



Using soil-compaction rates by the European Ground Motion Service (PS-InSAR) to estimate, at high spatial resolution, the site conditions of the Grenoble basin (French Alps) for its response to earthquakes

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Abstract. In the basin of Grenoble (France), we explore the potential of the compaction rates of Quaternary sediments as measured by PS-InSAR, and freely delivered by the Copernicus service EGMS, to serve as a new proxy for mapping site-condition parameters used in seismic-hazard assessment (fundamental resonance period T_0 of the soil and sediment thickness H_{bed}). The Grenoble basin is known for its strong site effect that largely amplifies seismic waves emitted by earthquakes.

5 We develop a specific processing protocol of the EGMS data to account for its high inherent noise (involving adequate spatial smoothing, and quality filtering of the measurements considered), and propose a statistical referencing so the developed models are fully independent of the EGMS dataset chosen as input. The models are applicable in Grenoble in high spatial resolution and result in over 100 000 new estimation points of the site conditions in the entire basin area. This work highlights the huge potential of satellite imagery to complement site-characterisation and microzonation studies specifically in urbanized valleys.

10 1 Introduction

When an earthquake occurs, the emitted seismic shear waves travel in the Earth crust at a shear-wave velocity V_S that depends on the rigidity of the media. When those waves reach the near surface, V_S can decrease drastically, especially in recent and loose sedimentary deposits. Those sediments, typically mapped as Quaternary geological formations, can lead to a significant impedance contrast with the seismic bedrock underneath that leads to trapping and resonance of the shear waves in the soil layer. As a consequence, the seismic waves are amplified both in amplitude and in duration, and can result in a large and destructive ground motion (Shima, 1962; Elgamal et al., 1996; Kramer, 1996). Called the lithological site effect, these effects can lead to an increase of building damage, as observed in multiple cities affected by strong earthquakes: e.g. Mexico City (Mexico) in 1985 (Bard et al., 1988), Northridge (California) in 1994 (Field et al., 1997), Kobe (Japan) in 1995 (Kawase, 1996), Boumerdes (Algeria) in 2003 (Laouami et al., 2006), Kaikoura (New-Zealand) in 2016 (Bradley et al., 2017), Mexico City (Mexico) in 2017 (Singh et al., 2018), and Kahramanmaraş (Turkey) in 2023 (Song et al., 2025).

Knowledge of the parameters describing site conditions in cities at risk of earthquakes is mandatory for the scientific study of site effects, ground-motion modeling, microzonation, and for providing input into seismic codes to ensure the resistance of



buildings. Examples of these parameters are time-averaged shear-wave velocity in the first 30 m of soil (V_{s30}), the engineering bedrock depth (H_{800}), the depth of the main impedance contrast corresponding to the whole sediment thickness above rock (H_{bed} , that we also call the seismological bedrock depth to differentiate it from H_{800}), and the fundamental resonance frequency (f_0) or period (T_0) of the soil. However, applying classical geophysical or geotechnical investigations to retrieve site conditions over wide areas at high spatial resolution can turn out very costly, both economically and time-wise (Cultrera et al., 2021). Because of this difficulty, it is a common practice to use more accessible parameters as proxies to retrieve soil parameters that influence the ground motion, both for the topographic (Bou Nassif et al., 2025) and lithological site effects (Wald and Allen, 2007; Allen and Wald, 2009; Zhu et al., 2020). For example, the topographic slope is commonly used as a proxy to evaluate V_{s30} (Allen and Wald, 2009), or it may be associated with the geological era to capture the site amplification (Loviknes et al., 2024). In this context, it is critical to develop new methods or proxies - efficient and low-cost, yet scientifically sound - to also obtain the spatial variations of H_{bed} and f_0 (or T_0) in populated alluvial valleys.

Avilés and Pérez-Rocha (2010) have first quantified a correlation in the sedimentary basin of Mexico City between (i) the rates of the long-term downward ground displacement (velocity in mm yr^{-1}) estimated from 960 on-field precise measurements during the time period 1983-2005, and (ii) the sediment thicknesses down to bedrock obtained from more than 10,000 boreholes and pits. Albano et al. (2016) and Michel et al. (2011) have also observed an apparent correlation between the ground-subsidence rates and T_0 in Mexico City and Grenoble (France), respectively. These two studies used displacement rates of the Earth surface measured from spaceborne Interferometric Synthetic Aperture Radar (InSAR).

The use of InSAR technique to monitor small elevation changes was introduced in 1989 by Gabriel et al. (1989). Since then, InSAR has been intensively used, among other cases, to detect and measure ground displacement, either from anthropogenic or natural origins, in multiple areas over the world (Bürgmann et al., 2000; Stramondo et al., 2008; Abidin et al., 2011; Sun et al., 2018; Liu et al., 2021). With this technique, it is possible to obtain the displacement of the Earth surface over large areas, with up to a metric spatial resolution (depending on the satellite and the land cover), and with a millimetric precision (Crosetto et al., 2016; Crosetto and Solari, 2023).

In 2014, the European Union launched the Copernicus Land Monitoring Service (<https://land.copernicus.eu>), in which one of the components, the European Ground Motion Service (EGMS - <https://egms.land.copernicus.eu/>) aims at measuring and monitoring the ground displacements and deformations at the European scale. EGMS uses the InSAR technique applied on satellite data coming from Sentinel-1 to deliver yearly updated products about the ground displacement (Crosetto et al., 2020; Costantini et al., 2021; Crosetto et al., 2021, 2026). Our study makes exclusive use of the EGMS data, which have the advantage of being freely accessible, with the main objective to evaluate their performance to retrieve site-condition parameters.

Our target area is the city of Grenoble in France, as previously addressed by Michel et al. (2011), that faces a strong lithological site effect (LeBrun et al., 2001; Cornou and Bard, 2003; Guéguen et al., 2007; Causse et al., 2009, 2023). It is a densely urbanized area located on a thick sedimentary basin, where we can take the best advantage of the InSAR method. As illustrated by the extensive studies, the case of Grenoble is used by seismologists as a reference test site for numerous site-characterization studies (Haghshenas et al., 2008; Ito et al., 2021) and 3D ground-motion numerical simulations (Chaljub et al., 2006, 2010; Tsuno et al., 2006; Causse et al., 2009; Moczo et al., 2018). As a result, the characteristics of the site effect



and the site conditions (amplification levels, resonance periods, 3D bedrock depth and seismic velocities) are very well known in this basin, which allows advanced studies on the physics of its site effect.

60 In this context, our study has two main purposes. The first is to find which site-condition parameters explain the best the downward ground-displacement rates observed in Grenoble. This will allow us to better understand the origin of the ground displacement in the basin, and to determine whether the observed rates are due to the natural compaction of the whole sedimentary column or of the superficial geological layer only. This exercise is possible in Grenoble because, contrary to the case of Mexico City, no industrial pumping of water or gas extraction that could influence the ground-displacement rates
 65 (Poland and Davis, 1969) are operating. The potential impact of building construction is also investigated. Answering this question will help us explore whether ground-displacement rates could serve as a proxy for site-condition parameters, and, if so, for which specific ones. The second purpose of our study is to demonstrate how the open-access EGMS data for Europe can be used to carry out this exercise. As shown in this study, these data exhibit high variability and noise, which complicates their analysis, since results may depend on the time period of satellite acquisition or on which Sentinel-1 swath is used. To
 70 avoid such dependencies and to quantify the physical phenomena of interest, we aim at setting up a processing methodology that leverages the various EGMS products available at the time of this study.

After a description of the study site and of the data used in Sect. 2, we detail in Sect. 3 all the processing steps that enable linking the spatial variations in the vertical ground-displacement rate, delivered by EGMS, as robustly as possible with those of T_0 in the Grenoble basin. We then show in Sect. 4.1 that the same processing scheme is just as effective when T_0 is replaced
 75 by the depth of the seismological bedrock H_{bed} , even though this depth was determined completely independently of T_0 and by using different geophysical methods. The relative contribution of near-surface site conditions to the downward ground displacement is examined using random-forest analyses in Sect. 4.2. Lastly, we give some recommendations in Sect. 4.3 for the use of EGMS data to map or predict the site-condition parameters T_0 and H_{bed} , and on the high spatial resolution achieved in that purpose. The discussion in Sect. 5 focuses on the physical phenomena that can explain the downward ground-displacement
 80 rates measured in Grenoble, and how the various lessons learned from this study and from the literature can feed into future similar studies in other valleys filled with Quaternary sediments.

2 Description of the study site, geophysical and satellite data

2.1 Description of the Grenoble basin

Grenoble is located in the southwest part of the French Alps (Fig. 1a). As shown in Fig. 1b, the city is built on a flat Y-shaped
 85 sedimentary valley, surrounded by sedimentary-rock mountain ranges (essentially limestones) in the North (Chartreuse massif) and in the West (Vercors massif), and by a crystalline massif (Belledonne) in the South-East. The soft thick sediments that compose the Quaternary sedimentary fill of the Grenoble valley are described by Nicoud et al. (2002). The valley was filled after the last glaciation, when the glaciers coming from the Grésivaudan and the Drac valleys retreated and left a lake that was filled with sediments. As a result, the topography of the area is quite peculiar. The slopes of the mountains surrounding the
 90 valley are steep and continue deep under the surface, under the sediment infill. The latter is mostly composed of monotonous



lacustrine and glacio-lacustrine sediments overlying a Jurassic rocky substratum. The most recent fluvial deposits (Holocene) are relatively thin (tens of meters) compared to the thickness of the preceding homogeneous lacustrine formation (hundreds of meters) from the Late Würm and Upper Pleistocene.

Regarding seismic hazard, the Alps are an area of active but slow crustal deformations, due to the collision of the African and Eurasian tectonic plates, and are experiencing at regional scale both uplift and horizontal deformations. In the western part of the Alps where Grenoble is located, the uplift rate ranges from 0 to 2 mm yr⁻¹, while the horizontal deformation exhibits weak values below 0.5 mm yr⁻¹ (Serpelloni et al., 2013; Nocquet et al., 2016; Sánchez et al., 2018; Sternai et al., 2019). Recent studies show that our study area is in compression, with an East-West shortening (Billant et al., 2015; Walpersdorf et al., 2025). These deformations result in stress accumulation, leading to moderate but continuous seismic activity (Calais et al., 2002; Walpersdorf et al., 2018; Mathey et al., 2021). The French SISMalp earthquake catalog, covering the period 1987 to 2023, contains more than 50 000 earthquakes of local magnitude between -1.8 and 5.0, all having occurred in the western Alpine belt (Langlais et al., 2024). Some significant earthquakes occurred in the vicinity of Grenoble: M_L 5.3 at Corrençon-en-Vercors in 1962 (20 km from Grenoble), M_L 5.3 at Annecy in 1996 (90 km from Grenoble), M_L 4.1 in Laffrey in 1999 (18 km from Grenoble). Grenoble is also only a few kilometers away from the Belledonne border fault, an active strike-slip fault which has the potential to generate earthquakes with magnitude 6 (Thouvenot et al., 2003). According to the Eurocode-8 regulation, Grenoble is located in zone 4 of seismic hazard, the highest for mainland France (CEN/TC 250/SC8, 2004).

Because of that level in seismic hazard, of its large sediment thickness and of its 3D complex Y-shaped geometry, the Grenoble basin has been a study zone for the earthquake ground-motion amplification due to the contrast in seismic velocity between the rock substratum and the sedimentary infill. In the basin, the amplification level can reach a factor of 10 over a wide frequency range from the fundamental resonance frequency up to 10 Hz as outlined by seismological measurements from the permanent French strong-motion network and from numerous temporary campaigns (Epos-France RAP, 1995; LeBrun et al., 2001; Cornou et al., 2003a, b, 2009; Pequegnat et al., 2008; Causse et al., 2009, 2023).

2.2 Available site-condition parameters

The Grenoble basin has been the focus of numerous geophysical, geological and geotechnical investigations over the last 30 years. The depth of the sediment-to-bedrock interface (H_{bed}) was precisely characterized by Vallon (1999) from gravimetric measurements, and interpolated to a 250 m-spacing regular grid (Fig. 1c). It corresponds to the depth of the impedance contrast between the Quaternary sediment infill and the Jurassic bedrock. The whole sediment thickness varies along the basin reaching up to 1000 m thick in the western part of the valley, giving a complex 3D shape to the sedimentary deposit forming the basin, with a rise of the bedrock in the southern part of the basin.

Seismic velocity profiling (seismic refraction and reflexion profiles, downhole seismic measurements at a 550 m deep borehole site reaching the bedrock) has outlined a laterally homogeneous sediment layering from ~ 50 m depth to the bedrock, resting on the 3D-shaped bedrock (Cornou, 2002; Dietrich et al., 2009). At the deep borehole site, S-wave velocities range from ~ 400 m s⁻¹ at 50 m depth to ~ 700 m s⁻¹ at the bottom of the sedimentary layers, and around 2500 m s⁻¹ at the top of the bedrock.

