DYNAMIC CAPILLARY PRESSURE IMPACT ON THE DESCRIPTION OF LNAPL DISTRIBUTION UNDER WATER TABLE FLUCTUATION

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Content

- Context
- *k-S-P* relations for characterization
- Dynamic vs static capillary pressure
- Experimental approach
- Perspectives

Context

Soil and aquifer contamination

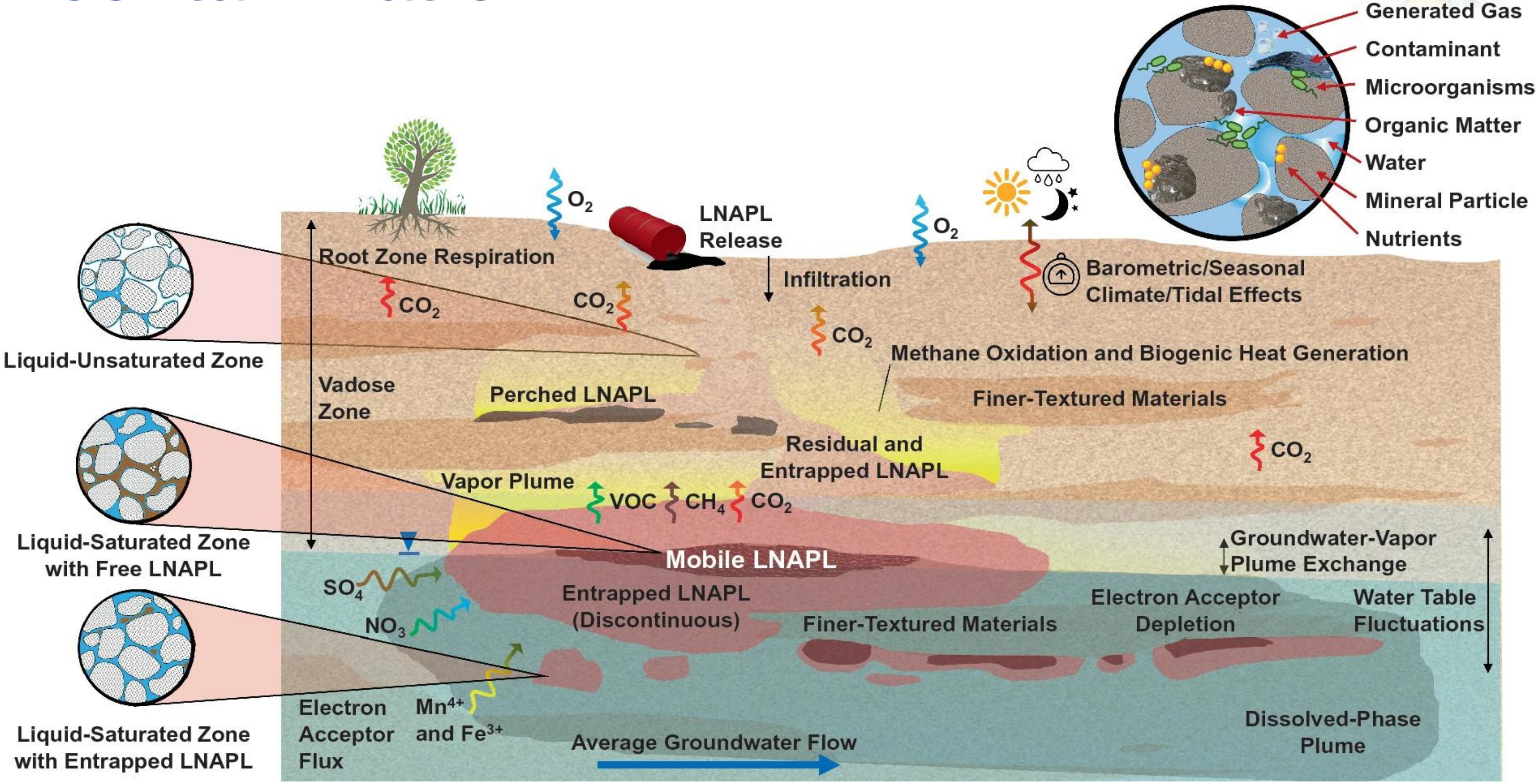
NAPL

LNAPL DNAPL

$\rho_{LNAPL} < \rho_{water}$

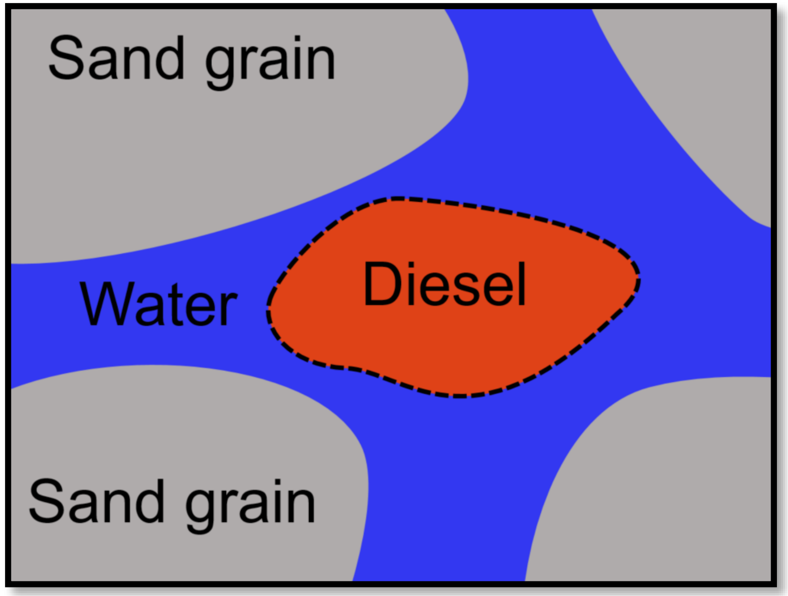
- Diesel
- Gasoline
- Motor oil and etc.

37.22% MTES (2018)



J. García-Rincón et al. (eds.), *Advances in the Characterisation and Remediation of Sites Contaminated with Petroleum Hydrocarbons*, Environmental Contamination Remediation and Management, https://doi.org/10.1007/978-3-031-34447-3_1

k – *S*- *P* constitutive relations for characterization



Co-existence of two or more immiscible fluids create:

- **The capillary forces : Capillary pressure**
- **Relative permeability of each fluids : ability of the fluids to move through the porous medium in the presence of the other fluid**
