Particle Filtering of Rainfall-Induced Slope Deformation: Fixed vs Sliding Window $\boldsymbol{R}$

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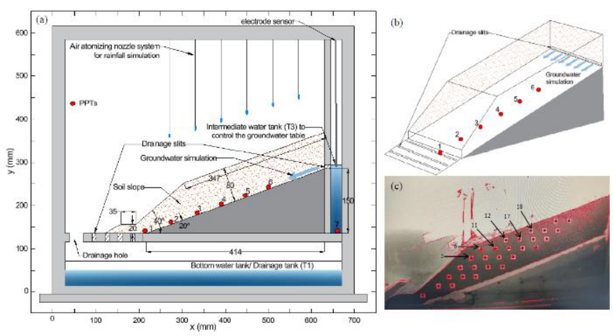
1. Introduction

Rainfall-induced slope deformation exhibits strong nonlinearity and regime shifts (early: pore-water pressure change dominates; later: displacement accelerates). In a deterministic FEM + SIS particle filter setting, the observation-error covariance $\boldsymbol{R}$ directly controls likelihood sharpness and can trigger weight collapse or preserve meaningful alternatives. This study compares two practical choices for $\boldsymbol{R}$ under joint assimilation of PWP + surface displacement: (i) Fixed $\boldsymbol{R}$ (time-invariant, sensor-based) and (ii) Sliding window $\boldsymbol{R}_t$ (time-varying, estimated from recent O–F residuals).

2. Centrifuge experiment and coupled FEM model

A centrifuge slope test applies concurrent rainfall (prototype 25 mm/h) and groundwater inflow. Observations consist of PWP (P2–P4) and surface displacements (ux5, ux6, ux11, ux12, ux17, ux18) within the failure zone.

A 2D three-phase (us–pw–pa) coupled FEM is used. Rainfall is imposed as a normal inflow on the slope surface, divided into upper/middle/lower segments to represent heterogeneous infiltration/runoff; model outputs are extracted at the observation locations.



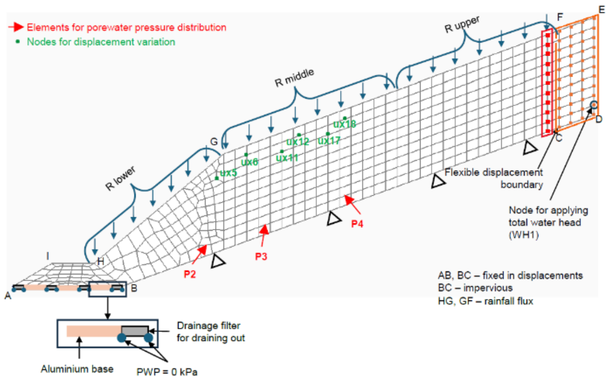


Figure 1. Experimental setting and numerical model/boundary conditions (Jayakody et al., 2024)

3. Assimilation window

Full-span updating from the beginning can cause rapid degeneracy because early updates are dominated by rainfall-driven PWP while displacement remains near the noise level. Therefore, updates are activated only after $t = 150$ s, when displacement becomes informative. To compare behavior across regimes, two end times are used: (i) Small deformation window: 150–178 s and (ii) Transition to acceleration: 150–189 s (ending at the onset of acceleration toward large deformation).

4. Observation-error covariance designs: Fixed $\boldsymbol{R}$ vs Sliding window $\boldsymbol{R}_t$

Fixed $\boldsymbol{R} = \mathrm{diag}(\sigma_1^2, \ldots, \sigma_m^2)$ is assembled from sensor specifications/calibration (diagonal, time-invariant). It is simple and reproducible but cannot adapt to regime shifts. Sliding window $\boldsymbol{R}_t$ estimates diagonal variances from past-only O–F residuals within a window: $n_{\mathrm{window}} = 18(=2m)$ and $27(=3m)$, where $m = 9$ observation channels. It can start too small (over-sharp likelihood) and grow later, effectively adapting to nonstationary mismatch; in practice, variance floors are used to avoid unrealistically sharp early likelihoods.

5. Results (Fixed vs Sliding window)

5.1 Small deformation regime (150–178 s)

Within 150–178 s, observations are PWP-dominant; displacement adds limited discrimination. Narrowing the window (starting at 150 s) increases posterior diversity compared with early updating. Fixed $\boldsymbol{R}$: displacement reproduction can remain insufficient when mismatch scale changes over time. Sliding window $\boldsymbol{R}_t$: often more conservative; if early $\boldsymbol{R}_t$ is very small, likelihood becomes too strict and accelerates early screening (window length controls sensitivity vs. stability).