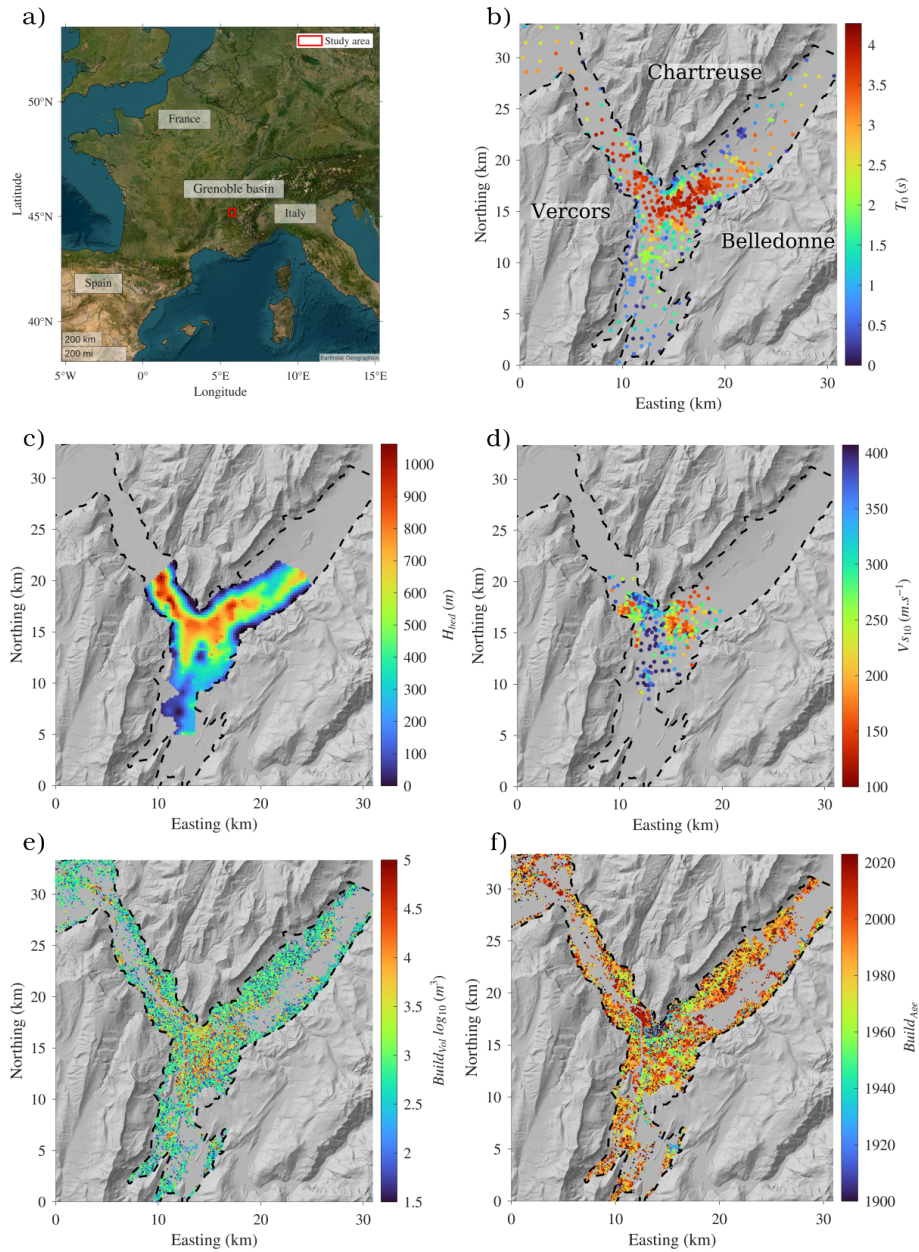


Figure 1. Maps of (a) location of the Grenoble basin in France, and of the site-condition parameters available in Grenoble: (b) fundamental resonance periods T_0 ; (c) bedrock depths H_{bed} from Vallon (1999); (d) time-averaged S-velocity over 10 m depth V_{S10} ; (e) approximate building volumes ($Build_{Vol}$), from the French Buildings National Database; (f) year of the last work permit on buildings ($Build_{Age}$), from the French Buildings National Database, when available. The dashed black line represents the demarcation of the study zone (the bottom of the Y-shaped valley).



125 More than 900 seismic ambient-noise measurements are available in the Grenoble basin, from various past experiments (e.g. for the most extensive measurements: Bettig et al., 2001; LeBrun et al., 2001; Cornou et al., 2003a; Hobiger, 2005; Guéguen et al., 2007; Cornou et al., 2009; Hollender et al., 2018; Perron et al., 2026), with duration from 20 min to several weeks, in order to retrieve the fundamental resonance periods using the H/V method (Nakamura, 1989). Since these seismic-noise recordings were processed and interpreted by different analysts, we reprocessed them homogeneously for this study following
 130 the SESAME guideline (Bard and SESAME Participants, 2004), with seismic-noise recordings duration from 20 min to 2 hours, time series divided in time windows of 50 s to 100 s, and smoothing of Fourier amplitude spectra using Konno-Omachi approach ($b=40$). The map of T_0 is displayed in Fig. 1b. The largest T_0 are found in the central and western parts of the basin, while the shortest periods are found on the basin borders and at the bedrock rise in the southern part of the basin, consistently with H_{bed} variations (Fig. 1c).

135 This is expected since the full thickness of the sedimentary column primarily controls the value of T_0 measured at the surface. It is worth underlining that both methods (gravimetric for H_{bed} and H/V for T_0) measure the effect of the same whole sedimentary column and detect the same interface in depth (from the seismological point of view: the strongest impedance contrast; from the geological point of view: the transition between the Quaternary sediments and the Jurassic limestones). The correlation of the downward ground-displacement rates with T_0 is studied in Sect. 3, while the correlation with H_{bed} is studied
 140 in Sect. 4.1.

A series of active and/or passive surface-wave measurements at more than 125 site locations within the basin and collection of more than 1,300 geotechnical boreholes (boreholes depth ranging between 10 m and 40 m) have allowed to characterize the spatial variation of shear-wave velocity of the first 10 to 30 m of the sediment fill (see Chaljub et al., 2021, and references therein). Spatial distribution of time-averaged shear-wave velocities in the first ten meters of soil (V_{S10} ; Fig. 1d) exhibits
 145 higher values in the areas where the highly energetic Drac river flooded the valley since the end of the draining of the lake (approximately 12000 years ago; Lacroix, 1971; Nicoud et al., 2002), bringing and depositing pebbles and more rigid material in the superficial part of the soil (no more than a few dozen meters deep). Lower V_{S10} values correspond to fine grained deposits (mostly clays and sands) from the Isère river. Since V_{S10} represents the rigidity of the near-surface sediments, the potential link between the downward ground-displacement rates and the compaction capacity of the shallowest layers is investigated in
 150 Sect. 4.1 and 4.2.

Beside site-condition parameters, we need to also investigate the influence of buildings on the long-term ground displacement. Indeed, as mentioned in the literature (Chen et al., 2005; Dang et al., 2014; Chen et al., 2015; Parsons et al., 2023), buildings have an influence on the settlement of soils due to the increase of stress applied. According to some observations, the total settlement due to very large buildings can exceed 100 mm (Bahar et al., 1995; Poulos, 2016; Stewart et al., 2023).
 155 However, the effect of man-made construction on the soil is very variable depending on the local properties of the soil, the building itself and the kind of foundation (Parsons, 2021). This settlement caused by new building surcharges is characterized by an initial and almost immediate linear phase. The second part of the settlement is due to the non-linear behaviour of the soil. This part is also divided in two phases of settlement, namely the primary and secondary consolidations. The primary consolidation is due to the evacuation of the overpressured water contained in the pores of the soil, while the secondary consolidation



160 phase corresponds to a long-term creep (Taylor, 1948). The magnitude and duration of each phase is controlled by the soil properties, but the secondary consolidation phase has a much lower rate of settlement, and this value tends to reduce over time (Augustesen et al., 2004; Liingaard et al., 2004; Mesri and Vardhanabhuti, 2005). In the literature, the settlement rates due to constructions can vary from 0.07 mm yr^{-1} to $4\text{-}5 \text{ mm yr}^{-1}$ (Parsons, 2021). In terms of duration, for clayed soil, the primary consolidation phase lasts from a few months to a few years, while the secondary consolidation phase can last from a few years
 165 to decades (Parsons, 2021). In some cases, its duration could even be considered as infinite (Mesri and Vardhanabhuti, 2005; Parsons, 2021). In particular, Stramondo et al. (2008) are able to distinguish different settlement rates at building locations in Rome using InSAR, and interpret the differences as differences in the consolidation phases.

To simplify, when considering buildings built on ground with the same mechanical properties, the settlement due to building loading mainly depends on the amount of the vertical stress applied (Giroud, 1968) and the duration since the end of the
 170 construction (Augustesen et al., 2004). Thus, a higher value of settlement rate is expected where the buildings are heavier and/or younger. In Grenoble, extensive information on the actual load and on the type of foundation at each building is not available. We can exploit a simplified estimation of where the heaviest and newest buildings are located by using the French Buildings National Database (<https://www.data.gouv.fr/fr/datasets/base-de-donnees-nationale-des-batiments/>), from which we can access the coordinates, the age of last construction permit, the occupied surface on the ground and the height of each
 175 building. We use these data to estimate a rough theoretical volume for each building ($\text{Build}_{\text{Vol}}$), which we assume in most cases to be proportional to the weight of the building. The map of $\text{Build}_{\text{Vol}}$ in Grenoble (Fig. 1e) highlights areas with either tall or large buildings, mostly constructed at the periphery of the city centre. We also map the age of the last construction permits ($\text{Build}_{\text{Age}}$), when available (Fig. 1f). However, this data should be treated with caution, as it refers to the date of the last structural modification to the building, which is not necessarily the date of construction. Less than 5 % of the buildings
 180 have a construction permit after 2015, hence, as most of the buildings in Grenoble are older than a decade, we do not expect a first-order correlation between their age/volume and the downward ground-displacement rates (which is confirmed by visually comparing the different maps in Fig. 1), so we rather use those building characteristics in Sect. 4 to investigate the origins of the residuals in the site-condition model.

2.3 Satellite ground-displacement rates

185 The InSAR method is based on two acquisitions of SAR images; for each pixel, the phase difference of the electromagnetic signal emitted by the satellite is computed. If the two images are acquired at different dates, from this difference, the displacement in the Line-Of-Sight (LOS) of the reflector surface is retrieved. Since the first application in 1989 by Gabriel et al. (1989), InSAR has become a powerful tool to measure the displacement of the Earth's surface (Massonnet and Feigl, 1998), whose main advantage is its dense spatial coverage compared to in situ measurements, although the temporal sampling is only one
 190 acquisition every few days or weeks depending on the satellite revisiting time. InSAR is adapted to monitor long-term surface elevation changes that range from mm yr^{-1} to cm yr^{-1} (Cavalié and Trouvé, 2024).

The ground-displacement rates used in this study were computed using Sentinel-1 SAR images and are delivered by the European Ground Motion Service (EGMS - <https://egms.land.copernicus.eu/>). Sentinel-1 is a constellation of satellites launched



by the European Space Agency (ESA). The revisit time of the area is 6 days until the failure of Sentinel-1b (in December
 195 2021), and 12 days after that. The satellites operate by default in interferometric wide swaths, with a swath of 250 km. The
 azimuth resolution is below 20 m, while the ground range resolution is below 5 m. The wavelength of the electromagnetic
 wave is 5.55 cm (Torres et al., 2012; Crosetto and Solari, 2023). EGMS aims at providing in open access updated and stan-
 dardized information regarding long-term natural and anthropogenic ground displacements over Europe (Crosetto and Solari,
 2023; Crosetto et al., 2016). EGMS released their first product in 2021 providing ground-displacement measurements between
 200 2016 and 2021 and has since provided annual updates, each covering a five-year period (e.g. 2018–2022, 2019–2023).

For France, EGMS delegates the processing of the Sentinel-1 data to the Tre-Altamira company, which uses the SqueeSAR®
 algorithm (Ferretti et al., 2023). This algorithm is based on the joint analysis of two types of reflectors, persistent scatterers
 (PS) and distributed scatterers (DS). While the PS are usually angular man-made structures (such as building roofs), roads
 or rock boulders that strongly reflect the electromagnetic waves and are located within a single pixel (4 m by 20 m), the DS
 205 are weaker reflectors from which the response is summed over an area larger than a single pixel in order to obtain a stronger
 response signal. The signal given by PS tends to be consistent over time, because the shape and nature of the reflector do
 not change, while DS tends to have a less good consistency in time. Despite this, the SqueeSAR® algorithm allows to obtain
 a high density of measurement points (MPs in the following) in urban areas (mainly due to the PS), while also providing
 some information about the ground displacement in less-urbanized environments (rather through the DS) (Ferretti et al., 2011;
 210 Crosetto and Solari, 2023). Since our study focuses on the urban area of Grenoble, where buildings and residences are densely
 concentrated, we can benefit from the maximum spatial resolution of the PS-InSAR technique.

