Consolidation and ripening modelling of the Kleirijperij pilot

Calibration, validation and hindcast

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Living Lab for Mud Overkoepelend onderzoek – project goals and focus

- EcoShape project, goal is to: *‘connect and build upon the different pilots in the EcoShape Living Lab for Mud, to boost development of applied knowledge’*

- Specific focus: develop practical knowledge on consolidation and ripening
  - Combine expertise of physical processes with numerical modelling and experience from large-scale pilots

- Large-scale pilots that are considered in this scope:
  - Kleirijperij
  - KIMA (Marker Wadden)

Project phases – this ppt is the deliverable of Phase C1

Phase A-D: Knowledge collection and development

- Phase A: Brief literature survey, compile knowledge on ripening, based on Kleirijperij inputs and internal Deltares research
- Phase B: Conceptual model, derive ballpark numbers for final volume and relevant timescales
- <u>Phase C1: hindcast modelling of Kleirijperij using existing numerical model (TUD – Vardon), focusing on different ripening strategies and treatment options</u>
- Phase C2: hindcast modelling of Markerwadden, focusing on heterogeneity in material properties
- Phase D: Adjust 1DV consolidation model (Deltares) to make it suitable for desiccation

Phase E-F: Apply knowledge through practical design rules and guidelines

- Phase E: Use theoretical understanding and lessons learned from projects to devise design rules and guidelines for adaptive management
- Phase F: Summarize findings in final report and guidelines to be published on Ecoshape website

Numerical modelling of ripening – research questions

Q4: Can different ripening strategies and treatments be accurately modelled using existing numerical models?

- Hindcast modelling of Kleirijperij pilot (4 different basins of Delfzijl location)
- Scenario analysis to study the effect of initial deposit height, climate change, and drainage.

Ripening (soil formation process)

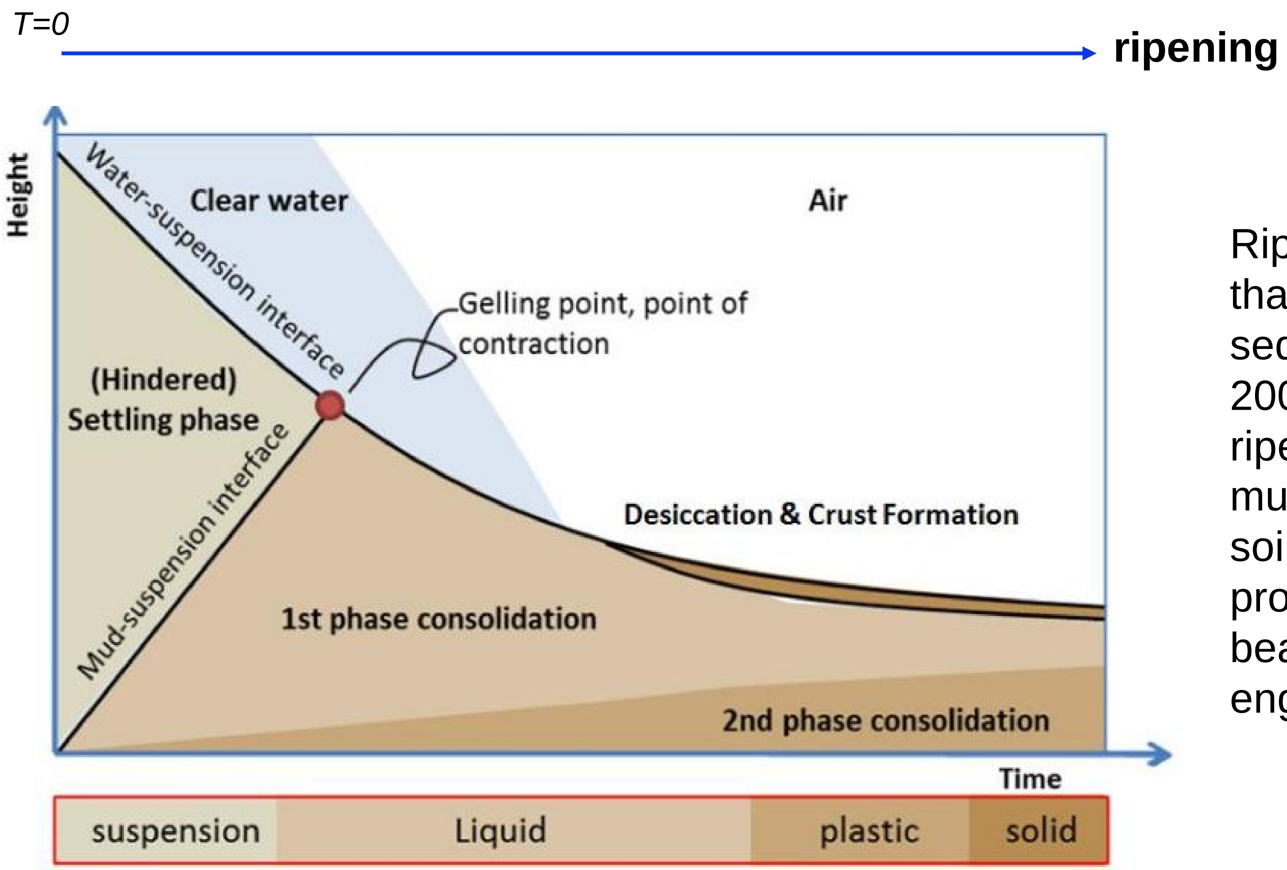


Figure 2-2: Evolution of deposited cohesive sediment over time, adapted from (van Olphen, 2016)

Ripening is a soil formation process that irreversibly converts waterlogged sediment into soil (Vermeulen et al. 2003). Put it simply, the (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.

Governing processes and driving forces

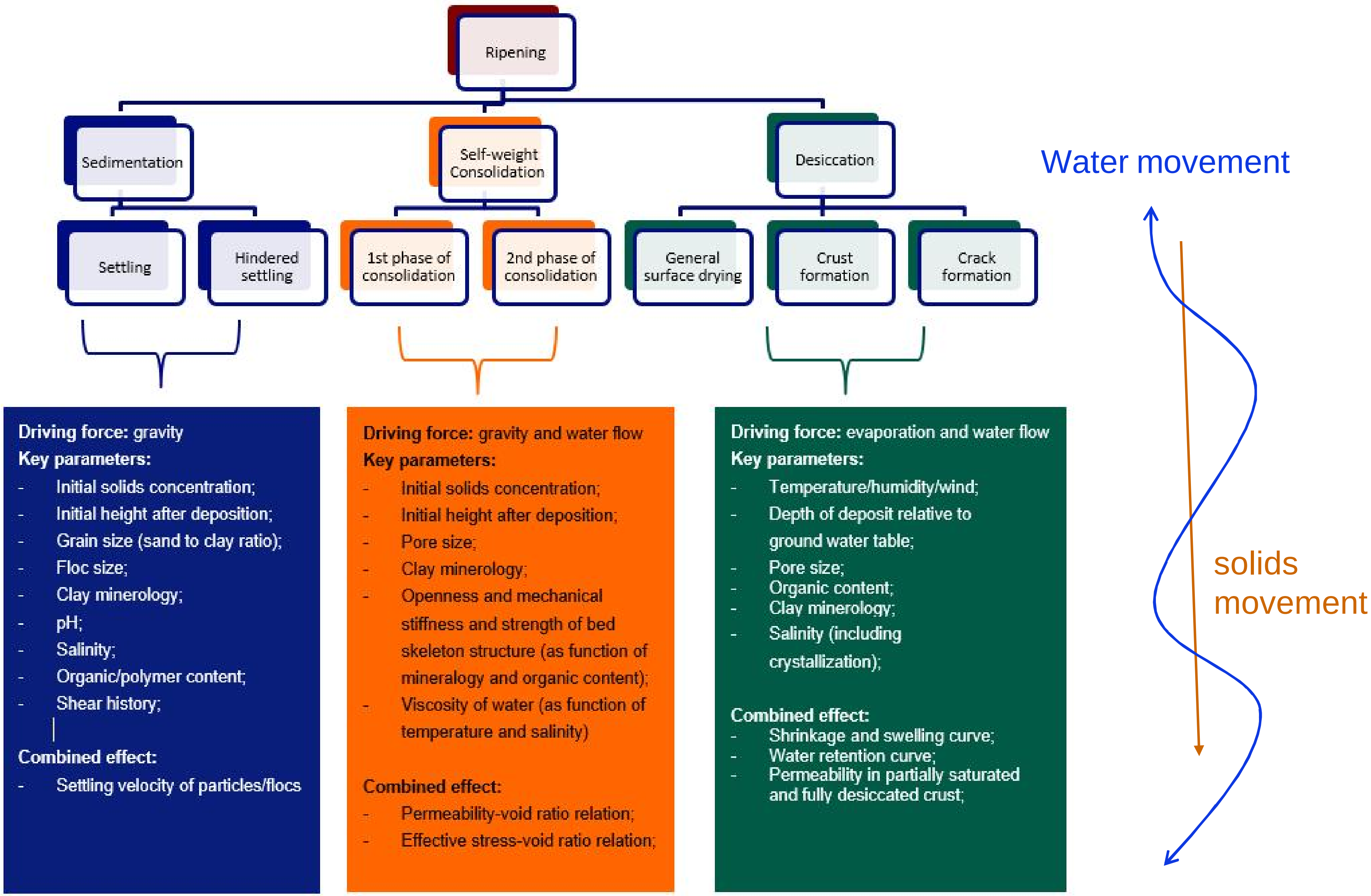


Figure 3: A summary of governing processes during ripening process (Meshkati et al., 2021).

Water movement in soil

Water (in a soil) has the tendency to move toward lower energy levels. This movement of water can be described in two fashions (that are identical eventually):

- water potential concept: in which the main components are gravimetric effect (+), matric suction effect (-), overburden effect (+) and osmotic effect (-). These effects define the potential energy of water at different depth points in a soil. Water migrate from higher potential energy to lower potential energy.

