in})
$$

""", style={'font-size': '13pt'})
r10_a2 =pn.pane.PNG("images/T03_TP10.png", width=300)


pn.Row(r10_a1, r10_a2)
```

Out[16]:

Darcy's Law:

$$Q(t) = -A_c \cdot K \cdot \frac{h_{out} - h_{in}(t)}{L}$$

Volumetric budget for standpipe:

$$Q(t) = -\frac{dV_t}{dt}(t) = -A_t \cdot \frac{dh_{in}}{dt}(t)$$

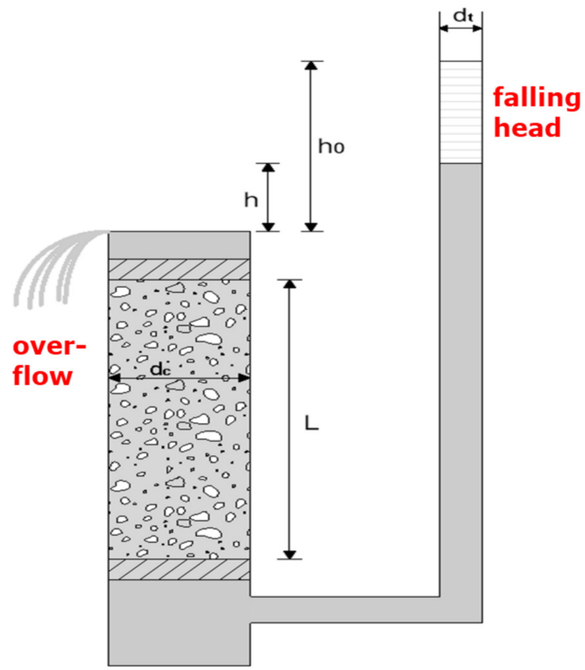
with
A_t = cross-sectional area of standpipe [L^2]
V_t = water volume in standpipe [L^3]

combine Darcy's law and the volumetric budget:

$$-A_t \cdot \frac{dh_{in}}{dt}(t) = -A_c \cdot K \cdot \frac{h_{out} - h_{in}(t)}{L}$$

solve for dh_{in}/dt:

$$\frac{dh_{in}}{dt} = \frac{K}{L}\frac{A_c}{A_t}(h_{out} - h_{in}) = \frac{K}{L}\left(\frac{d_c}{d_t}\right)^2(h_{out} - h_{in})$$



In [17]:
```
#
r10_a3 = pn.pane.LaTeX(r"""
Equation for falling head: $ \frac{dh_{in}}{dt}  = \frac{K}{L}\big(\frac{d_c}{d_t}\big)^2(h_{out}-h_{in}) $
<br> <br>
This equation is an ordinary differential equation of first order.
Providing hydraulic head $h_{in}(0)$ at the beginning of the experiment $(t = 0)$, it
may be solved by separation of variables:
$$
\frac{dh_{in}}{h_{out}-h_{in}} = \frac{K}{L}\bigg(\frac{d_c}{d_t}\bigg)^2 dt
$$
integrations on both sides by considering the initial condition:
$$
\int_{h_{in}(0)}^{h_{in}(t)}\frac{dh_{in}}{h_{out}-h_{in}} = \int_0^t \frac{K}{L}\bigg(\frac{d_c}{d_t}\bigg)^
2 dt = \frac{K}{L}\bigg(\frac{d_c}{d_t}\bigg)^2 \int_0^t dt
$$
determine integral functions:
$$
\Bigg[-\ln(h_{out} - h_{in}) \Bigg]_{h_{in}(0)}^{h_{in}(t)} = \frac{K}{L}\bigg(\frac{d_c}{d_t}\bigg)^2 [t]_0^
t
$$
insert limits of integration:
$$
-\ln\frac{h_{out}-h_{in}(t)}{h_{out}-h_{in}(0)} = \frac{K}{L}\bigg(\frac{d_c}{d_t}\bigg)^2 t
$$
solve for K:
$$
K = \bigg(\frac{d_c}{d_t}\bigg)^2 \frac{L}{t}\ln\frac{h_{in}(0)-h_{out}}{h_{in}(t)-h_{out}}
$$
""", style={'font-size': '13pt'})
r10_a3
```

Out[17]:

Equation for falling head: $\frac{dh_{in}}{dt} = \frac{K}{L}\left(\frac{d_c}{d_t}\right)^2(h_{out} - h_{in})$

This equation is an ordinary differential equation of first order. Providing hydraulic head $h_{in}(0)$ at the beginning of the experiment $(t = 0)$, it may be solved by separation of variables:

$$\frac{dh_{in}}{h_{out} - h_{in}} = \frac{K}{L}\left(\frac{d_c}{d_t}\right)^2 dt$$

integrations on both sides by considering the initial condition:

$$\int_{h_{in}(0)}^{h_{in}(t)} \frac{dh_{in}}{h_{out} - h_{in}} = \int_0^t \frac{K}{L}\left(\frac{d_c}{d_t}\right)^2 dt = \frac{K}{L}\left(\frac{d_c}{d_t}\right)^2 \int_0^t dt$$

determine integral functions:

$$\Big[-\ln(h_{out} - h_{in})\Big]_{h_{in}(0)}^{h_{in}(t)} = \frac{K}{L}\left(\frac{d_c}{d_t}\right)^2 [t]_0^t$$

insert limits of integration:

$$-\ln\frac{h_{out} - h_{in}(t)}{h_{out} - h_{in}(0)} = \frac{K}{L}\left(\frac{d_c}{d_t}\right)^2 t$$

solve for K:

$$K = \left(\frac{d_c}{d_t}\right)^2 \frac{L}{t} \ln\frac{h_{in}(0) - h_{out}}{h_{in}(t) - h_{out}}$$

In [18]:
```
# Given