EGMS delivers three different products, each one corresponding to an increasing level of processing: levels (2a) Basic, (2b)
 Calibrated, and (3) Ortho. The Basic product corresponds to the standard multi-temporal InSAR, where the displacement of
 each MP in the LOS is given. The value of displacement is relative to a single burst of acquisition (*i.e.*, a limited surface area,
 215 20 km × 80 km, of the SAR image). In the Calibrated product, EGMS processes the Basic product in order to integrate a GNSS
 reference frame, allowing the LOS displacements to be almost absolute and making it possible to compare them over several
 bursts (Crosetto and Solari, 2023). The Basic and Calibrated products are provided separately for Ascending and Descending
 tracks. Displacement values are provided directly at MP locations, which allows these products to be of very high spatial
 resolution in urban areas where many PS are available. The last level of processing is the Ortho product. To create this product,
 220 EGMS combines, when possible, the level 2b Calibrated LOS displacement rates from both Ascending and Descending tracks
 to retrieve the vertical (Up-Down) and horizontal (East-West) components of the displacement rates, assuming that the North-
 South motion (which is poorly constrained by the near-polar orbits of Sentinel-1) is varying smoothly in space and can be
 modeled by an interpolated GNSS velocity field. The resulting MPs are resampled over a 100 m-spacing regular grid, which
 implies a loss of spatial resolution compared to the previous levels 1 and 2. For all three of these products, EGMS provides
 225 displacement rates in mm yr⁻¹ with one digit after the decimal point. For a full and detailed description of the different EGMS
 products, see Crosetto and Solari (2023).

In this study, we use only the products from the levels Calibrated (2b) and Ortho (3), since level Basic (2a) does not allow
 for comparing results from one burst to another, and since Grenoble is covered by two bursts. As our goal is to evaluate the



effectiveness of these different products in describing the downward ground displacement, and since the displacements of
 230 level 2b Calibrated product are in LOS and the ones of level 3 Ortho product are vertical, we convert the LOS displacements
 of Calibrated product into vertical displacements at each MP by dividing by the cosine of the satellite incidence angle. This
 conversion assumes a small horizontal displacement compared to the vertical displacement, which is a rough approximation
 that will partly explain the uncertainties discussed in the following sections.

In the following, we call the converted Ascending orbit “ASC” and the converted Descending orbit “DES”. We call the
 235 vertical component of the Ortho product “VER” (for Vertical), and the East/West Ortho product “E-W”.

At the time of this study, we have at our disposal EGMS products coming from three time series of acquisition: 2015–2021,
 2018–2022, 2019–2023; and for each, the three products: ASC, DES and VER. The maps of the nine resulting datasets of
 vertical ground-displacement rate are presented in Fig. 2. In all those datasets (positive values upwards, negative downwards),
 we notice that at a large kilometric spatial scale, the Y-shaped basin of Grenoble is always visible with the lowest values
 240 of vertical ground-displacement rate within the area, indicating a clear sinking of the basin sediments. When looking at a
 hectometric scale inside the urbanized area, we notice however that the ground-displacement rates are spatially highly variable.
 This witnesses the ability of the InSAR method to capture different phenomena at different spatial scales: e.g. tectonic uplift,
 natural or anthropic ground displacement of the soils, building tilting or deformation, road deformation, etc. (Crosetto et al.,
 2025, who are also mentioning that the measures are affected by unavoidable and stochastic errors). Beside the large pattern
 245 of downgoing ground-displacement rate in the valley (Fig. 2), we observe also a small area of clearly stronger downward rate
 ($< -3 \text{ mm yr}^{-1}$) in the southern part of the valley, indicated by a solid black contour line in Fig. 2. This area will be discussed
 later as it shows specific T_0 values. In the surrounding mountainous zones, it is more difficult to detect a stable pattern, as
 the displacement values are very variable from one dataset to another. On those nine datasets, as expected with the PS-InSAR
 method, the highest density of MPs is located in the urbanized areas, while the forests or open-field areas are covered with
 250 fewer points.

The maps of the horizontal-displacement rates measured by EGMS (level 3 Ortho product) in Grenoble are displayed in
 Fig. 3 top row. Within the basin, the East-West displacement rates are between 0 and -1 mm yr^{-1} (*i.e.*, a slight displacement
 westwards). From their polarity, there is no clear evidence of basin stretching at the scale of our study zone. We can also notice
 that the largest values of horizontal-displacement rate are located on slopes, outside of the basin limits (dashed black line in Fig.
 255 3). One striking observation is the difference between the three datasets displayed: in the basin, the horizontal-displacement
 rates can be inconsistent.

If we want to account for the horizontal displacement when doing the projection from the LOS into the vertical displacement,
 we should use displacement values from both the Ascending and Descending tracks. Since the MPs are not located exactly at
 the same place on each track, it implies averaging the displacement over several MPs inside a certain area, and this inevitably
 260 results in a loss of spatial resolution (for example, Tamburini et al. (2010), and Ho Tong Minh et al. (2025), resample the
 Ascending and Descending tracks on a 50 m regular grid). In the case of EGMS, the resampling for the vertical product is
 done on a 100 m regular grid (Ferretti et al., 2023). Deliberately, we do not implement this process in order to exploit the
 higher density of MPs available in ASC and DES, and to assess whether it can contribute to the fine-scale prediction of site-

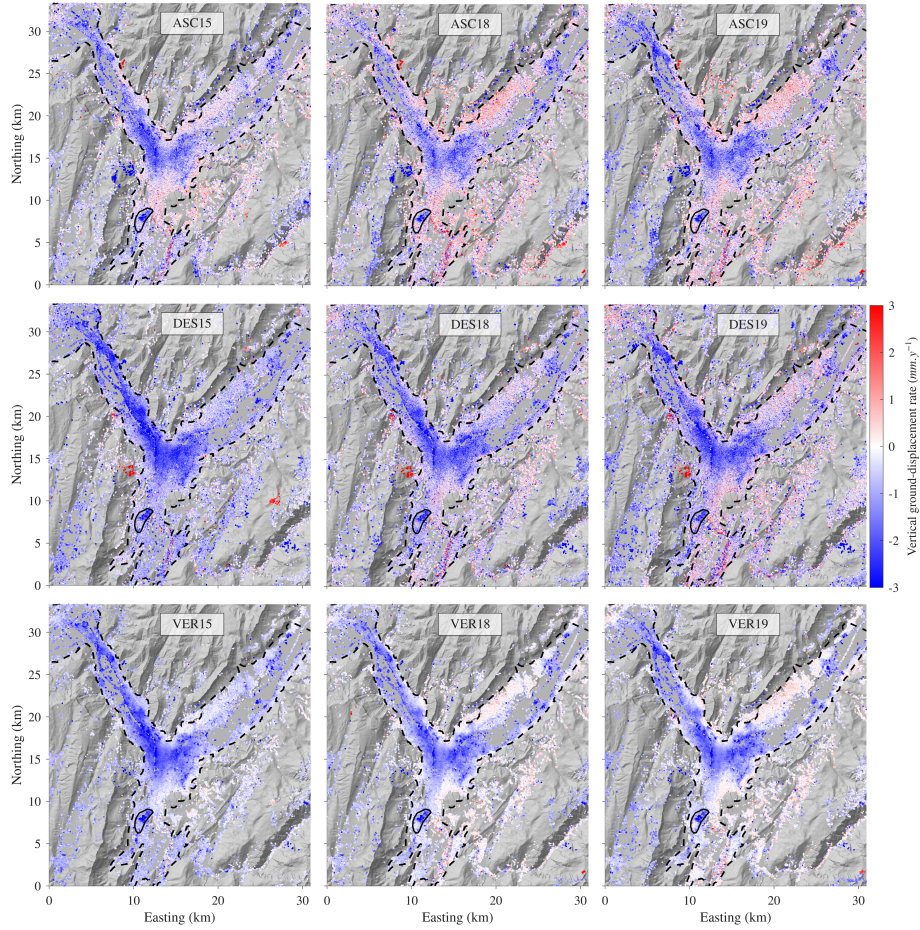


Figure 2. Maps of the different datasets of vertical ground-displacement rate available, at the time of this study, from the Copernicus service EGMS. First row: Ascending trace corrected of the cosine of satellite look angle (that we call ASC; EGMS product “Calibrated”). Second row: Descending trace corrected of the cosine of satellite look angle (that we call DES; EGMS product “Calibrated”). Third row: vertical component (that we call VER; EGMS product “Ortho”). Time series from 2015 to 2021 (first column), 2018 to 2022 (second column), and 2019 to 2023 (third column). Values are positive (red) for upward displacement rate, and negative (blue) for downward displacement rate. The solid black polygon delimits an excluded area of subsidence anomaly. The dashed black line represents the demarcation of the study zone (the bottom of the Y-shaped valley).

condition parameters. However to estimate where this approximation (*i.e.*, assuming small horizontal displacement compared to the vertical displacement) has the largest impact, Fig. 3 bottom row represents the following value, using the VER and E-W datasets:

$$Impact = \frac{1}{\exp\left(\left|\frac{VER}{E-W}\right|\right)} \cdot \alpha \quad (1)$$

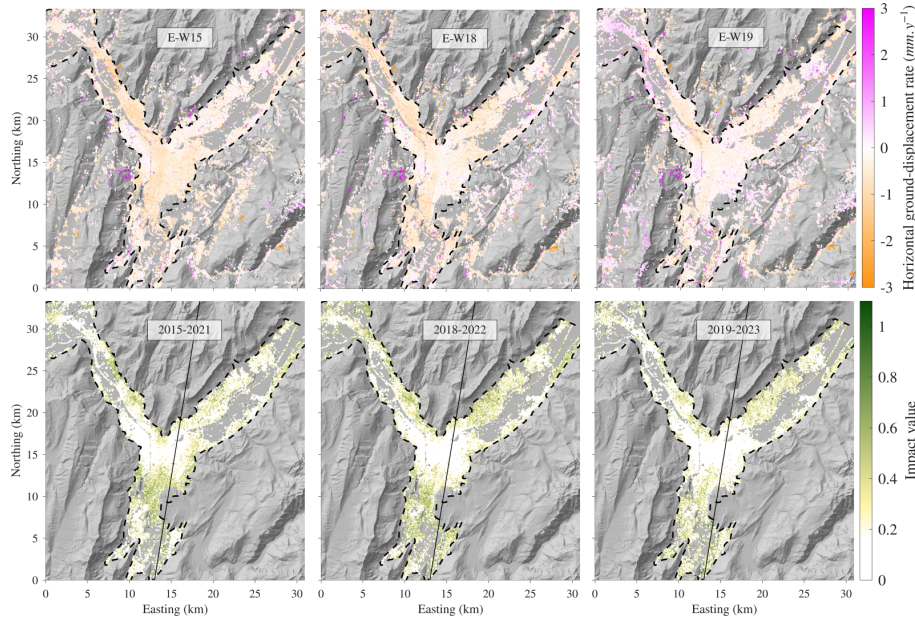


Figure 3. First row, maps of the different datasets of horizontal ground-displacement rate available, at the time of this study, from the Copernicus service EGMS. Negative (orange) values correspond to a displacement rate toward the West, while positive (pink) values indicate a displacement rate toward the East. Second row, maps of the impact value of the vertical-over-horizontal ratio of the ground-displacement rate, as defined by Eq. 1 and 2 in Sect. 2.3. We define that an impact value larger than 0.3 (greener dots, the maximum in our study zone being 1.1 reached only at a few points) indicates that the horizontal displacement rate is non-negligible compared to a significant value of vertical displacement rate. Thus we consider the greener locations to be of greater uncertainty for our correlations compared to the white ones. The thin black line indicates the eastern limit of the Sentinel 037 Descending track. For the two rows, the first column is the 2015–2021 time period of satellite acquisition, the second column 2018–2022, and the third column 2019–2023. The dashed black line represents the demarcation of the study zone (the bottom of the Y-shaped valley).

where VER is the vertical-displacement rate, E-W the horizontal-displacement rate, and α is a coefficient of importance computed as follows:

$$\alpha = \log_{10}(|VER| + 0.05) + \log_{10}(20) \quad (2)$$

The impact value is computed in a way that it tends to 0 when the horizontal-displacement rate (E-W) is small compared to the vertical-displacement rate (VER), or when the vertical-displacement rate is also close to 0. In places of small impact, the assumption to convert the LOS into vertical-displacement rate by dividing by the cosine of the satellite incidence angle can be considered as valid (because either the exact vertical-displacement rate is low, or the converted vertical value cannot be significantly biased by a low horizontal rate). On the other hand, the impact is larger when both horizontal and vertical displacement rates are non-negligible. In this case, the converted value can diverge from the exact vertical-displacement rate.



