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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Quaternary lava tubes distribution in Jeju Island and their potential deformation risks" *by* Jungrack Kim et al.

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(Please use attached supplement rather than this comment form as the figures are not clearly demonstrated)

General Responses

We appreciate all reviewer's helpful comments to acknowledge our weakness especially regarding description of InSAR processing and consequent logical deployment. We concentrated to enhance involved contexts.

Those few need to be identified first.

1) Ascending mode time series observations of Sentinel-1 do not exist (refer attached

Fig. 1). Therefore, we can't apply combined interpretations of ascending & descending mode such as horizontal/vertical decompositions. Together with expected weak surface deformations by lava tube collapse, the absence of ascending mode time series data leads us to adopt a sort of data fusion for focusing the candidate of LTDPs among many PS observations, i.e., ML approach together with NSBAS as stated in 2). We identified absence of ascending mode in text.

2) Therefore, we needed to find a way to classify suspicious LTDPs among only descending PS observations. As all reviewers appointed out, the estimated deformation signals by PS analysis are weak and the ascending mode are absent. The employment of NSBAS was for searching aligned LTDP on specific background deformations; thus NSBAS was not used for LTDP detection directly but for the regional classification of LTDP. Spatial analysis and ML applications played the same role too. Therefore the data processing flow can be described as attached Fig. 2.

3) In the previous draft, we used only few InSAR pair for NSBAS analyses for the definition of regional deformation. Herein we took the reviewers advice and re-established new NSBAS networks in overlapped period with PS analysis (see attached Fig. 3 (a)). The extracted NSBAS deformation maps have improved 30 by 30 meters resolution. The observations in new NSBAS results are as bellows

- The results are quite different according to the NSBAS processing parameter settings (attached Fig. 3 (b), (c) and (g)). The more strict criteria (higher loop threshold and phase coherence) of error filtering, the more similar SBAS outcomes to PS (attached Fig. 3 (f)) in the deformation point distribution and patterns.

- We propose NSBAS results employed in this approach represents the regional deformations. For instance, the regional deformation in Seogwipo sediments induced by the loading of heavy construction were well defined in NSBAS results (ellipse part in attached Fig. 3). Thus it can be used to classify the candidate LTDPs. In the same manner, the LTDPs were bounded spatially over NSBAS regional deformations and interpreted accordingly as shown in Figure 8 (in draft). Application of ML algorithm can be more stably established in the pre-filtered candidates by NSBAS and spatial analysis mask. The concept of this approaches are now more clearly summarized in the modified figures and text in section 3.

4) All laser scanning tasks were completed in 2015 by a private company by the contact with the local government and delivered to the Korean Speleological Society for the academic studies. However, we found the laser data have those problems

- Missing of meta data

- Georeferencing accuracy was very poor; it doesn't fit to known ground landmarks

- Large number of height points have data faults

Originally we intended to use laser scanning data on road crossing points and to model brittle deformation with laser 3D point over there. Then we could make an inter-comparison between the modelled deformation and InSAR observations. However, due to the above problems, our laser applications were limited only for shape analysis to roughly estimate deformation as shown in L.550-555 and Figure 9 (in draft). We have searched original laser scanning file but failed to trace. Thus we only can introduce some detailed of laser scanning data in section 2.2 of revised draft. At this moment it is all we can do.

5) We propose to re-write the draft including above context –

1. Introduction

2. Test sites and data sets

2.1 Geological background (1) The section is fully rewritten as the first and second reviewers suggested to be involved precedent studies. (2) New figure (Figure 1 (c) in revised draft) is appended to demonstrate the places of target lave tubes and their photos. (3) Text is checked by a geologists who has background in lava geomorphology.

2.2 Data sets (1) More description of TSL and new NSBAS data sets.

3. Methods (1) Two data processing flow charts (overall and InSAR processing flow) are appended. (2) InSAR processing flow is shown with exemplary case and detailed background as the reviewer suggested.

4. Results

4.1 Spatial analysis of lava tube distribution

4.2 InSAR processing (1) All InSAR processing results is concentrated in this section. (2) NSBAS/PS comparison centered on Seogwipo is introduced.

