# **28 years Three decades** of coastal subsidence **evolution** on the slow-moving Nice-Côte d'Azur airport area (France) revealed by InSAR : Insights into the deformation mechanism

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**Abstract.** Coastal areas can be tremendously biodiverse and host as well a substantial part of the world population and many critical infrastructures. However, there are often fragile environments and that face various hazards as such as flooding, coast erosion, land salinization or pollution, earthquake-induced land motions, or anthropogenic processes. In this article, we investigate the stability of the Nice-Côte d'Azur airport that has been built on reclaimed land in the Var river delta (French Riviera,

- 5 France). This infrastructure is has been a permanent concern since the partial collapse of the platform in 1979 and the on-going subsidence of the airport runways. Here, we used the full archive of ESA SAR images from 1992 to 2020 to comprehensively monitor the dynamics of the airport subsidence. We find found that maximum downward motion rate is slowing down from 16 mm/yr in the 1990s to 8 mm/yr today. However, sediment compaction is still active and an acceleration phase of the continuous creep leading to a potential failure of a part of the platform cannot be excluded. Our study demonstrates the importance of
- 10 remotely monitoring of the platform to better understand coastal land motions, which will ultimately help evaluate and reduce associated hazards.

## 1 Introduction

Global warming due to greenhouse gas emitted into the atmosphere is triggering a climate crisis<del>whose we can already see immediate signs, the impacts of which can already be felt in current times</del> with more frequent extreme weather events

- 15 such as flooding, heatwaves or wildfires. Another consequence due to this of the global warming is the rise of the sea level, and the impact on the stability of coastal urban areas where a substantial part of the world's population lives. Actually, as the Earth's atmosphere get warmer, solid water (glaciers and ice sheets) melts and increases the quantity of sea water, that also occupies more volume because of thermal expansion (Wigley and Raper, 1987; Frederikse et al., 2020). Those two combined processes are inducing sea level rise (SLR) whose amplitude will depend on which Representative Concentration Pathway
- 20 (RCP) emission scenario is followed. SLR is thus estimated for 2100-the year 2100 between 0.29 m and 0.59 m for a low emission scenario (RCP 2.6) or between 0.6 m and 1.1 m for a high emission scenario (RCP 8.5) (Oppenheimer et al., 2019). Even if the mean Earth temperature increase is kept below 2°C (compared to the pre-industrial period) within the next decades,

sea level will continue to rise for several centuries or more due to the system inertia (Schaeffer et al., 2012). This estimation is worrying as UN reports that 40% of the world population live within 100 km from the coast (whose-more than 600 million

people live in coastal areas that are less than 10 meters above sea level) and 8 of the 10 world's largest cities are near a coast.

- Even if the mean Earth temperature increase is kept below 2°C (compared to the pre-industrial period) within the next decades, sea level will continue to rise for several centuries or more due to the system inertia (Schaeffer et al., 2012). It is thus important to think how cities can adapt to this long-term process as SLR has already destructive consequences. One solution is to build sea barriers. Few of them have been already built around the world to contain, locally, sudden sea water rise that occurs
- 30 during extreme weather events as storms or high tides. Among the dozen of projects to impede the sea water to flood inland, we can mention one of the biggest barrier built in Venice (Italy) (Mooyaart et al., 2014). Venice is flooded regularly when high tides (acqua alta) hit the city. To protect the rich cultural heritage from the floods, a titanic project (Mose) has been implemented. It took advantage that Venice is built behind a lagoon with only four, relatively narrow (~ 400 m) openings to the Adriatic sea. A system with movable panels (flap gates) was set up to rise when high tides occur (Fice and Scotti, 1990; Mooyaart et al., 2014).
- 35 The project took 18 years and 6 billion dollars (plus about 100 million \$ per year for maintenance) (Kolbus, 2019). Sea barriers at larger scale don't exist yet. A famous project is the New-York Harbor storm surge barrier. But many arguments against make it very hypothetical. Among them, we can list the cost of the project, the duration (few decades), the "insiders/outsiders" dynamic, with only those behind the barriers receiving maximum protection, or the fact that the barrier could damage the zones outside its protection. But maybe the most relevant argument is just as for the Mose barrier, it won't protect the city from the
- 40 long trend sea level rise.

