Application of a new shallow subsurface deformation model to subsidence in the Groningen reservoir region, Netherlands

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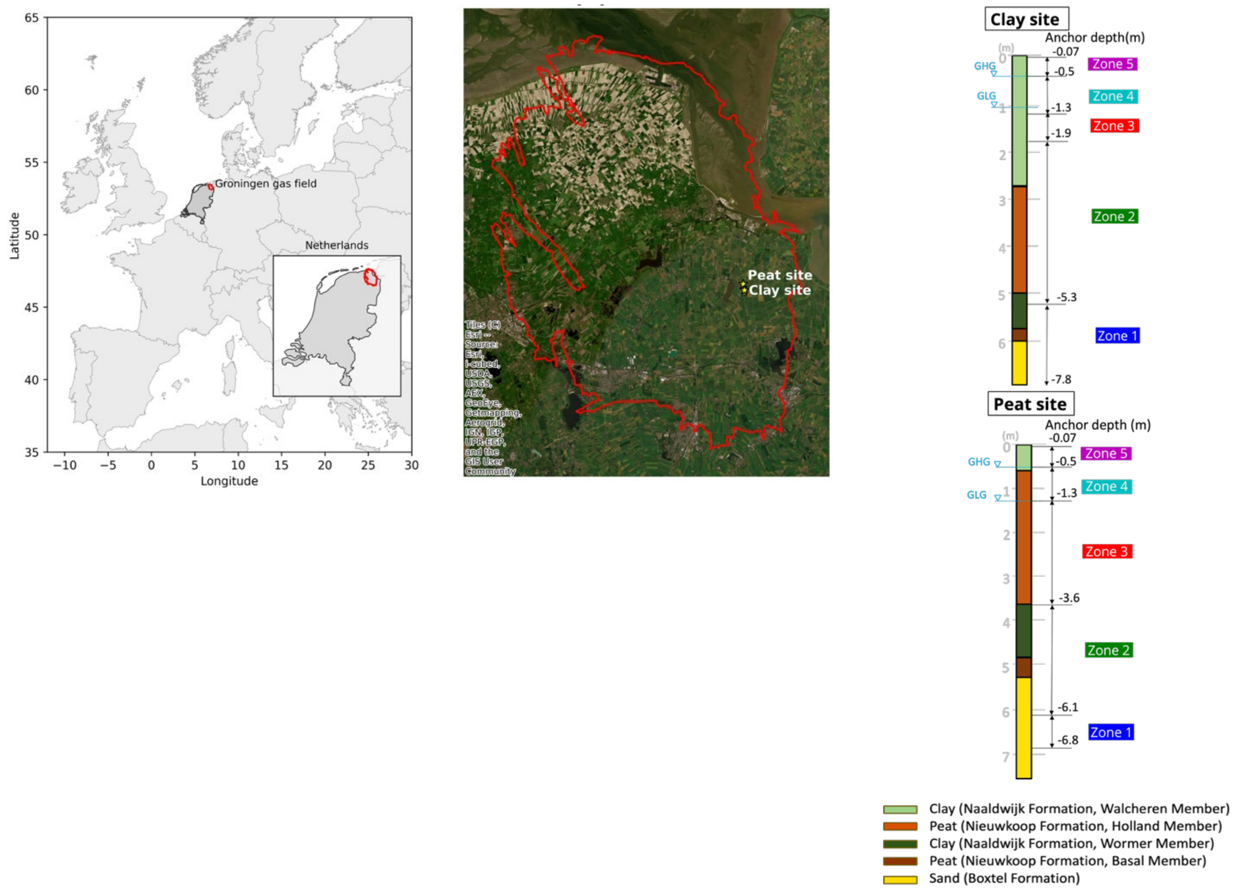
1 Introduction