5. Interpretation and discussion

6. Conclusion

All other proposed revisions considering the reviewer's comments are listed as below

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With interest is was reading the manuscript by Kim et al, submitted for publication in NHESS. The topic of lava bodies showing a post-emplacement deformation is debated amongst volcanologists since decades. Different ideas and hypothesis have been considered, such as loading effects, pore space reduction, viscoelastic and poroelastic subsidence and brittle deformation over cavities. A large number of observations worldwide, mainly from low viscous basaltic volcanoes, provides evidence for slow to spontaneous collapse into cavities and related hazards. The work by Kim et al. aims at adressing this topic at the Jeju Island, a unique place on earth where numerous lava tubes allow studying their post-emplacement deformation fields. The study uses mainly InSAR time series, but also some terrestrial laser scanning results to analyse deformation characteristics. While i agree that the topic of lava tubes and the potential of InSAR time series and the applied methods are well suited (and possibly correctly applied), i can not recommend publication of the work as is.

Answer: We appreciate the reviewer's helpful evaluation. We tried to address the reviewer's concerns as below.

(1) The language is awkward and make the text and many sentences hard to understand. If there were a limited number of language deficiencies, i would try correcting this (even though i am not a native speaker myself). But as almost every sentence has deficiencies and awkward and also improper wordings,i would suggest the authors let the language correct. The way it is now is simply unacceptable.

Answer: The rigorous language proofreading is being applied to that new draft.

(2) Improper terminologies are spread over the work. It even starts in the title, where "risks" is confused with "hazards", what is the difference between volcanic tubes and lava tubes, and so on.

Answer: We unified terminology, in which "risk" and "lava tube" are now prime use.

(3) logic organization missing. I recommend restructuring the work. First, the abstract shall provide a summary of the methods, work and findings. Presently the abstract focusses on InSAR, but does not even mention the TLS work carried out. The abstract highlights machine learning, which then is not even mentioned in the following introduction and data/methods sections. Please make sure the abstract is really a summary of the work provided.

Answer: The abstract was rewritten. TLS was auxiliary data in this study due to their data quality issues (please refer to (4) in the response to general comments). This part is mentioned in the introduction & abstract of new drafts as follows.

"... was up to few mm/year. The pattern and spatial distribution of detected deformations caused by potential lava tube fits to the geomorphological contexts and estimated surface migration analyzed from laser scanned lava tube shape. It was inferred to be caused by the instability of the shallow lava cavity..."

Introduction was also modified as the reviewer suggested to identify the use of ML.

(4) Clearly distinguish earlier data published by others, and own original results. For instance, geology maps (Fig. 1) are not referenced in the figure caption, similarly the distribution of lava tubes (fig. 3) is unclear where this data is coming from (i assume from literature? Maybe from Son et al. 2019?).

Answer: The source of data sets especially shown in Figure 1 (KIGAM, 2000, Son, 2019) and 3 are now identified (Son 2019; Hamm et al, 2005). And we check all text to clarify earlier data published by others and identify them.

(5) Please clarify why the PS was realized on a 2 year dataset and 75 images, whereas the SBAS on a 0.5 year dataset and 13 images only. I am not convinced by the statement in L 148.

Answer: Now SBAS network is extended to over 1 year period and 140 pairs were formed. Please see (3) in the general comments.

(6) In the chapter "results" i would expect to see results. Instead, authors start with a general introduction on the historical records and published tube maps and distribution, followed by a detailed methods section outlining the background of the PS and SBAS algorithms and so on. Despite the fact that this all should go to the methods section, it is hard to understand which Insar and PS processor have been used (Stamps?). But where are the results in the results section?

Answer: The imbedded method description is now move into new independent section (Section 3 Method). New section 3 described all data flow together with the details of employed InSAR processing (ordinary PS and NSBAS) and the introduction of algorithmic background. Please refer to (1) and (5) in the response to general comments. Section 4 now possessed only outcomes by InSAR and spatial analysis.

