Olivier Cavalié
Aix Marseille University, CEREGE
Technopôle de l'Arbois-Méditerranée
13545 Aix-en-Provence
cavalie@cerege.fr

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Dear Editor,

Quick note before to start the review. We submitted the 17th of October our article "28 years of coastal subsidence on the slow-moving Nice-Côte d'Azur airport area (France) revealed by InSAR: Insights into the deformation mechanism. It took more than three months (27th of January) before the article got assigned to two reviewers. In February, we got two positive reviews with minors comments. We replied thoroughly to the reviews. So we are a bit surprised that you decided to give a major review to the article.

However, your comments allow us to better explain the goals of the paper and why it is of great interest for the community (even if the study focuses on a specific location). We acknowledge that some recent references were missing on reclaimed land subsidence. So this new version of the manuscript is more complete.

This study includes some very new features. First of all, to our knowledge, it is the longest InSAR time series. Most study focuses on one satellite mission that covers less than 10 years. Only few study includes more than one satellite mission, and we didn't find any InSAR time series longer than 26 years (on Mexico city subsidence). Having a long times series does not only prove that we are able to integrate several disconnected data sets. We show in the study, that it allows to discriminate the type of deformation: In Cavalié et al. (2015), we used only 8 years of InSAR measurement on the NCA airport and couldn't detect the non-linear part of the deformation.

On top of having an extremely good quality and long InSAR time series. We believe that this article could encourage scientists to better integrate old spatial mission data in their analysis. Moreover, We modelled it with a mechanical process. To our knowledge, only mathematical model got used to characterize reclaimed land subsidence. We believe that using a physical approach makes much more sense and can interest the community.

We detailed below the changes we made according to the two reviews and your comments.

Yours sincerely,

O. Cavalié, F. Cappa, and B. Pinel-Puysségur

Reply to the editor's comments

(a) Introduction. You provide the reader background information to climate change and SLR as one part of future challenges in coastal area but your study is on subsidence in coastal areas. The background information and state-of-the art review of this part is very limited. Thus, I recommend to change the focus of the introduction to the topic of your manuscript on subsidence at coastal areas, monitoring of subsidence and the challenge of understanding and modelling these processes.

Thank you for the comment. We think that it is important to remind that the process of coastal subsidence happens in a context of climatic change and sea level rise. But we agree, that the manuscript is about coastal subsidence. So after a brief paragraph recalling the global context of SLR, we focused the introduction of coastal subsidence and why it is important to document it.

(b) Furthermore, please make clearer your objectives and research questions for this study at the end of the introductions. Therefore, I recommend also to clearly addressed the research gaps in the text above. Additionally, I suggest to provide a short overview as last paragraph which issue you will address in which of the following sections.

We further explained the objectives of the study from lines 69, namely understanding the physical mechanism of the coastal subsidence: "During the 2003-2011 period, InSAR data show essentially a steady subsidence. Here, we extended the time series in order to observe the behaviour of the airport platform over a longer period (1992-2020). To our knowledge, it is the longest time series on InSAR derived subsidence measurements, even longer than the 24 years of Mexico subsidence measurements by InSAR. This provides an opportunity to investigate new mechanisms driving vertical land motion in coastal areas. Actually, no physical process could explain a constant subsidence rate over several years. We thus processed the data from the ERS satellites between 1992 and 2001 and the data acquired by Sentinel-1 for the period 2014 - 2020. Then we discussed and modelled the information brought by these new data sets. In particular, we investigated if a model of creep compaction of the airport platform can explain the data. Unlike precedent studies, this model is not a simple mathematical function fit but it also includes a geomechanical framework for slow creep and the estimate of physical parameters of the slope materials. "

Finally, as suggested, we ended the introduction with giving an overview of the paper.

(c) Please make the overall scientific added value of your study clearer throughout the manuscript. What is the novel part? This needs to be done both at the beginning so we understand, but also in discussion, telling us 'why should someone outside of your study area be interested in the results'. If you were to explain the results of your case study to someone in another country, what would they gain from your case study?

