Physics-based uncertainty modeling of deep-seated landslides using InSAR: A case of El Forn (Andorra)

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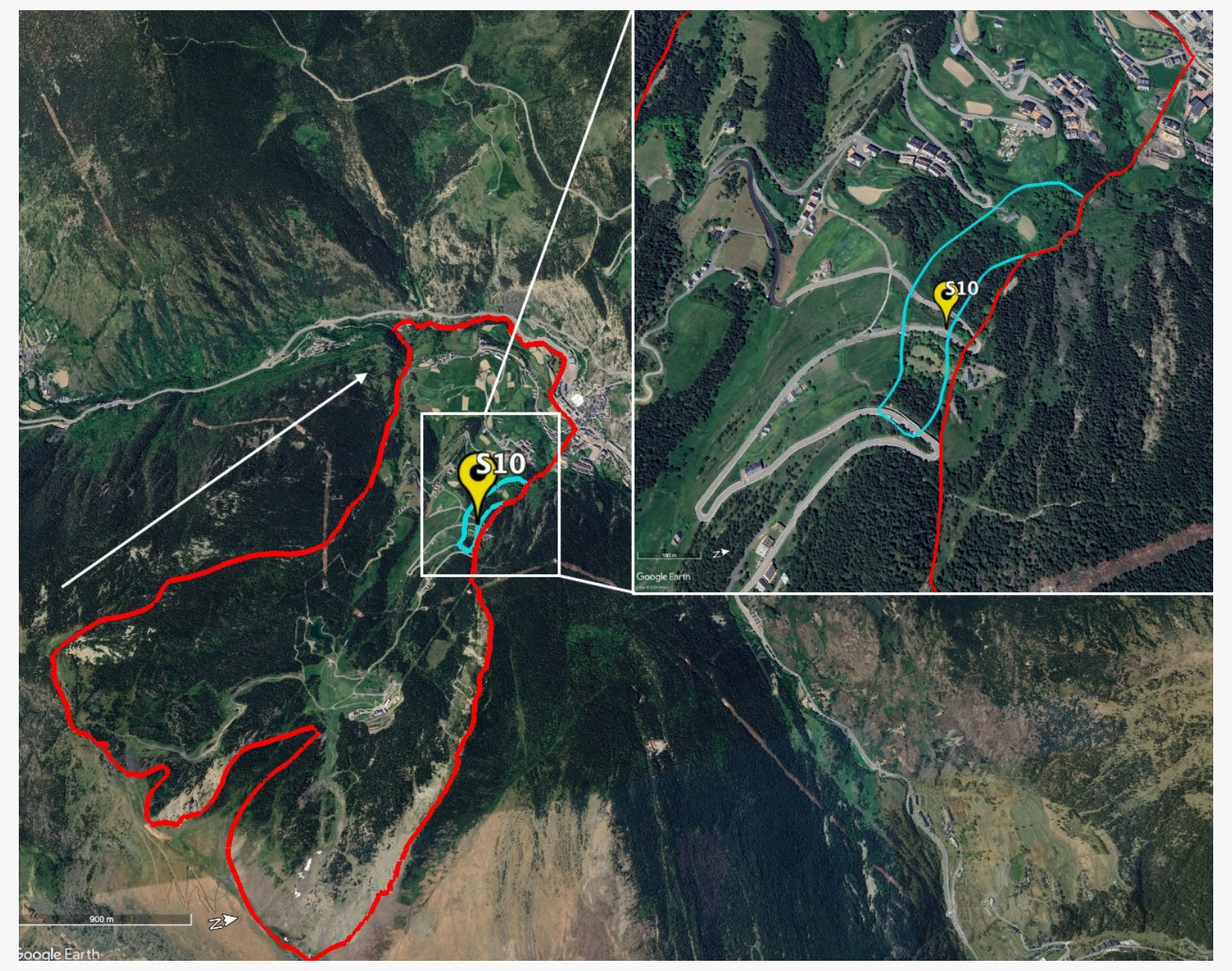
Abstract

This study addresses the modeling of deep-seated landslides, focusing on the El Forn landslide in Andorra, using remote sensing and data-driven approaches to create risk maps. A temperature-based model is adjusted with data from an instrumented borehole to determine material properties and conditions. The calibrated model is compared to Interferometric Synthetic Aperture Radar (InSAR) data, using the data for spatial analysis and creating a correlation map through kriging. This map leads to a physics-informed risk map indicating areas of instability. An uncertainty analysis of the model highlights its limitations but underscores the utility of such maps for policy and planning in areas prone to landslides. This approach provides a novel tool for assessing landslide risks, combining in-situ and remote sensing data for effective risk management.

Case Study Overview: El Forn, Andorra



Overview of the El Forn landslide with S10 borehole location and example readings.

The landslide considered in this work is the El Forn deep-seated landslide, nestled in the Pyrenees and situated just above the ski town of Canillo in Andorra. The landslide's 300 Mm^3 sliding mass creeps at an average rate of **0.5-2 cm/yr**. The primary borehole of interest in this study is referred to as **"S10"**, and is equipped with an extensometer, thermometer, and three piezometers. Note that the instrument readings of interest for this work are located at or below the **29m depth sliding surface.**

Physics-Based Model Overview

The physics-based model considered in this work is a temperature-based approach to forecasting and assessing deep-seated landslide stability, developed by Vardoulakis, Veveakis, and Seguí. More specifically, **we assume a rigid block sliding on a non-Newtonian rheology shearing surface.**

Energy Balance

$$\frac{\partial\theta^*}{\partial t^*} = \frac{\partial^2\theta^*}{\partial z^{*2}} + Gre^{\theta^*}$$