In Fig. 3 bottom row, we observe impact values well close to 0 in most of the basin, while largest impact values are limited to some edges of the basin (due to larger E-W displacement rates, Fig. 3 top row), especially in the northeastern and southern parts of the study area. In Sect. 3.4, some discrepancies between the results obtained can be explained because of the inexactitude of the conversion from LOS to vertical-displacement rates. In Fig. 3 bottom row, we also indicate the eastern boundary of the Descending track n°037 (black line). The edge effect of this track is significant, as a clear offset along a straight line parallel to that track boundary can be observed in all maps in Fig. 3. EGMS integrates all available tracks to process the products of level 3 (VER datasets), which causes these residual offsets in certain areas. The offset disappears before reaching the exact boundary of the track n°037 because EGMS performs a spatial averaging within each track, and the lateral extent of this averaging cannot exceed the track boundaries. For the DES datasets, we use only track n°139, which covers our entire area of interest, without using track n°037 (that covers only half of the target area), thereby avoiding the propagation of this offset. In this specific case and in the areas concerned, the DES datasets may be of better quality than the VER datasets.

Along with each value of ground-displacement rate, EGMS also gives two metrics in order to quantify the quality level of the measurement. The first metric is the temporal coherence, which corresponds to the “measurement-point coherence with respect to the linear regressed velocity” (without unit). The second metric is the root mean squared deviation (RMSE), “evaluated on the time-series residuals after applying a regression model of a third-order polynomial plus a sinusoidal component” (in mm) (Capes and Passera, 2025). For the ASC and DES datasets, both metrics are available. For the VER datasets, since each point does not correspond to an actual MP, the temporal coherence does not exist and only the RMSE is available. These quality parameters are used in Sect. 3.3.

2.4 Initial correlations between the rate of vertical ground-displacement and T_0

Figure 4a represents a scatter plot of the measured T_0 in the Grenoble basin associated with the closest value in space of vertical ground-displacement rates (here, the dataset VER 2015–2021), without any other processing. We observe a general trend of stronger downward rate as T_0 increases. In the following, the objective is to determine how the correlation between these two parameters can be optimized.

Before that, this figure also shows that a few sites with short T_0 values (around 0.7 s, gray dots) are associated with some of the strongest downward rates (up to -5 mm yr^{-1}). They correspond to the identified displacement-rate anomaly in the southern part of the basin highlighted in Fig. 2 by the solid black polygon. In this specific zone, three streams merge in the large Drac river. In the local urban masterplan, this area is known to be prone to frequent rise of the artesian water table that can lead to annual flooding (Rhodes, 2018). Before our study, only two H/V measurements were done in this area. In order to better characterize this specific zone, 10 additional H/V measurements and one active surface wave analysis were especially carried out (Unaldi and Simonnet, 2026). The T_0 values obtained with the new H/V measurements do not exceed 1 s, while the ground-displacement rates are up to -5 mm yr^{-1} , it is clearly a distinct behaviour compared to the rest of the study zone. The S-wave velocity profile exhibits a layer with $V_S < 100 \text{ m s}^{-1}$ in the first 10 m. Below, V_S is close to 200 m s^{-1} down to 30 m, and reaches 600 m s^{-1} below 30 m. These results indicate that the superficial and contemporary sediments in this specific zone are

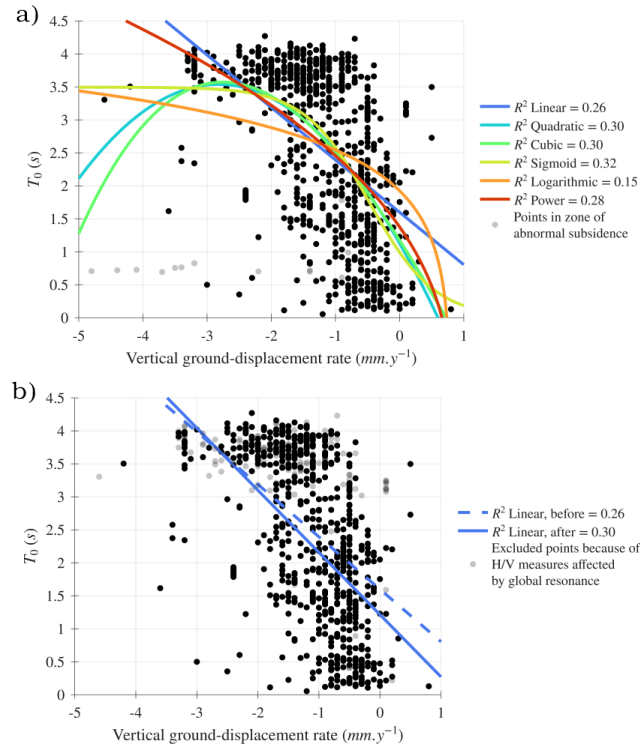


Figure 4. Scatter plots of T_0 versus the closest-in-space ground-displacement rate (VER15 dataset): (a) comparison of different regression models (colored curves), the gray points are excluded from the correlations because they are located in an area of subsidence anomaly (see Sect. 2.4; marked by the solid black polygon in Fig. 2); (b) comparison of the linear regression before (blue dashed line) and after (blue solid line) exclusion of the H/V measurement points that are in global resonance (gray points; see Sect. 3.1) and declustering of the H/V.

310 very soft compared to the rest of the valley (where $V_{S10} > 110 \text{ m s}^{-1}$), and prone to a larger deformation rate. Because they are clearly outliers in the scatter plot, we systematically exclude the T_0 points inside this area from our analysis.

2.4.1 Comparison of different regression models

In Fig. 4a, we also display six different ordinary least-squares regression models linking the T_0 to the ground-displacement rates: a linear model, a quadratic model, a cubic model, a sigmoid model, a logarithmic model and a power-law model. To
 315 compute the logarithmic and power-low models, the ground-displacement data must be strictly positive. Therefore, the values are first shifted by subtracting the maximum ground-displacement rate (so they all become negative), and their absolute values are then taken. The models are fitted to these shifted values, and the inverse operation is applied to obtain the curves presented in Fig. 4a.

For each regression, we consider the coefficient of determination R^2 as it indicates the proportion of target parameters
 320 explained by the input ground-displacement rates (Rawlings et al., 1998). For the nine ground-displacement datasets available,



we observe the following R^2 ranges: 0.08–0.37 for the linear model, 0.08–0.45 for the quadratic model; 0.13–0.46 for the cubic model, 0.08–0.48 for the sigmoid model, 0.00–0.24 for the logarithmic model, and 0.08–0.41 for the power model. We observe the highest values of R^2 for the VER datasets, while the R^2 doesn't exceed 0.22 for all models on the ASC and DES datasets. The datasets with systematically almost-null values of R^2 are ASC18 and ASC19, whatever the regression model. In the next
325 section, we describe how the low values of R^2 are a consequence of the level of variance in each of the ground-displacement datasets.

Overall, the difference in R^2 between the linear model and the other models is less than 0.15 on all datasets. In Fig. 4a, the divergence of the curves representing the different models is noticeable only for extreme values of ground-displacement rate (below -3.5 and above 0 mm yr^{-1}), where the models are poorly constrained due to the lack of data in those value ranges.
330 For this reason, in the following we apply only the linear least-squares regression to explore the link between site-condition parameters and ground-displacement rates. This is not necessarily the linear model that best explains the physics linking the two phenomena, but at this stage we do not have enough evidence on the Grenoble case to opt for a more complex model. The simple linear model was also the choice of Verberne et al. (2025) to correlate the thickness variability of Tertiary and Quaternary deposits with compaction rates in the coastal plain of the Netherlands. The advantage of choosing the simplest
335 model is that it limits the number of parameters that constitute the model, and the scatter plot (Fig. 4a) shows that a more complex equation will not provide a significantly improved fit to the data.

We define the parameter “delta slope” as the difference between the maximum and minimum slope values obtained from the nine linear regressions between the site-condition parameter and each of the nine EGMS ground-displacement rate datasets. Similarly, the “delta intercept” is defined as the difference between the maximum and minimum intercept values from these
340 nine regressions. In the following, we attempt to optimize the linear correlations by minimizing delta slope and delta intercept while increasing the R^2 with additional processing on the data. We also provide a physical and/or technical interpretation for the slope and intercept values obtained.

2.4.2 Impact of the variance in the EGMS datasets on the slope of a linear model

As explained in the previous section, we apply the normal linear regression. The expression of this model is the following:

345
$$Y = a \cdot X + b \tag{3}$$

where X is the predictor variable (in our case, the downward ground-displacement rate at the MPs), Y the response variable (the resonance period T_0 for example), a is the slope, and b the intercept of the model. Using the least-squares regression method, the slope and the intercept can be expressed as (Draper and Smith, 1998):

$$a = \frac{\text{cov}(X, Y)}{\text{var}(X)} \tag{4}$$



$$b = \bar{Y} - a \cdot \bar{X} \quad (5)$$

where $\text{cov}(X,Y)$ is the covariance of X and Y , $\text{var}(X)$ is the variance of X , $\bar{Y}$ is the mean of Y , and $\bar{X}$ the mean of X . As shown in Eq. 4, the slope of the linear model is directly linked to the variance of the predictor variable X : the higher the variance, the closer to 0 the slope. On the contrary, reducing the variance of the predictor variable increases the slope of the linear model. This observation is also called the regression-dilution phenomenon, as described by Hughes (1993) and Hutcheon et al. (2010). According to these authors, this phenomenon is related to the uncertainties in the predictor-variable dataset or to its random measurement errors. Greater errors or uncertainties will inevitably lead to a flattening of the linear model.

To deal with this problem, they recommend using more precise measurements or repeated measurements to better estimate the true values. In our study, we have nine datasets for the predictor variable, acquired through different geometries and at different time periods, all supposed to represent the same observation (the vertical displacement rate of the Earth's surface). Because of the relationship between the variance of the predictor dataset and the resulting slope of the linear model, we can expect the slopes of the nine models derived from the nine ground-displacement datasets to differ if these datasets do not have exactly the same variance. Here, we take advantage of the repeatability of the ground-displacement measurements to assess how their variance impacts the linear model we aim to derive.

Table 1 gathers some statistical information describing the nine ground-displacement rate datasets, together with the corresponding slope and R^2 of an initial linear least-squares regression performed between the T_0 and the closest value in space of ground-displacement rate. We observe that the variance of the ground-displacement rates is always twice larger on the ASC and DES datasets (> 1.2), compared to the VER datasets (0.56 to 0.77). This is expected because EGMS averages several measurement points from both Descending and Ascending traces on a regular 100-m grid to compute the Ortho product, which causes a variance reduction in the VER datasets due to that spatial averaging of points. For the same reason, the VER datasets always have the lowest number of MPs. Due to their lower variance, we also expect the linear correlations obtained with the VER datasets to better perform in terms of R^2 , at the cost of spatial resolution. This expectation is confirmed, where the R^2 of the regression tends to decrease as the variance of the dataset increases. As observed in Table 1, the median of the displacement rates is variable from one dataset to another, ranging from -1.06 to -0.39 mm yr^{-1} . The difference in median rate between the ASC and DES for the same acquisition period (2015–2021, 2018–2022 or 2019–2023) was expected due to the difference in satellite acquisition geometry, a known cause of acquisition bias in the measurement of the ground displacement. However, for the same product (ASC, DES or VER) across different acquisition periods, there are still some discrepancies in the median rate of the MPs. These discrepancies are partly observed in the variations of ground-displacement rates at the edges of the basin (Fig. 2).

In theory, these latter differences should have been eliminated with the GNSS calibration performed by EGMS (Sect. 2.3). The fact that some offsets persist suggests that the ground-displacement rates provided by EGMS are not fully absolute, at least not for the relatively low amplitudes of displacement rate observed in Grenoble (between -5 and +2 mm yr^{-1}), and confirms that the EGMS processing of the raw InSAR data varies from one time period to another.



Table 1. Values of variance, median, and number of available MPs (measurement points) in the nine datasets of vertical ground-displacement rate, and in the whole area of interest, before and after quality filtering of the MPs (temporal coherence ≥ 0.825 and RMSE ≤ 2.75 ; see Sect. 3.3), for all datasets available in EGMS at the time of this study. The slope and the R^2 of the initial linear correlation between the T_0 and the closest value in space of ground-displacement rate, and without further data processing, are also displayed (see Sect. 2.4.2).