Soft soils such as peat and clay are highly sensitive to hydrological forcing, with groundwater driven consolidation in the saturated zone and soil-moisture-driven shrinkage and swelling occurring in the unsaturated zone. The Groningen gas field area has experienced up to 37 cm of cumulative subsidence by 2018 since the start of the extractions in 1963 [1]. Although deep reservoir compaction at approximately 3000 m is the dominant driver, compaction of shallow Holocene peat and clay layers, and peat oxidation also contribute. Consolidation in saturated zone is relatively well understood (e.g. [2]) and correlations between surface deformation and meteorological forcing, precipitation and evapotranspiration (P, ET), is reported [3]. However, a mechanistic explanation of unsaturated-zone behaviour and delayed responses in low-permeability subsurface material remains incomplete. The aim of this project is to quantify the mechanical and hydrological properties of individual shallow Holocene subsurface layers that control land subsidence. To achieve this, we first analyse observation data from extensometers installed in Nieuwolda, Groningen, The Netherlands (Figure 1a and b) to understand the behaviour of clay and peat deposits at different depth and to analyse their response to precipitation, evapotranspiration, and groundwater fluctuation. The site is characterized by alternating clay and peat layers overlying a stable cover sand layer of Late-Pleistocene age. (Figure 1c).



(a) (b) (c)

Figure 1. Nieuwolda extensometer site. (a) Location of the Groningen gas field, the red line indicates the outline of the gas reservoir location, (b) Location of the extensometer site, and (c) Local soil profiles at the site; GHG denotes the average highest groundwater level and GLG denotes the average lowest groundwater level.

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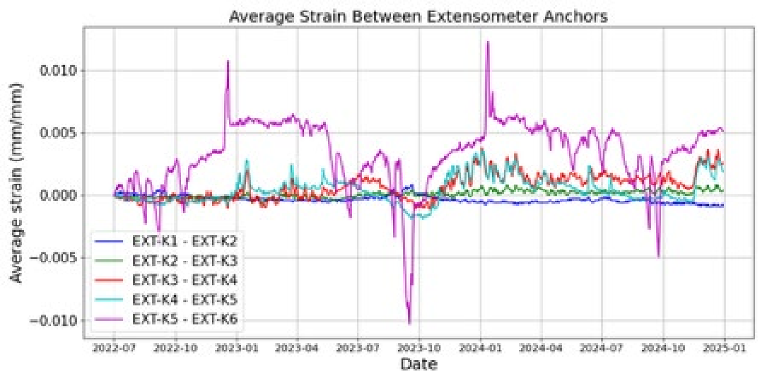
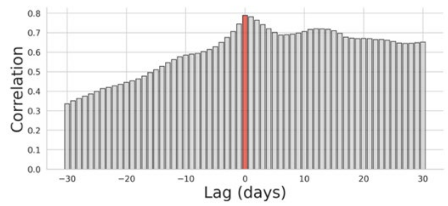
The extensometer time series shows layer compaction and swelling (Figure 2). The largest fluctuations occur above the groundwater level (Figure 2a). Surface deformation responds immediately to groundwater level changes (Figure 2b) and shows one day time lag relative to the meteorological forcing(P, ET) (Figure 2c). To reproduce these observations, we develop a one-dimensional hydro-mechanical subsurface deformation model to simulate deformation in both unsaturated and saturated zone. The model discretizes a soil column into elements, each assigned an effective saturation S_e updated at every time step. Elements with $S_e < 1$ are considered unsaturated and those with $S_e = 1$ indicate saturation. An innovation of this approach is its ability to simulate shrinkage and swelling in the unsaturated zone where the strongest fluctuations occur in the Holocene deposit. Although geological and hydrological property maps are available in the Netherlands, several key material parameters controlling the simulation results are missing, available at unsuitable special resolutions, or associated with uncertainty. To estimate these parameters and reduce model uncertainty, we apply Ensemble Smoother with Multiple Data Assimilation (ESMDA) [5] to calibrate six key parameters. Before applying ESMDA, we checked the sensitivities of the six key parameters to evaluate their influence on the simulations and to define the appropriate prior range for the ensemble parameter used in ESMDA. Our ongoing work focuses on upscaling the one-dimensional model to the regional scale by dividing the study area into parcels. Within each parcel, spatially averaged parameters represent effective parcel properties. We will estimate these effective parameters using the same inversion approach, with InSAR-based deformation data serving as observational data to constrain regional simulations. This extended abstract presents the analysis of the extensometer data, the methodology of the one-dimensional hydro-mechanical deformation model, the result of the parameter sensitivity analysis and its preliminary findings. The full inversion procedure and the regional upscaling will be addressed in a subsequent publication.