Gruntfest Equation

$$Gr = G_0\left(1+\frac{p_f}{p_{f0}}\right)^{(1+1/N)}$$

$$G_0 = m\frac{\dot{\gamma}_{ref}}{jk_m}\frac{ds^2}{4}\tau_{d,ref}$$

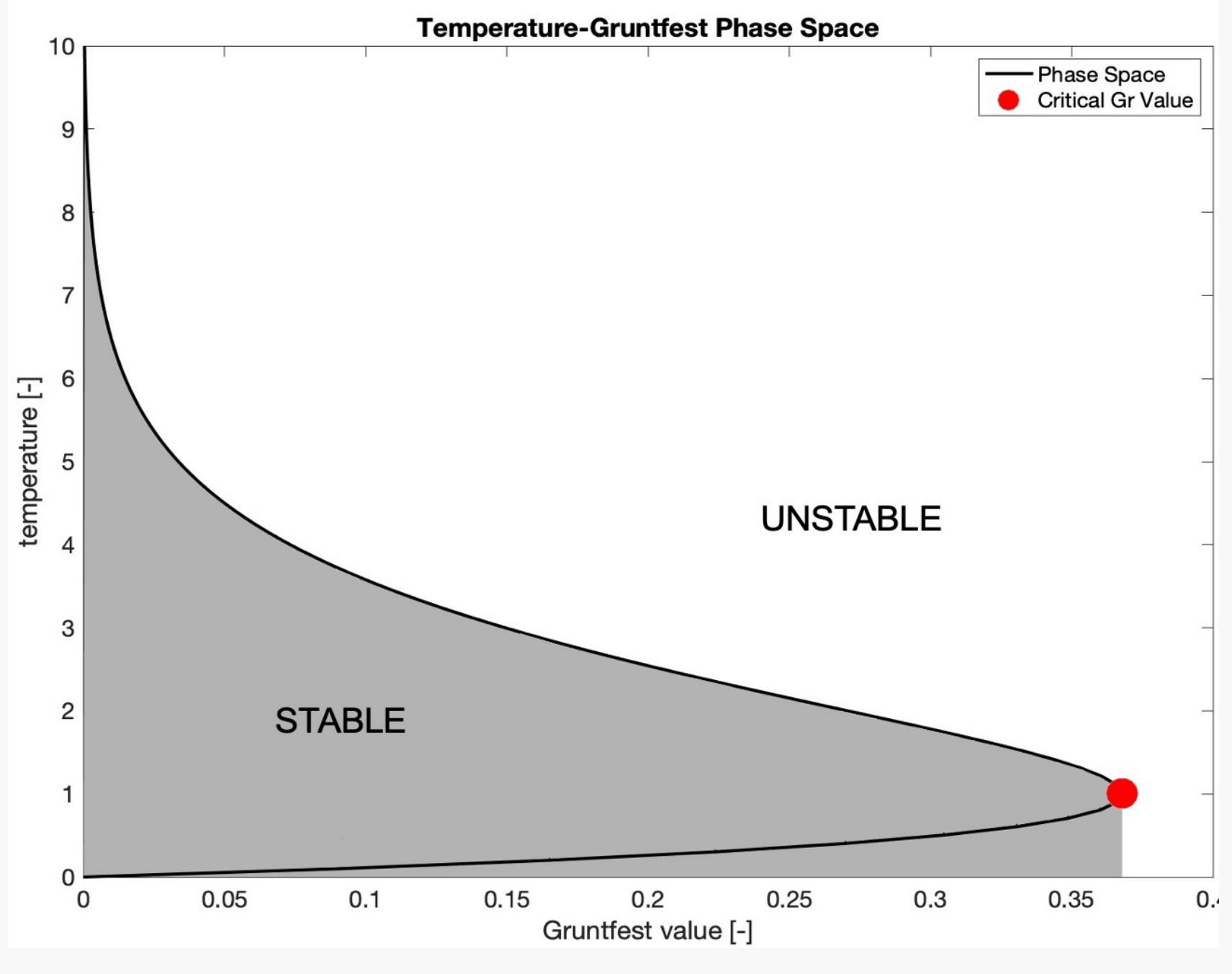
Simplified Energy Balance*

$$\frac{d\theta^*}{dt^*} = -\theta^* + Gre^{\theta^*}$$

Non-Newtonian Rheology*

$$\dot{\gamma} = \frac{\partial V}{\partial z} = \dot{\gamma}_0\left(\frac{\tau_n}{\sigma_{ref}}\right)^{1/N} e^{\theta^*}$$

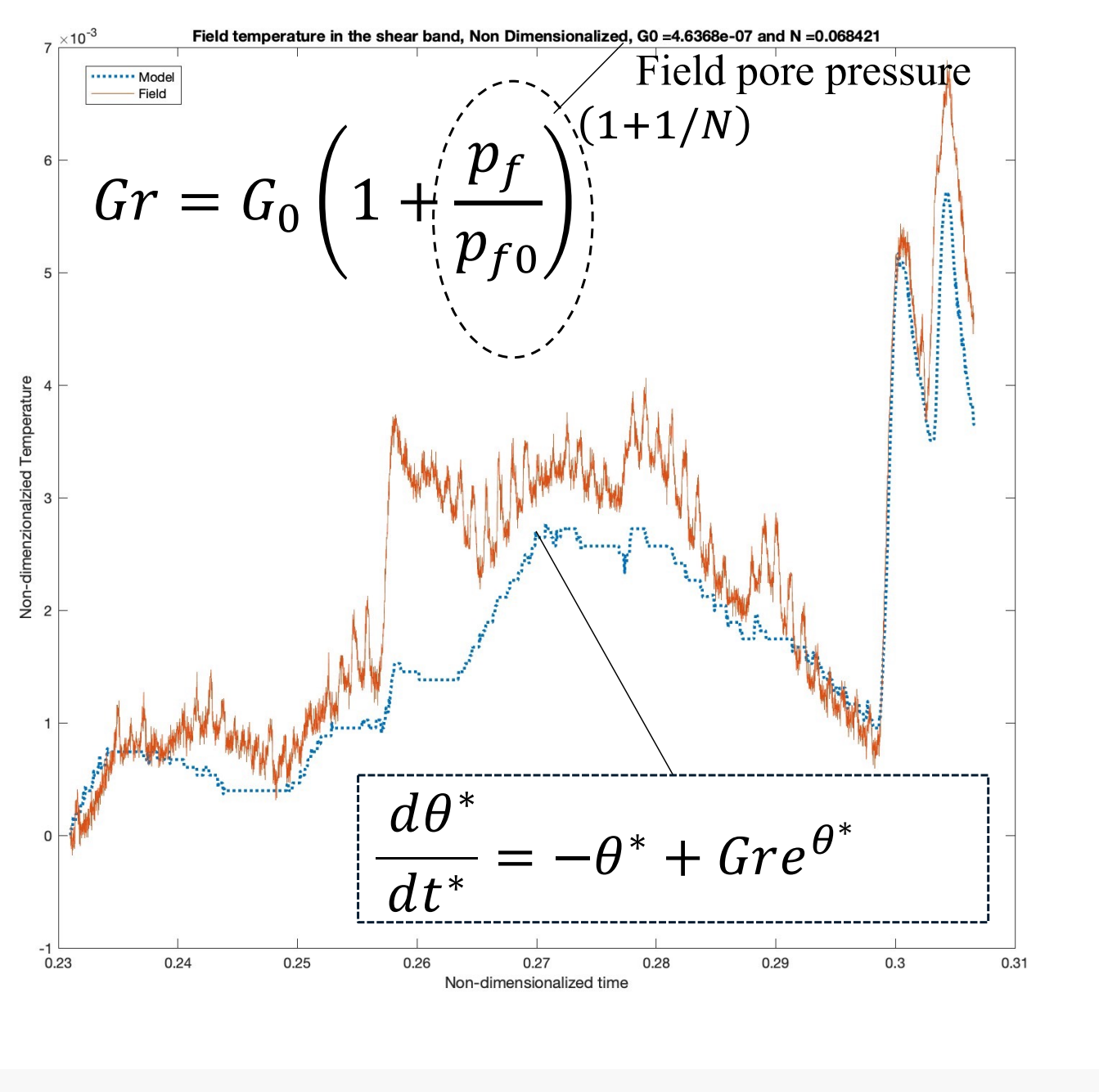
$$V = V_0\left(1+\frac{p_f}{p_{f0}}\right)^{1/N} e^{\theta^*}, \qquad V_0 = \dot{\gamma}ds\left(\frac{\tau_{n0}}{\sigma_{ref}}\right)^{1/N}$$



Temperature-Gruntfest phase space, with stable zone shaded in and critical Gruntfest value marked.