(7) Results figures are described very brief only. Fig. 4 shows the PS results over the entire island, but actually all velocities (in LOS i assume?) are below 1 mm/ year only. This is very low and i would expect a more critical assessment.

Answer: Figure 4 was now renewed to distinguish some strong deformations (see attached Fig. 3 (f)). In fact, the deformations of LTDP over road crossing points is not that small (please see Figure 7) which were used as training vector of ML. On the contrary, Jeju island has no known big deformation sources except Seogwipo city. In addition, please note that number of LTDPs from lava tube should be very small. Thus the overall very small deformation values in Figure 4 is as expected, and the robust of PS analysis was proved. Our major task is to choose small portion of potential LTDP among PS observations using ML and spatial analysis. In that manner, the major result to detect deformations by lava tube is not Figure 4 but Figure 8, which presents detected LTDP.

(8) I would suggest to first demonstrate the workflow on a smaller area before showing the entire island region. NSBAS results look different to the SBAS results, and for the reader it is very hard to understand relevance of the changes and colors seen.

Answer: NSBAS is an algorithmic extension of SBAS. We introduced NSBAS instead of SBAS to densify the observation of deformation and to confirm the regional deformation for scooping potential LTDPs. Therefore we claim NSBAS and PS observations have different natures and usages as we explained in the attached figures in response to general comments. This base will be also updated in the revised draft clearly.

In the last version, we used small number of InSAR pair for NSBAS processing; thus the deformation range were exaggerated. This was corrected in our new NSBAS outcomes.

Especially we would like to emphasize the NSBAS deformation pattern in Seogwipo city as shown in attached figure 3 of general comment. Seogwipo city is only sediment basin in Jeju and known as regional subsidence caused by heavy reconstruction. NSBAS results not only in 2017-2018 period of this study (attached Fig. 3 (b) (c) and (g)) but also 2020 period demonstrate (attached Fig. 3 (d) and (e)) strong subsidence. It proved the reliability of NSBAS processing and also highlight the characteristics of

NSBAS to detect regional deformations as we intended. PS are also showing many subsidence points in Seogwipo city as the whole area's deformation would induce the scatter's deformation behaviors. The other area's PS observations can't be large and potential LTDPs' signal are buried. Visual interpretation can't detect them appropriate and it's why we employed ML.

In Seogwipo sediment, we demonstrate processed outcomes as exemplary case by a step-by-step work flow as the reviewer suggested. Also we stated the base of Seogwipo city case in text in Section 4 together with quantitative analysis.

(9) All location names provided in the text must be shown in figures. For many of the sites and caves mentioned, i actually have no idea where to find it on the maps.

Answer: Figure 1 (c) is now appended to assign them.

(10) The exemplary analysis of the Manjang cave is very interesting. But this part of the analysis is only found in the discussion, not in the results. The TLS application and coverage is not even mentioned in the methods section.

Answer: The laser scanning of Manjang cave has never conducted due to the lack of local government's interest. Thus the rough sketch in Figure 9 is all we can find. We hope this draft's publication is a clue to persuade local government. Figure 1 (c) newly introduce to demonstrate all named places and TLS overages.

(11) Finally, a suggest the authors first to better structure their text and findings. Please provide an abstract that gives a good summary of all highlights. Provide an introduction that puts the approach and topic into larger context, and most importantly, review the available publications on collapsing and subsiding lava tubes elsewhere (on Hawaii, Iceland etc). Provide a data and methods section, where all data and methods are summarized. Provide a results section that is free from literature overview, referencing and speculation; results only, for both large scale and local scale studies, for InSAR, PS, SBAS, TLS and machine learning. Lastly, provide a critical discussion and study

risks (or better hazards).

Answer: Please see (5) in the general comment. Upon those structure, we appended proposed texts and information that the reviewer suggested. Other improvement in text according to reviewer's suggestions are as follows:

- In introduction we put references about Jeju and Hawaii's lava tube collapse (Orr et al. 2015; Olhoeft et al. 2000)

- Introduction to Data sets including TSL was now enhanced in section 2.2 Data Sets

- Method part in section. 3 are more enhanced flow chart and exemplary outputs in Seogipo sediment.