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However, sea rise is just one factor in the relative sea level changes and vertical ground motions can significantly amplify or reduce the effect of the global SLR. Indeed, sinking ground along the shoreline greatly magnifies the effects of sea level rise because both processes work together to worsen the situation (Milliman and Haq, 1996; Wöppelmann and Marcos, 2016; Wu et al., 2022). Indeed, uplift or subsidence along the coast are generated either by natural phenomena (sediment compaction

- 45 (Cahoon et al., 1995), global isostatic adjustment (Farrell and Clark, 1976; Kendall et al., 2005; Peltier, 2004), or tectonics (Atwater, 1987)) or by human activities (ground water (Galloway and Burbey, 2011) or hydrocarbon extraction (Métois et al., 2020), or land reclamation (Cavalié et al., 2015)). This last one becomes more and more frequent due to population growth in coastal areas. Subsidence due to human activities are often very localized and difficult to model. They are thus often not very well known and the underlying processes remain unclear. One of the most effective method to reveal them is to measure the
- 50 Earth surface displacements by InSAR (Bürgmann et al., 2000)(Bürgmann et al., 2000; Cavalié and Trouvé, 2022). Actually, the spatial sampling of the radar allows to map finely the location and the amplitude of these surface deformations. Indeed, And the more InSAR studies, the more coastal subsidence are revealed (Wu et al., 2022).

In the last few years, several studies on deformation measurements by InSAR over reclaimed lands have been published, showing the raising attention of the community for this subject. For example, Xiong et al. (2022) and Li et al. (2022) used

55 Sentinel-1 data, covering five years, to observe subsidence over several reclaimed lands in China. Other studies processed several datasets from different sensors in order to cover a longer observation period. However, due to the lifespan of the different SAR sensors, these datasets do not overlap in time and have temporal gaps. For example, the subsidence of Urayasu city (Japan) has been measured thanks to ERS-1/2 (1993-2006), ALOS (2006-2010) and ALOS-2 (2014-2017) InSAR time series (Aimaiti et al., 2018), leading to a gap between 2010 and 2014. In this case, the temporal profile of

- 60 the deformation was too irregular to enable any modelling that could connect the measurements across the temporal gap. However, in two other studies, the temporal profile of deformation was regular enough to be modelled and thus to recover a deformation spanning the whole observation timelapse: on the one hand, Park and Hong used a hyperbolic model to connect two InSAR time series measured by ALOS (2007-2012) and Sentinel-1 (2014-2019) on Busan reclaimed lands (South Korea); on the other hand, a settlement model (Plant et al., 1998) established during the preparation
- 65 of Hong Kong International Airport was used to connect time series acquired over this site by ERS-2 (1998-2000), ENVISAT ASAR (2003-2010), Cosmo-SkyMed (2013-2017) and Sentinel-1 (2015-2018) (Wu et al., 2020). Several models for subsidence measurements are compared in (Xiong et al., 2022), namely hyperbolic, Poisson and exponential models. However, in the precited studies, the deformation modelling is limited to a mathematical function fit without a theoretical mechanical framework and real physical parameters for soils and rocks.
- In this study, we process 28 years of SAR data to obtain high-quality surface deformation time series covering the Nice Côte d'Azur airport (NCA), located in the French Riviera (southeastern France) (Figure 1a). This critical economical infrastructure (it hosted 14.485 million passengers in 2019 before the pandemic) was built in the late seventies on reclaim lands over a narrow coastal shelf (1-2 km wide). Tragically, in October 1979, during the building phase, part of the airport extension collapsed in the sea, triggering a local tsunami that caused the death of 11 people (Figure 1b). Then, part of the project was cancelled (mainly
- 75 the construction of a commercial port attached to the airport) but the airport platform, which had already been completed, was used to build the two main runways that are currently in use (Figure 1e). For hazards, it is important to measure the long term deformation of this area.