Tuning the Physics-Based Model

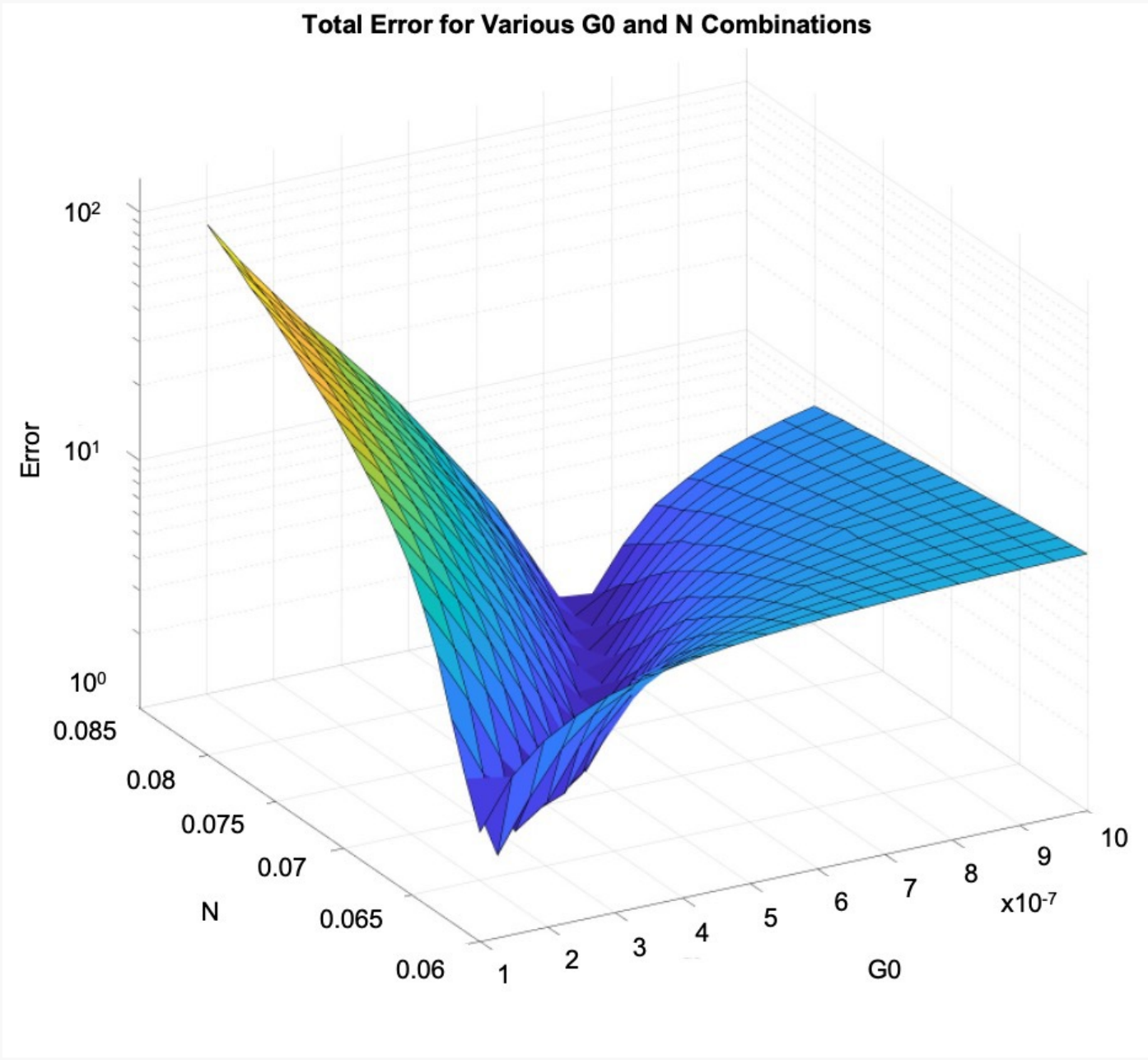
In order to determine the most appropriate combination of *N* and *G$_0$* that best tunes the physics-based model to the *in situ* data from borehole S10, the simplified energy balance is solved for by using the field pore pressure to solve for Gruntfest and eventually solve for temperature evolution as a factor of time. This model-output temperature is then comparable to the field temperature read in S10.



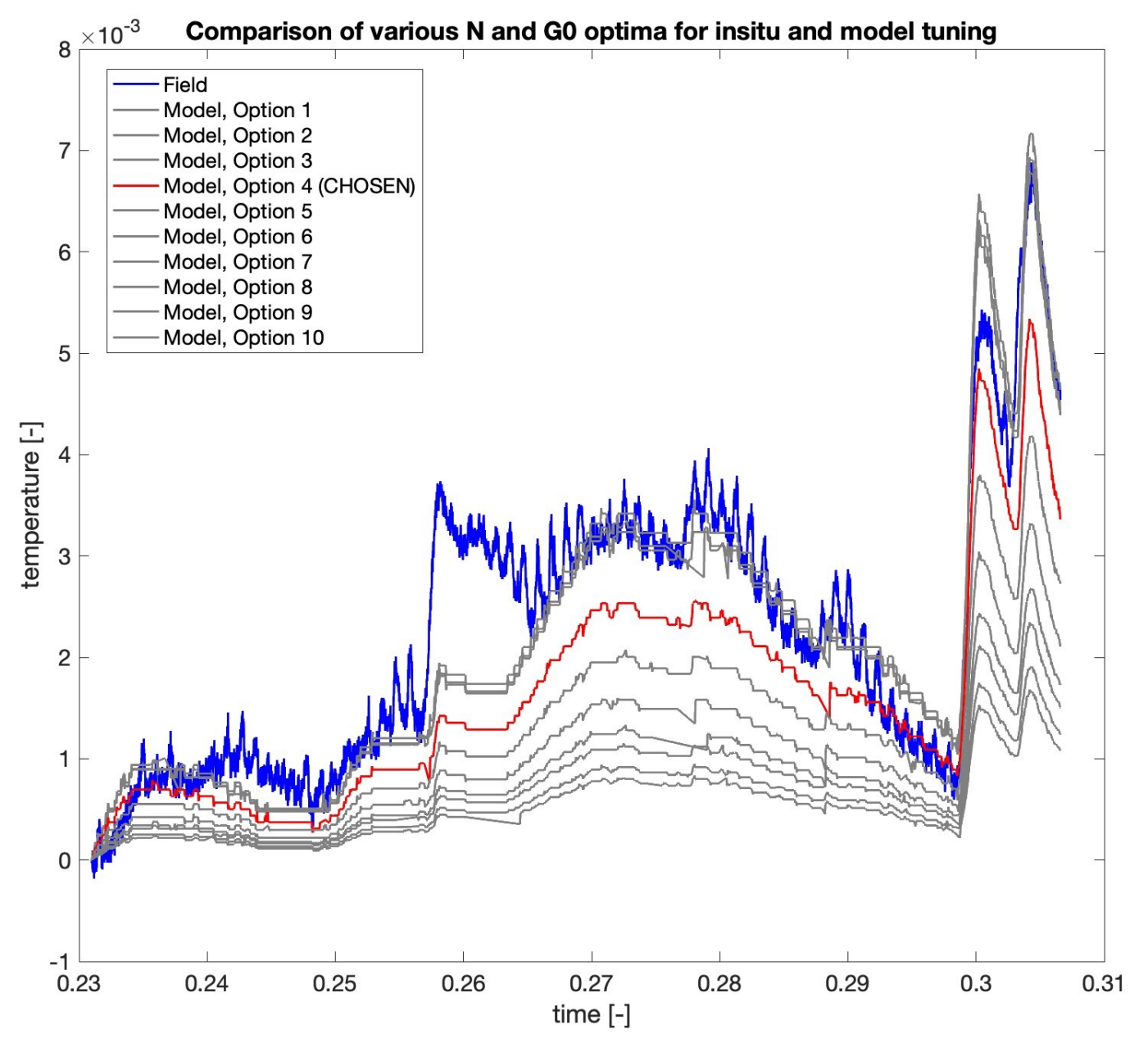
$$Gr = G_0\left(1+\frac{p_f}{p_{f0}}\right)^{(1+1/N)}$$

