Response to reviewer 2

I find the manuscript interesting, and the topic and experiments are relevant. Overall, I believe the manuscript would benefit from some clarifications and restructuring to enhance clarity and flow. Below are some suggestions for improvement:

- The manuscript presents two key novelties: (i) the coherence matrices method and (ii) the novel insights into the specific earthquake sequences that this method, along with the amplitude-based approach, helps uncover. However, while the introduction focuses more on the method (i), the conclusions emphasize the second (ii) novelty. Aligning these sections more closely could strengthen the manuscript.

  Following this comment and comments from reviewer 1, we have made the following change to the introduction to better outline the aims of the paper

  We also demonstrate that for some landslides, an InSAR coherence matrix approach can be used not only to constrain the timing of new landslides, but also to detect multi-stage failure such as reactivations (i.e. complete failure on one date followed by further failure within or connected to the landslide at a later date) and precursory motion (i.e. displacement on one date followed by complete failure of the same area at a later date).

  Changed to:

  We use the amplitude-based method of Burrows et al. (2022) to constrain the failure timing of new landslides. We also explore an approach based on interferometric SAR (InSAR) coherence matrices, a technique that has successfully been applied in landcover mapping (Giffard-Roisin et al. 2022; Jacob et al. 2020), but not yet tested for landslide timing. Here, we identify landslides where this method appears to identify multi-stage failure such as reactivations (i.e. complete failure on one date followed by further failure within or connected to the landslide at a later date) and precursory motion (i.e. displacement on one date followed by complete failure of the same area at a later date).

  In the conclusions, we have then made the following change to better highlight the novelty of the method as you suggest.

  "We have demonstrated that when a coherence matrix approach is used, we can detect not only single failures but also reactivations and thus build a more complete picture of landslide activity, although such methods cannot be applied to all landslides."

  Changed to *"We have assessed a new method for landslide timing detection based on InSAR coherence matrices. This approach, which is mainly applicable to larger events, can detect not only single failures but also reactivations and thus build a more complete picture of landslide activity."*

- The method could also be valuable in distinguishing landslides triggered by different rainfall peaks occurring close in time (e.g., Emilia Romagna in 2024). As you note, this introduces additional complexities, but it could be an interesting avenue for future research. The University of Bologna has open-sourced a highly accurate dataset for that event, which may be useful for further exploration.

  While this is true, we believe that more testing would be needed for the InSAR coherence matrix before it can be applied to rainfall events due to the sensitivity to changes in soil moisture detailed in Section 4.5.2.

New text at line 458 of the original manuscript *"Because of this sensitivity to soil moisture changes, further testing is needed before the InSAR coherence methods can be applied to rainfall triggered landslides. Landslides triggered by sequences of storms are also often poorly constrained in time, and while the amplitude-based methods can be applied in this case (as in Burrows et al. 2023), InSAR coherence could also be beneficial in study landslide reactivation and landslides in unvegetated areas."*

- The choice of thresholds for discarding landslides (<2000 m² for the amplitude approach with a 22x20 pixel size and <3600 m² for the coherence approach with a 60x66 pixel size) should be better justified. Additionally, it would be helpful to clarify why the amplitude-based approach includes landslides approximately five pixels in size, while the coherence-based approach includes landslides as small as a single pixel.

For the amplitude methods, it is necessary to have multiple pixels within the landslide polygon to calculate the metrics (e.g. pixel variability) used by Burrows et al. (2022). Therefore, the polygon needs to be larger than 22 x 20 m2. An analysis of the effect of landslide size on the sensitivity of the method was carried out in that paper.

Text changed at line 101 of the original manuscript from *"These metrics, particularly those relating to geometric shadows and bright spots, work best in forested areas and can be applied to medium-large landslides (> 2000 m2)."* to *"These metrics, particularly those relating to geometric shadows and bright spots work best in forested areas. The method is limited to landslides > 2000 m2 so that each polygon contains enough pixels to calculate metrics (e.g. pixel variability) and is more sensitive for larger landslides Burrows et al. (2022)."*

- If landslides below 2000 m² and 3600 m² are discarded because they are assumed to be too small for detectable changes, how does this impact the detection of reactivations? Are reactivations generally larger than these thresholds, or do you believe smaller reactivations can still be detected?

This is variable since a SAR pixel can be dominated by a single object and if that object moves, this could result in coherence loss. With the optical data we are using to verify the SAR methods, it is not possible to see how much of a landslide scar has reactivated, only whether or not the denuded area has increased in size. See our response to your next comment for the change we have made to the text.

- Regarding reactivations, do you primarily detect an increase in landslide area, or do you also observe failures within the existing scar?