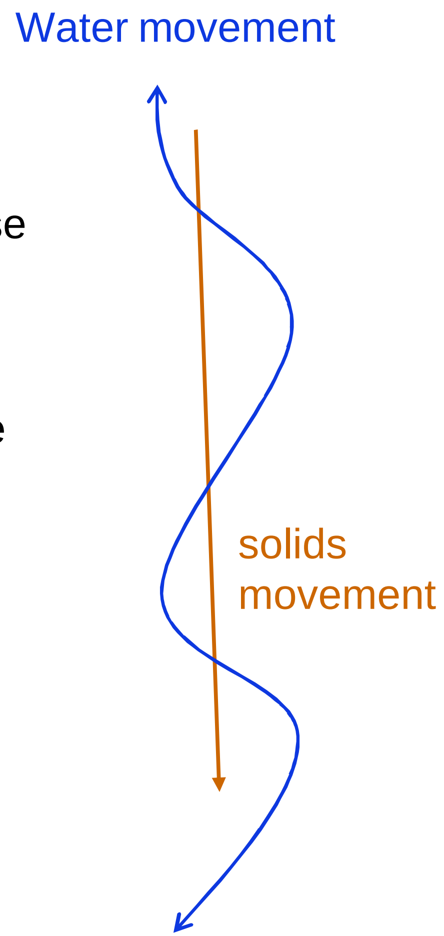
- excess pore pressure gradient concept: in which the main components are total stress, effective stress, hydrostatic pressure, pore water pressure and pore air pressure which all together collectively define the amount of excess pore pressure along the depth of a soil deposit. Water migrate from larger excess pore pressure to lower excess pore pressure.

These two concepts can be translated to each other:

gravimetric effect ~= hydrostatic pressure

matric suction effect ~= *f* (pore water pressure and pore air pressure)

overburden effect ~= *f* (total stress and effective stress)



Methodology

- We apply the Vardon (TUD) model to hindcast the Kleirijperij pilot

- Calibrate the Vardon model in two steps:
  1. First estimate based on values from literature and from Marker Wadden pilot
  2. Further calibration based on field data collected in Kleirijperij plot D15

- Use model to test effect of:
  - Different ripening strategies
  - (mechanical) treatment
  - Environmental (i.e. meteorological) conditions

- In this presentation, we included the relevant runs
  - not all scenarios we tested were included but these are available upon request

Vardon model - underlying assumptions and working principle (high level)

- Model computes the water content ratio for each cell in the model domain.
- Water is conserved, it either:
  - Flows down/up
  - Evaporates
- Water flow from high to low potential (analogy: flow from high to low pressure)

- Evaporation and flow of water determined by:
  - Shrinkage curve
  - water retention curve
  - Permeability curve
- The model requires several input soil material properties
  - 3 Constitutive relations for material behaviour

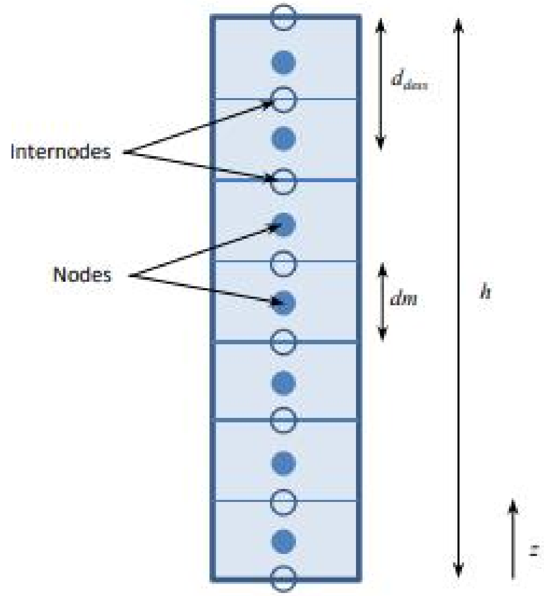


Figure 2 – Model domain

Theoretical formulation of the model (detailed)

The ripening model starts with the mass conservation of water in Cartesian (real) coordinate system for water in vertical-direction. Water transport in this model is governed by Darcy's Law (relying on K hydraulic conductivity) with the water potential made up from a gravimetric component, z, an overburden component, Ω (omega), and a matric suction component, φ (phi) (Vardoon, 2014 and Vardon et al., 2015):

$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left[K \frac{\partial}{\partial z}(z + \Omega(z) + \varphi(z))\right]$ (1), where: capital theta $\Theta = \frac{V_w}{V_T}$ is the water content.

However, Eq.1 is then adopted for Lagrangian (material level) coordinate system using the below transformations:

$\theta = \frac{\Theta}{1+e}$ (where small theta $\theta = \frac{V_w}{V_s}$ known as water content ratio); $dm = \frac{dz}{1+e}$, $K^* = \frac{K}{1+e}$; applying these transformations results in the final governing equation as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial m}\{K^*(1 + e + \gamma_b(1 + e)\frac{\partial e}{\partial \theta} + \frac{\partial^2 e}{\partial \theta^2}\int_z^{Z_s} \gamma_b(1 + e)\,\mathrm{d}m\frac{\partial \theta}{\partial m} + \frac{\partial \varphi}{\partial \theta}\frac{\partial \theta}{\partial m})\} \quad (2)$$

Thus, in this model, at each time step small theta θ (water content ratio) is calculated.

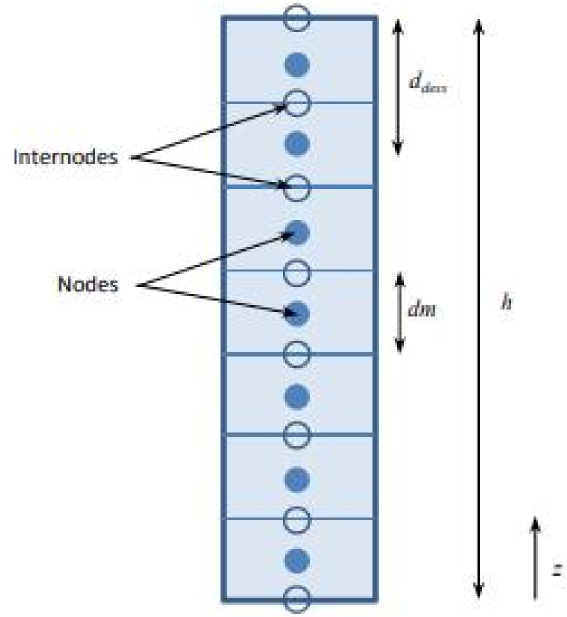


Figure 2 – Model domain

Capabilities and limitations in Vardon model

- **Capabilities:**
  - both the user input and the model estimated (empirical based) mode can be chosen for net evaporation-precipitation of the upper boundary condition;
  - bottom drainage and no bottom drainage conditions are available;
  - different initial deposit heights and (stacked) layers (at different time points) can be introduced in the model;
  - flow behavior in saturated and partially saturated conditions are taken into account;
  - effect of (a fixed) crack depth on permeability is taken into account; etc.

  Limitations:
  - the model does not include the settling phase;
  - the effect of successive (more than 2 cycles) drying and wetting cycles on soil properties such as shrinkage curve and water retention curve are not implemented in the model;
  - the model does not calculate the crack depth but accept a fixed value for crack depth that should be introduced as input parameter prior to modelling;
  - the model is only suitable for stacked layers of deposits with similar material properties; layers with different soli properties cannot be modelled; etc.

Constitutive relation 1: Shrinkage and swelling curve

The relation between void ratio e and water ratio θ due to soil deformation is modeled with a shrinkage curve (Fredlund et al., 2002):

$$e(\theta) = A_{sh}\left(\frac{\theta^{C_{sh}}}{B_{sh}^{C_{sh}}} + 1\right)^{1/C_{sh}}$$, shrinkage part of the curve

$$e(\theta) = v_h - b(\theta - \xi_h)^2$$, swelling part of the curve

$$b = \frac{v_h - v_z}{\xi_h{}^2}$$

At each time step θ is calculated, then using user defined shrinkage curve e (as an indication of deformation) will be calculated.

Green: user defined material parameters

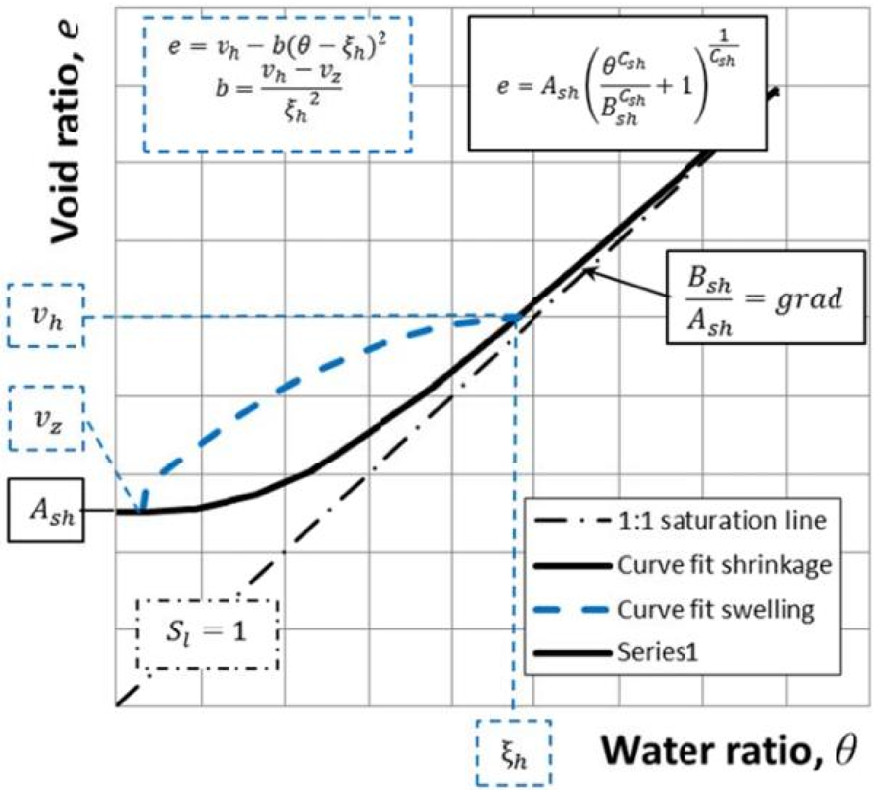


Figure 1 – Shrinkage curves

Vardon (2014)

Constitutive relation 2: Water retention curve

The suction is linked to the effective saturation (S_e), using a modified van Genuchten SWRC equation (1980):

$S_e = \frac{\theta - WCR}{WCS - WCR}$, where θ is the water ratio defined as $\frac{V_w}{V_s}$, WCR is the residual volumetric water ratio and WCS is the volumetric water ratio at full saturation.