$$\frac{d\theta^*}{dt^*} = -\theta^* + Gre^{\theta^*}$$

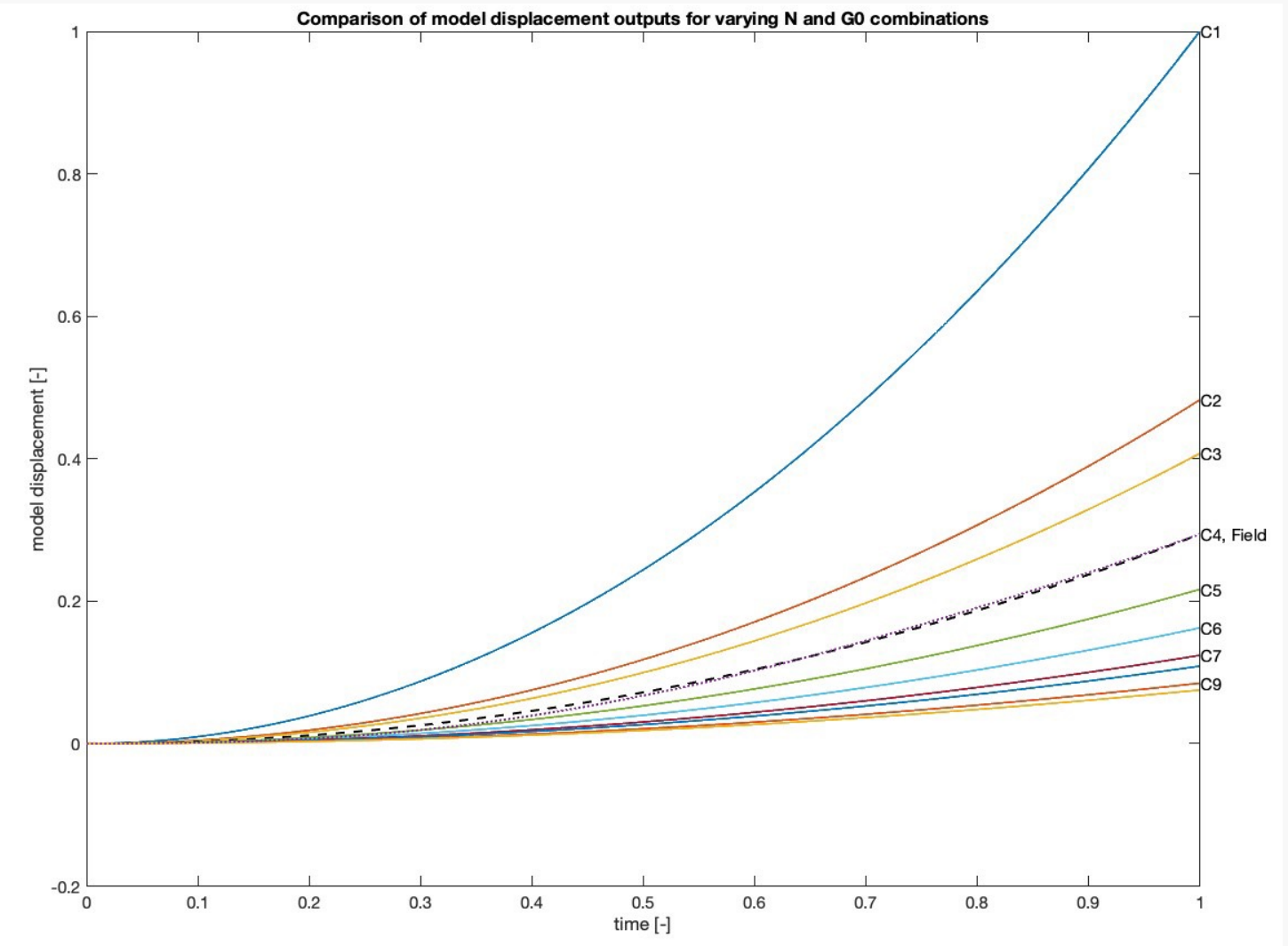
Example of comparison of model-output temperature with field temperature (S10) for one combination of N and G$_0$



Error mesh grid for field and model-output temperature readings for 400 combinations of N and G$_0$

