**Exam questions: Henk Huinink**

**Question 1: capillarity**

The general expression for the capillary pressure $P_c$ [Pa] is

$$P_c = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

where $\gamma$[N/m] is the liquid-gas interfacial tension and $R_1$ and $R_2$ [m] are the radii of curvature of the interface.

a) A drop of a wetting liquid is confined a liquid film between two parallel plates with area $A$ [m$^2$] separated by a distance $d$ [m]. The film has a pancake shape with a radius $R$ and of course a thickness $d$, where $d \ll R$. The capillary pressure obeys: $P_c = 2\gamma\cos\theta/d$. Derive this expression.

b) Proof mathematically that there is an attractive force generated by the confined drop that keeps the plates together. Note that in absence of the drop of liquid, there is only air between the plates that is fully equilibrated with the air outside this slit

c) What physical property in our exercise reflects the liquid-solid interaction? And explain how liquid-solid interactions promote an attractive force between the plates.

**Question 2: viscous flow**

Flow through a cylindrical tube with radius $r$ [m] and length $L$ [m] is driven by a pressure difference $\Delta p$ [Pa]. The discharge $Q$ [m$^3$/s] through the tubes is given by the following expression.

$$Q = -\frac{\pi r^4}{8\mu}\frac{\Delta p}{L}$$

In this expression $\mu$ [Pa s] is the viscosity.

a) Show that the permeability k [m$^2$] of a porous media consisting of parallel oriented cylindrical pores equals $k = \phi d^2/32$ ($\phi$ is the porosity and $d$ [m] the pore diameter ).

b) The permeability expression, given under a), only holds for laminar flow. However, in many problems in hydrology and petrology the assumption of laminar flow is perfectly valid. Explain why (include a discussion on the Reynolds number in your answer).

**Exam Introduction Porous Media 2019**

**Multi-Phase Flow in Porous Media Ruud Schotting**

A flow container is filled with homogeneous course sand. At the left hand side, a heterogeneity is included consisting of fine sand. See Figure 1.

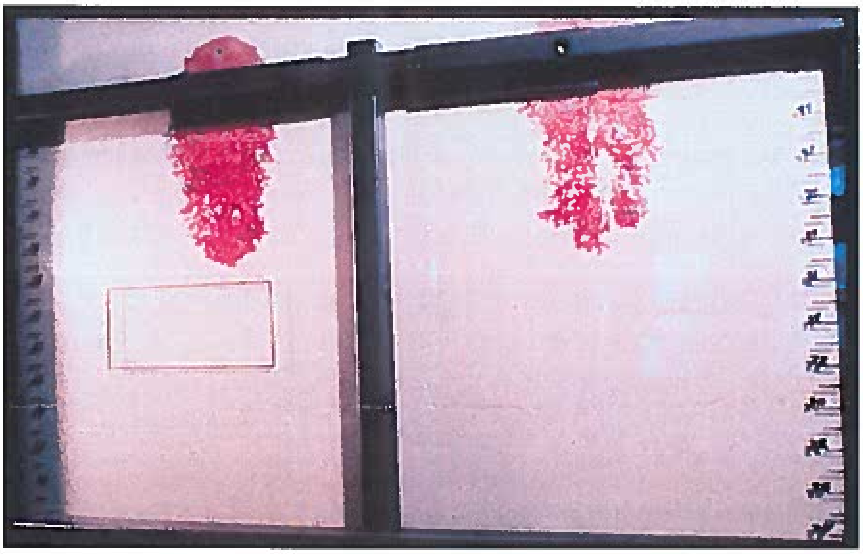

**Figure 1** Sand box filled with course sand and a fine sand heterogeneity

In the first experiment the tank is fully saturated with water. At the upper sand level in the tank two identical amounts of DNAPL (colored with red dye) are simultaneously released, see again Figure 1. The DNAPL moves downward due to gravity forces.

a. Explain the different patterns of the saturation distribution of the DNAPL plumes.

b. What will happen when the DNAPL (at the left hand side) reaches the top of the block of fine sand?

c. Next we repeat the experiment, but now the porous media in the flow container are **not** fully saturated with water. What happens in this situation when the DNAPL reaches the top of the block of fine sand?

d. Explain the concept of wettability in multi-phase flow.

e. What happens to the intrinsic permeability if the viscosity of the DNAPL increases due to lowering of the temperature of the flow tank and its content?

f. If the viscosity of the DNAPL increases, the travel time of the DNAPL towards the block of fine sand will increase too. It this true or not true? **Motivate** your answer!

g. In Figure 2. The relative permeability functions, i.e. "rel perms", are depicted for both the wetting and non-wetting fluid in a saturated, homogeneous porous medium.

