

## Authors' responses to reviewers' comments on paper EGUSPHERE-2024-1227

*Reconstruction and forecasting of slow-moving landslide displacement using a Kalman Filter approach*

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We would like to provide hereby responses to all comments received from referees on our paper, emphasizing changes brought to the paper accordingly. Original comments are recalled between quotes in italics, and our answers are given in plain font. Indicated lines numbers refer to the revised version of the manuscript. A tracked-changes version is also provided.

### Reviewer #1

*"This paper introduces a Kalman Filter-based methodology for reconstructing and forecasting slow-moving landslide displacements, using a simplified viscoplastic sliding model optimized through both synthetic and real-world data. The approach is validated with data from the Super-Sauze landslide in the French Alps, demonstrating its practical applicability and highlighting its potential for enhancing landslide prediction systems. In general, the manuscript is of interest and attempts to forecast displacement patterns of slow-moving landslides over different temporal horizons. The paper is well written and structured. However, in this reviewer's opinion it suffers some issues that need to be addressed before being considered for publication in Natural Hazards and Earth System Sciences (NHES). Specific comments are following below."*

We would like to thank the reviewer for the positive comments about our paper. Regarding the issues that are raised, we propose the following answers:

*"1) The necessity & novelty of the manuscript should be presented and stressed in the "Introduction" section, despite seven paragraphs."*

Thank you for the remark, we are sorry if the necessity and novelty were not clear enough. The introduction has been modified to make these aspects more explicit: in short, they can be explained as a need for continuous improvement in tools towards landslide monitoring on the one hand, and a use of combined mechanical model with Kalman prediction tools on the other hand. More precisely, an appropriate observer-based reconstruction and forecasting scheme is exhibited, a novel tuning methodology is proposed, and an illustration with a set of real landslide data is provided. We now also highlight even more clearly that the main focus of the study being on demonstrating the applicability of the Kalman filter methodology to the case of landslides, the developments are purposely based on a simple mechanical model with a low number of parameters.

Corresponding changes appear on lines 61-73.

*"2) The discussion of previous studies on Kalman filter method in landslide prediction should be strengthened in the introduction or methodology section to clarify its advantages and applicable conditions."*

Thank you for this emphasis on Kalman filter, we took the opportunity of introduction update to include more comments on such a tool, both from a general point of view and for landslide applications: in short, the interest of Kalman results are basically their optimality features, and when used with a mechanical model, powerful prediction they can provide thanks to their feedback connection with real data. A difficult issue with such tools is the tuning, and in the present work we provide a novel algorithmic method towards an appropriate tuning. Regarding landslides,

there are not so many previous studies with a Kalman approach, and we added a couple of references in that regard.

Corresponding changes appear on lines 54-64.

*"3) The methodology is just tested on a series of 16-days real data measured in the Super-Sauze landslide, France. How do you think that it would be extended to a scope of "slow-moving landslides", as presented in the Manuscript title?"*

Thank you for pointing this important aspect. We have addressed it via some additional comments in the description of the chosen test case (section 4.1). In short, we are indeed dealing with a landslide characterized by slow motions (on average between 1 and 30 mm/day for Super-Sauze landslide), although we focus here on a period of acceleration induced by increased water pressure, for which our simple mechanical model is well suited. Dealing with periods when the landslide is almost not moving may reach the limitations of our model (for which no motion is assumed whenever the water pressure becomes too low), and would probably require enriching the rheological behaviour assumed for the material

Corresponding changes appear on lines 196-220.

*"4) The displacement forecasting in this work is based on surface or ground displacement, which often fails to reflect the actual landslide kinematics. So your method would be extended to forecast subsurface deformation, especially for displacement or strain around slip surface? The authors should add a section on this topic."*

Thank you for this interesting comment. A remark about it has been added in the conclusion. In short, our approach indeed focuses on surface displacement, because this is the configuration for which we do have data. In case information about subsurface behaviour can be available, our claim is that the approach we propose is highly versatile and could be used as well if an appropriate mechanical model is available.

Corresponding changes appear on lines 303-305.

## **Reviewer #2**

*"This paper proposes a Kalman filter-based method for estimating (and forecasting) landslide displacement. Unlike existing models that assume time-invariant parameters, the proposed approach updates model states through time, allowing prediction of displacement trajectories while accounting for temporal variability in factors governing slope stability. Although the method is demonstrated on a single case study, which limits generalizability, the approach appears promising for integration into landslide early-warning systems. I have identified several points requiring technical correction. Please refer to the specific comments below for detailed suggestions."*

Thank you for the positive comments, and for pointing a list of possible improvements in the presentation. We have carefully taken all of them into account as follows:

*"#1 P.1, l.18-19 (in-text citations): Please standardize the order of multiple references within a single parenthetical citation—either alphabetical (APA style) or chronological—and apply it consistently throughout the manuscript. The ordering currently varies across sections."*

All occurrences of multiple references have been standardized (following a chronological option).