2 Extensometer data analysis in Nieuwolda, Groningen

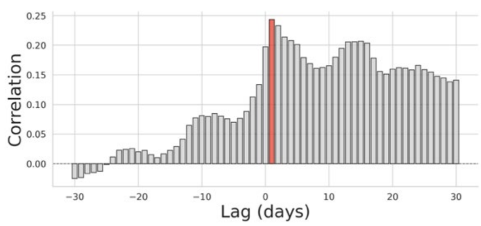
Two extensometers with six anchors measure vertical displacement at different depths (Figure 1c). We derive the average strains between adjacent anchors (Figure 2a). Strains at the peat site fluctuate most at the shallowest level (Zone 5), which is consistently above the groundwater table and remains unsaturated. Zones 1- 3 are permanently saturated, while Zone 4 alternates between saturated and unsaturated conditions. Zones 3 and 4 exhibit similar temporal trends, with smaller amplitudes compared to Zone 5. Zones 1 and 2 show only minor strain variations. The relationship between vertical surface displacement, groundwater level, and meteorological forcing is analysed using Pearson cross-correlation with time lags $k \in [-30, 30]$ days. Vertical surface displacement shows the strongest correlation with groundwater level fluctuations at zero lag (Figure 2b), indicating an immediate response. The correlation with net precipitation minus evapotranspiration peaks at a one-day lag (Figure 2c). Another extensometer site (clay site) shows a similar temporal pattern but with smaller correlations.



(a)



(b)



(c)

Figure 2. (a) Daily averaged vertical strain measurements at multiple zones recorded by the extensometer installed at the peat site in Nieuwolda, from July 2022 to January 2025, (b) Pearson's cross-correlation at time lags $k$days ($k \in [-30,30]$) between surface level and groundwater, and (c) between surface level and the net precipitation-evapotranspiration balance.

3 Coupled hydro-mechanical shallow subsurface deformation model

We develop a model to reproduce vertical deformation of a soft soil column that extends from the surface into the unsaturated and saturated zone (Figure 3b). This physically based deformation model employs a one-dimensional finite difference method to simulate the shallow subsurface deformation along the vertical profile. The model is formulated in one-dimension to maintain conceptual simplicity and to align with the spatially local input data available, such as groundwater monitoring data, precipitation measurement. The model computes changes in the pore pressure distribution in response to changes in surface pore pressure, groundwater level and void ratio. Subsequently, the model computes void changes, and the deformation is calculated based on the updated void ratio.

Following Terzaghi's principle, pore pressure in the model is represented as the sum of pore water pressure, ψ_w, and matrix suction, ψ_m. Effective stress, σ′ is given by Equation (1):

$$\sigma' = \sigma - (\psi_w + S_e \psi_m) \tag{1}$$

where S_e is effective saturation, σ is total stress. Pressure change is derived by the diffusion equation $\frac{\partial \psi_m}{\partial t} = K^2 \frac{\partial^2 \psi_m}{\partial x^2}$, hydraulic conductivity K is calculated by the Mualem–van Genuchten Formulation. In this formulation, only vertical stresses are considered. Stress states are assumed to be isotropic and are treated as scalar quantities acting in the vertical direction. To derive surface pore pressure time series from daily precipitation, evapotranspiration data and groundwater level, we separately use SWAP [4] prior to the deformation calculation (Figure 3a). SWAP solves the one-dimensional Richards's equation [7] to simulate vertical water flow using precipitation $P(t)$ and potential evapotranspiration $ET(t)$ as time-dependent forcing. The resulting surface pore pressure is used as input for the deformation model. It is important to note that SWAP does not account for vertical deformation when updating void ratio and water content whereas the deformation model assumes that changes in void ratio result solely from vertical strain. Consequently, this approach does not capture the physical behaviour correctly but is used to approximate the temporal trend of surface pressure.