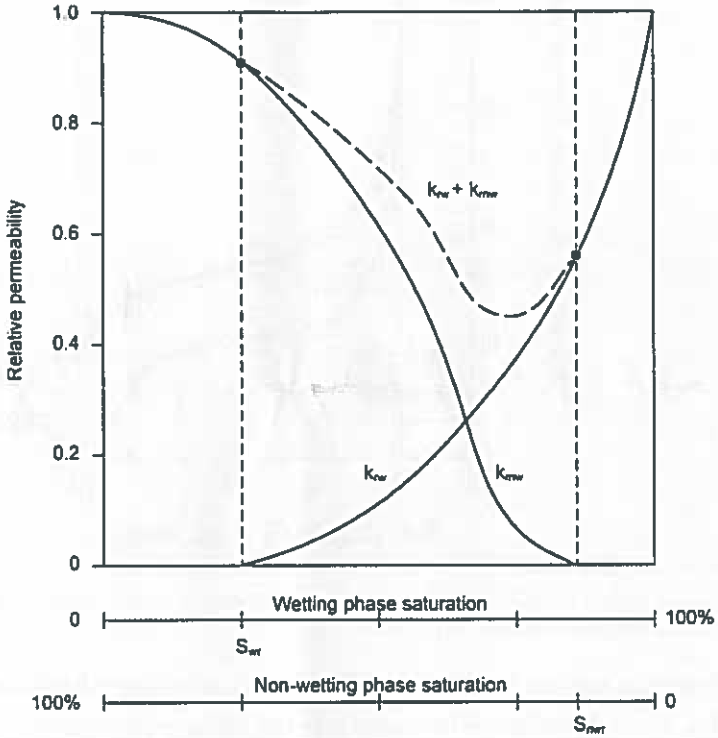


**Figure 2 Relative permeability functions for the wetting and non-wetting fluid, i.e. respectively water and DNAPL**

Figure 2. is taken from the book of Mayer & Hassanizadeh, 2005[1] The dashed line represents the sum of both relative permeability functions $k_{rw} + k_{rnw}$ . Note that, if both fluids are present $k_{rw} + k_{rnw} < 1$. Explain in words why this is the case.

h. The maximum relative permeability of the *wetting phase* is much less as compared to the maximum relative permeability of the non-wetting phase, see Figure 2. Explain this difference in words. Hint: it has something to do with the different wetting behavior of both fluids in the porous medium....

[1] Soil and Groundwater Contamination: Non-aqueous Phase Liquids, American Geopysical Union, Washington , DC, 2005

i. Explain the concept of entry (or imbibition) pressure in words.

j. Consider two horizontal cylinders containing the **same** type of porous medium. The $P_c$ ($S_w$) curves of this porous medium for both drainage and imbibition are given in Figure 3.

