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Conceptual model description

TKI Living Lab for Mud

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Aim of this document

- This document is part of TKI Living Lab for Mud Phase B: ‘Conceptual model’

- In this project, fundamental knowledge development of ripening is coupled to practical application

- The conceptual model serves to compute ballpark estimates and provide key parameters for the ripening process. We will discuss the different phases during this process separately.

- This presentation describes the conceptual model in spreadsheet ***B_Conceptual_model.xlsx***

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Description of ripening process (high-level)

Start point of ripening process

Possible end point of ripening process

Ripening is a soil formation process that irreversibly converts waterlogged sediment into soil (Vermeulen et al. 2003).

Put simply, (physical) ripening is about dewatering of fresh mud to an extent that it becomes a soil with suitable mechanical properties (e.g. consistency and bearing capacity) for a given engineering application.

For a detailed description of the relevant phases and processes, please consult the literature study:
A_literature_study.pdf by Meshkati et al. (2021)

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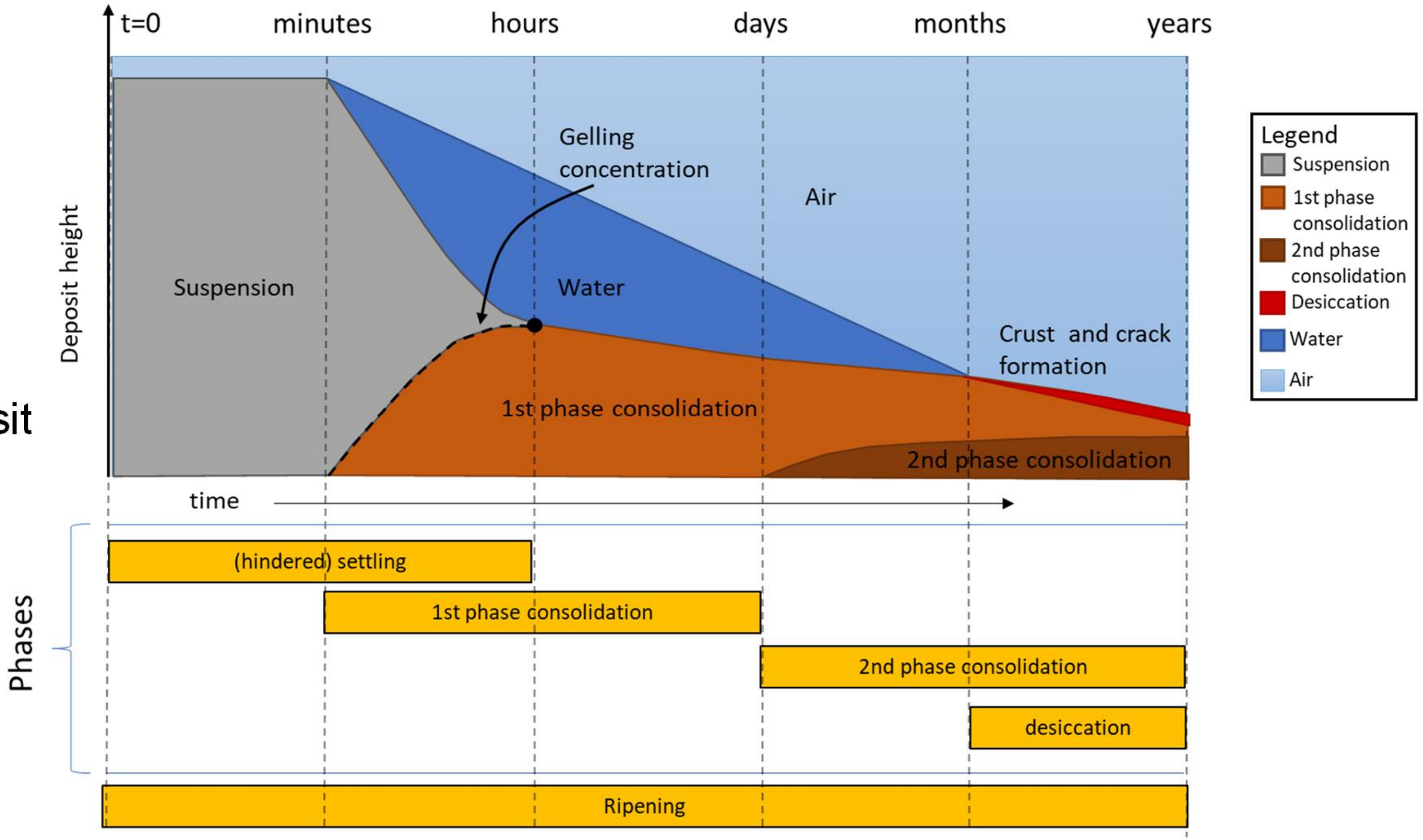
Phases in the ripening process