- InSAR results are now concentrated in Section 4 results

- ML analysis were re-allocated in interpretation & discussion with all risk assessments.

I hope these comments help improving the work. There is a lot to improve, but as i feel the very core of the manuscript is of potential interest for a broad readership, and as the methods used are on a high level, i am convident this might become a valuable publication. Major revisions required.

Answer: Thank you very much for your comments and encouragement.

Please also note the supplement to this comment:
https://nhess.copernicus.org/preprints/nhess-2020-321/nhess-2020-321-AC2-supplement.pdf

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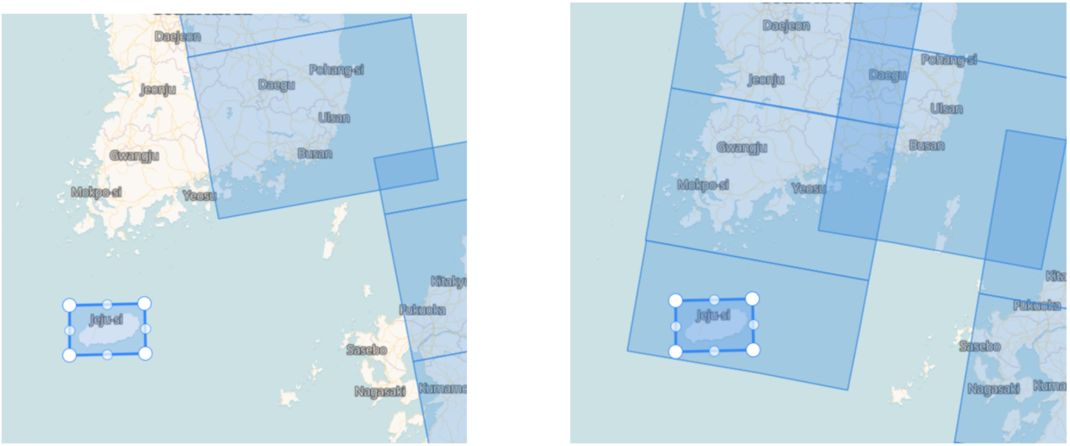


Ascending IW mode 2014-2021 Descending IW mode 2014-2021

Fig. 1.