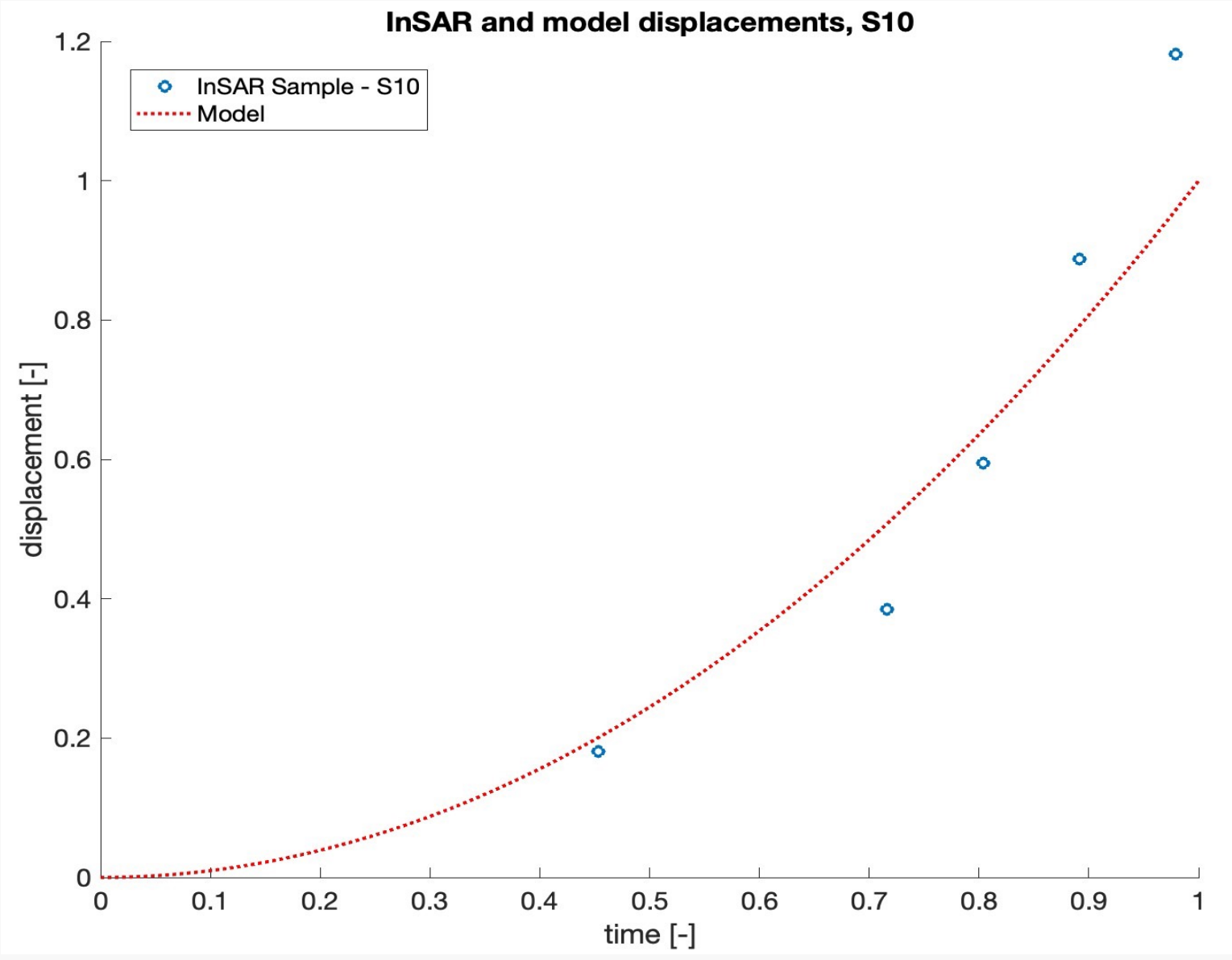


Temperature comparison of optimal N and G$_0$ combinations



Displacement comparison of optimal combinations of N and G$_0$ for the model

Linking InSAR

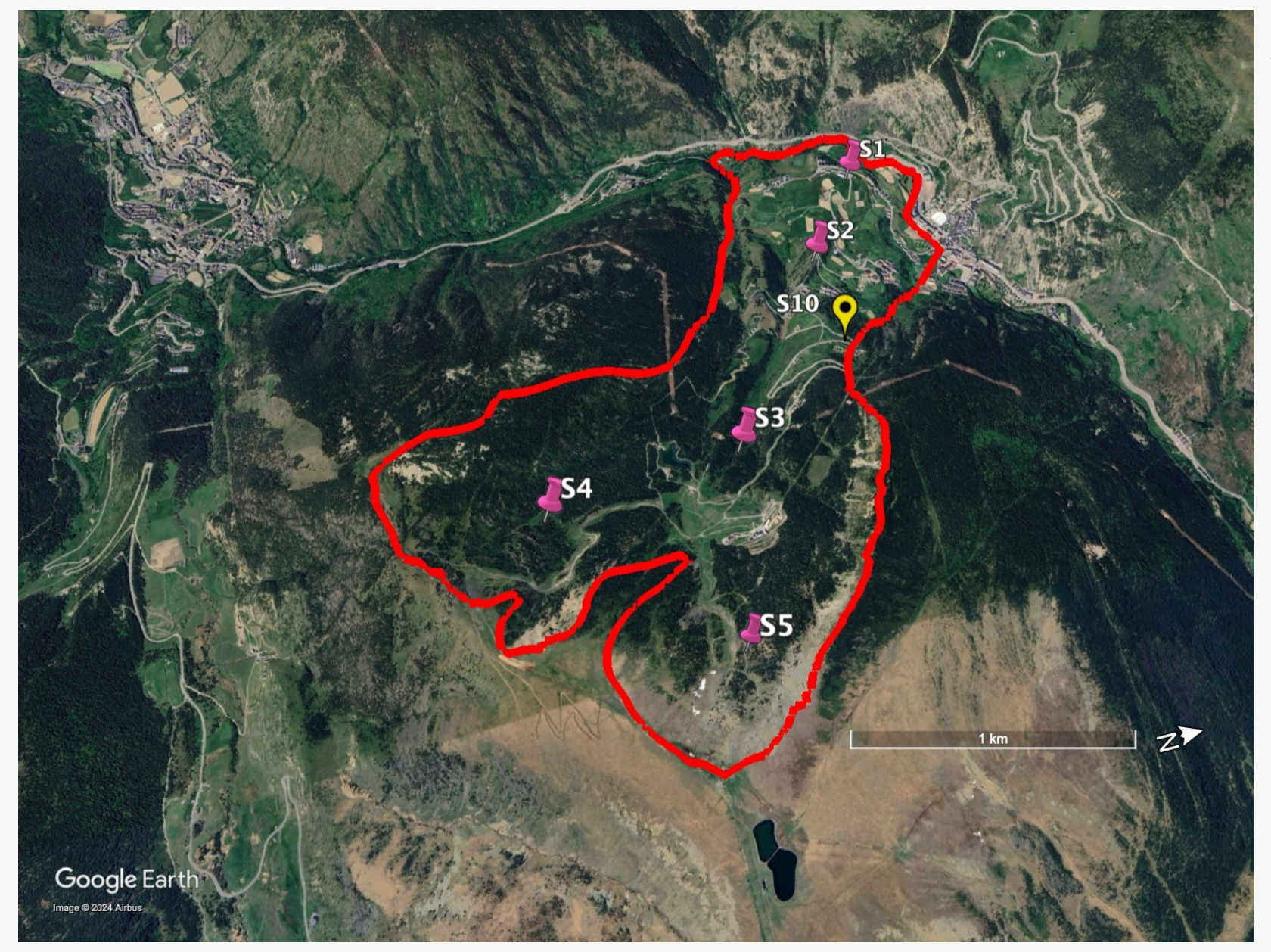


Agreement of InSAR and tuned-model displacements at S10 borehole location during the no-snow period of 2019.

In order to ensure that InSAR data fits the physics-based model displacement readings (after selection of the optimal *N* and *G$_0$* values), we compare the InSAR displacement readings during the same period of time over the S10 borehole with the tuned model-output displacement readings.

How does this method vary spatially along the landslide?