We think 2 aspects make our work valuable and innovative.

- Not only, we present the longest (to our knowledge) InSAR time series of a deformation, but the InSAR data are very clean and contain very little noise. Many studies, especially about coastal subsidence, show noisy InSAR results and don't give any noise estimate on the data.

- In this article, we compare InSAR displacement data with physic-based models. This is also a novelty, as many articles about coastal subsidence do not try to model the deformation or use only mathematical model. We added a sentence in the introduction "Unlike precedent studies, this model is not a simple mathematical function fit but it also includes a geomechanical framework for slow creep and the estimate of physical parameters of the slope materials".

Coastal subsidence is an issue that we find all around the world (as it is shown in Wu et al. (2022)), especially in south-east asia. Subsidence of reclaimed land is particularly problematic as it hosts (most often) critical infrastructures. Understanding the physical mechanism that drives those subsidences is thus of great interest.

(d) I also want to stress one of the comments by reviewer 2 about the structure of the manuscript. In the current version there is not a separation between methods, results and discussion. This would be an added value for the readers, thus I suggest to consider to follow a clear structure (methods, results, discussion) for the monitoring part and the modelling part.

We took into account your recommendation and reshaped the structure of the manuscript, in adding sub-sections. We have now a section 3 entitled "InSAR measurement of the NCA subsidence" divided into 3 subsections "Data and Method", "Surface displacements observed from 1992 to 2020",and "Noise Analysis and Discussion". The section "Creep Modelling" is shorter and straight forward. Adding subsection wouldn't improve the clarity of the message (in our opinion). And we end the article with a conclusion.

Reply to the reviewer #1

1. *My main suggestion is to insert a geological section, even simplified, of the area under study so that you can better confirm your hypotheses about the processes in place.*

Effectively, we didn't discuss the geology in this paper as we did it for the first paper (Cavalié et al., 2015). But, we agree that it would be good to add few elements and to refer specifically to the figures of the previous paper to backup the hypothesis of subsidence compaction. We added this section in the introduction :

Cavalié et al. (2015) published a first study showing that between 2003 and 2011 (the acquisition period of Envisat) **the Var delta as well as the airport that is located at its mouth, is subsiding. The spatial extent of this subsidence is strictly limited to the quaternary alluvium deposits of the delta and Var riverbed (Figure 4 in Cavalié et al. (2015)) Actually, on both sides of the riverbed, the subsidence rate quickly drops to zero where the transition from alluvium to conglomerate**

occurs. Moreover, the downward displacement rate increases toward the sea as the sediment layers get thicker and more recent (Figure 6 in Cavalié et al. (2015)). Indeed, it ranges from less than 1 mm/yr in the Var valley to a maximum rate of 10 mm/yr on the airport platform where sediments got brought in the 1970s to built the runways.

2. *I would also suggest that you include some references to the theoretical bases concerning creep phenomena (consolidation processes?) in clayey soils, appropriately accompanied by bibliographical references.*

Soils and rocks can exhibit creep behavior, which is the development of time-dependent strains at a state of constant effective stress (Bland, 1960; Findley et al., 1976; Jaeger and Cook, 1979). Creep behavior influences the long-term stability of grounds and movement of slopes. This time-dependent material behavior exhibits viscoelastic or viscoplastic characteristics that can be reproduced with different creep models of increasing complexity depending on the type of material and loading conditions (Jaeger and Cook, 1979). Several constitutive laws have been introduced in the past to study creep and this still is an active field of research in the rock physics labs and geophysical field studies.

Creep is the tendency of solid material to deform permanently under certain load that depend on time and temperature. Typical creep process has three phases which are primary creep (creep rate decreasing over time), secondary creep (constant creep rate) and tertiary creep (increasing creep rate until failure) as shown in Fig. 5a.