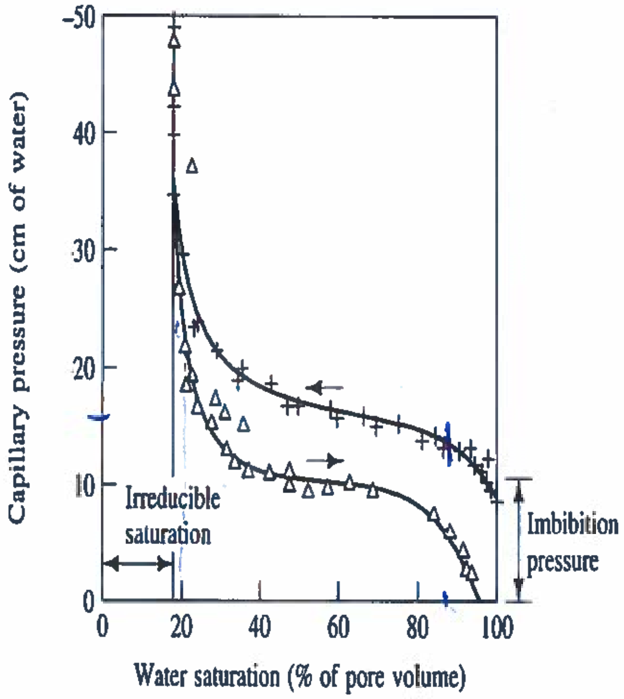


Figure 3 Capillary pressure-saturation curves for water-air (see larger version as an Appendix to this document)

Before connecting two columns at t = 0, the column at the right hand side has a water saturation of $S_R$ = 90 %. The column at the left hand side has, before connecting a water saturation of $S_L$ = 20 %. At t = 0 both columns are connected, such that the column at the right hand side is in a drainage state and the left hand column in an imbibition state.

1. Determine the corresponding capillary pressures $P_L$ and $P_R$ in both columns **before** connecting the two columns.
2. Assume that the pressure at the contact interface **after** connecting the two columns is equal to ($P_L$ and $P_R$)/2, i.e. the average value. Determine the saturation discontinuity at the interface for t > 0, and explain what is happening in the two columns w.r.t. pressure and saturation distribution along the horizontal axis of the combined columns. Hint: draw qualitative graphs
3. What is the equilibrium saturation for t -> infinity?

2 PHASE flow

# Formula sheet

Two-phase flow equations in porous media

$$n\frac{\partial(S_w\rho_w)}{\partial t} + \text{div}\,(\rho_w\bar{q}_w) = 0 \tag{1}$$

$$\bar{q}_w = -\frac{\kappa}{\mu_w}k_{rw}(S_w)(\text{grad}P_w - \rho_w\bar{g}) \tag{2}$$

$$n\frac{\partial(S_{nw}\rho_{nw})}{\partial t} + \text{div}\,(\rho_{nw}\bar{q}_{nw}) = 0 \tag{3}$$

$$\bar{q}_{nw} = -\frac{\kappa}{\mu_{nw}}k_{rnw}(S_{nw})(\text{grad}P_{nw} - \rho_{nw}\bar{g}) \tag{4}$$

$$S_w + S_{nw} = 1 \tag{5}$$

$$P_c(S_w) = P_{nw} - P_w \tag{6}$$

with

$$S_w(P_c) = \left(\frac{P_d}{P_c}\right)^{\lambda} \quad \text{Brooks-Corey} \tag{7}$$

and the simplified relative permeability functions

$$k_{rw}(S_w) = S_w^3 \quad \text{and} \quad k_{rnw}(S_{nw}) = S_{nw}^3 \tag{8}$$