EGMS dataset	Variance of ground-displacement rates ($\text{mm}^2 \text{yr}^{-2}$)		Median of ground-displacement rates (mm yr^{-1})		Number of MPs		Slope of the initial linear model	R^2 of the initial linear model
	Before MP quality filter	After MP quality filter	Before MP quality filter	After MP quality filter	Before MP quality filter	After MP quality filter		
ASC15	1.27	0.81	-0.52	-0.52	590 158	48 780	-0.34	0.11
ASC18	1.62	0.89	-0.39	-0.39	613 848	180 406	-0.26	0.08
ASC19	1.68	0.94	-0.52	-0.52	616 302	180 735	-0.24	0.08
DES15	1.26	0.84	-1.06	-1.19	558 509	40 918	-0.41	0.18
DES18	1.58	0.89	-0.79	-0.91	589 859	167 616	-0.33	0.15
DES19	2.22	1.00	-0.67	-0.79	912 044	170 983	-0.27	0.11
VER15	0.56	0.54	-0.70	-0.70	23 395	22 852	-0.79	0.26
VER18	0.63	0.61	-0.50	-0.50	23 702	23 324	-0.91	0.35
VER19	0.77	0.70	-0.40	-0.40	24 951	24 245	-0.91	0.38

As a result, the various datasets of ground-displacement rate cannot be compared straightforwardly. Nevertheless, we underline that all datasets presented in this study exhibit a visible downward ground-displacement rate inside the Grenoble basin. This stable dynamic suggests that a valid linear model can be derived for each of these datasets (even though some initial R^2 values are low, ranging 0.08–0.38, the overall linear trend can be improved). Any offset between the datasets will result solely in a difference in the intercept value of Eq. 3. Regarding their differences in variance, we observe that the number of MPs captured by EGMS increases with time (Table 1), especially in mountainous environments (Fig. 2), and that the variance follows the same trend. For all datasets (correlations not shown), the slope of the initial linear-correlation model ranges from -0.91 to -0.24, resulting in a delta slope of 0.67. As expected, the slope of the initial regression has a high variability from one dataset to another, in relation with the variance in the dataset of ground-displacement rate (see Eq. 4). This large delta slope over the nine datasets indicates that additional processing over the data, aimed at reducing the delta slope, is required to derive a single correlation model that would be independent of the ground-displacement dataset. This is the objective of Sect. 3.



3 Data processing, impact of MP quality, evaluation criteria for optimized linear correlations

395 3.1 Preliminary processing on each dataset

One particularity of the Grenoble basin is that some areas of the Y-valley are prone to global 2D or 3D resonance of seismic waves in the narrowest and deepest parts of the basin. This effect differs from the 1D resonance of stationary *S*-waves trapped in the soil column overlying a strong impedance contrast. When the thickness of the sediment layers is of the same order as the width of the valley and the impedance contrast between the sediments and the seismic bedrock is large enough, lateral interference of surface waves generated at the valley edges and vertical interference of body waves result in the formation of standing waves (Bard and Bouchon, 1985). Such 2D/3D resonance has been observed in Alpine valleys (Roten et al., 2006; Le Roux et al., 2012; Ermert et al., 2014). The standing waves exhibit fundamental resonance modes depending on the direction: in a 2D valley, perpendicular to the valley axis and parallel to the valley axis. The peak period measured by H/V is no longer the 1D fundamental period of the *S*-waves (T_0), but rather the fundamental period of the standing-wave modes that occur at a shorter period compared to the 1D case. In the Grenoble basin, Hobiger (2005) has observed such resonance phenomena in the western and eastern valley branches of the Grenoble basin, with measured T_0 underestimating the theoretical 1D T_0 by 33 % to 20 %, respectively.

These standing waves also exhibit constant resonance periods from one edge of the valley to the other, meaning they do not vary with local sediment thickness. As our study aims at linking the ground-displacement rates with the T_0 , we need to exclude H/V measurement sites where the global resonance can occur, by identifying the existence of resonance modes occurring at orthogonal directions. We must also exclude sites near the basin edge that show significant azimuthal variation in T_0 , as this is a signature of the complex wave-propagation characteristics associated with lateral heterogeneities (Matsushima et al., 2017).

We therefore follow the strategies proposed by Matsushima et al. (2017) and Sgattoni et al. (2023) based on the directionally dependence of H/V curves to identify sites exhibiting 2D/3D global resonances or peculiar basin-edge effects. At each H/V site (Fig. 1b), we perform a rotation of the horizontal component every 5 degrees and calculate the corresponding H/V curve. The extracted T_0 values for each considered azimuth are then compared. If the T_0 values are similar, wave propagation can be considered 1D, whereas a significant variation in T_0 with azimuth implies complex wave propagation or 2D/3D resonance. We thus remove the H/V measurement sites for which at least one of the following criteria is achieved: (i) the variation of T_0 across all azimuths is larger than 10 %, or (ii) at sites where the measured T_0 is longer than 3 s, the azimuthal difference between the two dominant resonance periods is between [70; 110] degrees. As a consequence, we exclude 202 H/V measurement sites (gray dots in Fig. 4b).

Furthermore, because the H/V measurements were done during different campaigns over more than 20 years, with sometimes the objective to densely characterize limited areas, their points are not regularly distributed in the basin and there are several clusters of high-density H/V measurement points (Fig. 1b). These clusters can induce a bias in the linear regression, as they increase the weight of recurrent pairs of ground-displacement rates and H/V measurements at the same location, compared to isolated pairs of values. To prevent this, we attribute a weight to each T_0 value in the regression calculation, which is the inverse of the number of other available T_0 in a radius of 100 m (this dimension is equivalent to the resolution of the EGMS



VER dataset; see Sect. 2.3). Following the same principle of declustering, we apply the same weight attribution to the V_{S10} values. The H_{bed} values are not weighted because they are already regularly distributed in space.

430 The exclusion of the H/V measurements supposedly affected by global resonance and by peculiar effects close to the basin edge, and the association of the remaining ones with a weight in the correlation increases the value of R^2 obtained by linear regression ($R^2 = 0.30$ after removing the global resonance and applying the declustering, versus $R^2 = 0.26$ before those two steps, Fig. 4b).

3.2 Spatial association of a value of vertical ground-displacement rate to each site-condition value

435 As a first step to derive a model that predicts site-condition parameters from the vertical ground-displacement rates, it is necessary to spatially associate one value of the second with each value of the first. As the PS-InSAR is a method that is based on the availability of Persistent and Distributed Scatterers, which largely depends on land cover and the presence of buildings, there is no control on where the measurement points are done, although they can be very dense in urban areas (Crosetto et al., 2016). On the other hand, measurements of site conditions are mostly performed outside of buildings. Hence, the MPs of
 440 ground-displacement rate and of site-condition parameters are rarely superimposed in space.

The most straightforward method to associate a ground-displacement rate to a site-condition parameter value is to simply consider the closest point in space, as already shown in Fig. 4b (correlation indicated by the blue line; $R^2 = 0.30$ on VER15). However, this approach is likely to be unreliable, because of the intrinsic high variance of the ground-displacement rates. We notice that in most places, even inside the close area surrounding any H/V measurement point (e.g. within 100 m of radius), the
 445 values of ground-displacement rate have a high variance, up to several mm per year, which leads to regression-dilution effect (see Sect. 2.4.2) that prevents R^2 reaching high values. In the less urbanized areas (at the valley edges or close to fields and public gardens), the lack of MP leads to some pairs [ground-displacement rate; site-condition parameter] being more than a few hundreds meters apart. In that case, we can doubt the physical link between the ground-displacement rate and the site-condition parameter.

450 To address these two limitations, it is necessary to exploit multiple measures of ground-displacement rate to statistically determine a value that best reflects the true ground-displacement rate (*i.e.*, a value free of outliers, or free of very punctual phenomena that concern only the human structure on which a given MP is taken). By doing so, it reduces the variance of the ground-displacement rates to be correlated to the site-condition parameters. This is the basic principle of the median-filter technique for noise reduction in image and signal processing (Tukey, 1977; Gabbouj et al., 1992). But the crucial point in this
 455 spatial smoothing technique is to determine how many MPs are necessary for an adequate filtering, or to what spatial extent several MPs should be considered in order to extract a meaningful median value.

First of all, we exclude any site-condition parameter location that does not have at least 4 MPs of ground-displacement rates inside a 1-km^2 box centered on itself. This criterion prevents the use of ground-displacement rates that are too far from the site-condition parameter location, while ensuring a sufficient number of points to compute a median. We choose a minimum of
 460 4 MPs because, in the case of the VER product, where MPs are distributed on a regular grid, the site-condition parameter falls in most cases within a square composed of 4 MPs. For all site-condition parameters that fulfil this condition, we then apply a



median filter to the surrounding values of ground-displacement rate. The optimized parameters for this filtering function are determined hereafter.

Our objective is to evaluate the possibility of deriving a unique equation linking the vertical ground-displacement rates to the site-condition parameter(s), regardless of which EGMS dataset is considered as input. To achieve this, we aim to minimize the differences between each slope of the nine linear models (delta slope) that can be derived at the time of this study. To determine the spatial extent of the median filtering needed to minimize the delta slope, we test the effect of different smoothing half-widths ranging from 10 m to 200 m. For each half-width, the median value of the ground-displacement rates closer than that distance from a site-condition point are associated with the corresponding site-condition parameter value. If less than 4 MPs fall within the considered half-width, then the 4 closest MPs are still considered regardless of their distances, though these must remain within a 1-km² box as explained previously. This procedure can lead to varying numbers of MP being used at different site-condition points, yet it guarantees consistent spatial smoothing across the valley. This test to determine the optimized smoothing half-width is performed with T_0 in Sect. 3.4, and with H_{bed} and V_{S10} in Sect. 4.1.

It is worth noting that, despite the median filtering applied, and whatever its half-width, 21 out of the 716 pairs of [ground-displacement rate; T_0] still exhibit a strongly peculiar behavior, such as a very high ground-displacement rate for a rather low T_0 value. These points are clearly outliers, and are therefore identified and excluded before applying the correlation in Sect. 3.4. This peculiar behaviour can be explained, for example, by urban public works that disturb the ground and thus cause very localized ground displacement (likely temporary, but lasting long enough to impact the satellite measurement periods). A similar procedure is applied to the pairs based on H_{bed} , though not detailed later for the sake of conciseness.

3.3 Impact of the MP quality

As detailed in Sect. 2.3, each ground-displacement rate provided by EGMS comes with quality parameters, namely, the temporal coherence (TC) and the RMSE for the level 2b Calibrated products, and only the RMSE for the level 3 Ortho products. In order to estimate the consistency of the ground-displacement rate and the level of noise in the displacement time series of a MP, Crosetto and Solari (2023) and Crosetto et al. (2025) recommend considering both parameters. The value of TC ranges from 0 to 1, and is an indicator of the MP coherence with respect to the linear displacement rate (0 indicates no coherence, while 1 indicates high coherence; Capes and Passera, 2025). As an example, if the time series of a MP displacement exhibits a jump, or scattered values, the temporal coherence will be rather low (and the RMSE rather high). By selecting only MPs with the highest TC and the lowest RMSE, we ensure to consider only MPs that exhibit constant and linear motion with a low displacement-rate variance over time, and conversely, to exclude MPs that exhibit non-linear displacement behaviour, which could be caused, for example, by recent construction works. In order to determine whether selecting minimum TC and maximum RMSE improves the correlation between ground-displacement rates and site-condition parameters, we analyze how the delta slope and the delta intercept of the nine linear models evolve with chosen [TC; RMSE] selection.

We define 7 quality levels (level 1 being the most restrictive) corresponding to 7 pairs of [TC; RMSE] values. The minimal value allowed for the TC is 0.700 (level 7) and increases to 0.850 (level 1) in increments of 0.025. The maximal value for the RMSE is 4.00 (level 7) and decreases to 2.50 (level 1) in increments of 0.25. For the VER datasets, only the RMSE criterion

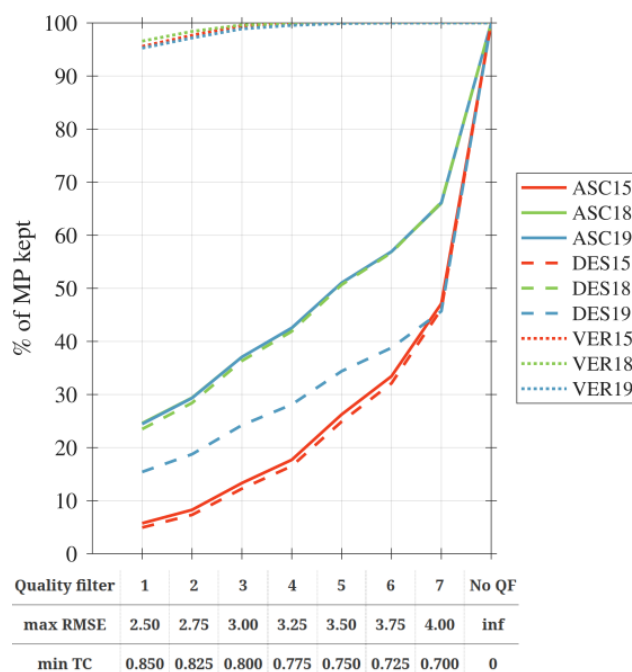


Figure 5. Evolution of the percentage of MPs kept after applying each level of quality filter (Sect. 3.3) on the nine datasets of vertical ground-displacement rate. Note that the curves for ASC18 and ASC19 are almost superimposed.

is applied, since the temporal coherence does not exist for these datasets. The bounding values are chosen in a way that with the lowest quality filter (level 7: $TC \geq 0.70$ and $RMSE \leq 4.0$), at least 45 % of the MP remains, while for the strictest filter (level 1: $TC \geq 0.85$ and $RMSE \leq 2.5$), this percentage drops to 5 %. Less restrictive levels of filter are not shown for the sake of clarity.