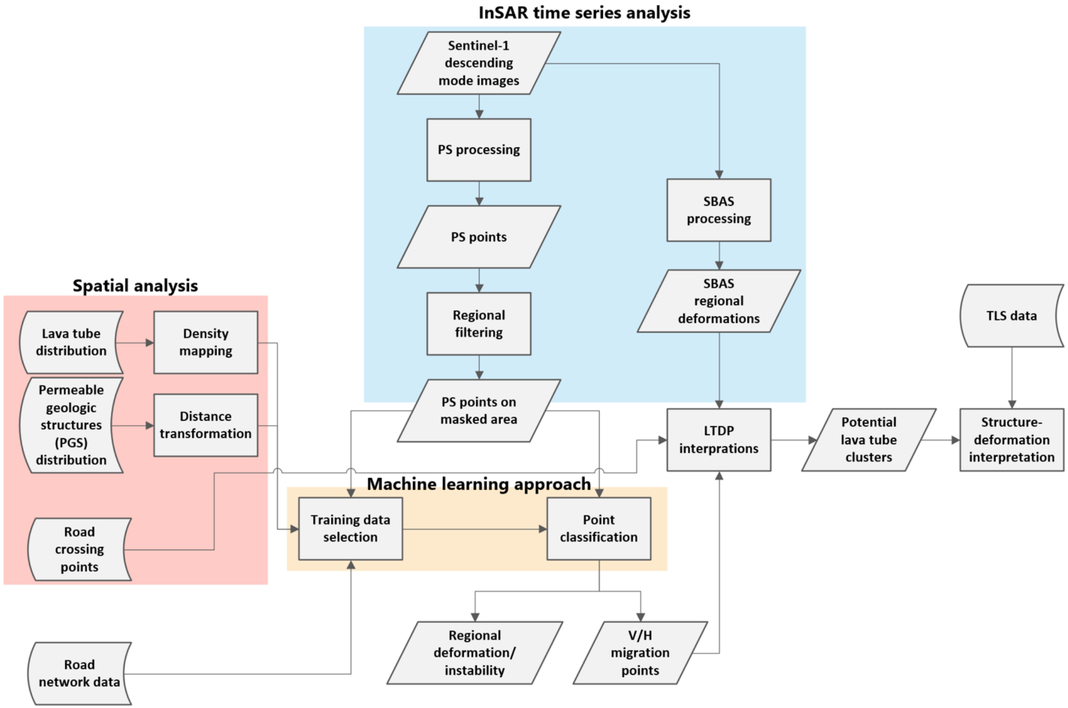
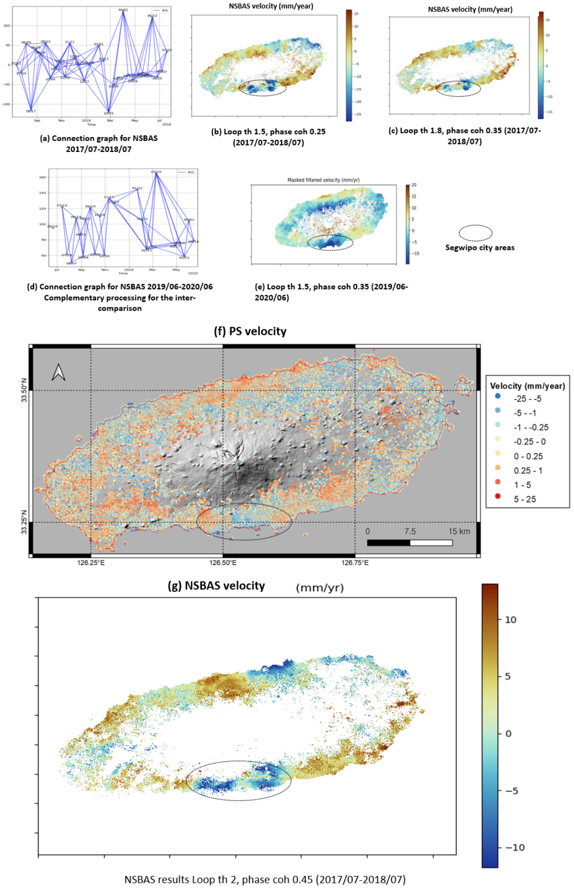

InSAR time series analysis
Sentinel-1 descending mode images
PS processing
PS points
Regional filtering
PS points on masked area
SBAS processing
SBAS regional deformations
Spatial analysis
Lava tube distribution
Density mapping
Permeable geologic structures (PGS) distribution
Distance transformation
Road crossing points
Machine learning approach
Training data selection
Point classification
Road network data
Regional deformation/ instability
V/H migration points
LTDP interprations
Potential lava tube clusters
TLS data
Structure-deformation interpretation

Fig. 2.



NSBAS velocity (mm/year)
(a) Connection graph for NSBAS 2017/07-2018/07
(b) Loop th 1.5, phase coh 0.25 (2017/07-2018/07)
(c) Loop th 1.8, phase coh 0.35 (2017/07-2018/07)
(d) Connection graph for NSBAS 2019/06-2020/06 Complementary processing for the inter-comparison
Masked filtered velocity (mm/yr)
(e) Loop th 1.5, phase coh 0.35 (2019/06-2020/06)
Segwipo city areas
(f) PS velocity
Velocity (mm/year)
-25 - -5
-5 - -1
-1 - -0.25
-0.25 - 0
0 - 0.25
0.25 - 1
1 - 5
5 - 25
0
7.5
15 km
33.50°N
33.25°N
126.25°E
126.50°E
126.75°E
(g) NSBAS velocity
(mm/yr)
10
5
0
−5
−10
NSBAS results Loop th 2, phase coh 0.45 (2017/07-2018/07)

Fig. 3.