- **Saturation by each fluid : amount of the fluid in the porous medium**

Question to answer :

Are dynamic effects important for modeling LNAPL distribution in a context of fluctuating water tables?

Dynamic vs Static capillary pressure

Literature review

General mass conservation of two immiscible phase flow

$$\emptyset \frac{\partial S_\alpha}{\partial t} = \nabla \cdot \left[\frac{k_{r\alpha}(S_\alpha)}{\mu_\alpha} \boldsymbol{k} \cdot (\nabla P_\alpha - \rho_\alpha \boldsymbol{g}) \right]; \quad \alpha = w, n$$

Static pressure

$$P_n - P_w = P_c(S_w)$$

Dynamic pressure

$$P_c^d(S_w) - P_c^s(S_w) = \tau \frac{\partial Sw}{\partial t}(Sw)$$

Hassanizadeh and Gray 1990

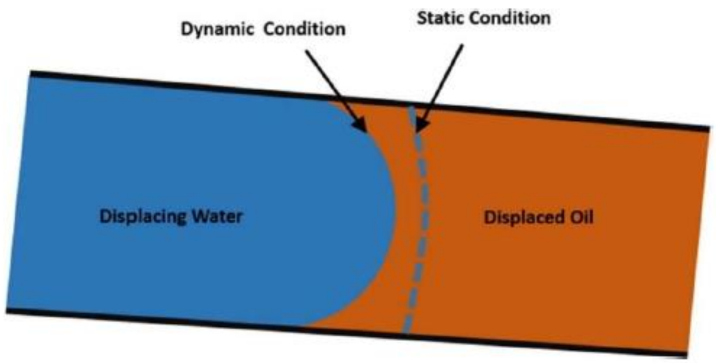
Weitz 1987 and Stokes 1987:

$$\Delta p = \frac{\gamma}{r_t} \left[-1 + K\,(Ca)^x \right]$$

De Gennes (1988):

$$\Delta p_d = (const) v\,(Ca)^{2/3}\, t^{5/3}$$

Dynamic effect can be as well applied to k_r however not many studies on this topic