Cavalié et al. (2015) published a first study showing that between 2003 and 2011 (the acquisition period of Envisat) part of the edges of the airport was subsiding at a maximum rate of 10 mm/yr. During this the Var delta as well as the airport

- 80 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
- 85 airport platform where sediments got brought in the 1970s to built the runways.

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 (Chaussard et al.). This provides an opportunity to investigate new mechanisms driving vertical land motion in

90 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

- 95 the slope materials. Through our investigations, we measured a deceleration of the maximum subsidence rates of the platform from 16 mm/yr (1992-2001), then 9.5 mm/yr (2003-2011) to 8 mm/yr (2014-2020) over the study area. The uncertainty on subsidence rates has been carefully estimated by two different methods, both leading to estimates of about 0.3 mm/yr for the three periods, more than an order of magnitude below the measured rates. We find that the non-linear surface displacement can be explained by a transient creep mechanism that fits the whole temporal evolution of observations. These
- 100 results are useful for future physics-based forecasting models of the coastal slope evolution.

In the following sections, we shortly relate the NCA airport history. Then, we present the InSAR measurement of the airport platform deformation, including a noise analysis of the generated data set. This latest point is rarely discussed in the subsidence studies, although it is crucial to accurately assess the hazard due to the subsiding area. Finally, we model the InSAR observation to better understand the underlying physical process of the platform subsidence and discuss the potential consequences of such vertical displacements.

## 2 History of the Airport construction

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For the first half of the 20th century, Nice only hosted an aerodrome made of a single dirt track. Nice airport history really started in 1944 when the allies and the Americans set up a logistics base in Nice and thus built the first tar runway (Figure 1c). In the following years, few limited inland extensions (several hectares) of the airport platform have been done to welcome

- 110 bigger planes. However, the airport is stuck between the sea and Nice city that prevents any development inland. As air traffic increased, it has been decided to extend the airport southward, on reclaimed land over sea in order to build a second runway. More than hundred of studies have been done as it is a real challenge to build there, notably because the continental shelf is very narrow (less than 2 km wide) and is bounded by very steep and deep slopes. The structural work of the platform was performed between 1975 and 1978 when 30 000 000 tons of material were brought from a neighbouring hill (Ollié, 1982).
- 115 The sediments were then dynamically compacted (with a 130 kg mass falling from 22-23 m high). Meanwhile a 3-km long seawall have been built to protect the platform from the sea storms. In July 1978, the structural work of the airport platform was finished while construction work continued to build a dyke where a commercial port would take place. Unfortunately, the 16th of October 1979, an undersea landslide triggered the collapse of this dyke (Figure 1b,d,e). As a result, the port project got dropped, and the next three years were dedicated to consolidate the airport platform. In 1982, the last stage of the work
- 120 including the construction of the pavement was achieved. The Nice airport was then inaugurated in 1983 (de la Tullaye, 1989). Since then, only minor changes were added and Figure 1e shows the shape of the airport platform as it is today.

is to combine different redundant paths between acquisition dates in order to reduce the phase noise level on the wrapped interferograms.

- ERS and Envisat interferograms are corrected for orbital and topographic components using DORIS and the ALOS DEM, 145 respectively. ALOS DEM is also used to correct Sentinel-1 interferograms. To help the phase unwrapping, interferograms are filtered and slightly downsampled by pixel multilooking with 2 looks in range and  $2 \times 5$  looks in azimuth for ERS and Envisat interferograms and 2 looks in azimuth and  $2 \times 4$  looks in range for Sentinel-1 data. The resulting pixel spacing is  $\sim 40 \text{ m} \times 40$ m. Interferograms are properly referenced using areas around the airport that has been proven to be stable (Cavalié et al., 2015). Finally, we used a constrained least-square inversion (Doin et al., 2012) in order to derive the surface displacement rates from
- 150 the interferograms. A temporal smoothing operator is applied to limit phase variations due to turbulent atmospheric delays (although atmospheric delays are limited as InSAR is a relative measurement and we work at small scale). Surface velocity maps shown in Figure 3 are derived from the linear component of the time series for each pixel.