"#2 P.2, l.51-52: Please revise to: "see Mishra et al. (2020a) for the iterative scheme (adjoint method), and Mishra et al. (2020b) for the continuous scheme (observer design)."

This has been corrected as suggested.

"#3 P.4, Figure 1: Include a concise legend explaining all symbols, even if described in the text. Also, provide source information (such as a URL) in the figure caption or in the reference list."

A list of symbols has been added, jointly with the URL of the used website source.

"#4 P.10, Figure 4: Clarify the datum for groundwater level (e.g., ground surface, block base, or a fixed benchmark). If the level is referenced to the base of the sliding block and the block thickness is 9 m, the vertical axis should not exceed 9 m."

The water table height is indeed referenced to the base of the sliding block (as shown in Fig.1), meaning that it remains below 9 m. This point is now explicitly mentioned in the caption. In addition, tick marks above 9 have been removed on the vertical axis of the figure.

"#5 P.10, Table 1: Do not italicize units, to avoid confusion between the symbol "m" and the unit "m" (meter)."

Italics have been removed (in Table 1, and all other occurrences).

"#6 P.11, l.201: The determinant of P0 is missing an equation number."

The equation number has been added.

"#7 P.12, Figure 5: If viscosity values are on the order of 108 Pa·s, consider expressing them as MPa·s for readability (e.g., 100 MPa·s)."

All figures with viscosity values have been re-edited with a scale in 100 MPa.s. Units in MPa.s have also been used throughout the text.

"#8 P.12, l.223: Remove the duplicated word "always."

This has been corrected.

"#9 P.16, l.275: Provide units for the viscosity (e.g.,  $1.1 \times 10^8$  Pa·s or 110 MPa·s)."

The unit has been added.

"#10 P.19, l.366: The citation for Pradhan et al. appears malformed. Please correct and include complete reference details."

The citation has been corrected.

## **Referee F. Ardizzone**

"The paper presents a methodology for reconstructing and forecasting slow-moving landslide displacements, as well as tracking the evolution of unknown parameters over time. The authors employ a Kalman Filter-based approach, integrating a simplified viscoplastic sliding model optimized using both synthetic and real-world data from the Super-Sauze landslide (French Alps). Their objective is to demonstrate the applicability of the method to a real case study and to highlight its potential for improving landslide prediction systems. The study builds upon the work

*presented in "Combined State and Parameter Estimation for a Landslide Model Using the Kalman Filter" (Mishra et al., 2021), yet it does not explicitly introduce further advancements. In my view, the paper requires several revisions before being considered for publication in Natural Hazards and Earth System Sciences (NHESS)."*

Thank you for the careful reading and the constructive comments. Our answers are as follows:

*"First, the introduction should provide a more focused review of the state of the art related to the specific topic, ensuring that the novelty of the proposed method is clearly emphasized in comparison to previous studies. This would allow the authors to better articulate the added value of their work."*

Sorry for the lack of clarity in the novelty, the introduction has been modified so as to remedy to this: in short the main contribution is a combined mechanical model with Kalman prediction tools. More precisely, an appropriate modelling is exhibited, a novel tuning methodology is proposed, and an illustration with a set of real landslide data is provided. More information about the interest of using Kalman tools, and our contribution is that specific area as compared to existing results has been included as well.

Corresponding changes appear on lines 52-77.

*"Furthermore, the method is applied to a mudflow, which does not fully align with the assumptions of the proposed model (Figure 1). I recommend explicitly addressing the limitations of the selected model in the context of this case study."*

Thank you for the remark. In fact, the Super-Sauze landslide is a slow-moving earthflow (average velocities between 1 and 30 mm/day for Super-Sauze) showing phases of accelerated motion (up to 400mm/day during spring season), rather than a mudflow. As also mentioned in our replies to the first Referee, the main focus of our study is on the Kalman filter methodology. As such, the study is based on a simple mechanical model that does indeed demonstrate strong limitations : block motion, halted motion during phases of low water pressure, etc.. These limitations are now more explicitly mentioned in the paper. We claim however that the proposed Kalman filter approach, including the specific calibration procedure, can be viewed as generic and may be coupled to more complex and realistic mechanical models in the future.

Corresponding changes appear on lines 196-209 and 312-315.

*"Lastly, I suggest extending the observation period of the landslide displacement data to enhance the robustness of the predictions."*

This remark about robustness is of course important, but we do feel that with the dataset we have considered, we cover quite a representative period where there is some displacement, with varying water table, and that extending the period would not bring much more information (except if going beyond our model validity). Besides, as mentioned in our replies to the first Referee, this 16-days dataset was chosen as it corresponds to a phase of landslide motion that our simple mechanical model can adequately represent.