Interfacial shape in porous media under static and dynamic conditions by (Y. Li et al. 2017)

k_r – relative permeability
k – intrinsic permeability
P_c^d – dynamic capillary pressure
w – wetting phase
n – non-wetting phase
P_c^s – static capillary pressure
Ca – capillary number
γ – surface tension
v - length of contact line present in one cm2 of interface

Dynamic capillary coefficient

Stauffer

$$\tau = \frac{\alpha\phi\mu_w}{\lambda k}\left(\frac{P^d}{\rho_w g}\right)^2$$

[τ] = [Pa * s]

Joekar-Niasar and Majid Hassanizadeh

$$\mu_{eff} = \mu_{nw}S_{nw} + \mu_w S_w$$

Mirzoye Mas model (with Buckingham Π – theorem implementation)

$$\tau = C\frac{P^d V^{1/6}}{\sqrt{g}}\left(\frac{\emptyset}{\lambda}\times\frac{\rho}{M}\right)^a\left(\frac{k}{V^{2/3}}\right)^b (S_w)^c; \rho = \frac{\rho_{nw}}{\rho_w}; M = \frac{\mu_{nw}}{\mu_w}$$

Barenblatt theory :
τ is equal to redistribution time “equilibrium time”

Civan’s model:

$$\tau = \frac{\tau_o}{(S_w - S_{wi})^a}, a > 0$$

$$\tau_o = \tau_w(1 - S_{nwi} - S_{wi})^b, b > 0$$

$$\tau_w = \frac{\mu_w}{2k^o_{rw}k}$$

- Existence of different models of dynamic capillary coefficient
- Not obvious dependence of τ on parameters like:
  - Pore geometry
  - Fluid properties
  - Flow properties

Dynamic capillary coefficient

τ decreases with increasing water saturation

the relation between τ and saturation looks different depending on the fluid pairs, need more studies