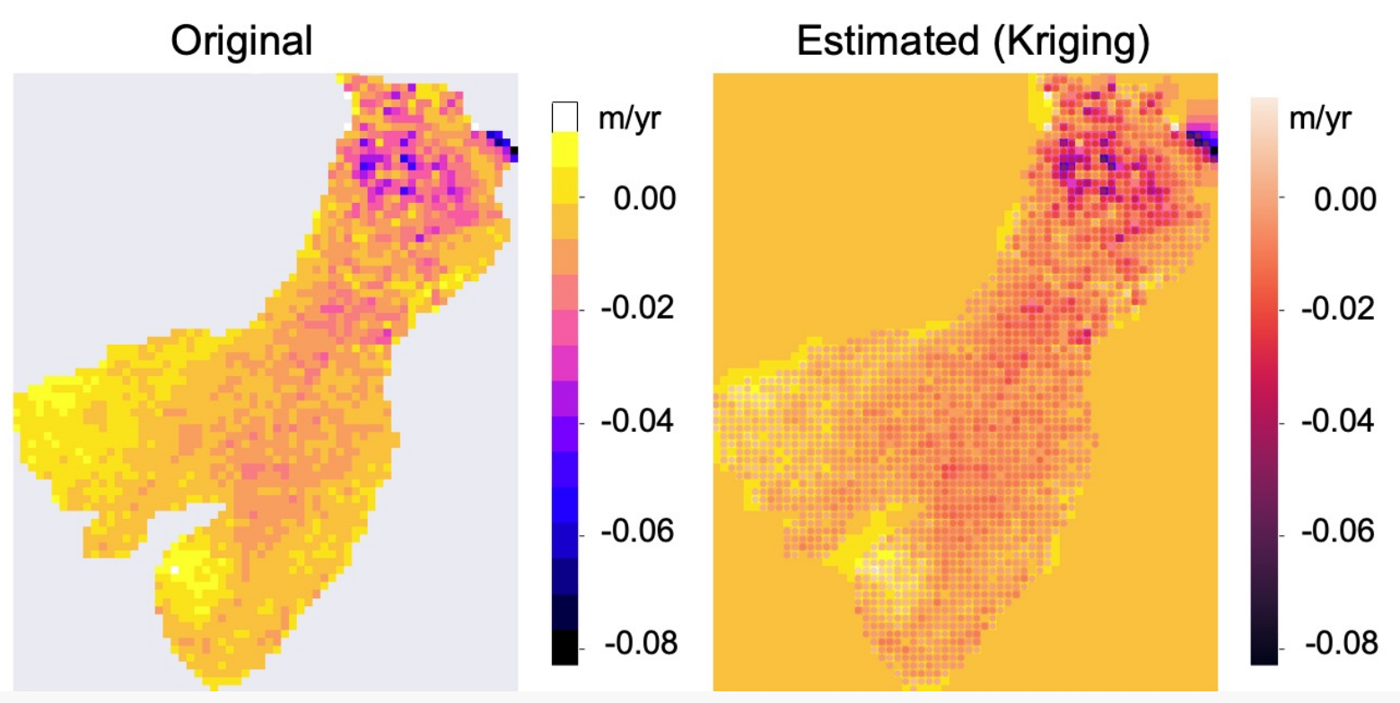
Spatial Variability and Forecasting



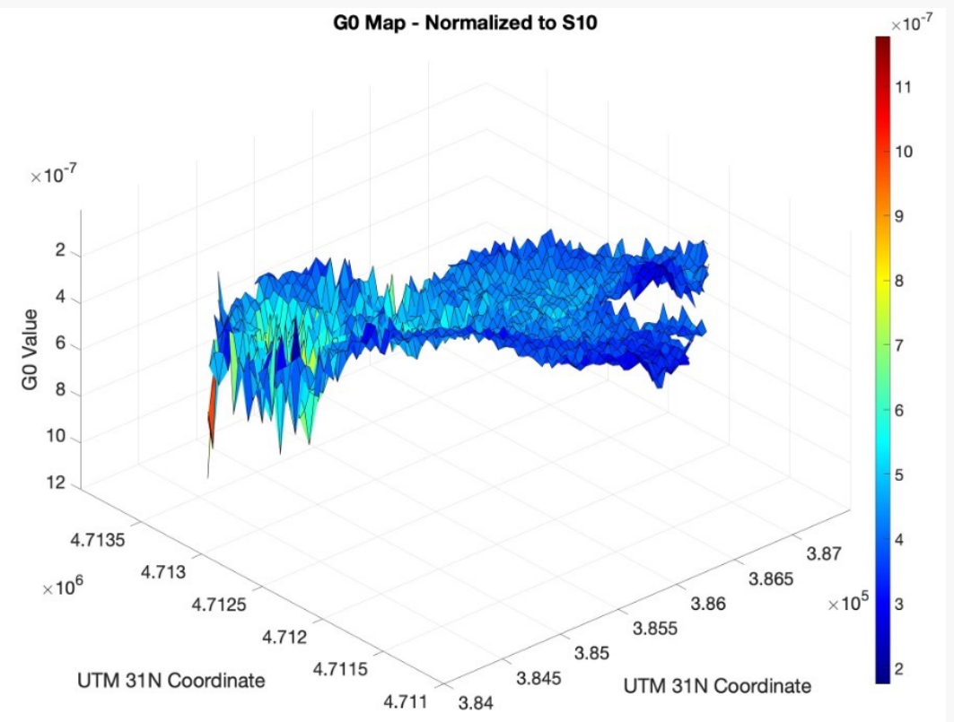
Assumptions

1. Fixed value of *N*
2. Constant pore-pressure across the landslide (aquifer)
3. Rigid block assumption allows velocity and the Gruntfest parameter become linearly related.

Perform **ordinary kriging** of the 2019 no-snow period's average-velocity InSAR readings and create a high-fidelity ordinary kriging map over the scarp of the landslide (n=2000) .