In this work, tertiary creep is not modelled. We used the Burgers model, composed of a Kelvin model and a Maxwell model (Jiand and Wang, 2022), which is well adapted to accurately describe the characteristics of the primary and secondary creep stages (Jaeger and Cook, 1979), a behavior representative of the surface displacement measured by InSAR on the airport platform. A number of research works have previously demonstrated that this creep model was successfully used to model deformation of soils and surface displacement of landslides (You et al., 2013; Liao et al., 2022)

Bellow are the new references that we added in the manuscript :

- Bland, D. R., The Theory of Linear Viscoelasticity, New York: Pergamon Press, 1960.
- Findley, W. N., J. S. Lai, and K. Onaran, Creep and Relaxation of Nonlinear Viscoelastic Materials, New York: North-Holland Publishing Company, 1976.
- Jiang Z., Wang H., 2022, Study on Shear Creep Characteristics and Creep Model of Soil-Rock Mixture Considering the Influence of Water Content, Front. Phys., 21 June 2022, Sec. Interdisciplinary Physics Volume 10 - 2022, https://doi.org/10.3389/fphy.2022.819709
- Liao, M., Cui, D.; Bao, X., Qiao, Z., Zhao, C. Creep Characteristics of Soil in the Sliding Zone of Huangtupo Landslide. Appl. Sci. 2022, 12, 12439. https://doi.org/10.3390/app122312439

3. *Title and other comments*

We agree that starting with 28 years is not the best way for a title. As the duration of the subsidence is important, we change for :

”Three decades of coastal subsidence on the slow-moving Nice-Côte d’Azur airport area (France) revealed by InSAR : Insights into the deformation mechanism”

We also modified the manuscript according for your comments.

- L25: done
- L44: There are actually 2 brackets and global isostatic adjustment and tectonics are included in natural phenomena
- L48: We added a recent reference
- L63: The comment focused only on the constant rate and not on the nature of the phenomena

Reply to the reviewer #2

1. *About the structure of the manuscript. The authors follow a structure of InSAR method – InSAR measurements – uncertainty – creep modeling, with methods, results, and discussion together. If possible, I suggest reorganizing them into Methods, Results, and Discussion*

We followed the recommendation of the editor and gathered all the InSAR parts under one section that we subdivided into Data and Method, results, and discussion (about the noise in the data, notably).

It seems important to us to separate the observations from the modelling. Actually, InSAR measurements are ”facts” and show clearly the ongoing subsidence of the airport platform at least since 1992 (date of the first ERS SAR images) and probably since the late 1970s when the platform was built. The noise analysis allows also to understand the accuracy of the measurements. The modelling part is thus fed by the robust InSAR measurements and it seems logical to introduce InSAR and Modelling one by one.

Understanding the deformation is more complex because it requires a detailed knowledge of the platform underground. Such work has been done in few papers cited in the article, but it can’t give the full picture. Moreover, models are always a simplified view of reality, although modelling is the only way to have an idea about how the airport deformation will develop. Thus, it was important to add a modelling section (that we didn't do in Cavalié et al. (2015)). But, we think it's important to keep separate from the observations.

Finally, our discussion/conclusion brings face to face observations and modelling to elaborate some recommendations about how to handle this particular situation where a critical infrastructure might be at risk.

2. *The authors used the Heaviside step functions for reconstructing the time series. Why this function was chosen? Are there some other functions that can also be applied in this situation? Some information/discussion can be added.*

InSAR measurements have been computed from three independant datasets (corresponding to 3 different satellites generations : ERS, Envisat and Sentinel-1) with no overlapping periods. So direct measurements cannot give the offsets from one time series to the following one (red dots on the figure 3d of the paper). To simulate the 2 "artificial" offsets (between ERS and Envisat, and between Envisat and Sentinel-1), the Heaviside step is the most natural way (and standard way) to do. But it is only to simulate the offset due to the lack of overlap between time series. Otherwise, we assume a logarithmic evolution of the subsidence.