higher permeability means lower τ, but not so clear

55 points, 7 independent studies

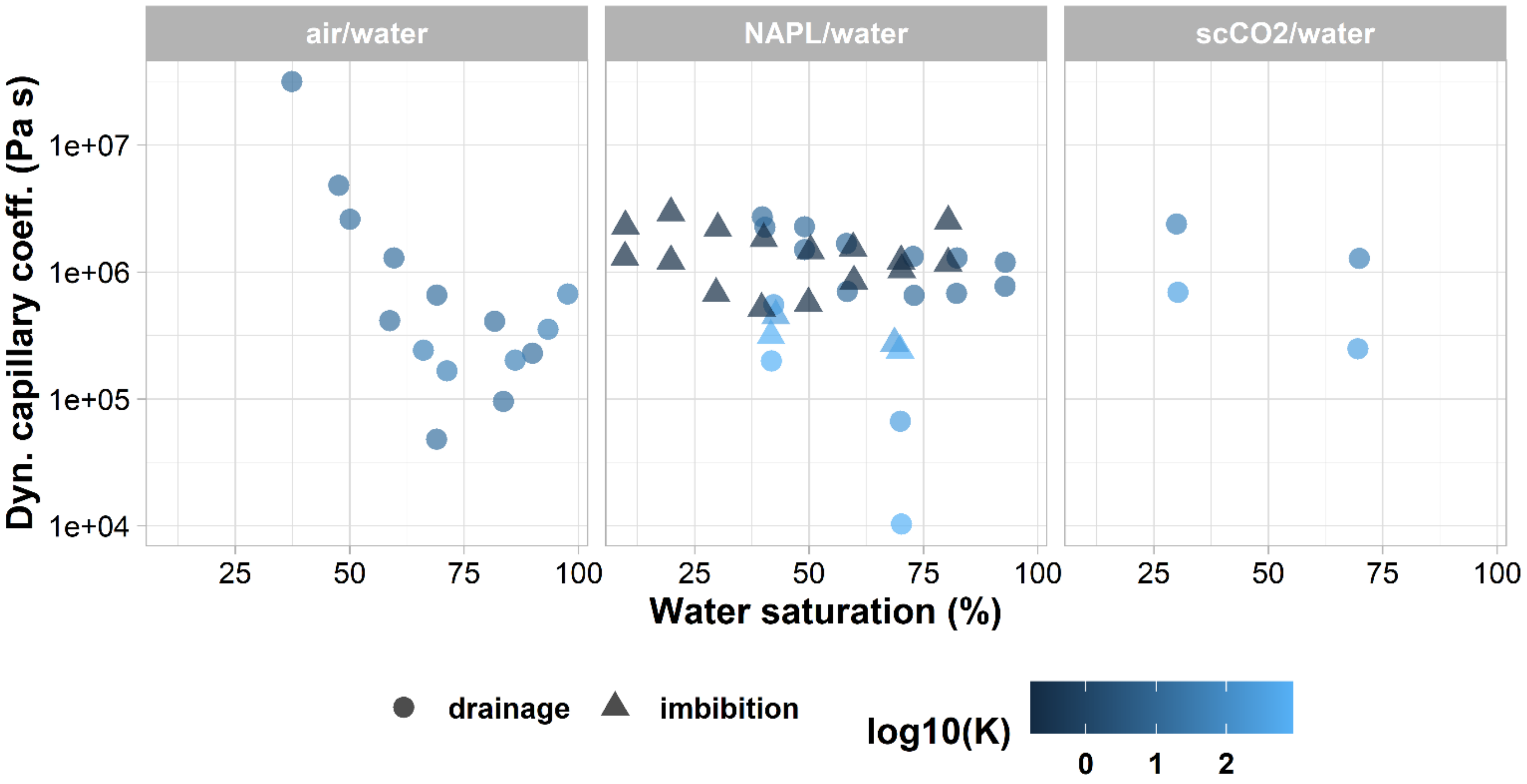
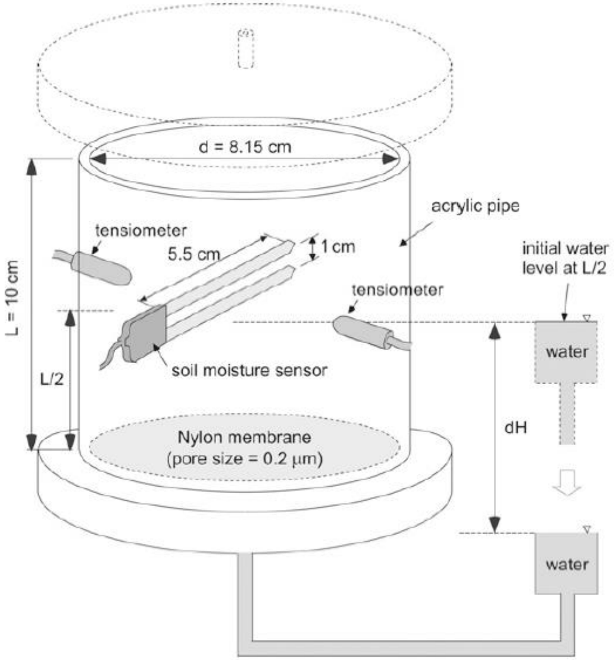


Figure 8. Summary of results of 7 studies (Abidoye and Das 2020; Mirzaei and Das 2013; Goel and O'Carroll 2011; Kalaydjian 1992; Zhuang et al. 2017; Sakaki, O'Carroll, and Illangasekare 2010; Camps-Roach et al. 2010)