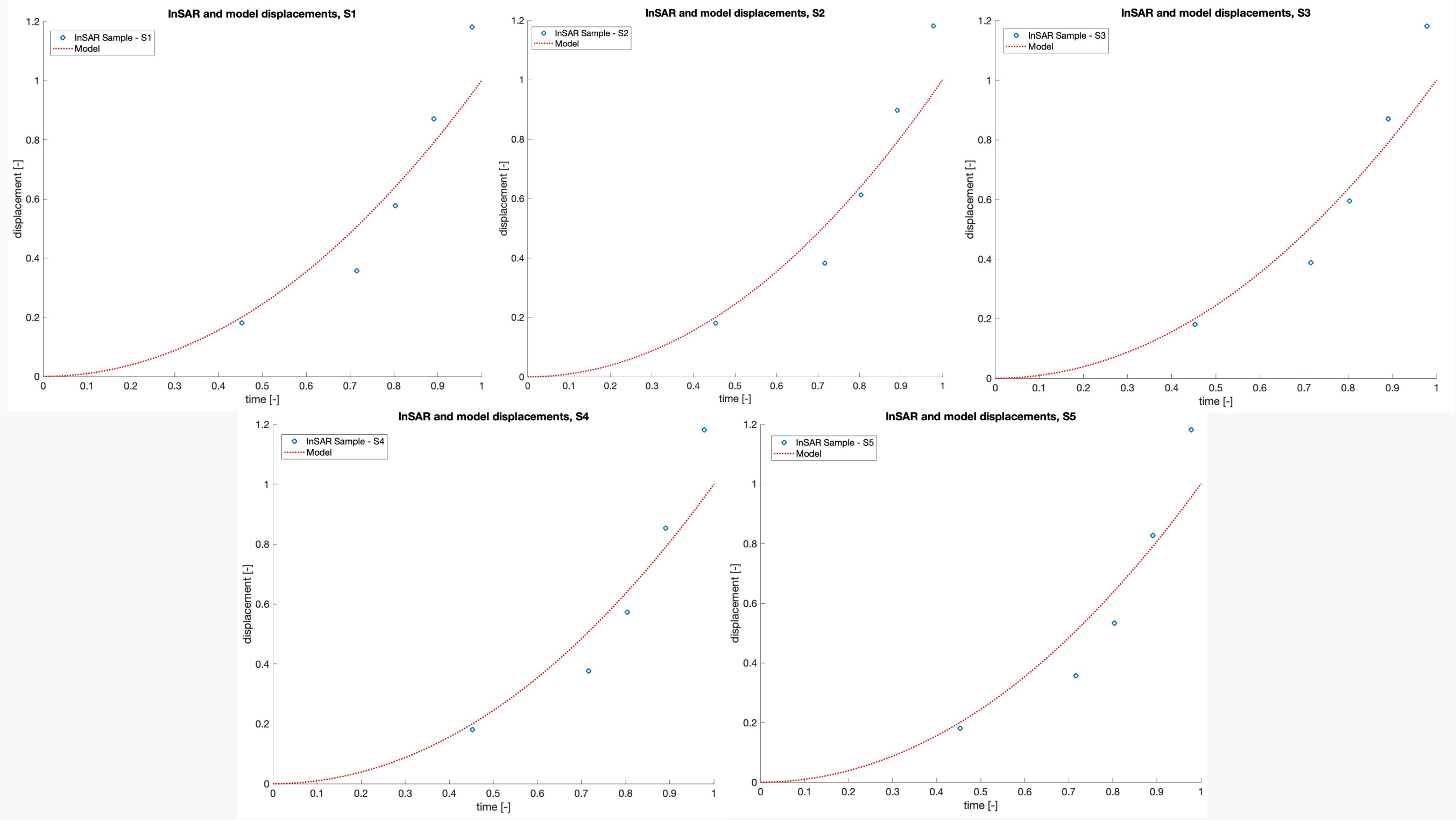


High-fidelity ordinary kriging output of the El Forn landslide average velocity (no-snow period, 2019).



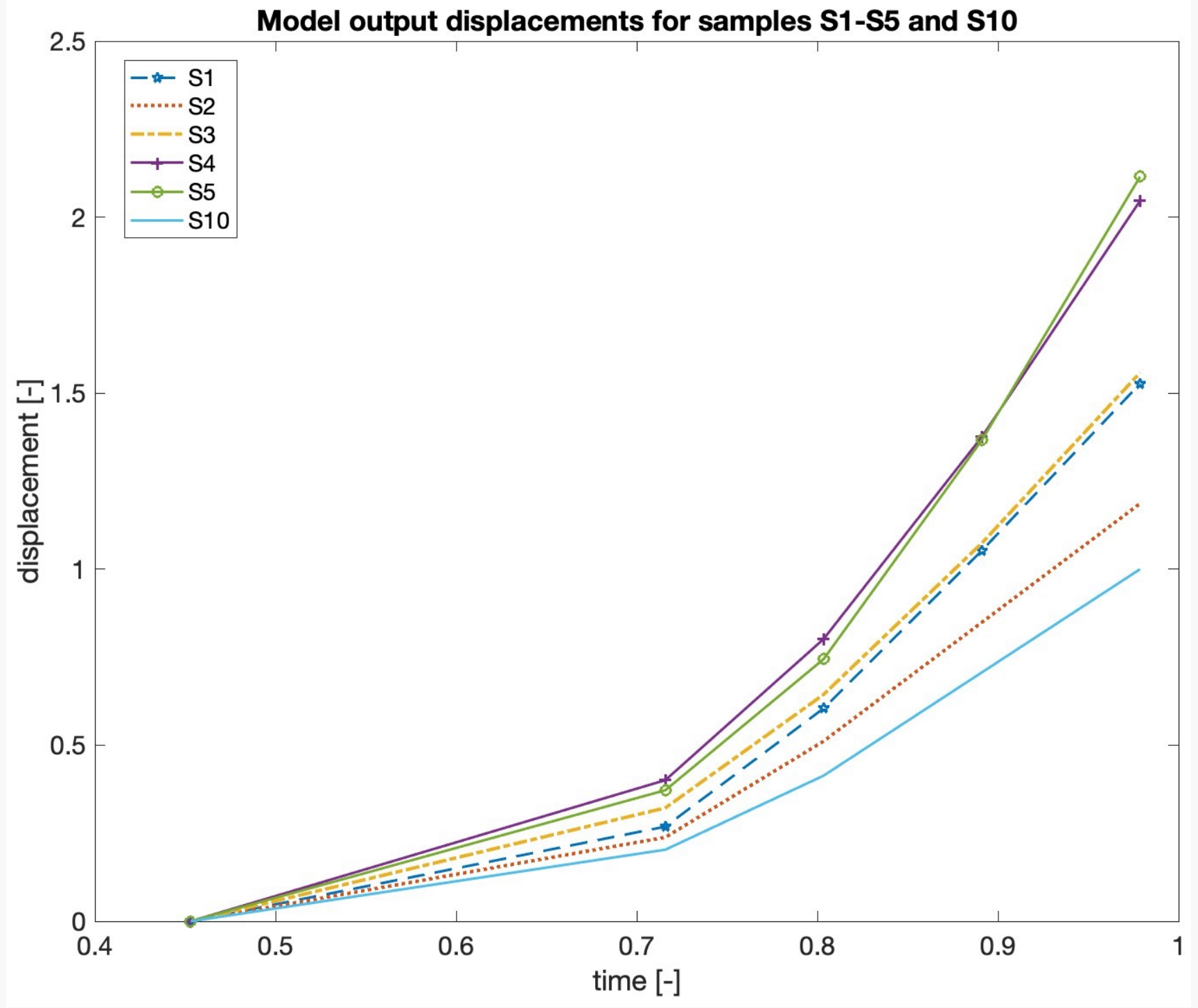
G$_0$ map normalized to S10 (assumed ground truth) built from ordinary kriging.

Individually compare the model-displacement of samples with InSAR displacements to see if InSAR fits each model displacement output at each sample point (S1-S5):



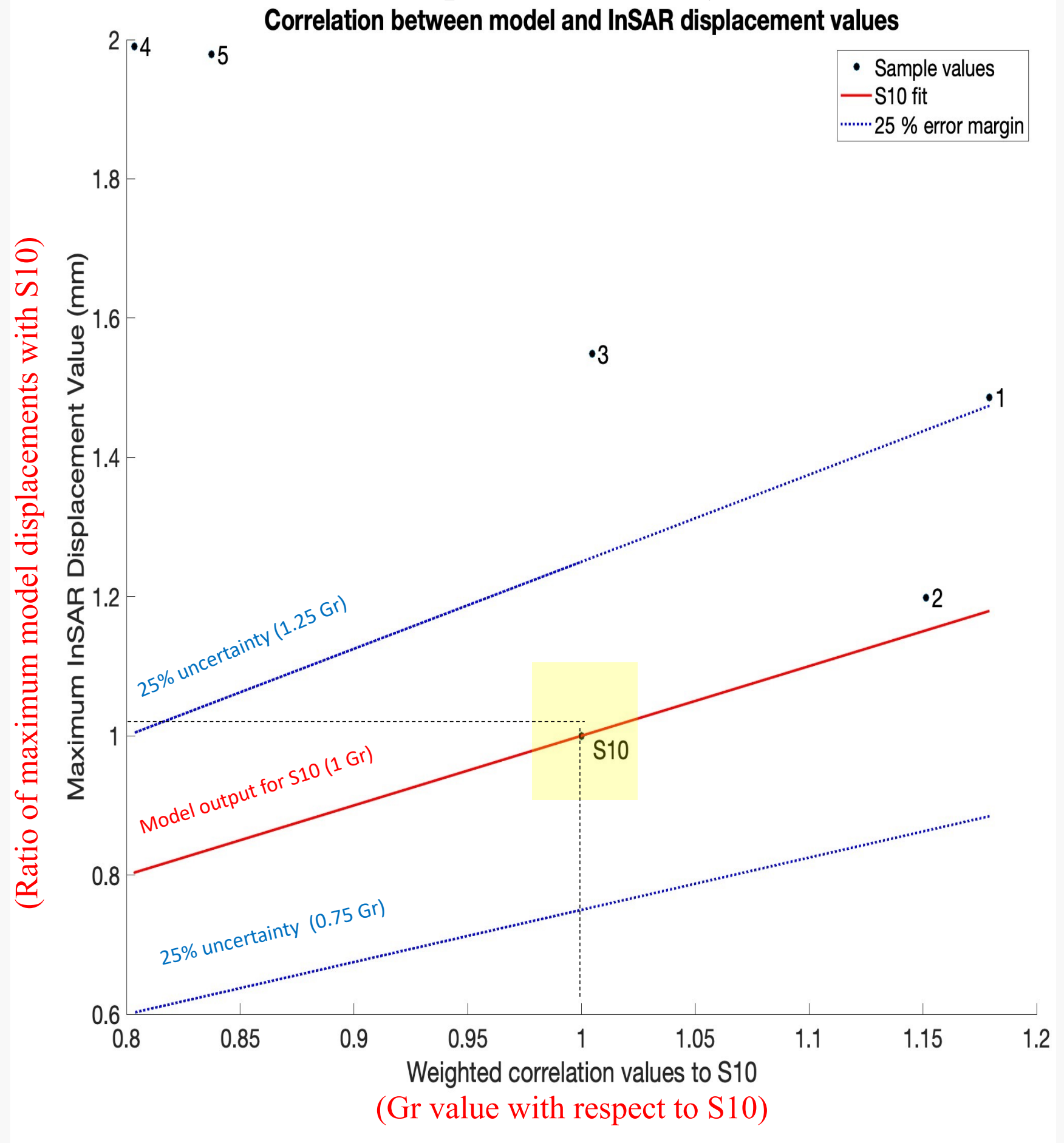
Comparison of model-insar displacement outputs for Samples S1-S5