500 Figure 5 represents the percentage of MPs kept after application of the quality filtering for each EGMS dataset. This figure shows that as soon as a quality filter is applied, the loss of MPs can be very large (at least 30 %) for the ASC and DES datasets, meaning that the estimation of the ground-displacement rate is not reliable in a lot of points. It is important to note that despite the drastic reduction in the number of MPs, their number is still largely enough to perform the correlations, since there are hundreds of thousands of MPs before filtering (see Table 1). For the VER datasets, the exclusion of MPs is very limited,
 505 even for the most restrictive quality filter n°1. This observation is expected because, to compute a MP in the VER products, EGMS averages all available MPs within a 100-m radius from the Ascending and Descending components, hence reducing the variance of the initial measures (Crosetto and Solari, 2023; Ferretti et al., 2023). Furthermore, the DES19 dataset has a peculiar behaviour because its loss of MPs is larger compared to the ASC19. This means that despite the number of MPs being the largest in this dataset (see Table 1), the quality associated with them is generally lower.

510 Figure 6 shows, at different spatial scales, maps of ground-displacement rate obtained before and after applying the level 2 quality filtering ($TC \geq 0.825$ and $RMSE \leq 2.75$), for the DES19 dataset. Even at a large scale (Fig. 6a and 6b), differences are



visible between the two maps, particularly along the edges of the basin, with displacement rates closer to zero in the filtered version (Fig. 6b), while the center of the basin is relatively unchanged in both maps. Zooms at the kilometer scale show the impact of the quality filter at small spatial scales, which varies depending on whether we are looking at an urban area (Fig. 6c and 6d) or at a mountain area (Fig. 6e and 6f). Many MPs in the mountainous area are discarded by the quality filtering (Fig. 6f) because the density and quality of EGMS MPs decrease in non-urbanized areas, where stable radar scatterers are less abundant. On the contrary, the MPs of highest quality are mainly located in the urbanized area (Fig. 6d) because buildings and man-made structures act as strong and stable reflectors both in space and time.

In Fig. 6c, the intrinsic variance of the ground-displacement rates at short (< 100 m) spatial scale is clearly visible. This is due to the fact that the InSAR technique is sensitive to all kinds of millimetric displacements: ground deformation due to the sediment compaction, but also local thermal expansion of buildings for example. However, as shown in Fig. 6d, the quality filtering of the MPs helps in reducing this variance. Table 1 indicates that at the scale of the whole study area, the variance of the ground-displacement rates is reduced by at least 30 % on the ASC and DES datasets for the level-2 quality filtering, while it is almost unchanged for the VER datasets. The counterpart of this reduction is a significant drop in the number of MPs (up to 93 % of the PS are discarded for ASC and DES datasets for that level of quality filtering, while the loss is only of a few points on the VER datasets). Note that the DES19 dataset has the largest variance, before and after quality filtering (Table 1).

However, in order to produce the Ortho product (level 3, VER datasets), EGMS does not proceed to any quality filter of the MPs from the Ascending and Descending tracks (Passera, 2026). This means that low quality MPs can also impact the VER datasets when a large proportion of them are present within a 100 m by 100 m cell in one of the two initial tracks. In that sense, our implementation of a quality filter on the MPs of the ASC and DES datasets is more strict than the EGMS processing to generate the VER datasets.

For each of the quality filters described above, we apply the spatial median smoothing described in Sect. 3.2 on the datasets of vertical ground-displacement rates. Then, the least-squares linear regression between them and the T_0 dataset is performed for every possible combination of smoothing half-widths and quality filters. In Sect. 3.4, we evaluate how these processings impact the delta-slope value of the nine linear models, in order to identify which combination of smoothing half-width and quality filter minimizes the delta slope.

3.4 Optimization of the linear correlation between T_0 and vertical ground-displacement rates

The impact of the spatial smoothing (Sect. 3.2) and of the quality filtering (Sect. 3.3) on the parameters of the linear models obtained after least-squares regression between the nine EGMS datasets of vertical ground-displacement rates and T_0 is shown in Fig. 7, left column. The parameters we examine are the slope of the linear model, its intercept, and the variance of the data used in the correlation. For each combination of smoothing half-width and quality filter, we obtain 9 models and thus 9 values for these parameters. In order to define the optimized linear model that is as independent as possible from the EGMS dataset, we need to identify the combination that minimizes the L1-norm deviation between the 9 values of each parameter (referred to as delta slope, delta intercept, delta variance).

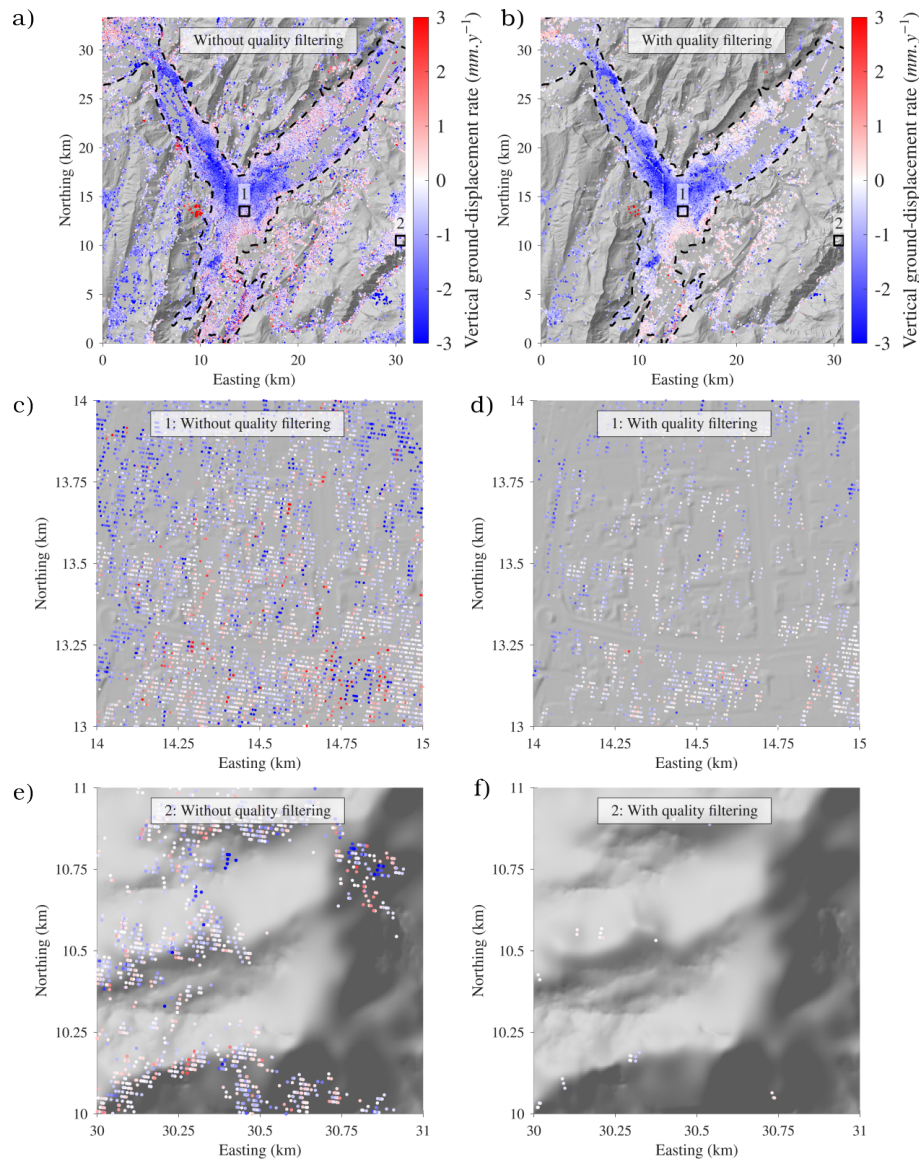


Figure 6. Impact of quality filtering on the MPs of vertical ground-displacement rate illustrated on the DES19 dataset, by comparing the obtained maps without quality filtering (left column) and with a quality filter (right column) configured by temporal coherence ≥ 0.825 and $\text{RMSE} \leq 2.75$ (see Sect. 3.3 and 3.4), for the whole area of Grenoble including basin and mountains (a and b), for a 1-km² zoom inside the densely-urbanized city center (c and d), and for another 1-km² zoom in a non-urbanized mountainous area (e and f). Both zoom locations are indicated by the numbered black squares on the top panels.

545 Figure 7a shows the evolution of delta slope. Regarding the impact of the spatial smoothing of the ground-displacement rates, the value of delta slope decreases with the smoothing half-width, from 10 m to 120 m, then tends to slightly increase

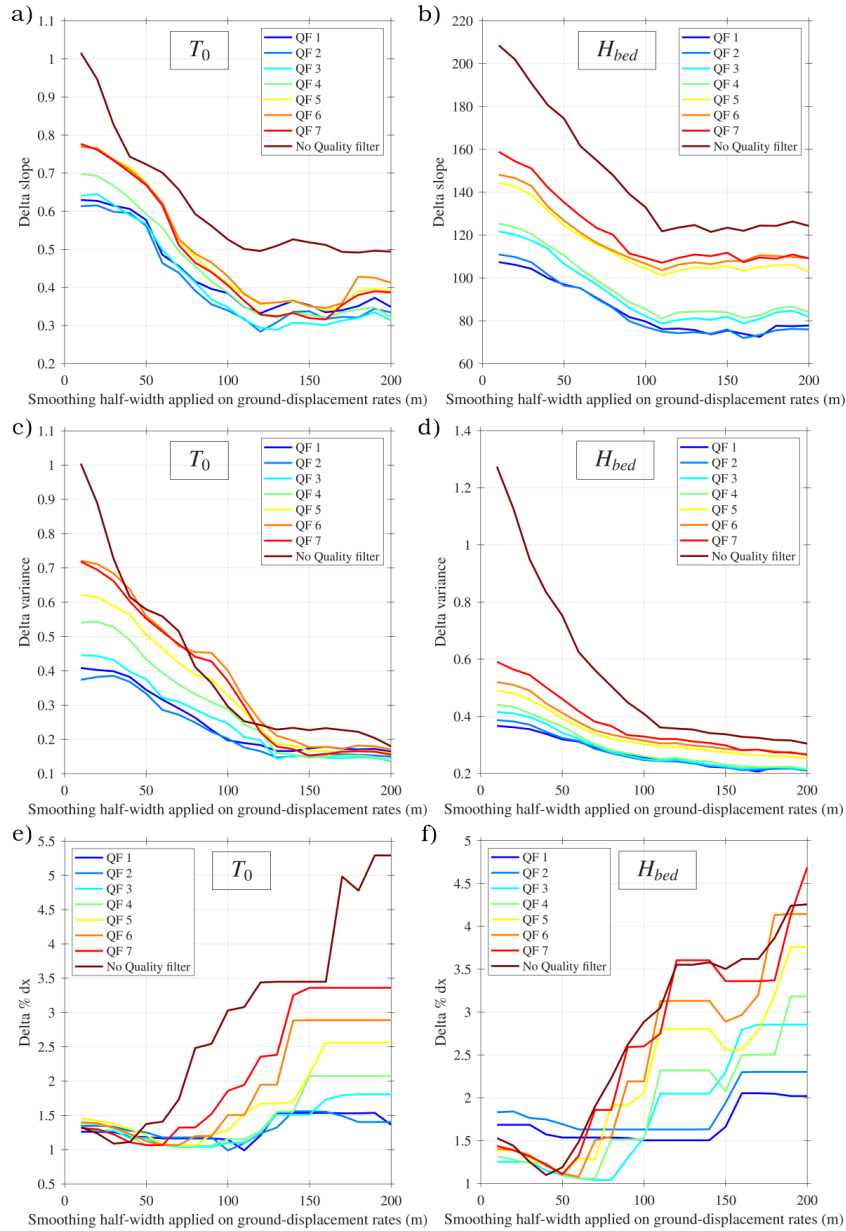


Figure 7. Evolution of the parameters delta slope (a and b), delta variance (c and d) and delta %dx (e and f) as a function of the smoothing half-width (x-axis) and quality filtering (QF, colored lines) applied on the MPs of vertical ground-displacement rate, for their linear regression with T_0 (left column) and with H_{bed} (right column). These delta values represent the difference between the maximum and minimum values of the considered parameter across the nine EGMS datasets used in this study (see Sect. 3.4).

for larger half-widths. As for the impact of the quality filter (colored lines), it can be observed that the delta slope decreases as



the quality filter becomes stricter. The minimal value of delta slope is found for a smoothing half-width of 120 m and for the quality filter $n^{\circ}2$ (temporal coherence ≥ 0.825 and $RMSE \leq 2.75$).