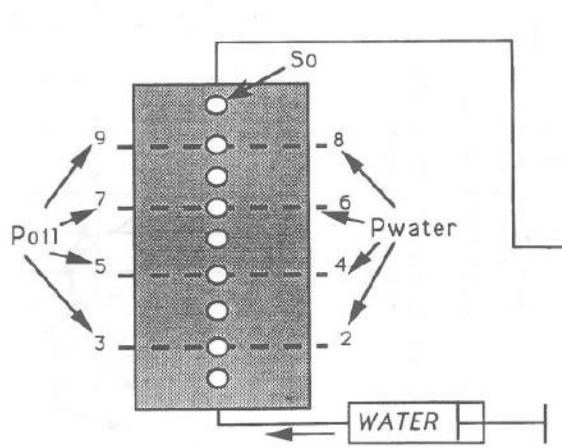
Dynamic capillary coefficient



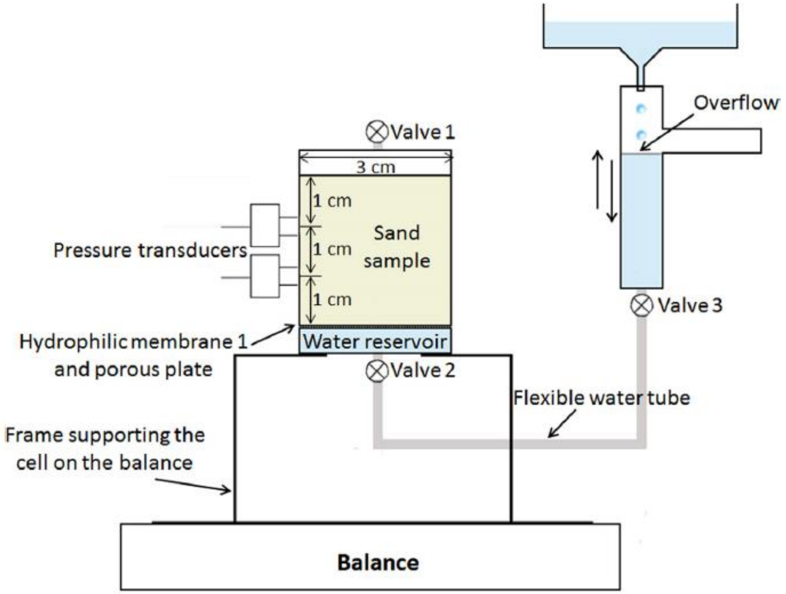
Setup of the experiment by *Sakaki et al. 2010*

- Water – air pair
- Concluded:
  - τ hysteretic
  - Threshold for τ to be non-negligible is not clear

- Oil – water pair
- Concluded:
  - dyn P_c depend on Ca on (q) specifically



Setup of the experiment by *Kalaydjian 1992*



Setup of the experiment by *Zhuang et al. 2017*

- Water – air pair
- Concluded:
  - Confirmed τ hysteretic
  - Dependence on S_w is non-unique

Literature review conclusion

- Literature review shows:

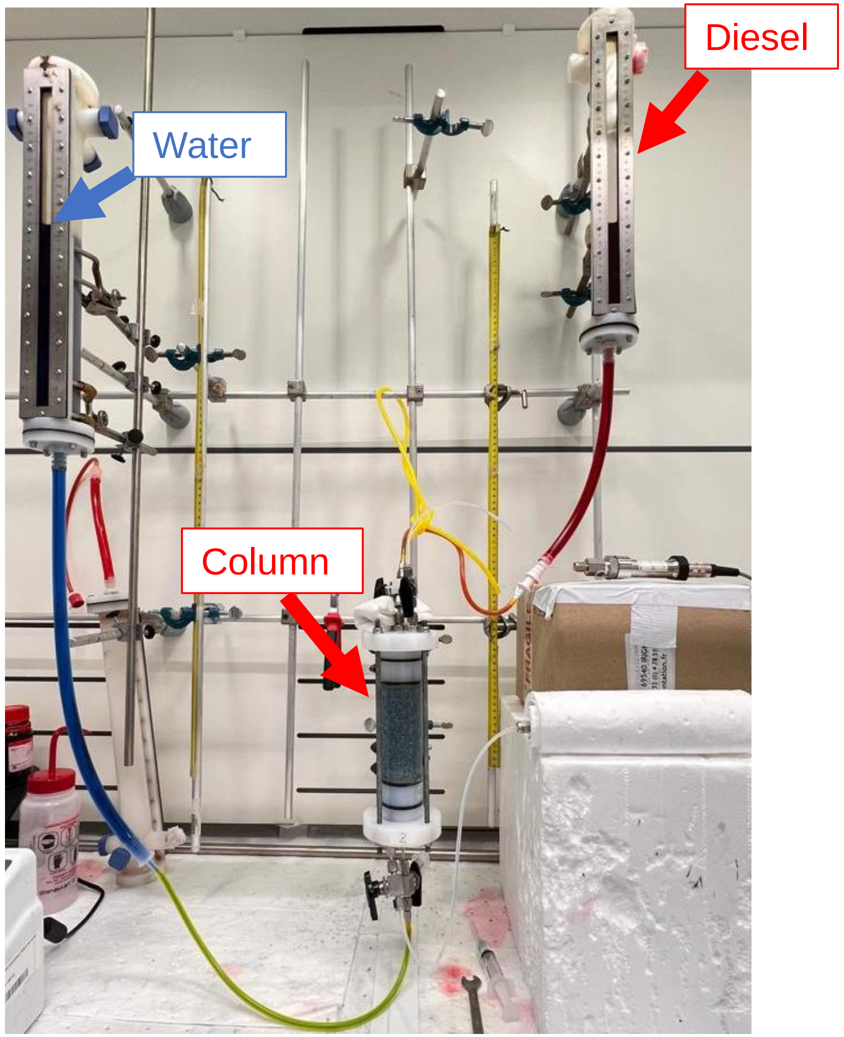
  - Dynamic conditions have the impact on modelling of multiphase flow and different models on this point, widely used: Hassanizadeh and Gray's
  - less studies in dyn k_r and more in P_c
  - More focus on τ and less on saturation change rate and Ca
  - There is an impact of parameters like fluid properties and pore geometry on τ