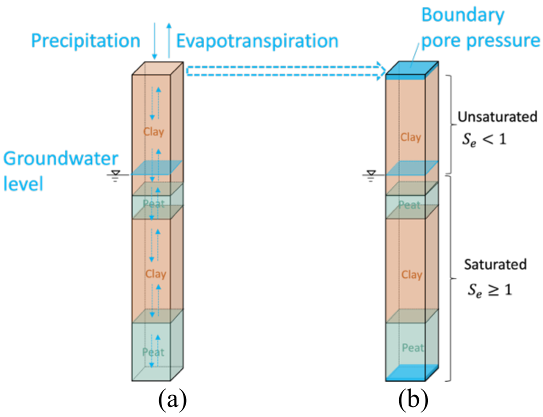


Figure 3. Schematic of the coupled modelling framework, (a) Step 1, Calculation of the pore pressure at the surface with SWAP model, and (b) Step 2, Calculation of one-dimensional subsurface deformation.

The Soft soil creep (SSC) formulation [6] is used to calculate void ratio changes (Equation (2)). Under the assumption of one-dimensional vertical deformation, lateral strains are neglected and soil volume changes occur only in the vertical direction. Consequently, the volumetric strain equals the vertical strain, and the change in void ratio is directly related to the vertical strain.

$$\frac{\partial e}{\partial t} = \frac{\partial e_e}{\partial t} + \frac{\partial e_c}{\partial t} = \frac{\partial \sigma'}{\partial t} \cdot \frac{\kappa^*}{C \cot \phi + \sigma'} + \mu^* \cdot \frac{1}{\tau_{\text{ref}}} \left(\frac{\sigma'}{\sigma'_{vm}} \right)^{\frac{\lambda^* - \kappa^*}{\mu^*}} \tag{2}$$

where $\frac{\partial e_e}{\partial t}$ is the elastic component of the void ratio change, $\frac{\partial e_c}{\partial t}$ is the creep component of the void ratio change, $\kappa^*, \lambda^*, \mu^*$ represent the modified swelling, compression, and creep index respectively, τ_{ref} is a reference time for creep in the isotach formulation, σ'_{vm} is the pre-consolidation pressure, C is cohesion[kPa] and ϕ is internal friction angle[°]. This formulation assumes the isotach hypothesis, where the void ratio changes occur along surfaces of constant strain rate in the $e - log\sigma'$ space. Using the void ratio changes derived by the SSC model, the column height is calculated. The total height of the soil column h at time step j is computed as:

$$h^j = \sum_i^n \left(\frac{1 - \left(e_{0,i} - e_i^j\right)}{1 + e_{0,i}} \right) \cdot h_{ini,i} \tag{3}$$

where $e_{0,i}$, e_i are the initial void ratio and the current void ratio of element i, $h_{\text{ini},i}$ is the initial thickness of element i.

4 Parameter sensitivity

Our eventual goal is to estimate material parameter values from the extensometer time series. In the interest of a well-conditioned inversion problem, we first explore the sensitivity of the forward model to variations in six key parameters, κ, λ, μ, K_{sat}, Over-consolidation rate (OCR), and $C\ cot\ \phi$. To provide a reference for comparison, synthetic data are generated using a vertically homogeneous soil profile with typical clay parameter values. Groundwater level, precipitation, and evapotranspiration measured at the Nieuwolda site are used as input forcing. Parameter ranges used for sensitivity tests are selected based on values reported in the literature and from laboratory tests. The parameters used to generate synthetic data are within these ranges. The simulated time series of surface deformation for different parameter values are shown in Figure 4. Figure 4 a and c show that $Ccot\phi$ and K_{sat} influence the short-term deformation response. Variations in $Ccot\phi$ significantly change the amplitude of deformation, ranging from approximately 0.5 to 1.5 times the reference synthetic data. For K_{sat}, the impact during swelling is relatively minor, whereas shrinkage behaviour is more sensitive to its variation. In contrast to $Ccot\phi$ and K_{sat}, Figure 4b shows that OCR controls the time-dependent deformation behaviour associated with the creep component of the SSC model. Figure 4d-f present the sensitivity of μ under different combinations of κ and λ. Model responses depend strongly on the relative values of κ, λ and μ. When $\lambda - \kappa$ is small (Figure 4 d), μ strongly controls the time-dependent behaviour. For large $\lambda - \kappa$ (Figure 4 f), the deformation response becomes less sensitive to μ. Intermediate values of $\lambda - \kappa$ (Figure 4 e) provide better agreement with observations, indicating that a balanced ratio between λ, κ, and μ is required to reproduce field behaviour.