550 The delta variance (Fig. 7c) is also reduced by both increasing the smoothing half-width and the exclusion of MPs of poor quality. This is an expected observation, since these two processes are specifically designed to reduce variance. However, applying a smoothing with a large half-width or applying a strict quality filtering inevitably results in a loss of spatial resolution. To preserve the high spatial resolution of the MPs as much as possible, we have to also keep the smoothing half-width as moderate as possible. The delta slope is minimized for a smoothing half-width of 120 m, which also corresponds to one of the
 555 lowest values of delta variance. Larger half-widths further reduce the delta variance, but they also increase the delta slope; the reduction in delta variance appears too negligible to justify choosing a smoothing half-width greater than 120 m.

Figure 8 displays the nine scatter plots and optimized linear correlations obtained after all the processing steps described in Sect. 3.1 to 3.3, and by applying the optimized choice of a 120-m smoothing half-width combined with the quality filter $n^{\circ}2$ (temporal coherence ≥ 0.825 and $RMSE \leq 2.75$). Table 2 summarizes the resulting parameters. As expected, the variance of
 560 the ground-displacement rates has been decreased (compare the scatter plots in Fig. 8 with the one in Fig. 4b), which leads to increased slopes in the optimized models compared to the initial ones (initial results given in Table 1 and to be compared with the optimized ones in Table 2; in absolute value: at least $+0.54 \text{ s mm}^{-1} \text{ yr}$). The resulting delta slope is now 0.29, which is an improvement compared to the results on the initial models (delta slope = 0.67). The R^2 now ranges from 0.38 to 0.57, also showing a significant increase in the level of correlation (compared to the initial R^2 given in Table 1).

565 It remains to examine the impact of the processing on the delta intercept. It has already been discussed in Sect. 2.4.2 that the values of ground-displacement rate can not be considered as fully absolute, hence, the values of intercept of the nine linear models can not be straightforwardly compared, because at first order they are linked to the shift of median ground-displacement rate between each dataset (Table 1). All of the nine values of intercept are significantly positive (Table 2).

Moreover, a null ground-displacement rate on the bedrock surrounding the sedimentary valley would be achieved only if it
 570 is free of large-scale tectonic motion affecting the whole area, such as global uplift for example. Since the EGMS datasets used in this study are calibrated with a GNSS model that takes into account those kinds of large-scale deformation (Passera, 2026), the positive value of intercept could be the result of this calibration reflecting weak tectonic uplift in the area of Grenoble. This uplift, although small in magnitude, has indeed been verified by geodetic measurements (Serpelloni et al., 2013; Nocquet et al., 2016; Sánchez et al., 2018; Sternai et al., 2019).

575 Addressing this issue on the intercepts requires a dedicated referencing of the vertical ground-displacement rates that we developed specifically for this study. For the sake of clarity, our referencing procedure is described in the Appendix A1. To sum up, it is based on the observation that the required shift that should be applied to the ground-displacement rates to correct for the nonzero intercept in each of the linear correlations (denoted dx in the following) corresponds to a percentile (denoted $\%dx$) almost identical in all the nine distributions of ground-displacement rates. This enabled us to develop a statistical reference
 580 framework as described in the Appendix A1.

Figure 9 is a flowchart that summarizes all the different steps implemented to obtain the optimized T_0 model presented in this work (left side of the flowchart).

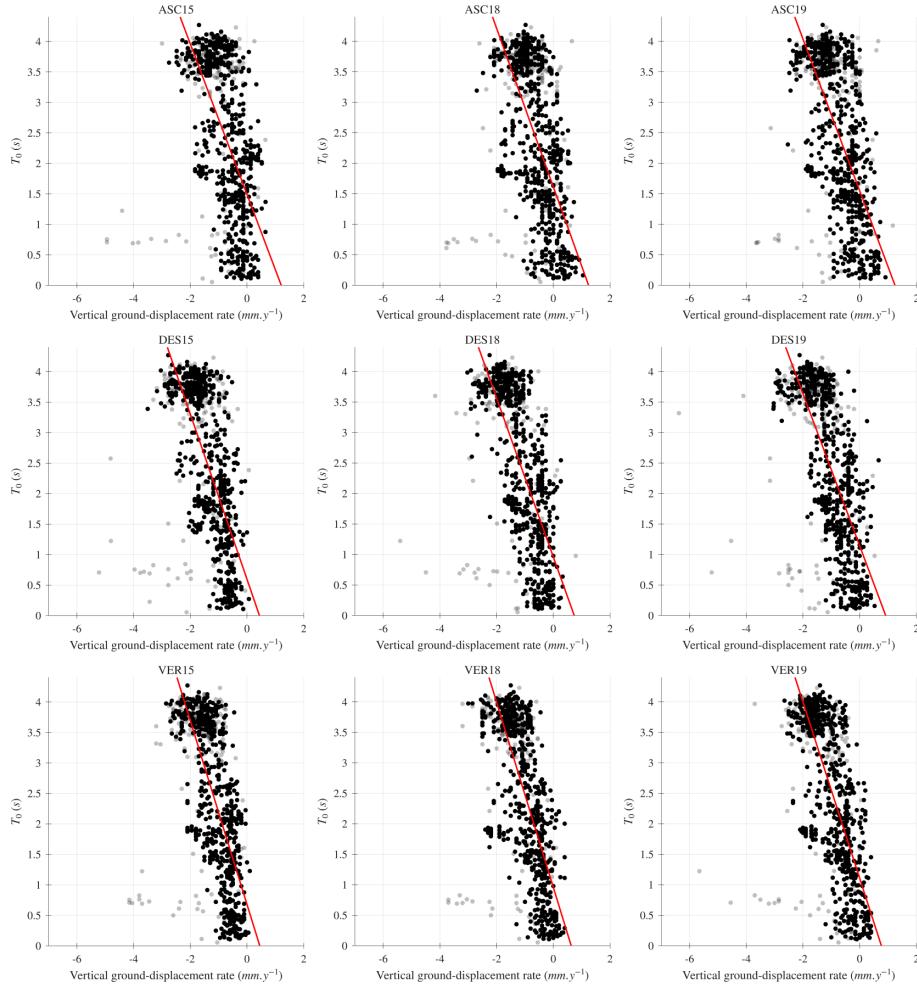


Figure 8. Scatter plots and ordinary least-squares linear regressions of the vertical ground-displacement rates with the resonance periods T_0 in the Grenoble basin, for the nine datasets of ground-displacement rate shown in Fig. 2. All data are processed according to Sect. 3, including spatial smoothing and quality filtering of the ground-displacement rates. The slope, intercept and R^2 of each linear fitting (red lines) are given in Table 2. Gray points are defined either as outliers or as MPs where the value of T_0 may be biased by global resonance (see Sect. 3.1), and are therefore not considered in the regression calculation. The used EGMS datasets are indicated at top of each plot.



Table 2. Results of the nine optimized linear correlations obtained between the vertical ground-displacement rates and the fundamental-resonance periods T_0 . For each EGMS dataset, the slope and the intercept of the linear model are computed with the ordinary least-squares linear regression, and the corresponding coefficient of determination (R^2 ; Rawlings et al., 1998) is given. The value of dx corresponds to the value of ground-displacement rate needed to shift their distribution in order to correct for the non-zero value of the intercept. We also indicate the percentile of this dx value ($\%dx$) in the distribution when considering all the ground-displacement rates in the whole Grenoble area (basin and mountains).

EGMS dataset	Slope of the optimized T_0 linear model	Intercept of the optimized T_0 linear model	R^2	dx (mm yr^{-1})	$\%dx$
ASC15	-1.23	1.49	0.38	1.21	99.33
ASC18	-1.30	1.61	0.46	1.24	98.44
ASC19	-1.25	1.55	0.46	1.25	98.77
DES15	-1.36	0.60	0.50	0.44	99.11
DES18	-1.30	0.96	0.51	0.74	98.24
DES19	-1.25	1.14	0.52	0.92	98.10
VER15	-1.51	0.68	0.52	0.45	99.18
VER18	-1.52	0.96	0.56	0.63	98.35
VER19	-1.45	1.11	0.57	0.77	98.63

4 Adequacy of various site-condition parameters to vertical ground-displacement rates, application and accuracy of final model

585 4.1 Results of the linear correlation of vertical ground-displacement rates with other available site-condition parameters in Grenoble

As mentioned in Sect. 2.2, we have at our disposal four other parameters to compare with the vertical ground-displacement rates: H_{bed} , V_{S10} , $\text{Build}_{\text{Vol}}$ and $\text{Build}_{\text{Age}}$. Other studies of land subsidence in alluvial valleys around the world frequently show that Holocene soil layers tend to compact more rapidly than older Quaternary sediments (Becker and Sultan, 2009; Higgins
 590 et al., 2014). Most of the infill of the Grenoble basin is composed of lacustrine sediments, deposited during the Pleistocene after the Würm glacial period and younger than 34 300 years (Nicoud et al., 2002). They constitute a very large proportion

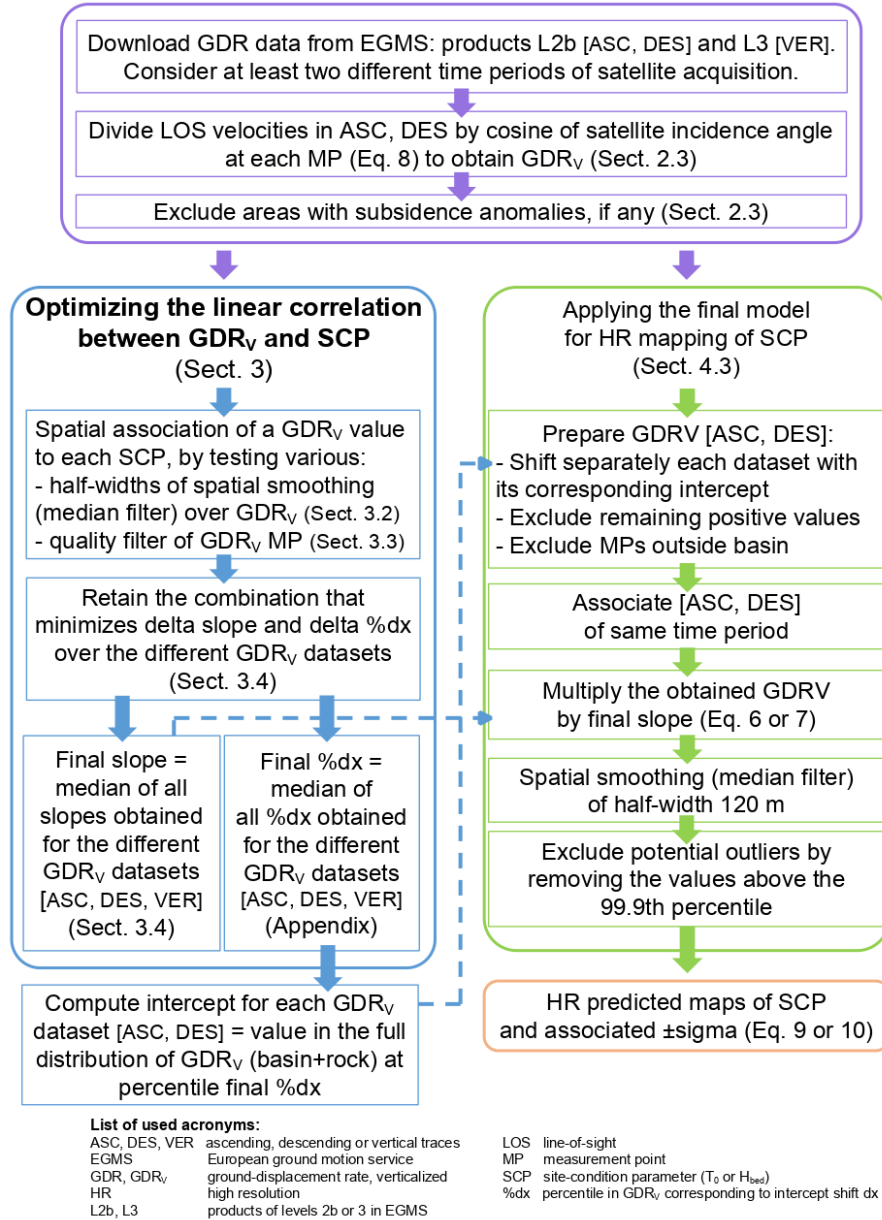


Figure 9. Flowchart summarizing the different steps performed in this study in order to: (i) optimize the linear correlation between the vertical ground-displacement rates and the site-condition parameters (blue box) and (ii) use the obtained final linear model for the high-resolution mapping of site-condition parameters, T_0 and H_{bed} , and the associated sigma (green box). The corresponding explanatory sections are indicated. Note that this processing has been developed only in the Grenoble area, and that it might not operate in strictly the same way for other areas. The list of the acronyms used in the flowchart is indicated at the bottom.