#### 4 Surface displacements observed from 1992 to 2020

#### 3.1 Surface displacements observed from 1992 to 2020

- 155 Figures 3a-c shows the averaged vertical ground velocity for the ERS (1992-2001), Envisat (2003-2011) and Sentinel-1 (2014-2020) periods. Note that the color scale changes to match the maximum velocity value. This representation allows to see that the spatial displacement pattern is steady through the whole observation window, although the amplitude decreases in time. This is a major update compared to the 2015's study (Cavalié et al., 2015) where the time window was too short to measure reliably any slow down of the surface displacement. Thus, with this new dataset, we have the opportunity to measure subsidence 160 rate variations over a 28 year long period of time.

To better observe the temporal variations of the airport platform subsidence, Figure 3d shows the displacement evolution of pixel  $P_1$  that is located in the maximum subsidence area (Figure 3a). As the changes of the carrier frequency between each generation of satellites prohibit cross-interferogram (Envisat-Sentinel-1 for instance), the time series is discontinued. Thus, Figure 3d shows the three trends for each satellite period (red dots). A simple linear regression reveals that, for  $P_1$ , subsidence

165 rates were in average 16 mm/yr, 9.5 mm/yr and 8 mm/yr for the periods 1992-2001, 2003-2011, and 2014-2020, respectively. We thus observe a deceleration of 50% of the subsidence rates over 28 years. To better visualize the evolution of the pixel displacement through the full period, one can make the assumption that no sharp motion took place between the 3 measured periods and that the shape of the motion follows a logarithmic function (with Heaviside step functions to take into account the discontinuities):

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$$f(t) = a \log\left(1 + \frac{t}{b}\right) + cH_1 + dH_2 + e$$
 (1)

where t is the time,  $H_1$  and  $H_2$  are two Heaviside step functions, and a, b, c, d, and e are some constants. By inversion, one can determine them and thus reconstruct the time series (Figure 3d).



**Figure 3.** Projected vertical ground velocity (mm/yr) measured from (a) ERS (1992-2001), (b) Envisat (2003-2011), and (c) Sentinel-1 (2015-2020) data. Note that the color scale changes and is adapted to show the persistent patterns of deformation over time. Black dot in (a) shows the location of pixel P1. (d) Time series of P1 vertical displacement. Red dots correspond to the three times series computed independently. Black circles represent the reconstructed time series by constraining the displacement as a logarithmic function.

Our InSAR processing strategy turns out to be very effective and shows very nice results both in time (Figure 3d) and

- 175 spatially (Figures 3a,b,c). Actually, on maps, land subsidence is clearly localised in the riverbed (we are able to detect velocity slower than 1 mm/yr) and then over the airport platform where the downward velocity increases. Qualitatively, we observe little noise in the data and unlike many studies about subsidence, we don't see any areas with artificial uplift due to atmospheric delays. Indeed, velocity drops sharply to 0 over the consolidated conglomerate located on each side of the riverbed. However, it is important to quantify the error bars on the data as it is often an important parameter for
- modelling the deformation. 180

Estimating the noise level is both very important and tricky in InSAR and thus it is often either ignored in the published InSAR studies or theoretical values are given. However, several methods have been developed to estimate the noise correlation, notably to compute the InSAR data covariance matrix that are used in the inversion to retrieve parameters of the underlying geophysical phenomena (Sudhaus and Sigurjón, 2009). In the previous study (Cavalié et al., 2015), authors evaluated the 185 uncertainties of the velocity maps by looking at the dispersion of surface velocity measurements in a nearby location where no surface displacement is expected. As a result, all velocity variations observed in the InSAR data are due to noise. Assuming that the noise level is similar on the nearby deformed area, a 1- $\sigma$  error can be computed. With this method, Cavalié et al. (2015) estimated a 1- $\sigma$  error of 0.25 mm/yr for the mean subsidence rate occurred between 2003 and 2011. Similarly, using the time

series, one can estimate the temporal dispersion of a pixel located on a stable area. Moreover, if the temporal evolution of