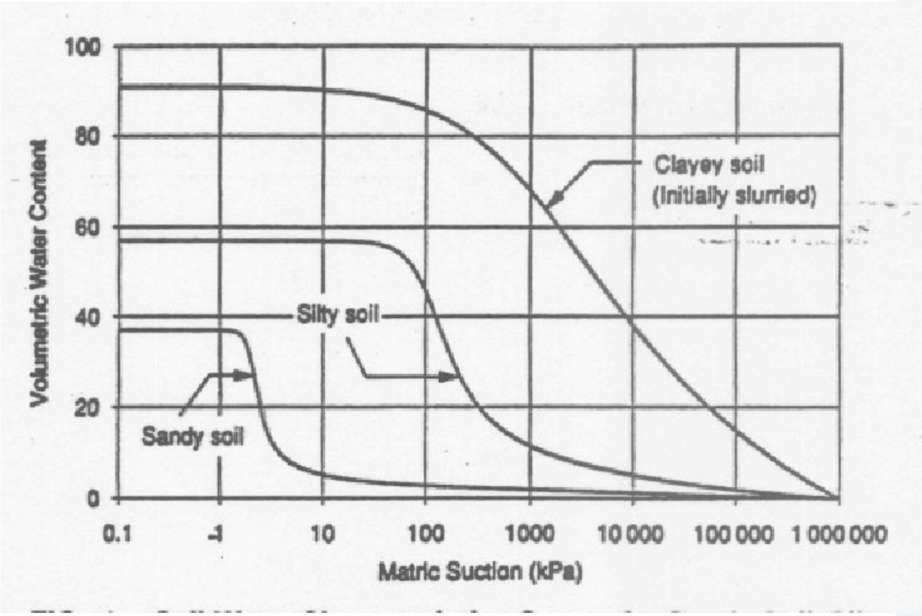
The modified van Genuchten SWRC equation used in the model as below:

$$S_e = \left(1 - \frac{\ln|1+\varphi/\alpha_{WRC}|}{\ln 2}\right) \frac{1}{\left(1+(\varphi\alpha_{WRC})^{n_{WRC}}\right)^{m_{WRC}}} ,$$

$$m_{WRC} = 1 - \frac{1}{n_{WRC}}$$

$$\varphi = P_a - P_w$$

Green: user defined material parameters



Leong and Rahardjo (1997)

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Constitutive relation 3: Hydraulic conductivity

The hydraulic conductivity K^* is defined as: $K^* = K_{sat}\ K_{rel}\ K_{dess}$ where:

K_{sat} = $10^{(A\theta - B)}$, in fully saturated condition;

$K_{rel} = S^{\delta}$, in partially saturated condition where S is degree of saturation defined as $\frac{\theta}{e}$;

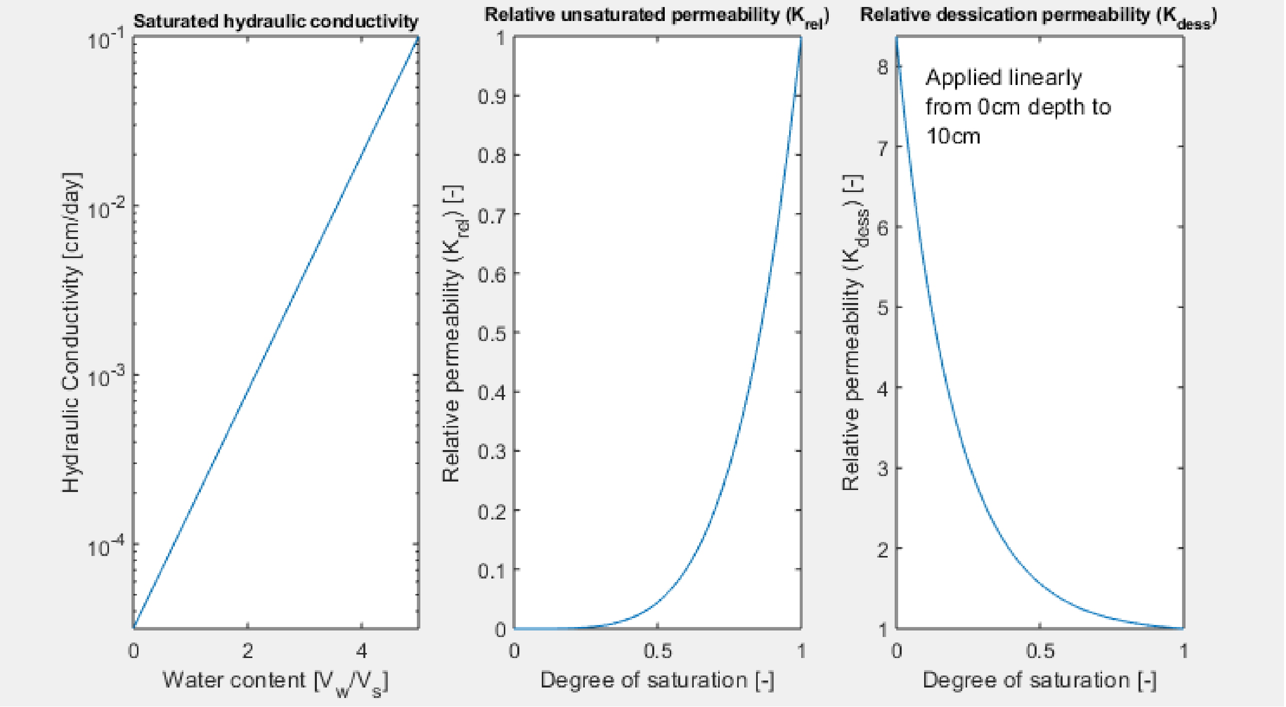
K_{dess} = $(1 - \epsilon_{dess}) + \epsilon_{dess}\exp(\xi_{dess}(1 - S))$, in the top layer to replicate the effect of crack (d_{dess});

Note below the top desiccated crust layer K_{dess} = 1

At each time step θ is calculated,

then using the equations above

K^* will be calculated.



Green: user defined material parameters

User defined material parameters

		Vardon et al., (2015)	Yao (2017)	Sijbrandij (2017)	Sijbrandij (2017)	Current study (2021)
	Parameters/Material	Thickened tailings – 40% Sc	f-MFT– 32% Sc	H1 50% clay, 50% silt	H3 55% clay, 42% silt, 3% sand	**Calibrated for D15**
Shrinkage	A_{sh}	0.48	0.68	0.45	0.3	0.43
	B_{sh}	0.48	0.68	0.45	0.3	0.43
	C_{sh}	4.5	4.47	3	3	2.7
	ν_h	1	-	1	1	1
	ξ_h	1	-	1	1	1
Water retention	WCR	0.2	0.04	0.1	0.1	0.2
	WCS	2.2	5.91	8.16	6.2	6
	α_{WRC}	0.11	0.92	3.93	2.83	3
	n_{WRC}	1.23	1.15	1.235	1.159	1.15
	m_{WRC}	0.18	0.13	0.19	0.137	0.13
	a-modified	10000	500000	100000	100000	10000
Permeability	A	1.6	0.78	0.9	0.9	0.7
	B	4.4	5	6	5	4.5
	δ	3	3	3	3	3
	ϵ_{dess}	0.05	0.05	-	-	0.05
	ξ_{dess}	5	5	-	-	5
	d_{dess}	10	10	-	-	10

Case study: Pilot Kleirijperij, Delfzijl, The Netherlands

ρ_w=1.008 [ton/m3]; density of water;

ρ_s= 2.51 [ton/m3]; specific gravity

ρ_b = 1.19 [ton/m3]; initial bulk density;

W = 300 [w%], initial gravimetric water content;

SC = 25 [w%]; initial solids content;

$\theta = W \frac{\rho_s}{\rho_w}$ =7.48 [-], water content ratio;

D7, D9, D10, and D15 all have drainage from the bottom;

D7, D10 and D15 are filled only once while D9 are filled twice.

Plot nr	T0 [date]	Initial height [cm]
D15	9-4-2018	165
D10	10-4-2018	159
D7	10-4-2018	100
D9	12-4-2018 13-7-2018	110 100

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User defined material parameters

		Vardon et al., (2015)	Yao (2017)	Sijbrandij (2017)	Sijbrandij (2017)	Current study (2021)
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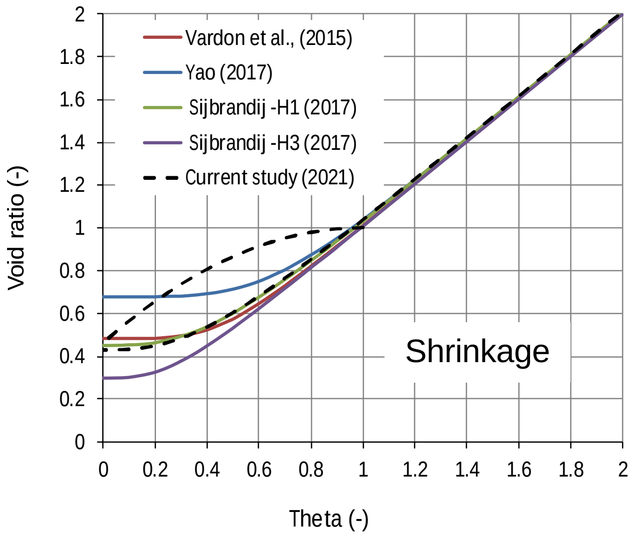
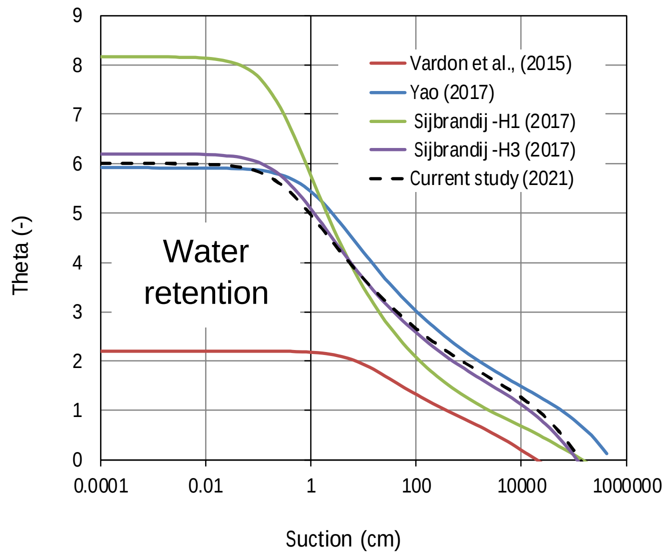
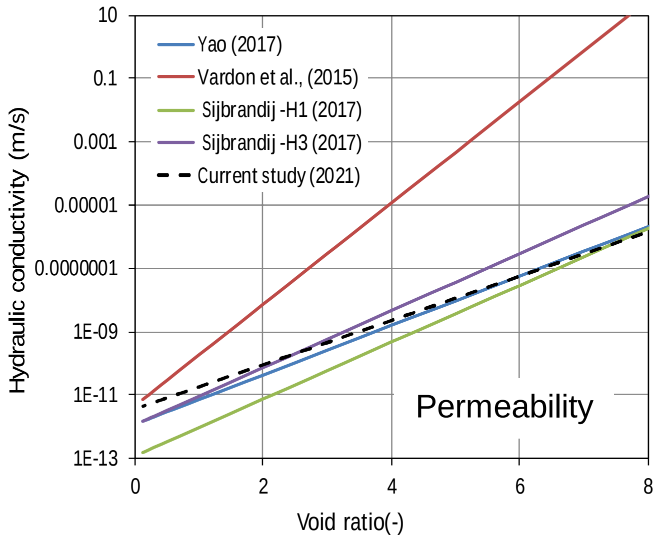
Permeability	A	1.6	0.78	0.9	0.9	0.7
	B	4.4	5	6	5	4.5
	δ	3	3	3	3	3
	ϵ_{dess}	0.05	0.05	-	-	0.05
	ξ_{dess}	5	5	-	-	5
	d_{dess}	10	10	-	-	10