- Ripening consists of three main phases:

1. Settling
2. Consolidation
3. Desiccation

- These phases have in common: a flux of water from inside the deposit to outside of the deposit
- Driving force:
  - Phase 1 and 2: gravity
  - Phase 3: evaporation



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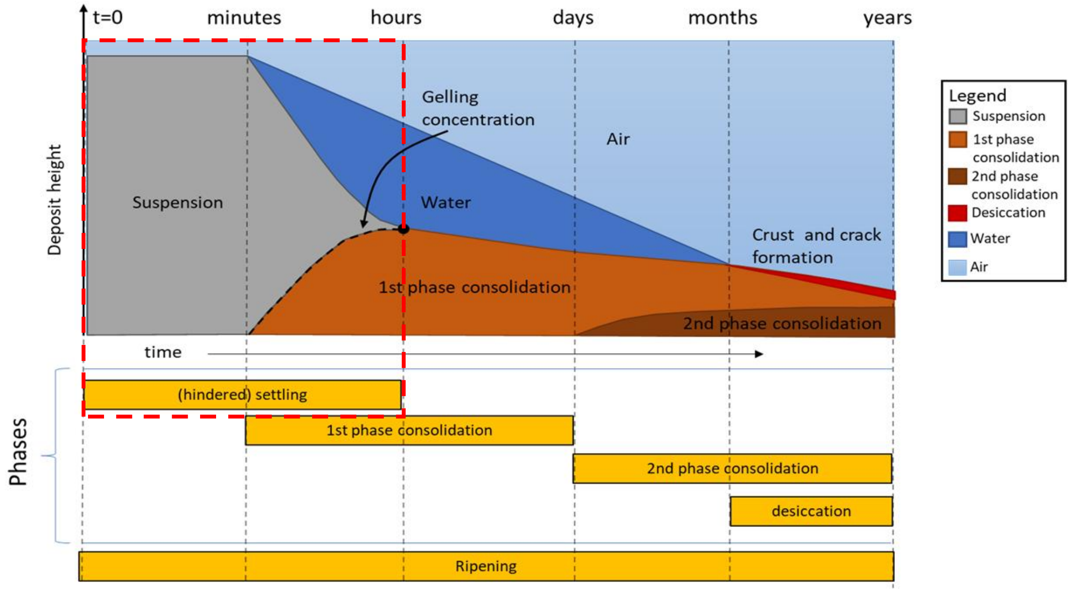
1. Settling phase – description

- Ballpark numbers and provide key parameters are discussed separately for each phase



1. Settling phase	
General description	from dilute suspension to concentrated suspension
Detailed description	particles in suspension, zero effective stress
Driving force	gravity
Time scale	hours to a few days

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1. Settling phase - Key parameters and ballpark estimates