$P_c = Ph$

$\frac{2\gamma}{r} = \rho g h$

$P_c =$

$P_c = \frac{2\gamma}{r}$

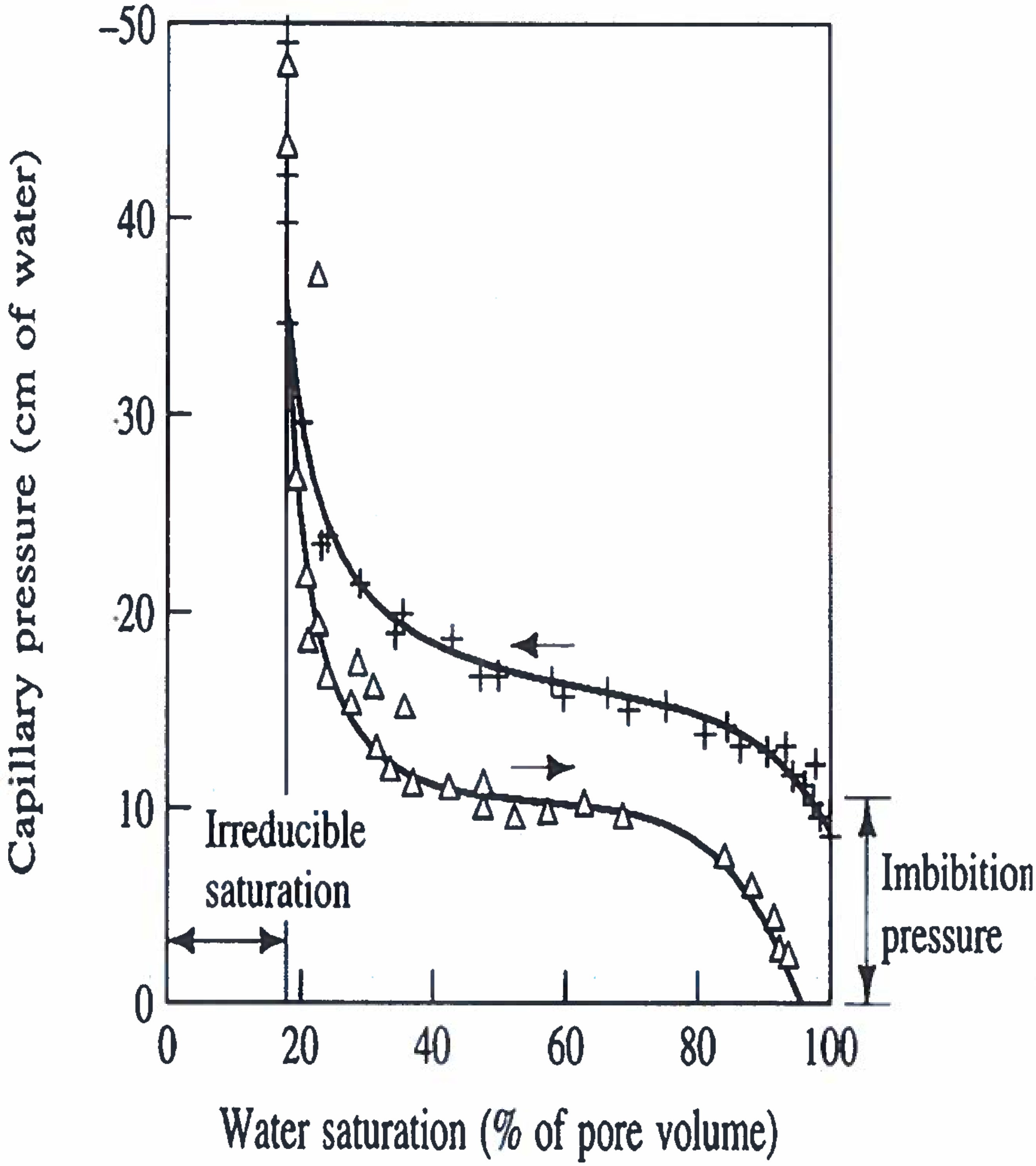


Figure 3 Large version of figure 3

**Question Leo Pel:** During the lectures an example was given of salt damage to a brick masonry wall on one of the oldest buildings in New Orleans (USA).

*Figure 1: A picture of Madame John's Legacy build in 1788 and the salt damage seen nowadays*

The salt damage seen is a nice example of conservation going wrong, i.e., by a wrong intervention during the conservation of this building one has gotten more salt damage. In order to understand this we have to look more closely. New Orleans has been built in a swapy area with high groundwater levels which contain high amounts of sodium salts. If we have a look at the cross-section of the outer wall we get figure 2.