- Questions to answer:

  - What is the magnitude and the dependent parameters of the term inside the Hassanizadeh models in our context?
  - What is the magnitude and the dependent parameters of the dynamic relative permeabilities in our context?
  - How the answers to these questions change considering the fluid pairs, as the situation inside the vadose zone can be model as two two-phase flow (water-oil and oil-air)?

Experimental approach

1D Column quasi – static condition



Setup

- **Objective** :
  - Measuring the pressure difference between the fluids
  - under a quasi-static condition
  - based on different steps in hydrostatic pressure

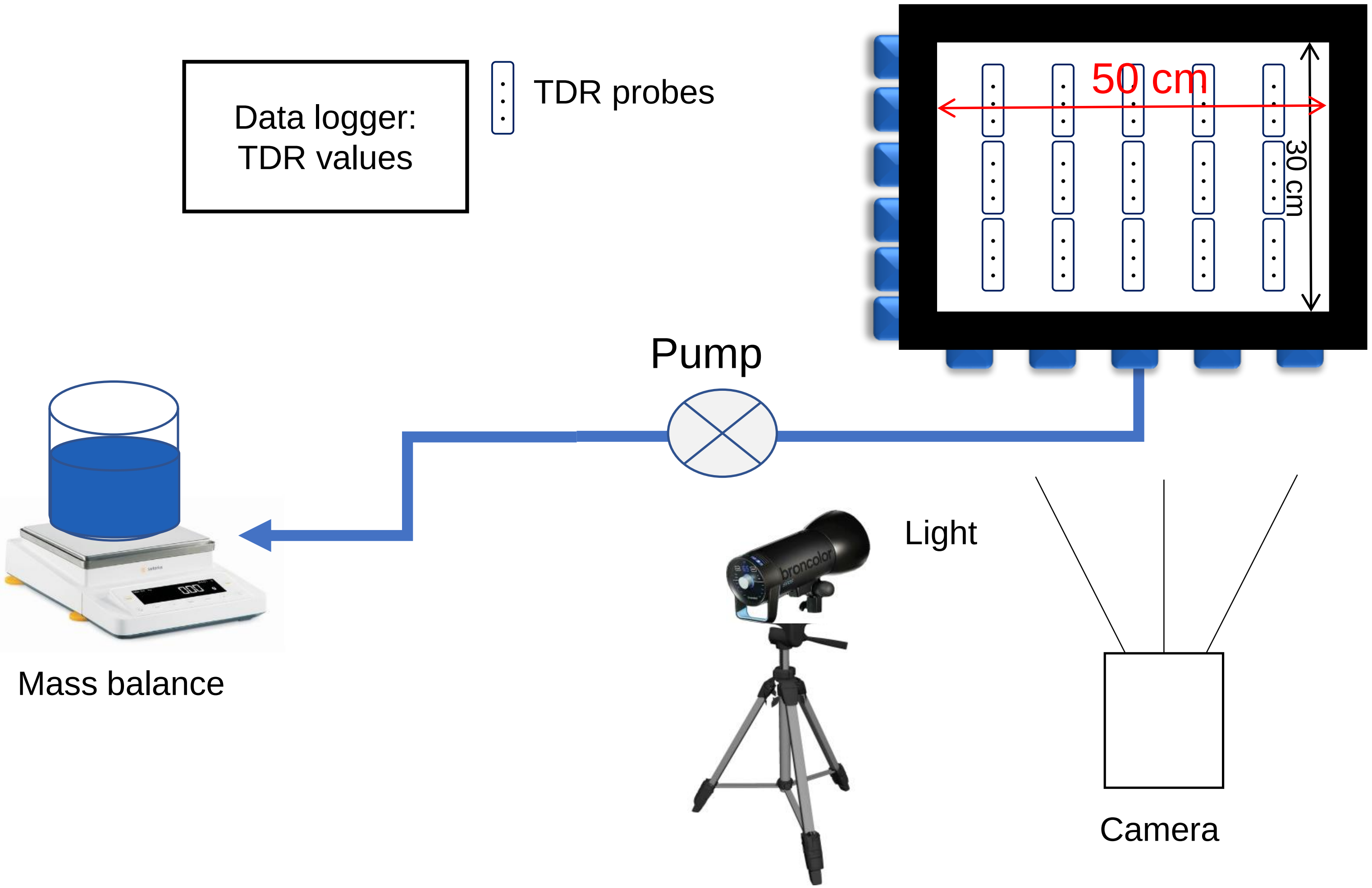
- **Sand properties** :
  - ∅ ~ 0.37 ÷ 0.40