L = 15 # cm, length
L_m = L/100 # m, length
d_c = 10 # cm, diameter column
d_t = 2 # cm, diameter tube
h_d0 = 5 # cm, head difference at start
h_dt = 0.5 # cm, head difference at time t
t = 528 # min, total time
t_s = 528*60 # sec, total time in seconds

#solution using the developed equation

K = (d_t/d_c)**2 * ((L_m)/t_s)*np.log(h_d0/h_dt)

#Output
print("The conductivity in column is {0:1.2E}".format(K),"m/s \n")

if K < 1.67*10**-5:
    print("Silt or silty sand")
else:
    print("to check further") # to be completed later.
```

```
The conductivity in column is 4.36E-07 m/s

Silt or silty sand
```

HOME WORK PROBLEMS

Darcy's Law and Intrinsic Permeability

There is no obligation to solve homework problems!

Try to submit within next 2 weeks.

In [19]:
```
#
r_h3a = pn.pane.Markdown("""
## Homework Problem 3 ##


**A**. Derive an expression for hydraulic conductivity *_K_* for the constant-head permeameter shown in the f
igure.<br><br>
**B**. The hydraulic conductivity of a sample (length 10 cm, diameter 4 cm) is to be determined.
The water depths a<sub>1</sub> and a<sub>2</sub> equal 6 cm and 3 cm, resp. A water volume of 250 ml passed t
he sample during an experimental period of 36 s. <br> <br>
**C**. Which material could be contained in the sample?
""", width = 400, style={'font-size': '13pt'})
spacer2=pn.Spacer(width=50)
r_h3b = pn.pane.PNG("images/T03_TH3.png", width=500)
pn.Row(r_h3a,spacer2, r_h3b)
```

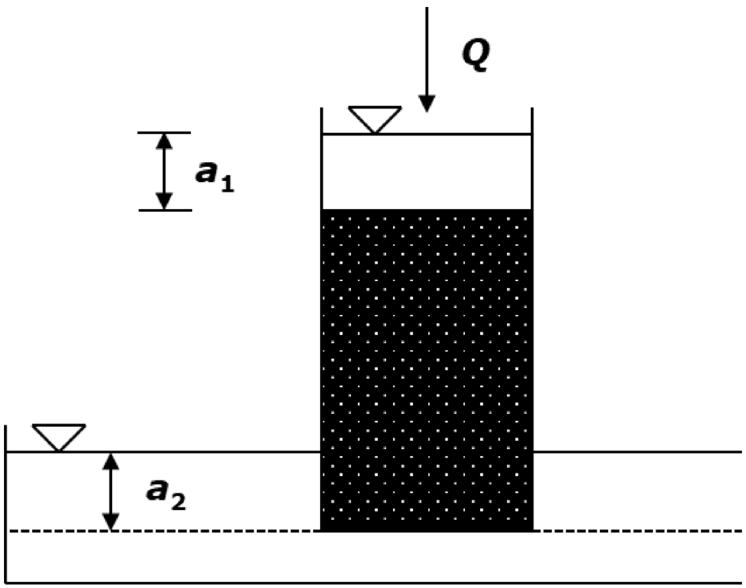
Out[19]:

Homework Problem 3

A. Derive an expression for hydraulic conductivity *K* for the constant-head permeameter shown in the figure.

B. The hydraulic conductivity of a sample (length 10 cm, diameter 4 cm) is to be determined. The water depths a_1 and a_2 equal 6 cm and 3 cm, resp. A water volume of 250 ml passed the sample during an experimental period of 36 s.

C. Which material could be contained in the sample?



Homework Problem 4

In [20]:
```
#
r_h4 = pn.pane.Markdown("""
A Darcy experiment is performed by a falling-head permeameter using water at 20°C.
Length and diameter of the sample are 20 cm and 6 cm, resp. The inner tube diameter is 4 cm.
The following data are available for the time-dependent hydraulic head difference :
""", style={'font-size': '13pt'})