3. *Similar to the above comment, why viscoelastic Burger's model was used? Are there some other models appropriate to this study area? Some information/discussion can be added.*

See the response to a similar question of the reviewer 1:

Soils and rocks can exhibit creep behavior, which is the development of time-dependent strains at a state of constant effective stress (Bland, 1960; Findley et al., 1976; Jaeger and Cook, 1979). Creep behavior influences the long-term stability of grounds and movement of slopes. This time-dependent material behavior exhibits viscoelastic or viscoplastic characteristics that can be reproduced with different creep models of increasing complexity depending on the type of material and loading conditions (Jaeger and Cook, 1979). Several constitutive laws have been introduced in the past to study creep and this still is an active field of research in the rock physics labs and geophysical field studies.

Creep is the tendency of solid material to deform permanently under certain load that depend on time and temperature. Typical creep process has three phases which are primary creep (creep rate decreasing over time), secondary creep (constant creep rate) and tertiary creep (increasing creep rate until failure) as shown in Fig. 5a.

In this work, tertiary creep is not modelled. We used the Burgers model, composed of a Kelvin model and a Maxwell model (Jiand and Wang, 2022), which is well adapted to accurately describe the characteristics of the primary and secondary creep stages (Jaeger and Cook, 1979), a behavior representative of the surface displacement measured by InSAR on the airport platform. A number of research works have previously demonstrated that this creep model was successfully used to model deformation of soils and surface displacement of landslides (You et al., 2013; Liao et al., 2022)

3. We also modified the manuscript according to your comments.

- L2: done
- L5: ok
- L7 : ok
- L12 : we changed the sentence.
- L18 : done
- L23: done
- L34: done
- L49: we replaced "Indeed" by "And"
- L56: done
- L57-58: we agree that it sounds strange and we removed this sentence
- Line 76: Yes you did understand it properly. The mass was dropped from the top of a crane. I doubled check the reference and it turns out that it is 23 m and not 22 m... I corrected the number in the manuscript.
- L84: We changed "Since" for "Since then"
- Caption Figure 2: we change the sentence by adding "image pairs processed into"
- L108-109: Resolution in raw SAR images are different for range and azimuth axis and also depend on the satellite. For ERS and Envisat, SAR images have a better resolution in azimuth (by a factor 5) compared to range. On the contrary, Sentinel SAR images have a better resolution in range (by a factor 4) compared to azimuth. So, if we want a ∼square ground pixel, we need to add extra multilooking in the better resolved direction.

- L119: ok

- L145: Spatially, pixels can be affected by different sources of noise. One type is due to the distribution of scatterers inside a resolution cell (or pixel) and of their temporal evolutions. In this case, the noise is really pixel dependent. For example, if vegetation grows between the 2 SAR acquisitions or if the ground get eroded, the pixel coherence will decrease and the measurement will be more noisy. On the contrary, pixels on urbanized areas usually show a low noise level as the scatterers (roads, buildings) inside a pixel do not change between the acquisitions. Therefore, it would not make sense to study the noise level of the interferograms in the hills nearby the airport as vegetation and erosion are two factors that will increase the noise content of those pixels compared to the pixels located on the airport platform. Moreover, wave delays in the atmosphere are also heterogeneous and thus impact pixels differently. Studying the noise of the area of interest is thus better if it is possible.

- L160-161: we agree and completed the paragraph

- L190: This is the uncertainty we estimated previously (Figure 4).

References

Cavalié, O., Sladen, A., and Kelner, M.: Detailed quantification of delta subsidence, compaction and interaction with man-made structures : the case of the NCA airport, France, Nat. Hazards Earth Syst. Sci., 15, 1–12, https://doi.org/10.5194/nhess- 15-1-2015, 2015.

Wu, P.-C., Wei, M., and D'Hondt, S.: Subsidence in Coastal Cities Throughout the World Observed by InSAR, Geophysical Research Letters, 49, https://doi.org/10.1029/2022GL098477, 2022.