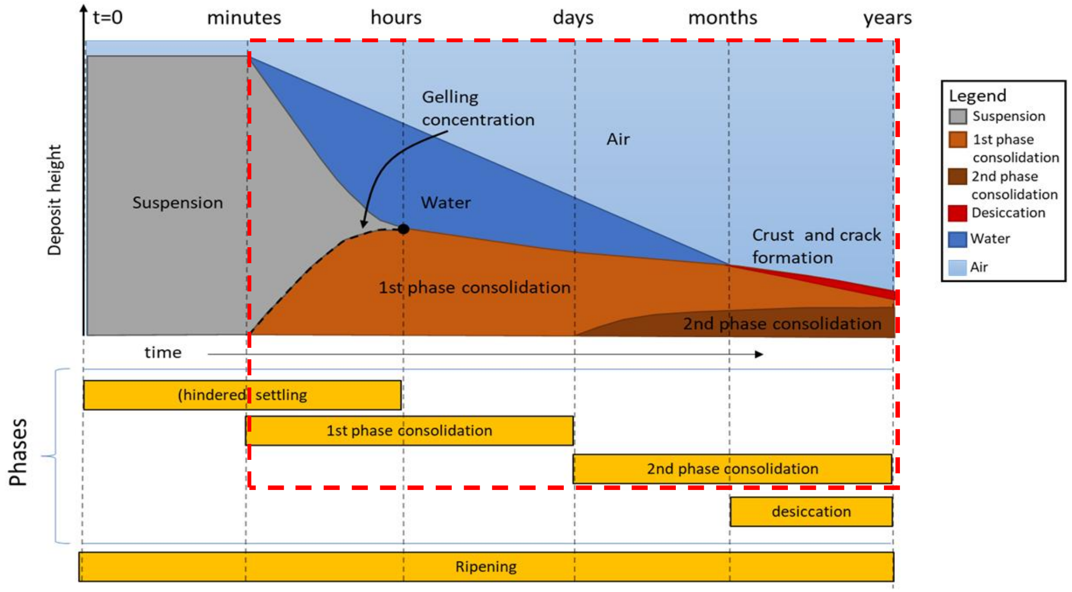
Key parameter/ constitutive relation	symbol
Initial concentration	c_0
Initial height	h_0
Settling velocity at low concentration	$w_{s,0}$
Gelling concentration	c_{gel}

Assuming: linear settling rate
For a deposit with given area: *A* [m^2]

Ballpark estimate	formula
time scale for settling (t_s)	$t_s = \frac{h_0}{w_{s,0}}$
end height (h_e)	$h_e = h_0 \frac{c_0}{c_{gel}}$
final_concentration (c_{gel})	Material property!
volume decrease by outflowing water (V_{set})	$V_{set} = A(h_0 - h_e)$

2. Consolidation phase – description

- Ballpark numbers and provide key parameters are discussed separately for each phase



2. Consolidation phase	
General description	concentrated suspension to consolidated bed
Detailed description	Consolidation phase consists of two sub-phases: 1. effective stress still negligible, permeability effect dominates (advection, primary consolidation) 2. effective stress becomes dominant (diffusion, secondary consolidation) during 1st consolidation phase, there is some concurrent settling and primary consolidation going on decreasing settling rate, effective stress gradually develops, (positive) excess pore pressure
Driving force	gravity
Time scale	from hours to years, strongly depending on layer thickness and permeability

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2. Consolidation phase - key parameters

Key parameter/ constitutive relation	symbol
initial height	h_e
initial concentration	c_{gel}
height at beginning of 2nd consolidation phase	h_2
density of solids	ρ_s
density of water	ρ_w
permeability-void ratio relation	*k-e*
effective stress-void ratio relation	*k-σ'*
fractal theory: fractal dimension	n_f
fractal theory: permeability parameter	K_k
fractal theory: effective stress parameter	K_p

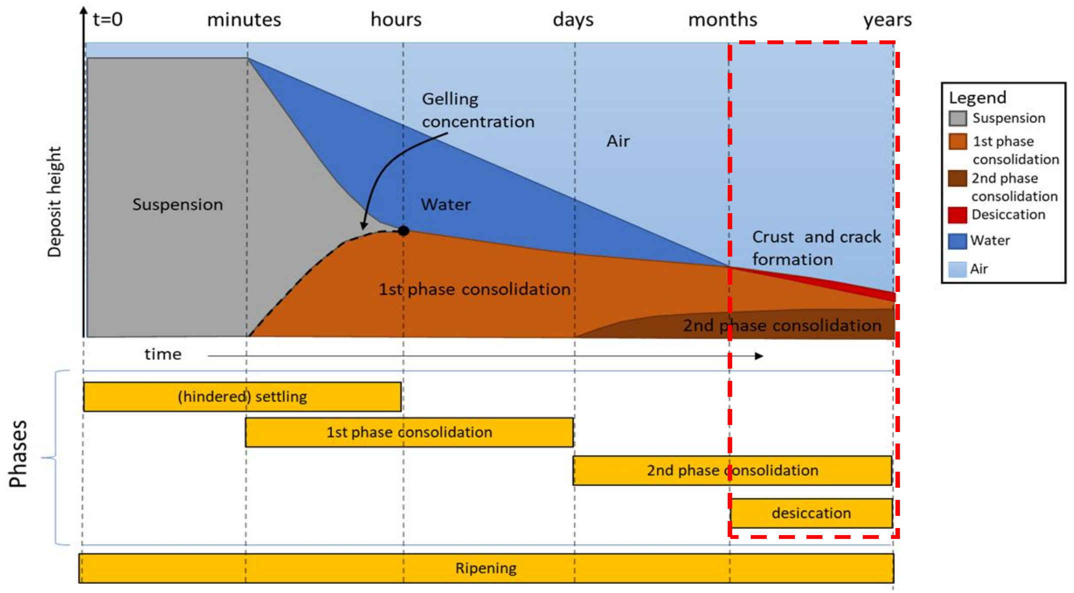
2. Consolidation phase – ballpark estimates