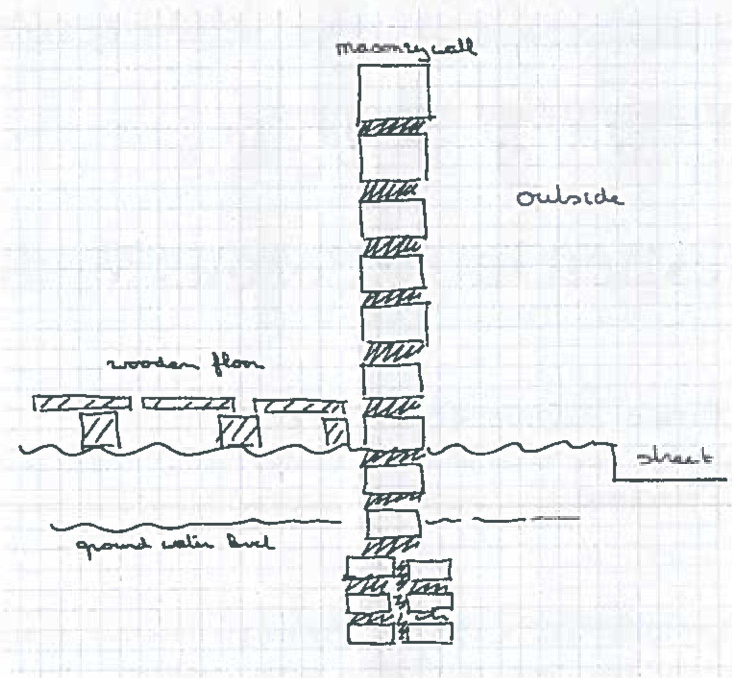


*Figure 2: A cross section of the outer wall where the salt damage appeared after the restoration of the building*

Hence we see a basic masonry wall construction and a high ground water level. Inside there used to be a wooden floor made out of planks with large cracks in between. During the restoration it was decided to replace the wooden floor by a concrete floor. It was only from this moment on one started to see salt damage appear on the masonry wall. Could you explain this? What advise would you give the conservators?

**Question on poro-elasticity 2019**

**David Smeulders**

a) What is the difference between the Young's modulus and the constrained modulus?
b) If the constained modulus of a certain material would magically be increased would the seismic wave in this material propagate faster or slower?
c) Same question if the density of the material would be increased.
d) Explain the principles of the jacketed and unjacketed tests for saturated porous media by making a sketch of the experimental set-ups that are typically used.
e) Complete the table below and explain the meaning of $p$, $p_e$, $\phi$, $\sigma$, $K_b$ and $K_s$

| | dp | dσ | dϕ | $dV_b/V_b$ | $dV_s/V_s$ |
|---|---|---|---|---|---|
| unjacketed | $dp_e$ | | | $-dp/K_b$ | |
| jacketed | 0 | | | $-d\sigma/K_b$ | $-d\sigma/(1-\phi)K_s$ |

f) What is the Skempton test for saturated porous media?

# Exam question Intro Porous Media

**Suzanne Hangx**

## Question 'Structure of Porous Media'(15 points)

a. What three main types of porous media are there, and what are their main characteristics? Name three examples of each (5 POINTS)

b. For packs of spherical particles with the same size, what are the three main packing configurations? Illustrate each configuration with a simple sketch of the packing structure.

c. Your colleague in chemical engineering needs a bed reactor pack of regular catalyst beads to perform an experiment. They need a pack that is regularly packed. They want you to advise on the porosity that can be achieved by regularly packing of their catalyst beads. What porosity values can you tell them each of the different packing structures can provide them with?

d. After thinking through your advice, your colleague decides that in order for the experiment to succeed they need a tighter packing (i.e. lower porosity). What two bead aggregate properties do you suggest they can adjust to control the packing porosity? What new types of beads would they need to request from the manufacturer (keep in mind: the composition of the beads cannot be changed, as this will affect their catalyst properties!).

## Question 'Processes Impacting Porous Media' (10 points)

a. Explain how the flow or injection of fluids can impact the permeability of a (fractured) material through i) chemical reaction with and ii) sorption of fluid to the material.

b. In which scenarios could these processes play a role?

c. The country of Moto has vast volumes of volcanic rocks, like basalt, which is rich in Ca-pyroxene, in the subsurface, but not many other resources. To make more money, they plan to sell off the subsurface space to countries with high $CO_2$ emissions so that these countries can use their basalt formations to mineralise $CO_2$ into $CaCO_3$, thereby mitigating climate change. They think that by initiating the first set of fractures, the 60% solid volume increase of reaction will lead to further self-fracturing of the basalt body helping the process of mineralisation along. The aim is for Moto to become filthy rich by this technology, cleaning up the mess of other countries. They have asked you to evaluate their plans to see if this idea will work. In your expert opinion, what are the main challenges this technology will face?

..... **The End** .....