- **Diesel properties** :
  - ρ = 823 kg/m3

Grain size (mm)	Fluid pair	Equilibrium time
1 – 1.25	**LNAPL - water**	**1 hour**
0.1 – 0.35	**LNAPL - water**	**4 hours**

Experimental approach

2D tank experiments

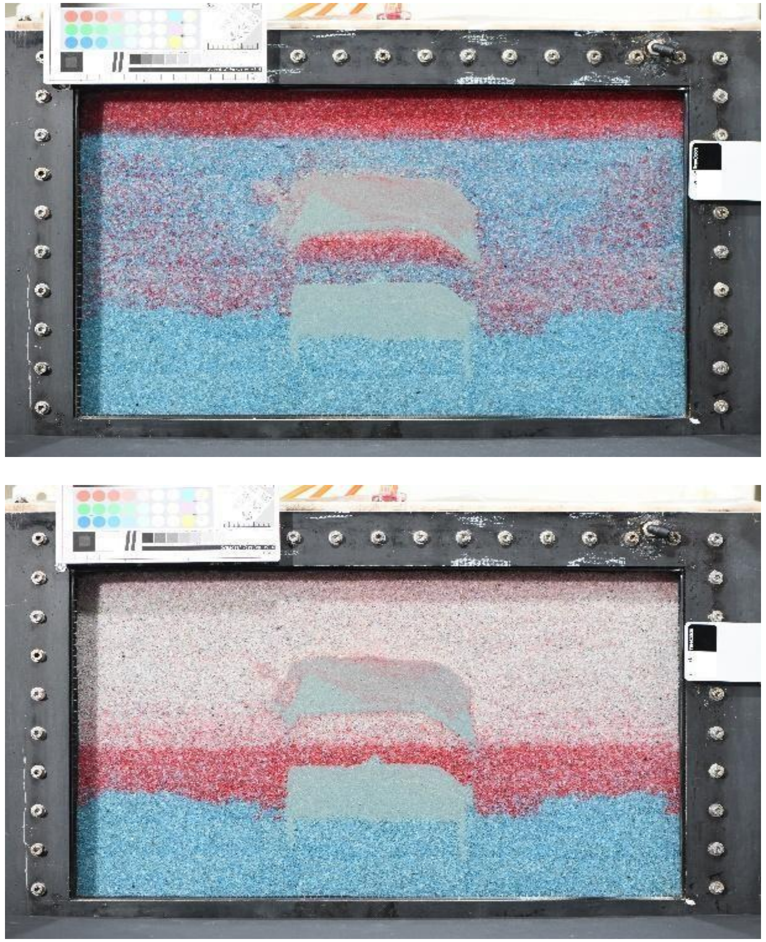


Drainage - imbibition experiments on the 2D scale:

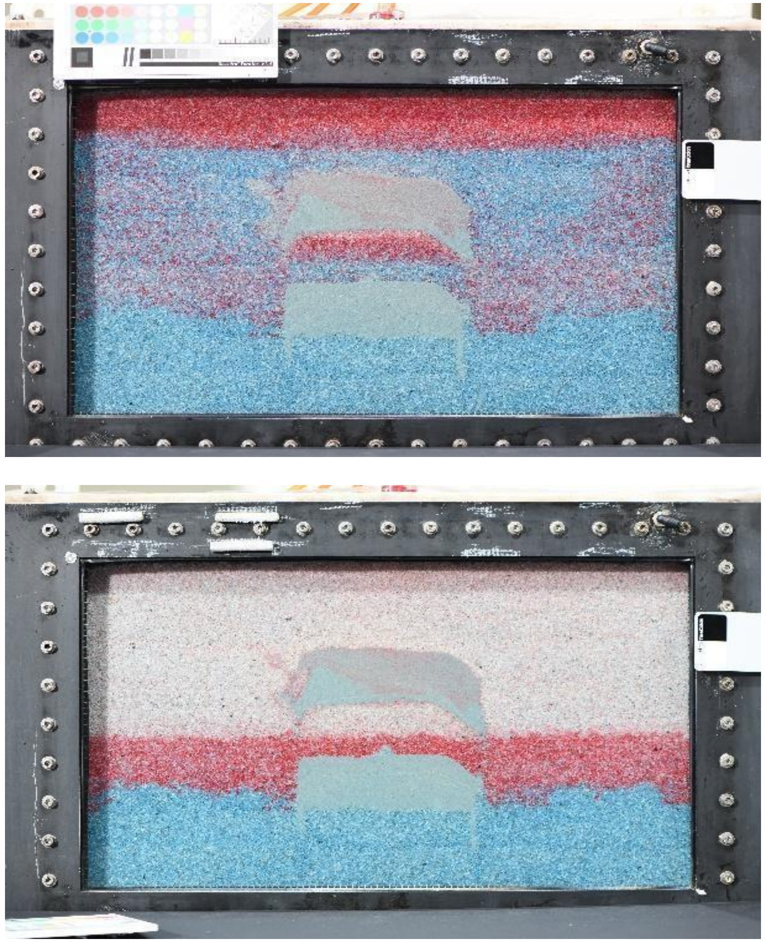
- Simulation of groundwater table fluctuation : impact of hysteresis
- Imaging and TDR probes for saturation values
- See the impact of the aquifer temperature change on residual saturation (TDR probes)
- With two low permeable lenses : impact of the structure of the area on the fluids distribution

Experimental approach

2D tank experiments



4^{th} cycle of drainage-imbibition at 10°C

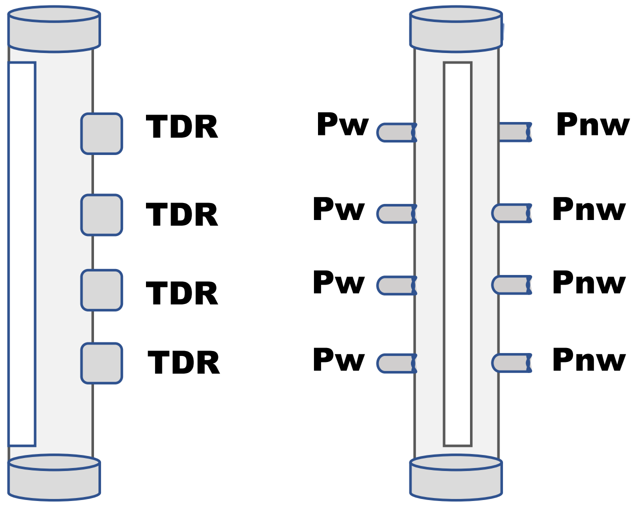


1^{st} cycle of drainage-imbibition at 20°C

Nurzhaugan Omiraliyeva internship report

Perspectives

- Experimental investigation of the tao dependency on the porous media and fluid properties: experiments in 1D under dynamic conditions
- Treatment of the results of experiments in 2D
- Numerical modelling of the experiments with the Hassanizadeh and Gray model of Pc



THANK YOU FOR YOUR ATTENTION!

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