Constitutive relations

1. Shrinkage and swelling
2. Water retention
3. Hydraulic conductivity







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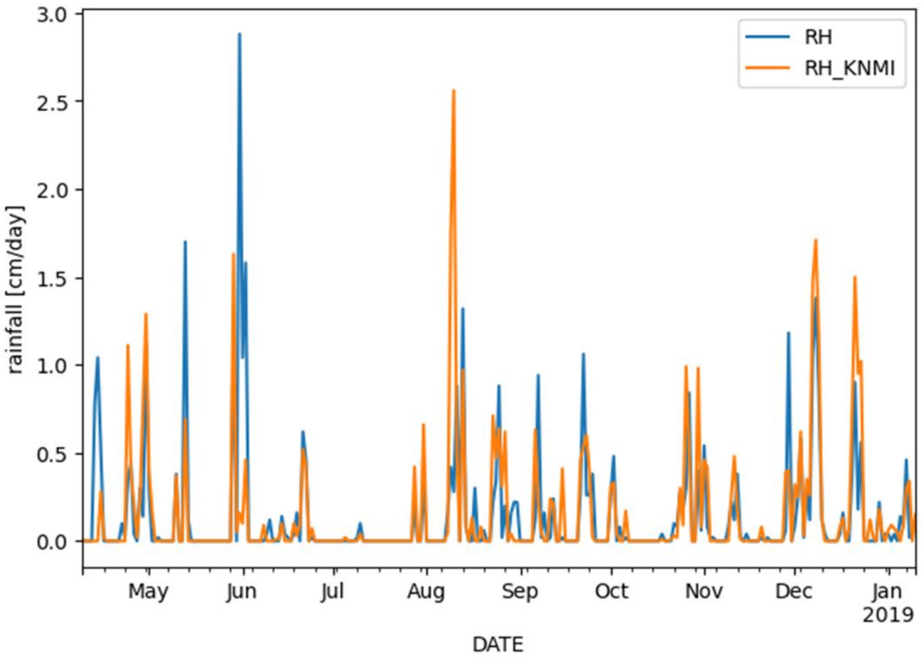
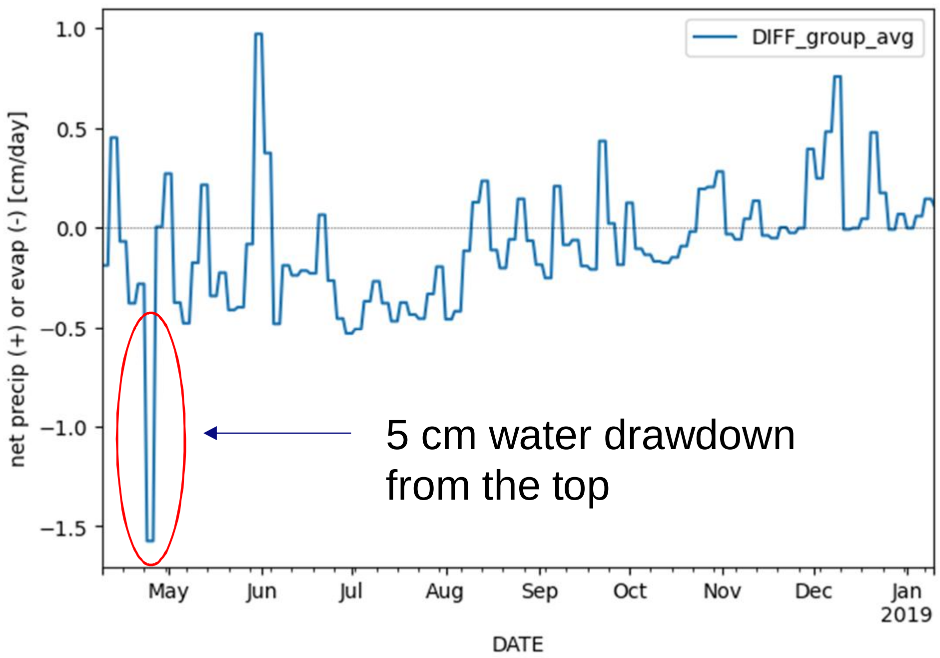
Weather model input

Left: rainfall measured by weather station at the Kleirijperij Delfzijl site vs. the KNMI rainfall at Eelde; Right: the net precipitation-evaporation as model input





Model input:
Precipitation>> Weather station data at the site
Evaporation>> KNMI at Eelde station

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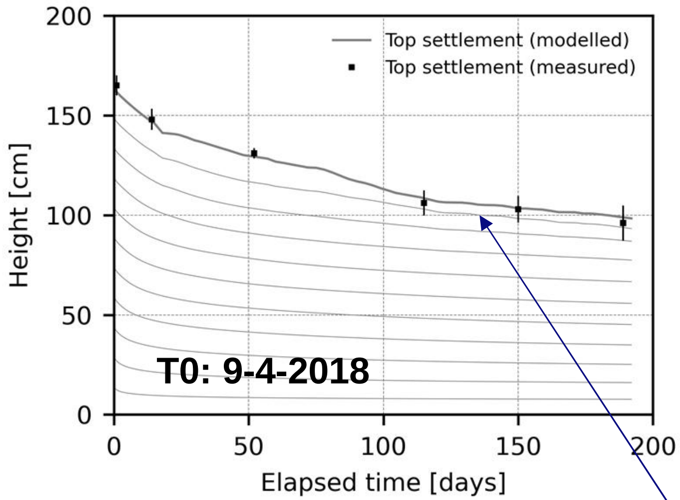
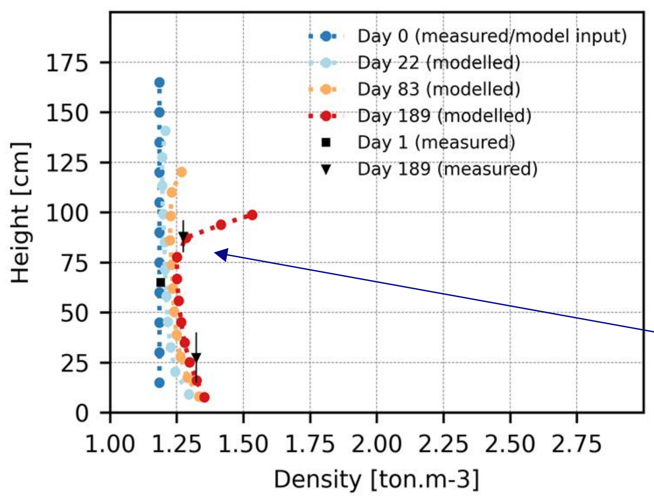
Calibration of the model with D15

Simulation for first 200 days; after that D15 was reworked/plowed.





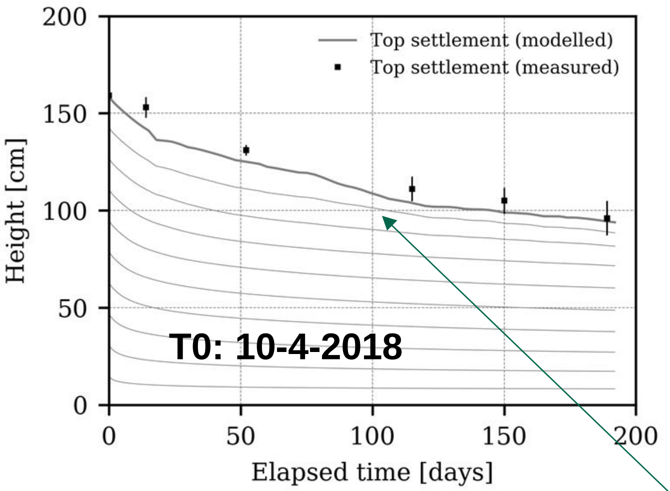
Estimated averaged height based on DEM measurement by drone. Bars show the standard deviation of variation in estimated heights in the plot;

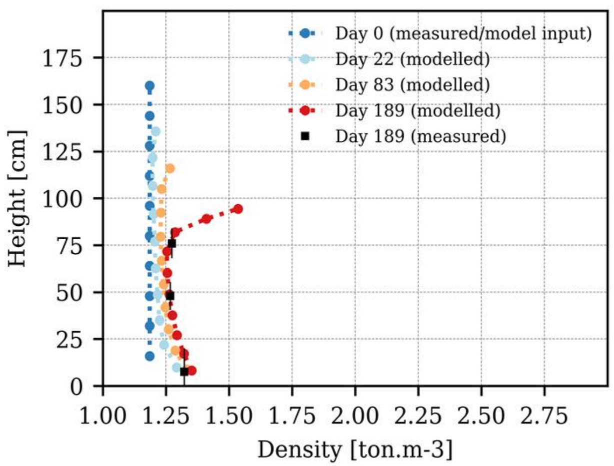
Measured water content ratio after core sampling;