- 190 the surface displacement is simple enough (as it is the case for the NCA airport), one can remove a deformation model and then observe the residue dispersion. The advantage is that the 1- $\sigma$  error is computed directly in the subsiding area (and not for a pixel located nearby that can be affected by other local sources of noise). Figure 4 displays the InSAR signal residue (after removing the logarithmic function estimated from Equation 1) for the pixel  $P_1$  (shown on Figure 3a). Overall standard deviation on displacement  $\sigma_d$  is ~4.2 mm. Interestingly, we see that data dispersion is very similar for the ERS, Envisat and
- Sentinel-1 time series (that have been processed independently). As in Fattahi and Amelung, if we assume that the residue is a 195 Gaussian white noise, the uncertainty on the deformation velocity  $\sigma_v$  can be estimated for each time series as:

$$\sigma_v = \frac{\sigma_d}{\sqrt{\sum_{i=1}^N (t_i - \bar{t})^2}} \tag{2}$$

where  $t_i$  are the acquisition dates,  $\bar{t}$  is the mean acquisition date and N the number of acquisitions.  $\sigma_v$  is estimated to 0.27 mm/yr for ERS, 0.28 mm/yr for Envisat and 0.32 mm/yr for Sentinel-1 dataset. Interestingly, the estimate for Envisat dataset

is very close to the 1- $\sigma$  above mentioned error of 0.25 mm/yr estimated by a different method. Deformation velocity derived 200 by InSAR using SBAS type techniques (Berardino et al., 2002) may be biased due to phase misclosure (De Zan et al., 2015). Recent studies suggest that this phenomenon is due to the temporal change of scattering mechanism (Ansari et al., 2021): it occurs either on vegetated areas where the scatterers vary in time due to growth or decay of the vegetation and also on bare soils where moisture level changes according to precipitation events. However, our study is focused on an urbanized area that 205 should not be prone to this bias.

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Figure 4. Displacement residues for  $P_1$  (InSAR times series minus the fit function estimated with equation 1). Residue dispersion is ~4.2 mm.

# 4 Creep Modelling

The time series of surface displacement data estimated from InSAR analysis shows a non-linear transient evolution over 28 years (1992 to 2020) (Figure 3d). This reflects a progressive and long-term deformation —of the sub-surface layers. Actually, 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).

Previous studies of the submarine slope stability in the area of the Nice airport indicated that the geological formations below

- 215 the airport deform with a slow creep process Dan et al. (2007); Stegmann et al. (2011)(Dan et al., 2007; Stegmann et al., 2011). A clay layer is suspected to be the creeping section of the continental slope below the sea level and a potential contributor to the origin of submarine landslide Leynaud and Sultan (2010)(Leynaud and Sultan, 2010). Consequently, it is important to investigate the creep process to explain the slope deformation and failure. In addition, the time series of surface displacement measured from 1993 to 2019 1992 to 2020 indicates that the displacement is mainly vertical and the horizontal component is
- 220 negligible. This behavior suggests that a creep compaction is probably at play.

Several models have been developed to describe creep and failure in rocks Jaeger and Cook (1979) (Jaeger and Cook, 1979). Creep represents strain increase with time. A typical creep curve indicates three different regions: the primary, secondary and tertiary creep region (Figure 5a). Once the material experiences an instantaneous strain, as a result of sudden loading, the

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with a constant strain rate. The strain rate in secondary stage is the minimum strain rate of a creep deformation. The last stage of creep deformation is the tertiary creep regime characterized by very high strain rate and eventually failure.

primary creep region begins and has a decreasing strain rate with time. This behavior continues until the secondary stage starts

The shape of the observed displacement at the surface of the airport is similar to the shape of the primary and secondary creep stages of the theoretical creep curve. A viscoelastic Burger's model can effectively reflect the primary and secondary creep stages of rock creep process; however, it cannot describe the acceleration phase of tertiary creep. Here, we use an extended Burger's creep model made up of a series of Maxwell and Kelvin bodies (Jiang and Wang, 2022) to reproduce the InSAR observations. Such viscoelastic model was previously employed to model soil deformation Yao et al. (2021) (Yao et al., 2021), fault relaxation after earthquakes Sun and Wang (2015) (Sun and Wang, 2015), landslide creep Zou et al. (2013) (Zou et al., 2013; Liao et al., 2022) and is often used in geology to illustrate the effects of both strain and stress relaxation. The transient creep ( $\delta$ ) with time (t) is analytically calculated as follows:

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$$\delta(t) = \sigma_0 \left[ \frac{1}{E_M} + \frac{t}{\eta_M} + \frac{1}{E_{K_1}} \left( 1 - \exp\left(-\frac{E_{K_1}t}{\eta_{K_1}}\right) \right) + \frac{1}{E_{K_2}} \left( 1 - \exp\left(-\frac{E_{K_2}t}{\eta_{K_2}}\right) \right) \right]$$
(3)

where  $E_M$ ,  $E_{K1}$ ,  $E_{K2}$ ,  $E_{K_1}$ ,  $E_{K_2}$  are the elastic moduli of the Maxwell body, the first and second Kelvin bodies, respectively;  $\eta_M$ ,  $\eta_{K1}$ ,  $\eta_{K2}$ ,  $\eta_{K_1}$ ,  $\eta_{K_2}$  are the viscosity of the Maxwell body, the first and second Kelvin bodies, respectively;  $\sigma_0$  is a constant uniaxial load. The transient Kelvin component of the rheology is considered to be dominant at short timescales, while the Maxwell component dominates at long timescales Jaeger and Cook (1979)(Jaeger and Cook, 1979). With this 1D model, 7 parameters need to be adjusted. We used an adaptive grid search method to invert the parameters. We set up the search range of each parameter to explore a large number of possible solutions, that is about 2.3 million of solutions. For the goodness of fit of the best-fit solution, the misfit between the observed ( $obs_i$ ) and model-predicted ( $pred_i$ ) displacement is estimated with the reduced chi-square ( $\chi^2$ ), defined as:

$$\chi^2 = \frac{1}{N-m} \sum_{i=1,N} \left( \frac{\operatorname{obs}_i - \operatorname{pred}_i}{\sigma_i} \right)^2 \tag{4}$$

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with N is the number of observations, m is the number of model parameters, and  $\sigma_i$  is the uncertainties (4.2 mm here).

Figure 5b shows the best fit numerical solution to the measured displacement over time. The model provides a satisfying fit of observations and adjusts the data with a reduced chi-square of 0.18957, and leads to  $\sigma_0 = 0.099$  MPa,  $E_M = 32.1$  MPa,  $E_{K_1} = 0.86$  MPa,  $E_{K_2} = 0.47$  MPa,  $\eta_M = 42.63$  MPa/yr,  $\eta_{K_1} = 16.21$  MPa/yr,  $\eta_{K_2} = 9.61$  MPa/yr. These values are consistent with the range of values obtained in laboratory experiments conducted on clays under triaxial compression condition Xue et al. (2020)(Xue et al., 2020). The difference between the observed and modeled displacements reflects mostly the data

250 Xue et al. (2020)(Xue et al., 2020). The difference between the observed and modeled displacements reflects mostly the data dispersion as we find a very similar standard deviation, 4.1 mm, for the residues (data minus model). Thus, this result suggests



Figure 5. (a) Strain-time plot for a conventional creep experiment. On this typical creep curve, the three creep phases (primary, secondary, and tertiary) are labelled. (b) Time series of the measured displacement and the best fit numerical solution using the extended viscoelastic Burger's model. The model adjusts the data with  $\chi^2 = 0.18957$ .

that a transient creep mechanism properly models our observations of the vertical displacement associated with a long-term compaction of materials. Based on this assumption, the airport deformation is still in primary stage of the creep process.

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Although the data are well reproduced with an extended Burger's creep model, which allows to investigate a transient rheology for viscous compaction, an extension to a creep damage model in a three-dimensional stress state would be adapted to explore the full non-linear visco-elasto-plastic behavior with potential damage accumulation and accelerated creep (tertiary creep stage in Figure 3d) toward dramatic failure. However, the 1D viscoelastic creep model used here is well adapted to explain the data with a satisfying fit over the 28 years of observation.