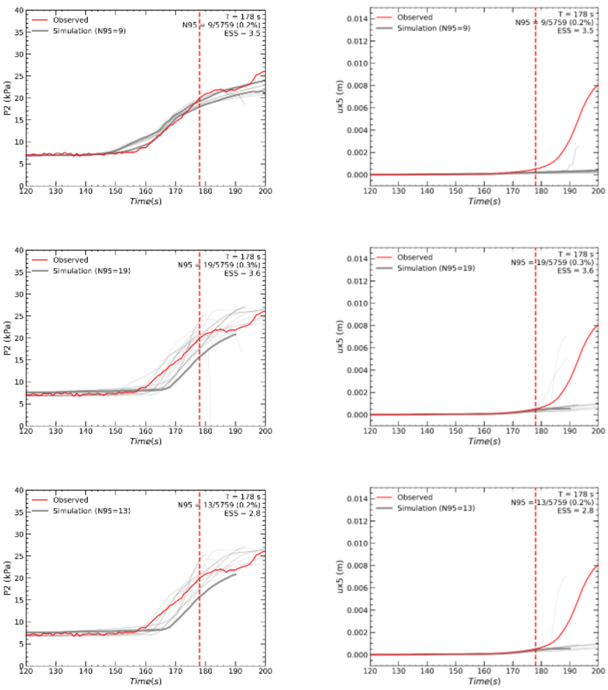


Figure 2. Posterior-selected trajectories at *t*=178 s: Fixed $\boldsymbol{R}$ vs Sliding window $\boldsymbol{R}_t$ (n_{window}=18, 27)

5.2 Transition to acceleration (150–189 s)

Extending the window to 150–189 s injects rapid late-stage displacement into the likelihood, strengthening discrimination. Fixed $\boldsymbol{R}$: posterior can over-concentrate; displacement fit may still lag, depending on fixed scale choice. Sliding window $\boldsymbol{R}_t$: adapts to regime shift and can preserve an alternative scenario (branching / incipient-failure path), providing a risk-sensitive outlook for decision making.

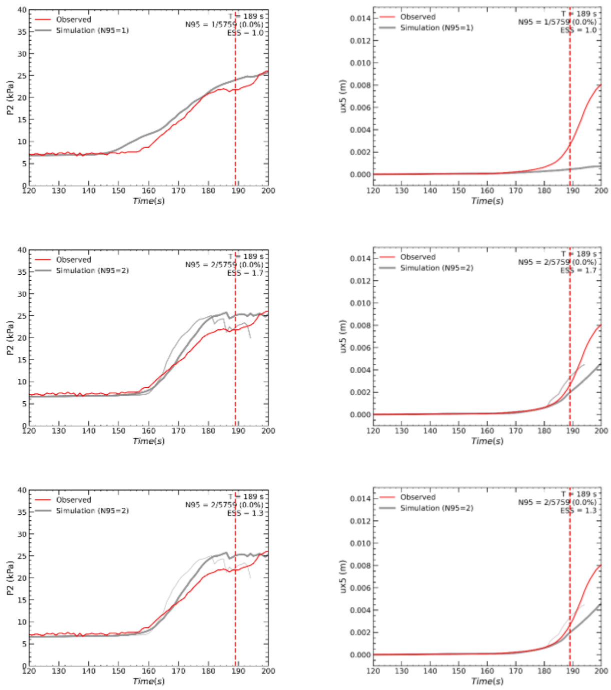


Figure 3. Posterior-selected trajectories at *t*=189 s: Fixed $\boldsymbol{R}$ vs Sliding window $\boldsymbol{R}_t$ (n_{window}=18, 27)

6. Conclusions

Update scheduling (start at 150 s) is as important as $\boldsymbol{R}$: it avoids early low-information updates and mitigates degeneracy. Fixed $\boldsymbol{R}$ is simplest but can be brittle under nonstationary dynamics. Sliding window $\boldsymbol{R}_t$ is effective for regime shifts: it can soften/strengthen likelihood in time and retain meaningful alternatives but needs careful window length and variance-floor handling. In practice, it is recommended to start with $n_{\text{window}} = 2m$ (responsive) and increase toward $3m$ (stable) when approaching acceleration.

Reference

Jayakody, S.H.S., Uzuoka, R., Ueda, K., Saito, K., 2024. Centrifuge modeling of slopes subjected to groundwater flow and rainfall infiltration. In: Unsaturated Soils: Advances in Geo-Engineering. Springer, Cham.