Visualizing Spatial Uncertainty



Compare model displacement outputs for each simple with each other to understand spatial variability.

Samples S4 and S5 noted to move markedly faster than samples located closer to the toe of the landslide, including assumed ground-truth S10.

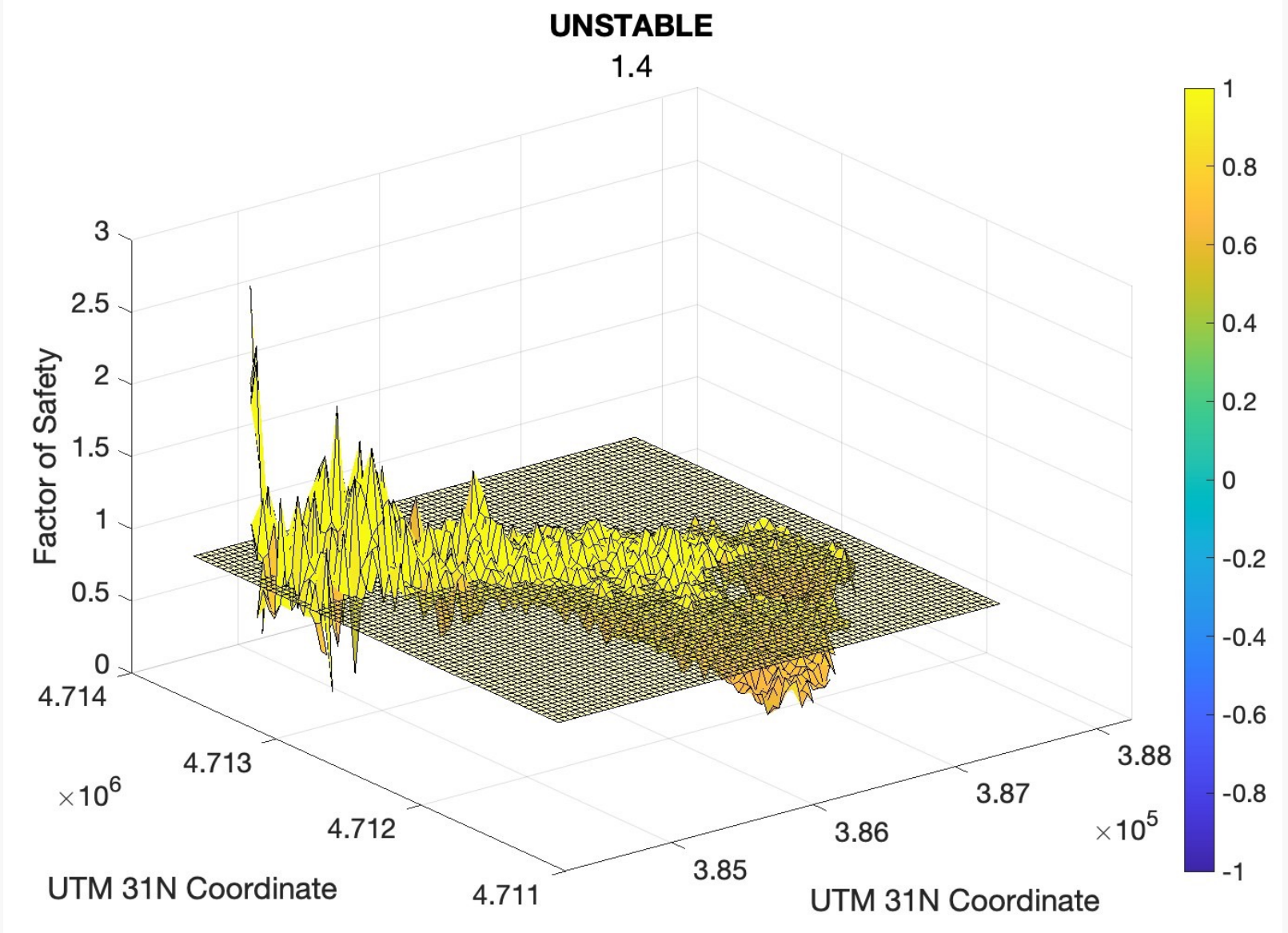


Visualizing an uncertainty envelope (25%) around, S10.

A 25% uncertainty envelope of ratio of model displacement of each sample with S10 as a function of the weighted correlation with respect to S10 **visualizes which parts of the landslide hold more uncertainty with this method.**

<u>Uncertainty in Gr across landslide can represent variation in loading (pore pressure, shear stress, etc.)</u>

Extension to a Physics-Based Hazard Map



Physics-based hazard map for scenario $p^* = 1.4$

$$p^* = \frac{p_f}{p_{f0}}$$

$$FS = \frac{Gr_{pixel}}{Gr_{crit}}$$

Lau, R. E., & Veveakis, M. (2024). A data-driven approach to physics-based risk models for deep-seated landslides. *Authorea Preprints*. https://doi.org/10.22541/AU.171156464.44816252/V1

Lau, R., Segui, C., Waterman, T., Chaney, N., & Veveakis, M. (2023). *InSAR-Informed In-Situ Monitoring for Deep-Seated Landslides*. https://arxiv.org/abs/2311.01564v2

<u>Additional References:</u>

Physics-based model: Seguí, C., & Veveakis, M. (2021). Continuous assessment of landslides by measuring their basal temperature. *Landslides*, *18*(12), 3953–3961. https://doi.org/10.1007/s10346-021-01762-x

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