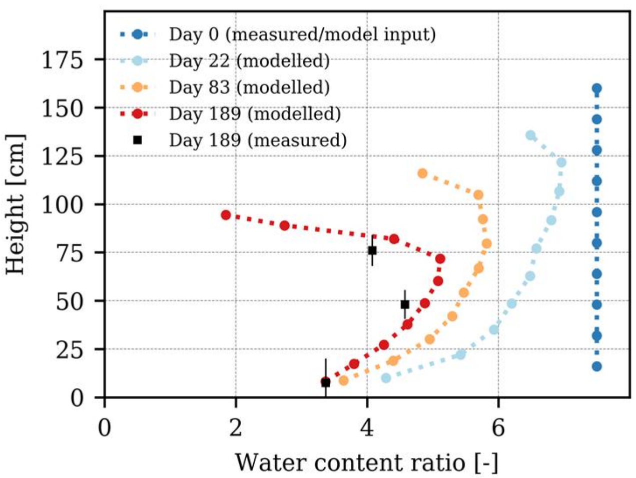
	Parameters /Plot	Calibrated values D15
Shrinkage	A_{sh}	0.43
	B_{sh}	0.43
	C_{sh}	2.7
	ν_h	1
	ξ_h	1
Water retention	WCR	0.2
	WCS	6
	α_{WRC}	3
	n_{WRC}	1.15
	m_{WRC}	0.13
	a-modified	10000
Permeability	A	0.7
	B	4.5
	δ	3
	ϵ_{dess}	0.05
	ξ_{dess}	5
	d_{dess}	10

Validation of the model with D10

Simulation for first 200 days







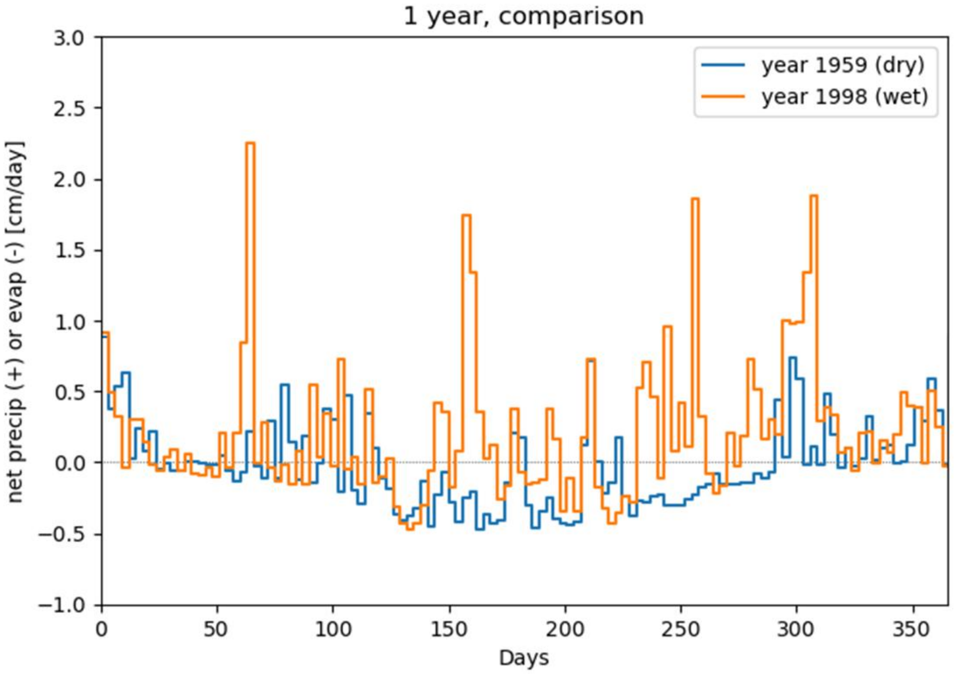
Slight underestimation of height by model;

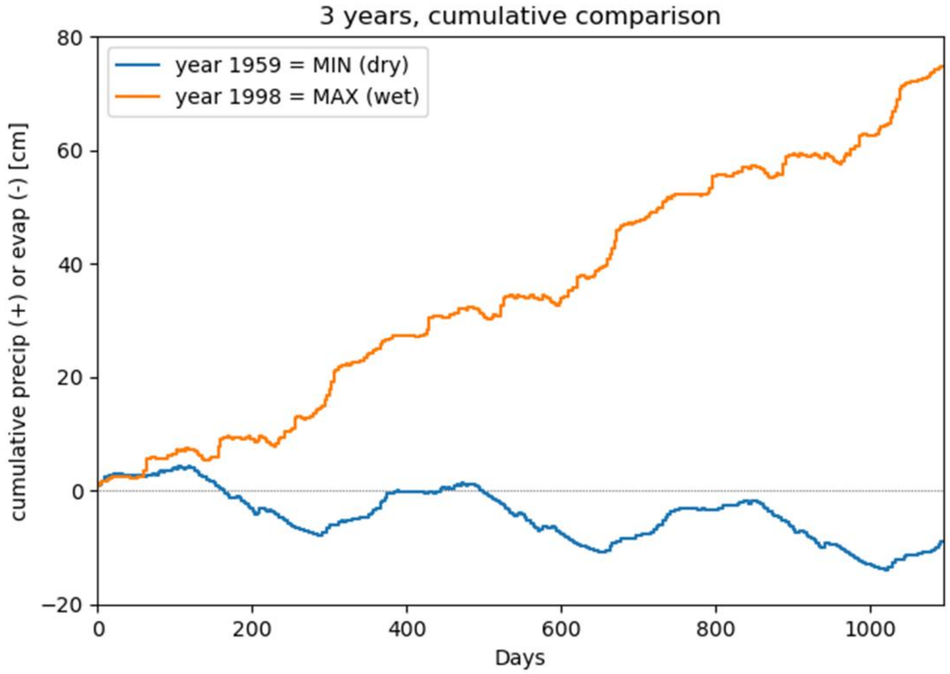
Fairly good prediction of heights and water content ratios in D10

	Parameters /Plot	Calibrated values D15
Shrinkage	A_{sh}	0.43
	B_{sh}	0.43
	C_{sh}	2.7
	ν_h	1
	ξ_h	1
Water retention	WCR	0.2
	WCS	6
	α_{WRC}	3
	n_{WRC}	1.15
	m_{WRC}	0.13
	a-modified	10000
Permeability	A	0.7
	B	4.5
	δ	3
	ϵ_{dess}	0.05
	ξ_{dess}	5
	d_{dess}	10

Scenario analysis: effect of climate + initial deposit height

Hypothetical historical weather data was used as extreme weather conditions to hindcast.



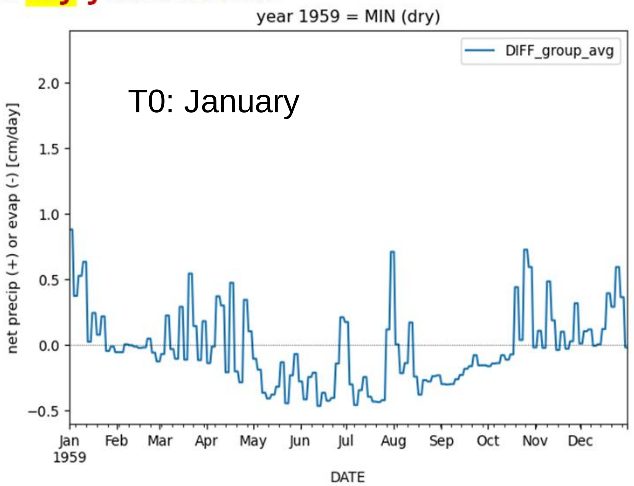


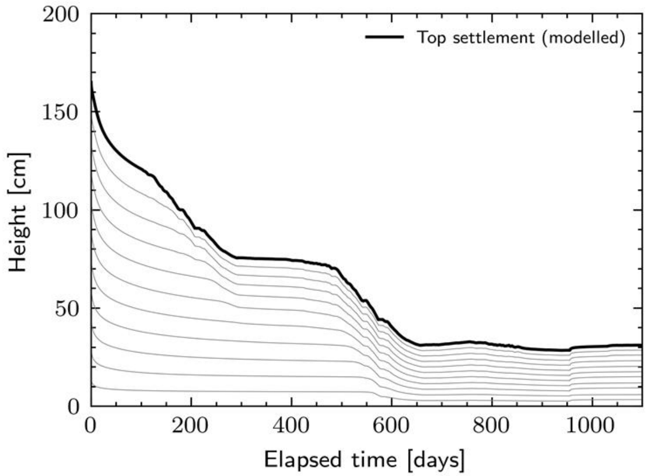
KNMI at De Bilt
Group period of 3 days
Single year is duplicated in 3 years

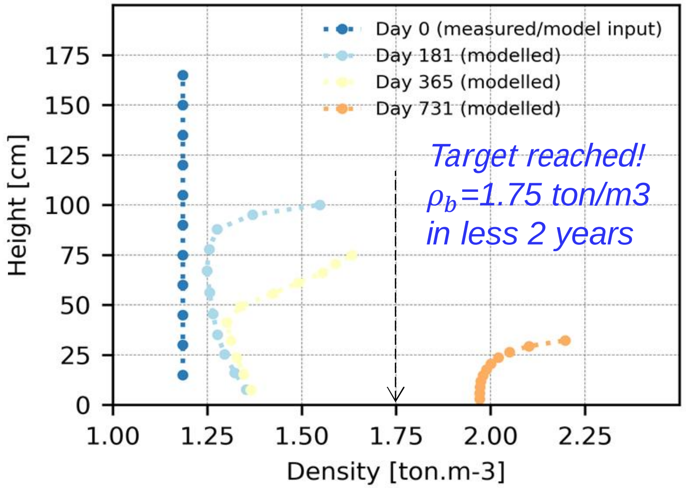
Scenario analysis: effect of climate + initial deposit height (160cm)