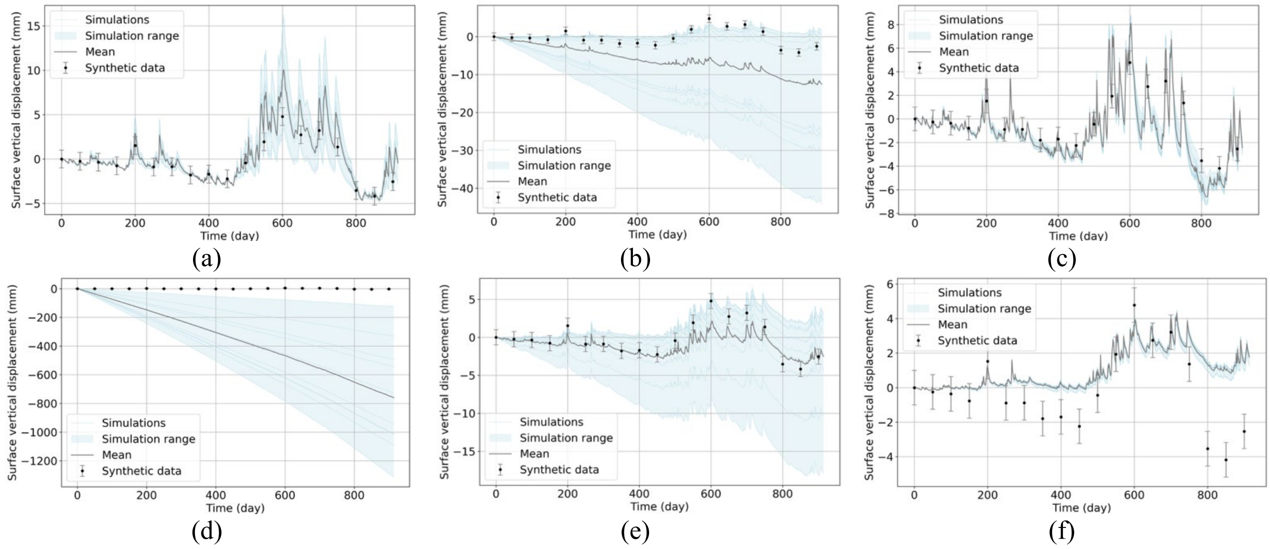


Figure 4. Simulated surface-deformation time series for different parameter values, showing the sensitivity of the model to (a) $C\ cot\ \phi$, (b) OCR, (c) K_{sat}, and the sensitivity of model to μ with variations of κ, λ. (d) $\kappa = 0.15, \lambda = 0.2$, (e) $\kappa = 0.15, \lambda = 0.3$, (f) $\kappa = 0.087, \lambda = 0.3$.

5 Preliminary conclusion and discussion

Extensometer measurements indicate that, on a time scale of 2-3 years, shallow deformation is primarily controlled by wetting-drying processes in the unsaturated zone, driven by groundwater fluctuations and meteorological forcing.

The developed model reproduces the observed behaviours by capturing deformation in the unsaturated zone and its response time, however, uncertainties in material parameterization and results remain. The ratio between the isotach parameters λ, κ, and μ strongly influences the simulation results. In particular, the ranges of $\lambda - \kappa$ and $\frac{\lambda-\kappa}{\mu}$, which govern the balance between elastic and creep behaviour, require further investigation. The present model accounts for consolidation, shrinkage, and swelling driven by precipitation, evapotranspiration, and groundwater-level fluctuations. Other mechanisms and factors, such as peat oxidation, crop rotation, and drainage, are not included in the current formulation. Our ongoing research evaluates layer-specific parameterization to better represent stratigraphic heterogeneity and will be reported in future research.

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