r_h4b = pn.pane.PNG("images/T03_TH4a.png", width=400)

r_h4c = pn.pane.Markdown("""
**A.** Convert times to seconds and plot the logarithm of the ratios of head differences ln(Δh(0)/Δh(t)) vs.
 time t.
(Use the coordinate system on next page). <br><br>
**B.** Determine the slope of the corresponding regression line.<br><br>
**C.** Determine hydraulic conductivity K.<br><br>
**D.** Determine intrinsic permeability k.<br>

""", style={'font-size': '13pt'})
r_h4d = pn.Column(r_h4, r_h4b, r_h4c)
r_h4e = pn.pane.PNG("images/T03_TP10.png", width=400)
spacer2=pn.Spacer(width=50)
pn.Row(r_h4d, spacer2, r_h4e)
```

Out[20]:

A Darcy experiment is performed by a falling-head permeameter using water at 20°C. Length and diameter of the sample are 20 cm and 6 cm, resp. The inner tube diameter is 4 cm. The following data are available for the time-dependent hydraulic head difference :

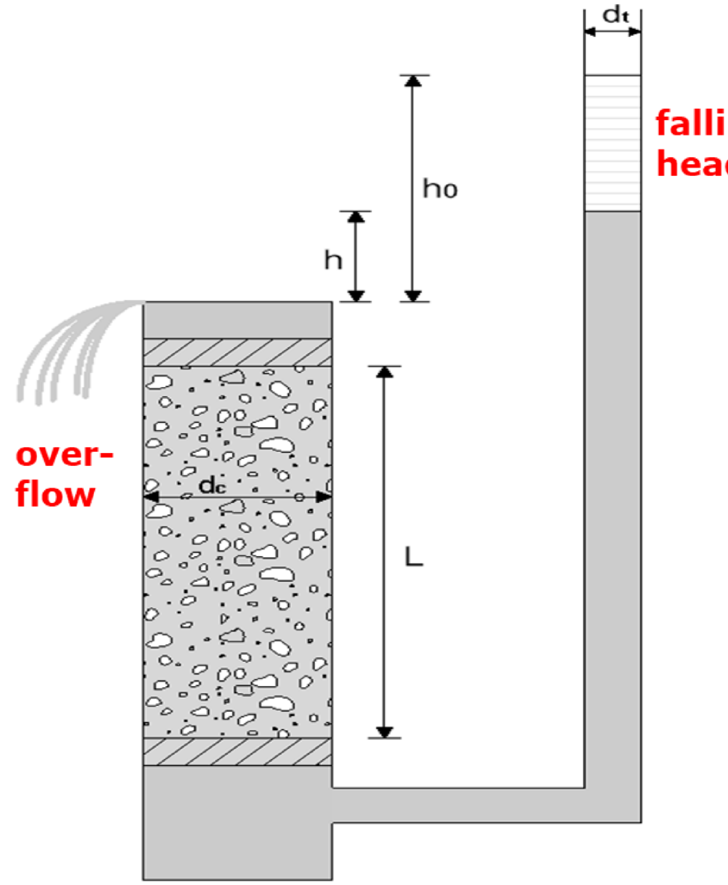
t (min)	0	5	18	23	27	29
Δh (cm)	36.9	33.6	26.3	23.9	22.1	21.3

A. Convert times to seconds and plot the logarithm of the ratios of head differences ln(Δh(0)/Δh(t)) vs. time t. (Use the coordinate system on next page).

B. Determine the slope of the corresponding regression line.

C. Determine hydraulic conductivity K.

D. Determine intrinsic permeability k.



In [21]:
```
#
fig, ax = plt.subplots(figsize=(8, 6))
plt.grid(axis='y', linestyle='--')
plt.xlim((0, 1800)); plt.ylim((0,0.7))
plt.xlabel("t(s)", fontsize=12 )
plt.ylabel(r"ln($\Delta h(0)/\Delta h(t)$)(-)", fontsize=12);
```