Simulation of first 1096 days using hypothetical historical weather data

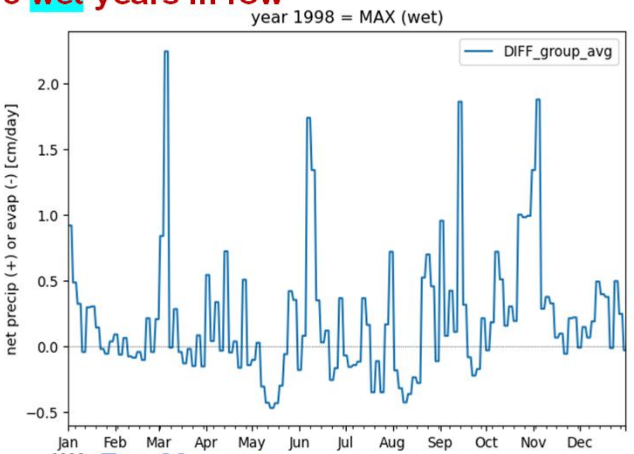
3 dry years in row

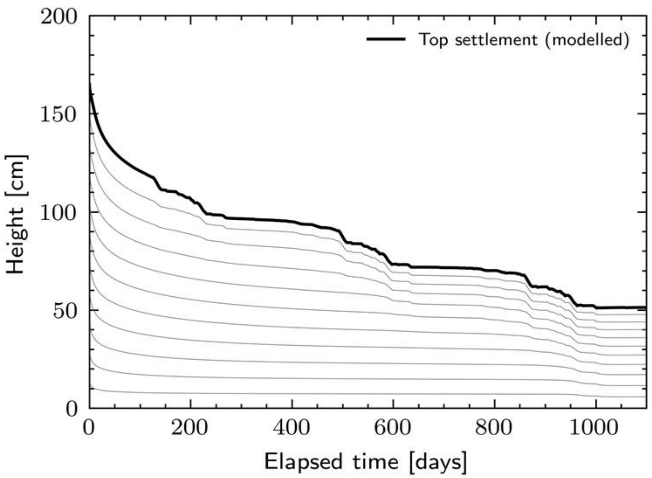


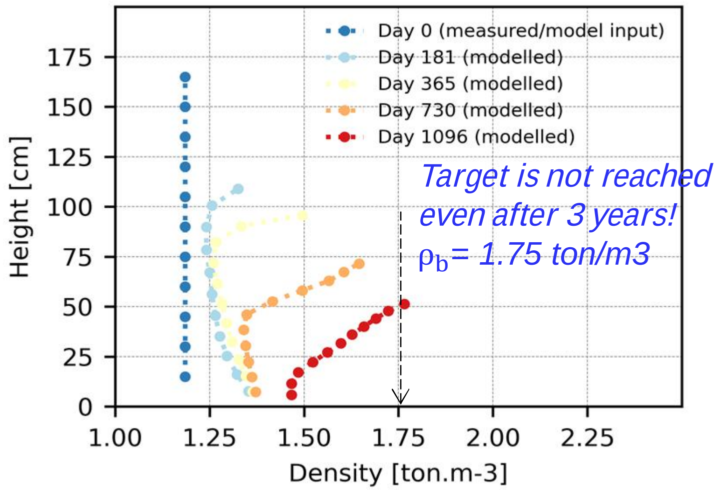




3 wet years in row







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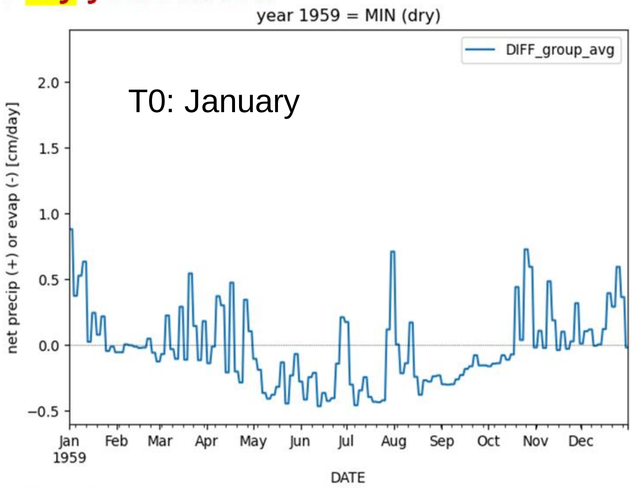
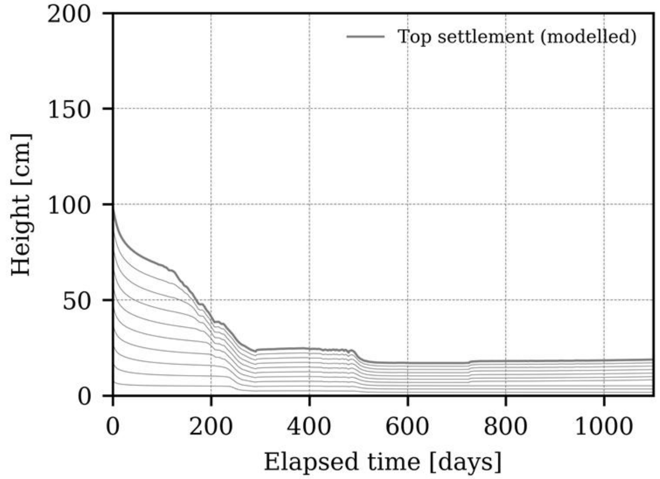
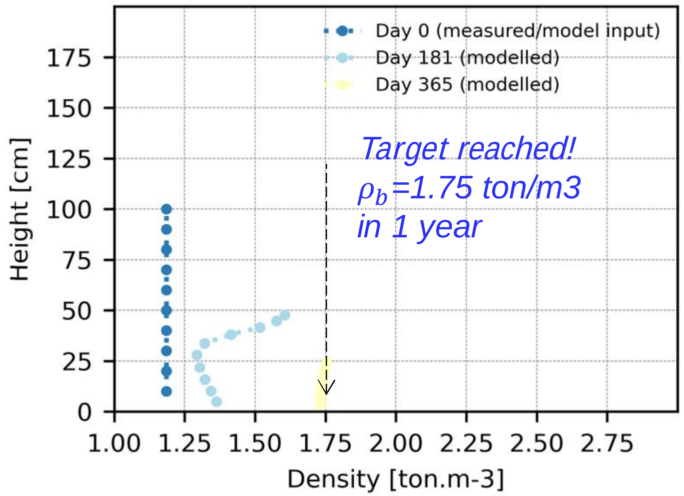
Scenario analysis: effect of climate + initial deposit height (100 cm)

Simulation of first 1096 days using hypothetical historical weather data

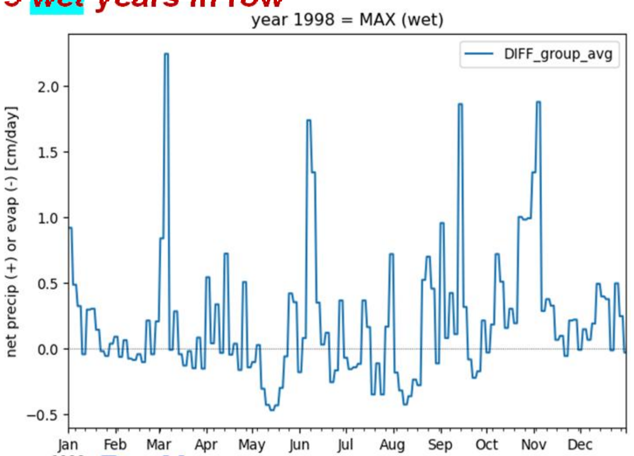
3 dry years in row

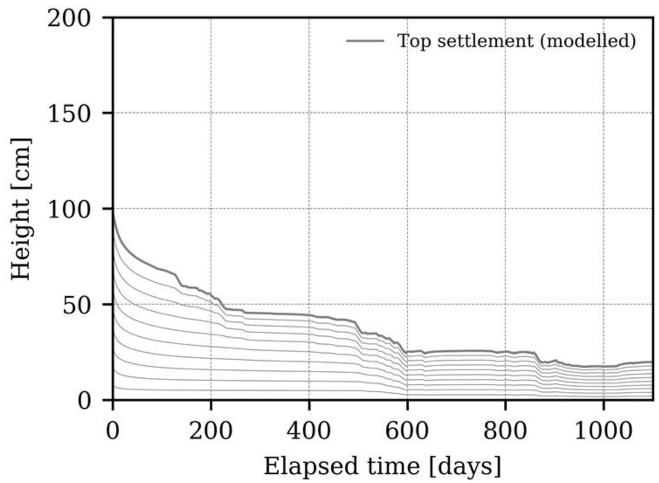


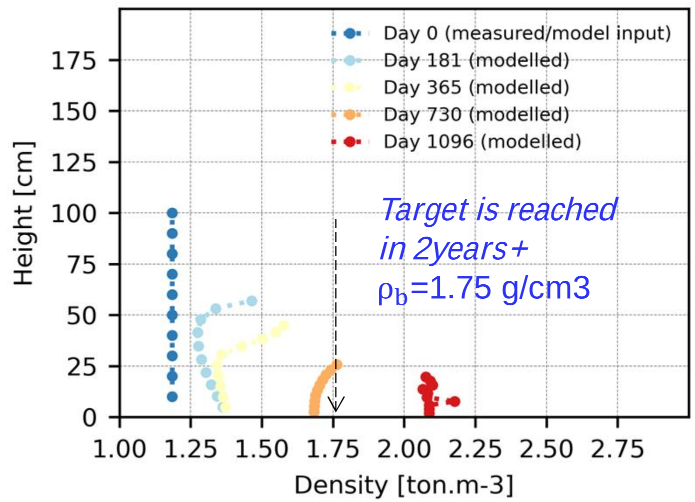




3 wet years in row





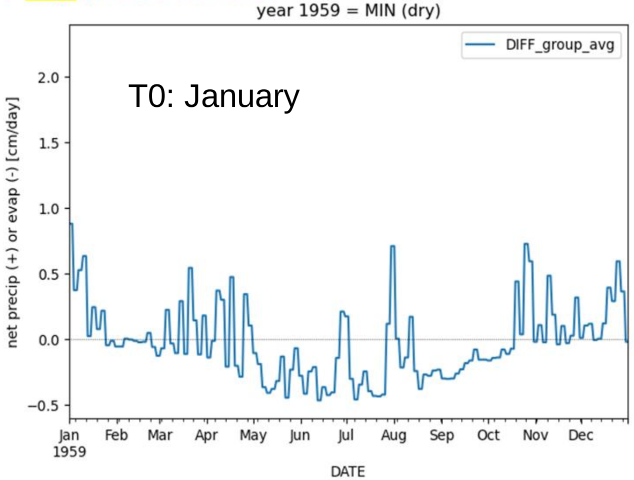


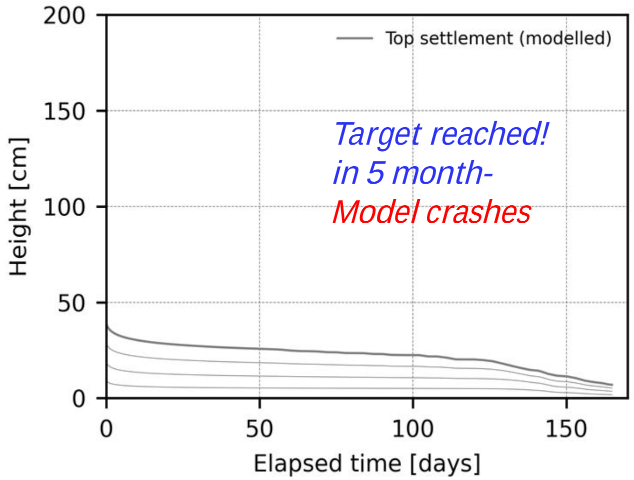
Deltares

Scenario analysis: effect of climate + initial deposit height (40cm)