Assuming: negligible advection in first phase, Terzaghi approximation for 2nd phase consolidation, $e = \rho_s / c_{gel} - 1$, accounting for mud fraction only, deposit with given area A [m²]

Ballpark estimate	formula
Fractal scalar parameter (n)	$n = \frac{2}{(3 - n_f)}$
Consolidation coefficient (c_v)	$c_v = n \frac{K_p K_k (1 + e)}{e \rho_w g}$
Gibson height (ζ)	$\zeta = h_e \frac{c_{gel}}{\rho_s}$
Final height (h_f)	$h_f = \frac{n}{n-1} \frac{K_p}{g(\rho_s - \rho_w)} \left(\frac{g(\rho_s - \rho_w)}{K_p} \zeta \right)^{\frac{n-1}{n}}$
Final concentration (c_f)	$c_f = c_{gel} \frac{h_e}{h_f}$
Time scale for consolidation (t_c)	$t_c = \frac{2h_2^2}{c_v}$
Volume decrease (V_{cons})	$V_{cons} = (h_e - h_f) A$

3. Desiccation phase – description

- Ballpark numbers and provide key parameters are discussed separately for each phase

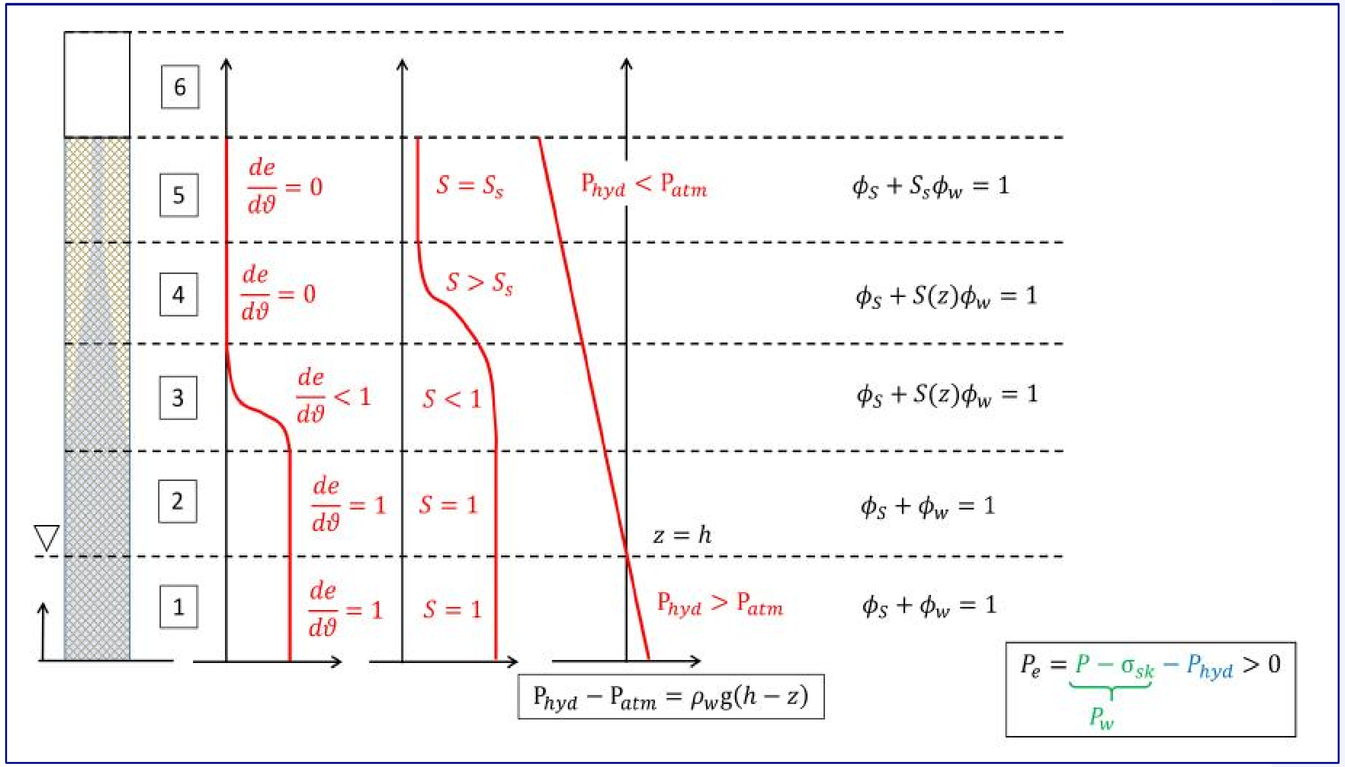


2. Consolidation phase	
General description	From consolidated bed to dry mud
Detailed description	Small remaining settling, but strong increase in strength Strong increase in effective stress, negative pore pressure (i.e. suction driven by evaporation) Takes place in upper layers above water table exposed to atmosphere Consolidation continues below water table (i.e. concurrent consolidation and desiccation) Desiccation may strongly slow down if surface exposed to air completely dries out (even the cracks), reworking is then necessary to keep the process going.
Driving force	evaporation
Time scale	from months to years, strongly depending on layer thickness and climatology (potential evaporation, rainfall)

3. Desiccation phase – conceptual sketch

- <u>5 zones can be discerned in deposit, each with different characteristics</u>

1. consolidation zone below the water table, compaction by gravity
2. fully saturated zone above the water, compaction by suction
3. suction larger than air entry value, unsaturated zone (but still with compaction, outflowing water is partially replaced by air)