### In this study

# 260 5 Discussion and Conclusion

Land use is particularly disputed in coastal areas as they are often highly populated. The intense human activities lead to an increase of various hazards of which vertical land motions due to superficial soil compaction. This latest phenomena can be caused either by natural or anthropogenic phenomena and can lead to further coast erosion, flooding or land salinization in case of ground water pumping. Actually, most of subsidence affecting the costline near big cities are

- 265 related to ground water pumping (especially in south-east Asia, like in Jakarta for example), but subsidence is a natural common feature of large river deltas (Nil, Missipi, or Po rivers, for instance) and are due to compaction of the Holocene sediment strata. In the Var delta (french Riviera, France), we observe the interaction between the natural compaction of the unconsolidated Holocene sediments in the Var river delta with the construction of a man-made infrastructure (the NCA airport) that brought an additional superficial load on top of the sediment. This extra-load leads to amplify
- 270 drastically the subsidence rate as observed in Cavalié et al. (2015). In the case of the Var delta, hazard is also amplified

by the fact that the overload of sediment has been used to reclaimed land over sea in a place where the continental shelf is narrow and the undersea topography quickly drops to -2500 m (Figure 1). Understanding the mechanism and thus the evolution of sediment compaction is essential to evaluate the danger caused by the coast subsidence.

Therefore, we use SAR interferometry to measure and analyze the temporal evolution of the ground displacement on the

- 275 Nice Côte d'Azur airport platform over a long period of 28 years. Extending the observation window to study the long-term subsidence leads to substantial improvements in the understanding of the ongoing mechanisms along this coastal area. Indeed, the previous study Cavalié et al. (2015) (Cavalié et al., 2015) measured the airport platform subsidence using only the Envisat data that span the 2003-2011 period. This relative short period of observation impeded to detect accurately non-linearity of the surface displacement and its change rate. By adding the ERS and Sentinel-1 data, the observation window more than tripled
- (1992-2020) and times series of the surface displacement clearly reveal a transient non-linear deformation with decelerating subsidence rate over time, that is expected for ground layer compaction. Then, we used a simple analytical Burger's creep model to constrain the mechanisms and rheology at play. The data are properly explained by the primary and secondary creep phases, highlighting a slow viscoelastic deformation at multiyear timescales. The best-fit solution allows to retrieve reasonable mechanical values of the airport sediments that have been brought to build the platform extension. Our study thus proves that the long-term InSAR data can improve our understanding of the surface processes and the subsurface material properties.
- Although the subsidence rate deceleratessince, at least, for 28 years, our results show that the compaction of the sediment is still active and its future evolution is uncertain and still at stake. Indeed, if compaction zones bands are developing under the airport platform, creep process could potentially lead to accumulated material damage toward failure. Thus, through our investigations, the data indicates that the stability of the airport platform should be monitored continuously with additional high-quality space and land observations together with submarine instrumentation on the continental slope right below the airport. In an era in which climate change and sea-level rise pose unprecedented threats to coastal ecosystems and urbanizations Shirzaei and Burgmann (2018); Shirzaei et al. (2021)(Shirzaei and Burgmann, 2018; Shirzaei et al., 2021), the long-term observations of ground motions from space is essential to monitor the stability of coastal environment and will inform managers and policymakers identify zones with exposure to hazards.
- 295 Data availability. Raw data used in this study are freely available online. Sentinel-1 SAR images are from the PEPS platform (https://peps.cnes.fr/rocket/#/search). ERS and Envisat SAR data were obtained free of charges through a ESA cat1 project (https://earth.esa.int/eogateway/catalog/ers-1-2-sar-im-10-sar\_im\_0p- and https://earth.esa.int/eogateway/catalog/envisat-asar-im-10-asa\_im\_0p-?text=envisat%20asar%20im%20l0%20%5Basa\_im\_0p%5D, respecively). The digital elevation model is freely available from JAXA (https://www.eorc.jaxa.jp/ALOS/en/-dataset/aw3d30/aw3d30\_e.htm). ERA-5 global reanalyses of atmospheric data are distributed by the
- 300 ECMWF (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). Velocity maps shown in Figure 3 are archived on Zenodo (https://doi.org/10.5281/zenodo.7038263).

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