Simulation of first 1096 days using hypothetical historical weather data

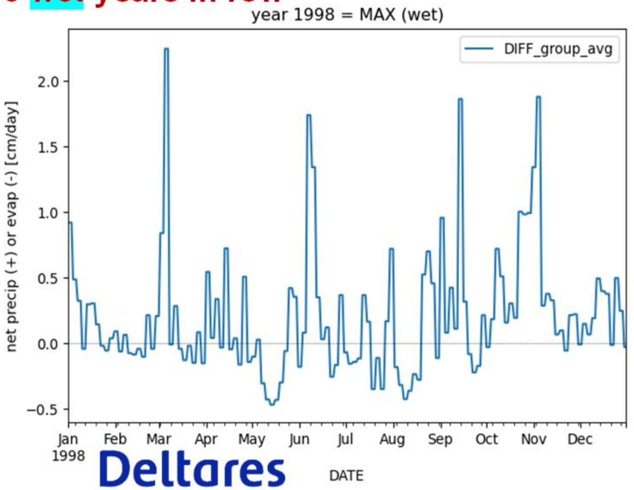
3 dry years in row

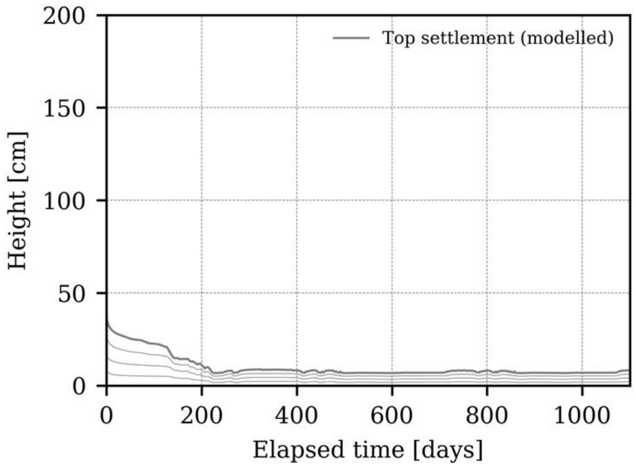


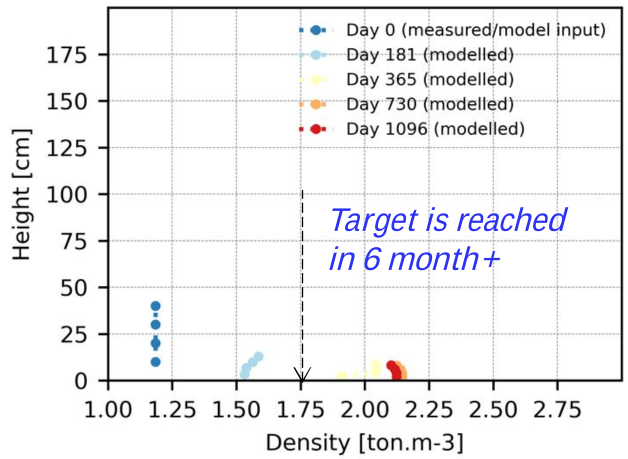


Simulation crashes

3 wet years in row



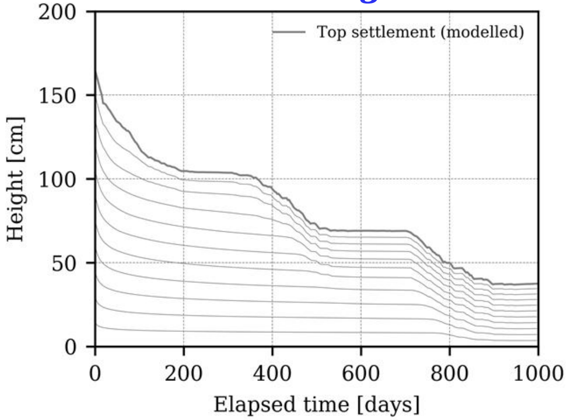




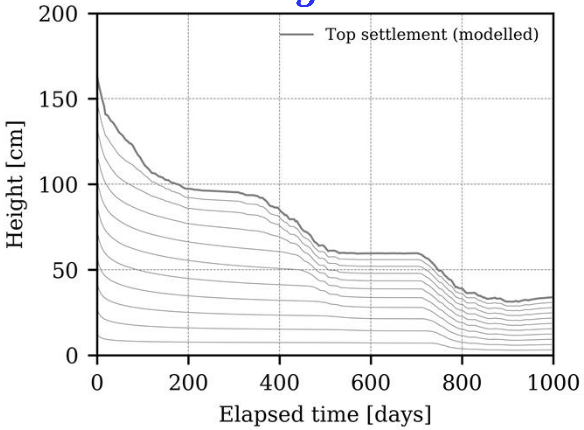
Scenario analysis: effect of bottom drainage + initial deposit height (160cm)

Simulation of first 996 days using actual weather data **T0: 9-4-2018** **Tend: 31-12-2020**

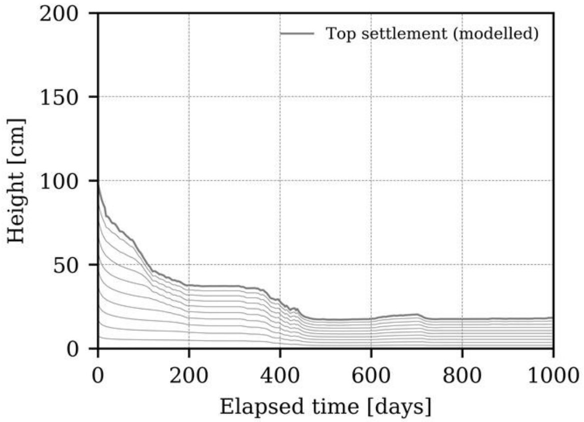
without drainage

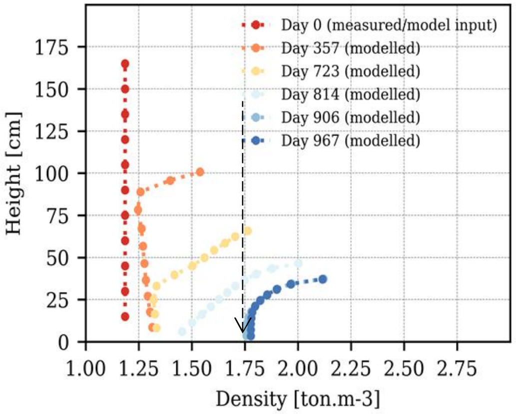


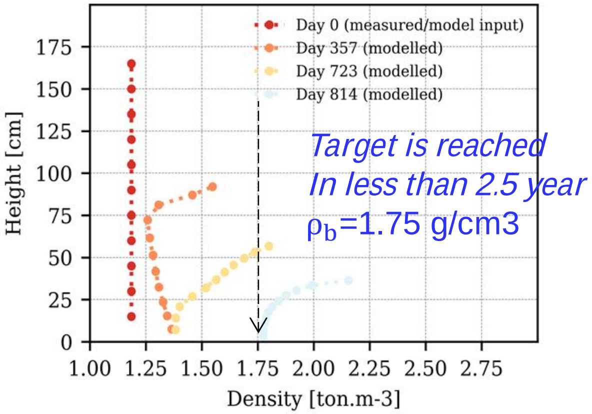
with drainage

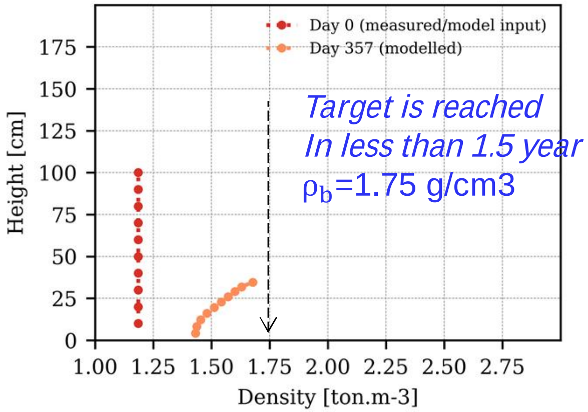


with drainage







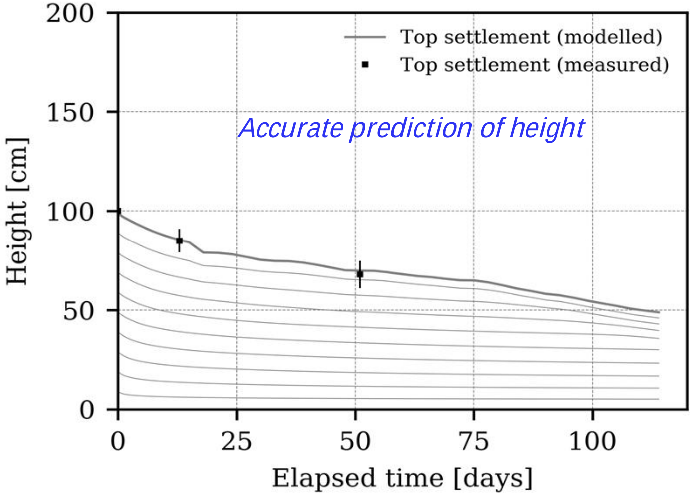


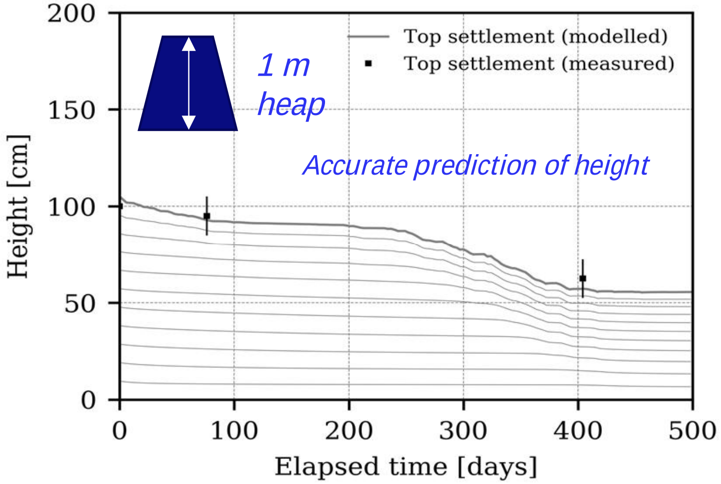
Deltares

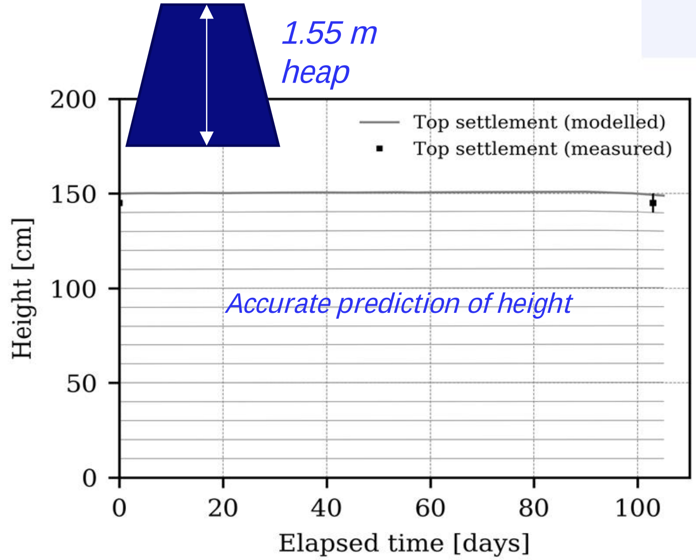
In presence of base drainage boundary condition, the targeted density of 1.75 ton/m3 is achieved 3 months earlier compared to no base drainage.