4. soil compaction stops, but saturation may still become lower (outflowing water is completely replaced by air)
5. no compaction, saturation constant at minimum level (but some small, residual water flow might still be possible due to pressure (suction) gradients)
6. atmosphere (only air, no solids or water)



3. Desiccation - key parameters

Key parameter/ constitutive relation	Symbol/description
Initial height	h_f
Potential evaporation rate	E
Minimum void ratio	e_{min}
Residual saturation	S_r
Density of solids	ρ_s
Water retention (Van Genuchten)	*WRC*
Shrinkage/swelling	*SC*
Permeability (saturated and unsaturated hydraulic conductivity)	*PC*

full WRC, SC and PC required for numerical modelling but not for ballpark estimates assuming sufficient reworking

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3. Desiccation phase – ballpark estimates

Assuming: deposit is sufficiently reworked throughout desiccation phase, deposit with given area *A* [m^2]

Ballpark estimate	**formula**
Time scale for desiccation (t_r)	$t_r = h_f \frac{1 - c_f/\rho_s}{E}$
Final concentration (c_r)	$c_r = \frac{\rho_s}{1 + e_{min}}$
Final height after complete desiccation (h_r)	$h_r = h_f \frac{c_r}{c_f}$
volume decrease (V_{cons})	$V_{cons} = (h_e - h_f)A$
Remaining solids fraction ($\phi_{s,r}$)	$\phi_{s,r} = \frac{1}{1 + e_{min}}$
Remaining pore fraction ($\phi_{p,r}$)	$\phi_{p,r} = \frac{e_{min}}{1 + e_{min}}$
Remaining water fraction ($\phi_{w,r}$)	$\phi_{w,r} = S_r \frac{e_{min}}{1 + e_{min}}$
Remaining air fraction ($\phi_{a,r}$)	$\phi_{a,r} = (1 - S_r) \frac{e_{min}}{1 + e_{min}}$

Summary

- Ballpark estimates for the settling, consolition and desiccation phases are presented in the conceptual model

- Required parameters to compute estimates for settling (1), consolidation (2) and desiccation (3):

1. Settling: c_0, h_0, $w_{s,0}$, c_{gel}

2. Consolidation: h_e, c_{gel}, h_2, ρ_s, ρ_w, n_f, K_k, K_p

3. Desiccation: h_f, E, e_{min}, S_r, ρ_s