Failures within an existing scar are not visible in the optical imagery, making it difficult to verify when we do and do not detect them. While we agree that this is an important thing to test, it would require data that we do not have for this event. In response to this and your previous comment, we have added the following sentence to Section 4.4 (Line 390 of the original manuscript):

"To confirm that these are indeed reactivations, comparison against a different dataset, such as field surveys, ground-based SAR or high resolution DEMs would be necessary, but this is beyond the scope of this study."

- How do you account for geometric distortions? For example, do you remove shadowed areas a priori, or do you rely on the assumption that using both orbits provides a high probability of capturing meaningful data?

  The code described in Burrows et al. (2022) automatically applies a shadow and layover mask to the data as part of the amplitude methods. We have not applied one to the coherence methods, but landslides that are affected by shadow and layover in one SAR orbit will be noisy and susceptible to geometric decorrelation. Therefore if they are assigned a timing based on coherence, it will be from the other orbit.

- Figure 2 is crucial but could be made clearer. A suggested improvement would be to plot coherence on the y-axis and real dates on the x-axis, with coherence values represented as horizontal lines extending from the date of the first image to the last. Not sure this would help, but it is worth a try.

  We tested the style of plot you suggest, but feel that the division into co-event, pre-event and post-event by minimising the residual is easier to understand if the coherence data are displayed as they are. In addition, plotting the coherence as a matrix is how it has been done in various other studies which use coherence for other applications (Jung and Yun, 2020; Giffard Roisin et al. 2022; Jacob et al. 2020 – full citations in manuscript) and we want to be consistent with this body of literature. However, we have improved Figure 2 by splitting it into two figures where panel (a) is now shown alongside coherence maps and panel (b) is shown alongside time series of multispectral imagery that show multi-stage failure

- The validation of this approach is thorough and well-executed. However, I have some questions regarding the terminology. In Section 2.4, you state that optical and SAR data can agree, disagree, or partially agree. Could you expand on what "partially agree" means? Additionally, framing it this way implies there is no ground truth. However, in cases where high-resolution optical imagery confirms a reactivation linked to a specific shaking event, wouldn't that be considered ground truth? Even a few well-validated cases could be sufficient to support the analysis and conclusions.

  By partially agree, we meant, for example, the case where we think the landslide failed on 05/08 and 19/08 based on the coherence, but from the optical, the landslide failed in 05/08 only. This would mean the two datasets partially agree (that the landslide failed during 05/08) but partially disagree (over whether or not the landslide failed on 19/08).

  To clarify this, we have changed the text at line, by adding the text in bold font at line 217 of the original manuscript:

  "Since both optical and SAR data can therefore yield multiple failure stages for a given landslide, a comparison between these two might agree, disagree or partially agree ***(i.e. in the case of multi-stage failure, agree for one detected failure timing, but not for another)"***

  To better support the analysis, we have divided the old figure 2 and, for the coherence matrix example showing the reactivation, we have added multi-spectral planet imagery showing the landslide failing during EQ2 and then growing in size during EQ4. There are thus two examples shown in the paper: this new figure and figure 5 of the original manuscript.

- It would be helpful to explicitly state that the conclusions are valid for landslides above a certain size threshold, as smaller failures may behave differently.

In response to this and comments from reviewer 1, we have added an analysis of how landslide size affects the sensitivity of the InSAR coherence to section 3.2 as follows

"Within the landslides examined, larger landslides were more likely to be assigned a timing by the InSAR coherence methods than smaller landslides. The inventory of Ferrario contained 87 landslides > 10000 m2, 38 in the range 8000-10000 m2, 75 in the range 6000-8000 and 171 in the range 3960-6000 m2 of which 70 (80%), 25 (66%), 46 (61%) and 86 (50%) were assigned a timing respectively."

- In the abstract, I recommend opening with the importance of attributing landslides to specific triggers to highlight the study's relevance.

  In response to this comment, new text has been added at line 2. *"This information is crucial for understanding their triggering conditions."*

- Line 11: "sequences of triggers" → "sequences of earthquakes." "sequences of triggers" has been changed to "earthquake sequences" in the revised manuscript**.**

- Section 2.2 could be removed, as it does not seem directly relevant to the study. Lines 75-84 have been removed from the revised manuscript

- Line 103: "somewhat simpler" → Consider rewording to "We modify the approach as we can assume landslides occur concurrently..." for clarity.

  Thank you for your suggestion

  "The case of earthquake-triggered landslides is somewhat simpler since we can assume that all landslides are concurrent with one of the earthquakes. Therefore, we slightly modify the method to make use of this information."

  Has been changed to *"Here we modify the method since we can assume that all landslides are concurrent with one of the earthquakes."* In the revised manuscript

- Line 465: Could you clarify what kind of precursory activity you are referring to?

  Yes we have rewritten this sentence to clarify our meaning

  "However, in at least one case, our SAR techniques identified precursory activity prior to complete failure." has been changed to

  "However, in at least one case, our SAR techniques identified precursory activity: small movements during one earthquake in an area that then failed during a later earthquake."