Hindcast modelling: effect of reworking and mounting in D7

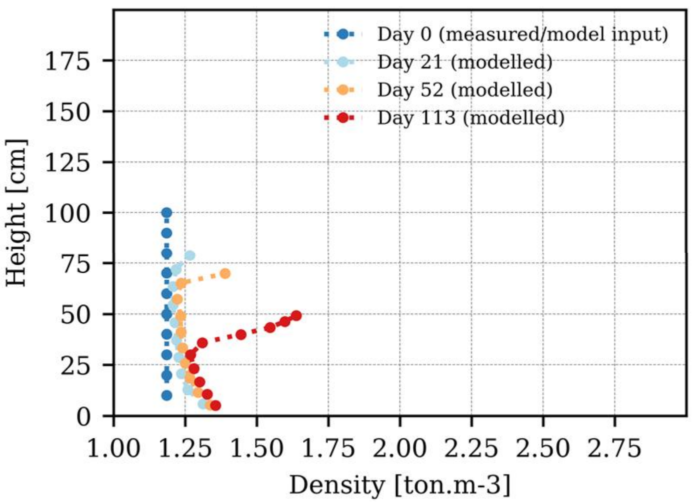
Simulation of first 714 days

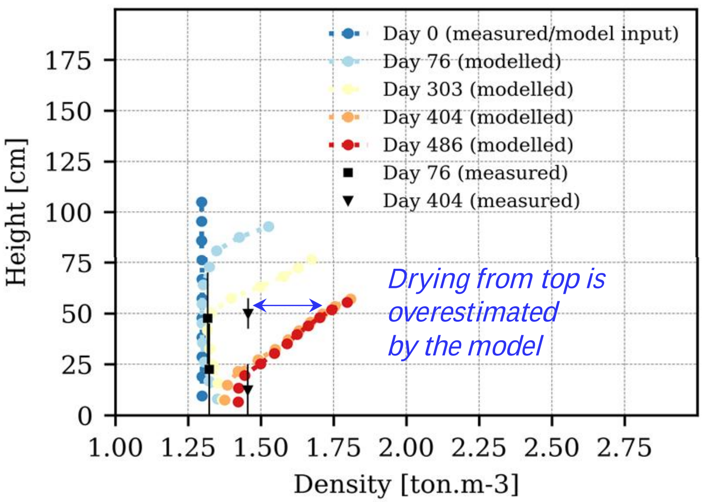


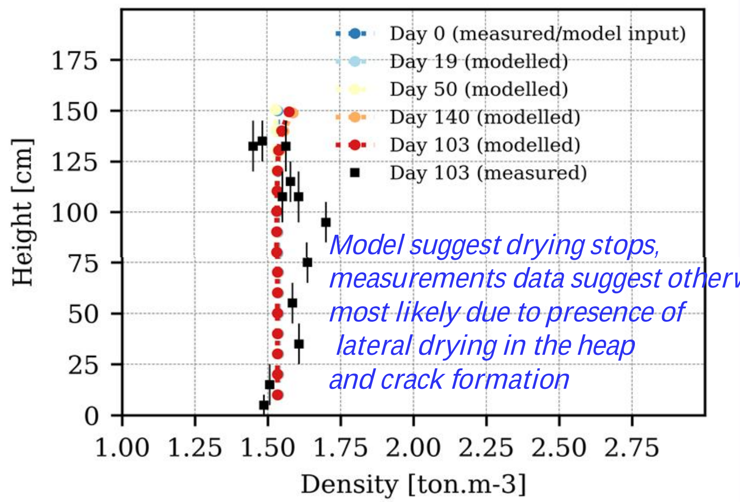




T0: 10-4-2018



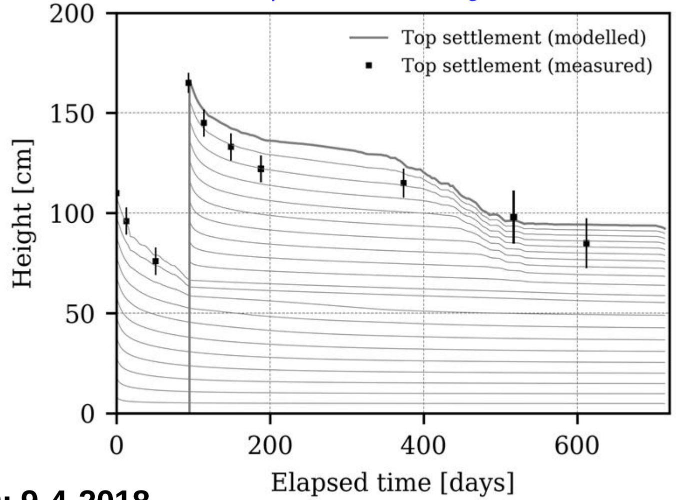


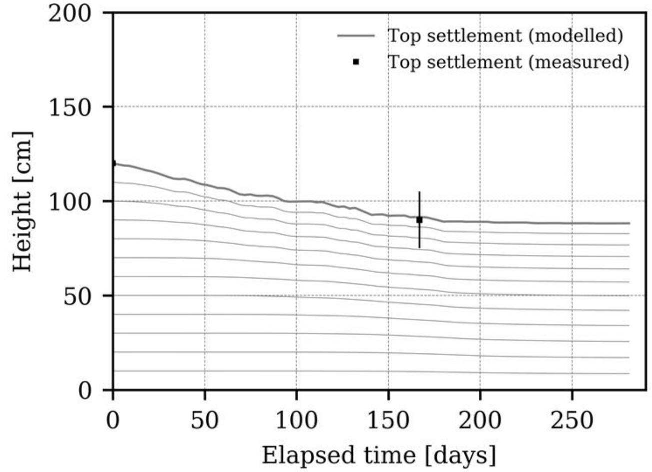


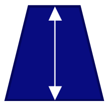
Hindcast modelling: effect of layering, reworking and heap in D9

Simulation of first 714 days

Accurate prediction of height

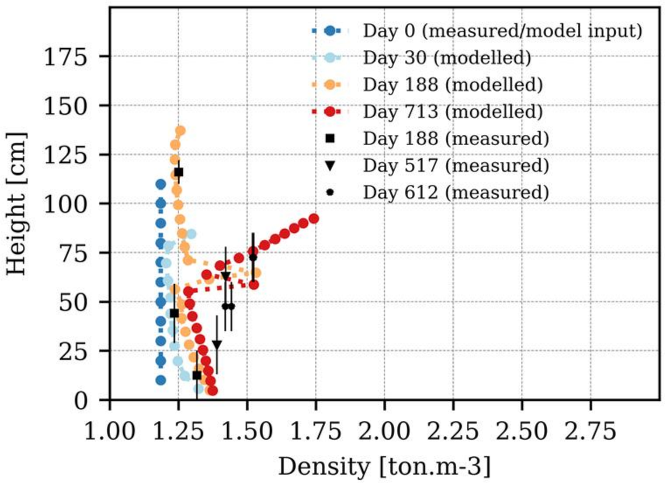


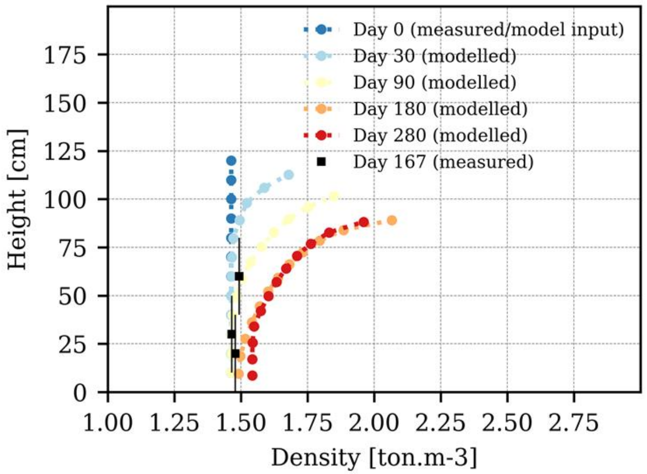




1 m heap

T0: 9-4-2018





Takeaways

- We successfully calibrated and validated the Vardon ripening model for the Kleirijperij pilot. We then used it to perform hindcast modelling and scenario analysis for Kleirijperij.
- In general, simulation results are in good agreement with field data for the first year, with regard to both settlement and density profiles.
- At a later stage, the agreement with regard to the density of the crust is sometimes less. This may be explained by:
  - assumed effect of dry crust on permeability (e.g. crack formation)
  - reworking (inclusion of air pockets, 2D/3D effects in mounts)
  - changing material properties by alternating drying-wetting in the crust
- We studied the effect of three design factors: drainage, initial deposit height and climate. We found that:
  - The initial deposit height is the most important factor steering the time scale of the physical ripening process. An initial deposit height between 40 to 60 cm seems to be optimal for rapid consolidation and desiccation.
  - The difference between dry and wet years is substantial. In 3 subsequent wet years ripening proceeds less than in 2 subsequent dry years.
  - In case of higher initial deposit heights the presence of drainage can speed up the ripening process by several months (3 months in 3 years).

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