(several hundred meters thick) of the sedimentary infill compared to more recent layers. The most superficial layer (variable thickness but no more than a few dozens of meters thick) is composed of alluviums from the two current rivers (Drac and Isère) crossing the valley. According to Nicoud et al. (2002), they deposited during the Holocene less than 12 000 years ago. We are interested in determining whether a more rapid compaction of the Holocene layer can be observed in the Grenoble basin from the EGMS observations, and whether it is a highly localized signal or a basin-wide dominant trend. Regarding $\text{Build}_{\text{Vol}}$ and $\text{Build}_{\text{Age}}$, as urbanization can influence the ground displacement (due to the added weight of new buildings on the soil), we need to assess whether their impact can be observed in our data.

First, the analysis of the first-order correlation between those four parameters and the vertical ground-displacement rates is done to assess whether they can better explain the rates observed in Grenoble compared to the fundamental resonance period T_0 . For $\text{Build}_{\text{Vol}}$ and $\text{Build}_{\text{Age}}$, since urbanization is not a continuous phenomenon, a preliminary processing is performed: for each cell in a 100-m regular grid, the most recent $\text{Build}_{\text{Age}}$ and the sum of the $\log_{10}$ of $\text{Build}_{\text{Vol}}$ of all the buildings contained within the cell are retained. Next, for the four parameters H_{bed} , V_{S10} , the 100-m grids of $\text{Build}_{\text{Vol}}$ and $\text{Build}_{\text{Age}}$, the same protocol as indicated in Sect. 3 is applied to determine the values of spatial smoothing and quality filter that minimize the delta slope over the nine linear least-squares regressions derived from the nine EGMS datasets of vertical ground-displacement rates.

The results obtained with H_{bed} are shown in Fig. 7, right column. Figure 7b shows the evolution of delta slope. The main result is that the parameters that minimize delta slope for T_0 (smoothing half-width 120 m and quality filter $n^{\circ}2$) also lead to a delta-slope value close to the minimal one for H_{bed} . As for the delta variance, it exhibits very similar behavior on T_0 (Fig. 7c) and H_{bed} (Fig. 7d). The nine optimized linear correlations obtained for H_{bed} after this processing are shown in Fig. 10. The protocol applied to obtain these results is described in Fig. 9, left side of the flowchart, and is fully identical to the one applied to T_0 . The gray points in Fig. 10 represent the outliers excluded from the correlation: 74 couples of [H_{bed} ; ground-displacement rates] values are clearly outliers on at least one of the datasets, and note that 29 of them are located in the zone of subsidence anomaly already highlighted in Sect. 2.4. Table 3 summarizes the main resulting parameters of the nine optimized linear correlations. The R^2 value is larger than 0.40 for all EGMS datasets, suggesting a significant level of correlation, and comparable to the one obtained with T_0 . Taken together, these results show that for two independent site-condition parameters (T_0 and H_{bed}), obtained with two different acquisition methods (the first with H/V noise measurements, the second with gravimetry measurements), the same protocol allows to obtain the optimized linear model linking the ground-displacement rates to T_0 or H_{bed} with a $R^2 \geq 0.38$. Note also that dx (the values needed to shift the ground-displacement rates in order to correct for the nonzero intercepts; see Appendix A1) are almost similar for T_0 and H_{bed} for each dataset (Tables 2 and 3).

Regarding the site-condition parameter V_{S10} , and the urbanization parameters $\text{Build}_{\text{Vol}}$ or $\text{Build}_{\text{Age}}$, there is no satisfactory level of correlation with the ground-displacement rates ($R^2 < 0.1$, and delta slope not improved regardless of the spatial smoothing and quality filter applied on the ground-displacement rates; results not shown). The only two parameters for which a sufficient level of first-order correlation has been found are T_0 and H_{bed} . However, in the next section, to better quantify the relative contribution of all the available parameters when used in combination, we use a Random Forest regression analysis.

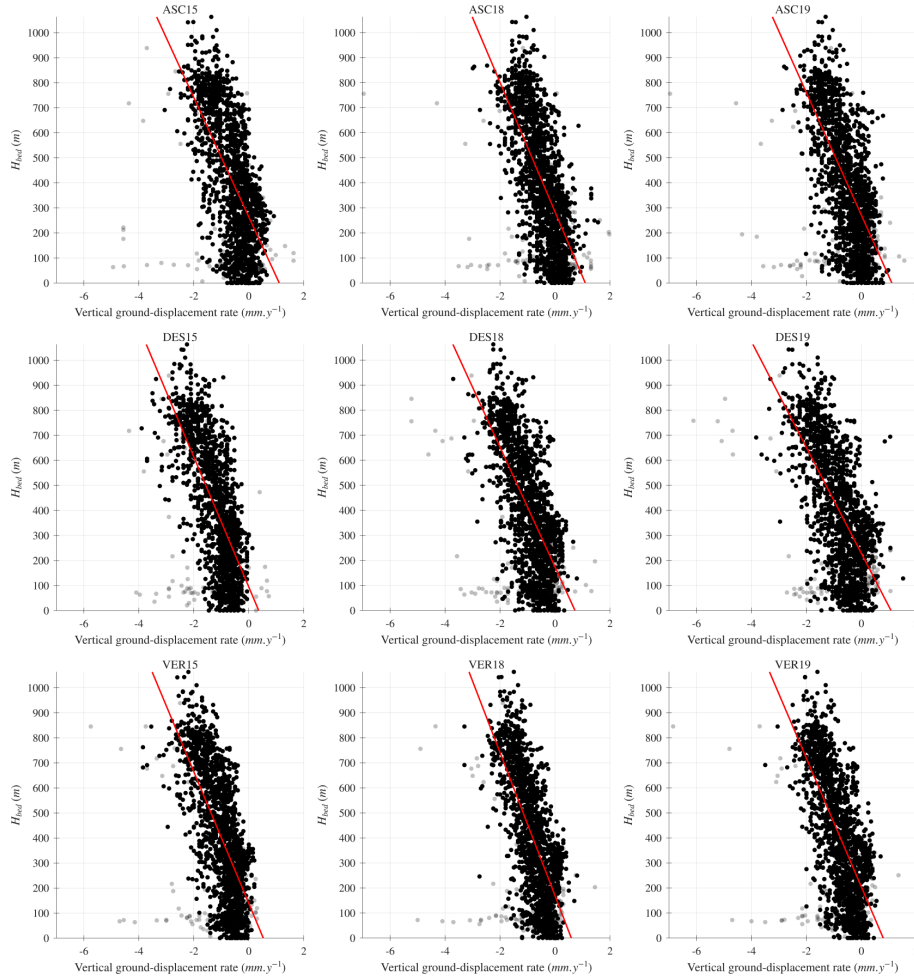


Figure 10. Scatter plots and ordinary least-squares linear regressions of the vertical ground-displacement rates with the bedrock depth H_{bed} in the Grenoble basin, for the nine datasets of ground-displacement rate shown in Fig. 2. All data are processed according to Sect. 3 and 4.1, including spatial smoothing and quality filtering of the ground-displacement rates. The slope, intercept and R^2 of each linear fitting (red lines) are given in Table 3. Gray points are defined as outliers (see Sect. 4.1) and are not considered in the regression calculation. The used EGMS datasets are indicated at top of each plot.

625 4.2 Relative contribution of each parameter

The Random Forest multi-parameter regression is based on the splitting of the dataset into multiple decision trees that are trained independently. The outcome of the algorithm is an average of the predictions by all the training trees (Breiman, 2001). It is particularly suitable for evaluating the relative importance of each input parameter (Grömping, 2009; Karashi et al., Submitted), in our case to study the relative influence of each parameter [T_0 , H_{bed} , V_{S10} , $Build_{Vol}$, $Build_{Age}$] when considered all together on the origins of the vertical ground-displacement rates observed in Grenoble.



Table 3. Results of the nine optimized linear correlations obtained between the vertical ground-displacement rates and the bedrock depths H_{bed} . For each EGMS dataset, the slope and the intercept of the linear model are computed with the ordinary least-squares linear regression, and the corresponding R^2 is given. The value of dx corresponds to the value of ground-displacement rate needed to shift their distribution in order to correct for the non-zero value of the intercept. We also indicate the percentile of this dx value (% dx) in the distribution when considering all the ground-displacement rates in the whole Grenoble area (basin and mountains).

EGMS dataset	Slope of the optimized H_{bed} linear model	Intercept of the optimized H_{bed} linear model	R^2	dx (mm yr^{-1})	% dx
ASC15	-238.40	264.03	0.40	1.11	99.08
ASC18	-258.57	283.40	0.44	1.10	97.79
ASC19	-244.68	270.74	0.42	1.11	98.23
DES15	-259.88	93.86	0.48	0.36	98.75
DES18	-239.37	173.08	0.44	0.72	98.24
DES19	-211.61	227.73	0.44	1.08	98.99
VER15	-263.01	138.48	0.46	0.53	99.40
VER18	-285.81	168.22	0.49	0.59	97.77
VER19	-257.02	203.81	0.46	0.79	98.63

Overfitting has to be considered in Random-Forest regression and it arises when the model learns the noise pattern in the dataset and reproduces this noise in the model. In order to avoid this issue, during the splitting of the dataset, a random fraction of the data is set aside and forms the “out-of-bag” (OOB) dataset, used to compare the predictions by the trained model on the OOB dataset. To estimate whether there is overfitting or not, two metrics are computed: the coefficient of determination (R^2) and the OOB coefficient of determination (OOB- R^2); those two values ranges 0 to 1, where 1 indicates a perfect fit of the model to the data and 0 no fit. If there is overfitting, the model trained on the main dataset will not perform well when used with the OOB dataset, hence, the two values R^2 and OOB- R^2 will be significantly different. The model parameters (numbers of trees and depth of the model) are adjusted until the model doesn’t show overfitting. The Random-Forest regression also returns the relative importance of each parameter used as an input to predict the output.

In the following, we use the function ExtraTreesRegressor from the Python sklearn package (Pedregosa et al., 2011). For this analysis, we focus on a limited study area (square of 5 km by 5 km, as shown in Fig. 11) close to the center of the valley, that



Table 4. Cases tested using Random-Forest regression (see Sect. 4.2) with different input and output parameters, and relative importance of the input parameters.

Case n°	Input parameters	Output parameter	R^2	OOB- R^2	Importance of the input parameters
1	T_0 ; V_{S10}	Vertical ground-displacement rates	0.62	0.58	90 %; 10 %
2	H_{bed} ; V_{S10}	Vertical ground-displacement rates	0.59	0.54	87 %; 13 %
3	Vertical ground-displacement rates; V_{S10}	T_0	0.65	0.62	92 %; 8 %
4	Vertical ground-displacement rates; V_{S10}	H_{bed}	0.61	0.57	90 %; 10 %
5	T_0 ; H_{bed} ; V_{S10} ; Build _{Age} ; Build _{Vol}	Vertical ground-displacement rates	0.65	0.61	81 %; 9 %; 9 %; 0 %, 1 %

is chosen especially because the bedrock depth is not correlated with its distance to the edges of the basin (complex 3D shape of the sediment-bedrock interface). By doing so, we ensure that the Random Forest will not capture a linear effect between the ground-displacement rates and their distance to the edges of the basin.

645 All the parameters given as input or output to the Random-Forest algorithm must be evaluated at the same spatial locations, although not necessarily over a regular and complete grid. For the sake of simplicity, only the VER15 dataset is used in the following tests; the effect of spatial smoothing and quality filtering is not tested here because the VER datasets are already smoothed over a length of 100 m and qualified by EGMS. As some of our data are sparse, we linearly interpolate each value of T_0 , H_{bed} and V_{S10} on a regular grid with points spaced 100 m apart. Then, the ground-displacement rate from the
 650 VER15 dataset closest to each point in this grid is kept. For the information relative to the buildings (Build_{Vol} and Build_{Age}), we proceed differently because interpolating those data doesn't make physical sense. Instead, for the volume, we sum the logarithm of the volumes of all buildings that are within a 100-m cell centered on each point of the grid. For the age, we keep only the most recent year of all the buildings that are located within each 100-m cell. Finally, if at least one of the parameters cannot be evaluated on a point of the grid due to lack of data, then this point is excluded from the Random-Forest analysis. The
 655 resulting maps of the six parameters are displayed in Fig. 11.

Table 4 summarizes the results of a few significant tests among the ones performed. When two site-condition parameters are used in input to predict the ground-displacement rates, the couples with the highest R^2 (≥ 0.59) are [T_0 ; V_{S10}] and [H_{bed} ; V_{S10}] (cases 1 and 2 in Table 4), with relative contributions [90 %; 10 %] and [87 %; 13 %], respectively. Note that the order of the input variables does not change the result. The use of T_0 or H_{bed} leads to the same performances, meaning that the two
 660 parameters are equivalent for the Random-Forest analysis. Indeed, by looking at Fig. 11a, 11b and 11c, one can observe that the three maps are very similar in terms of spatial features.

When the three site-condition parameters [T_0 ; H_{bed} ; V_{S10}] are used together as inputs to predict the ground-displacement rates, the value of R^2 is only slightly improved ($R^2 = 0.65$). The relative contribution of the parameters is [81 %; 9 %; 10 %].

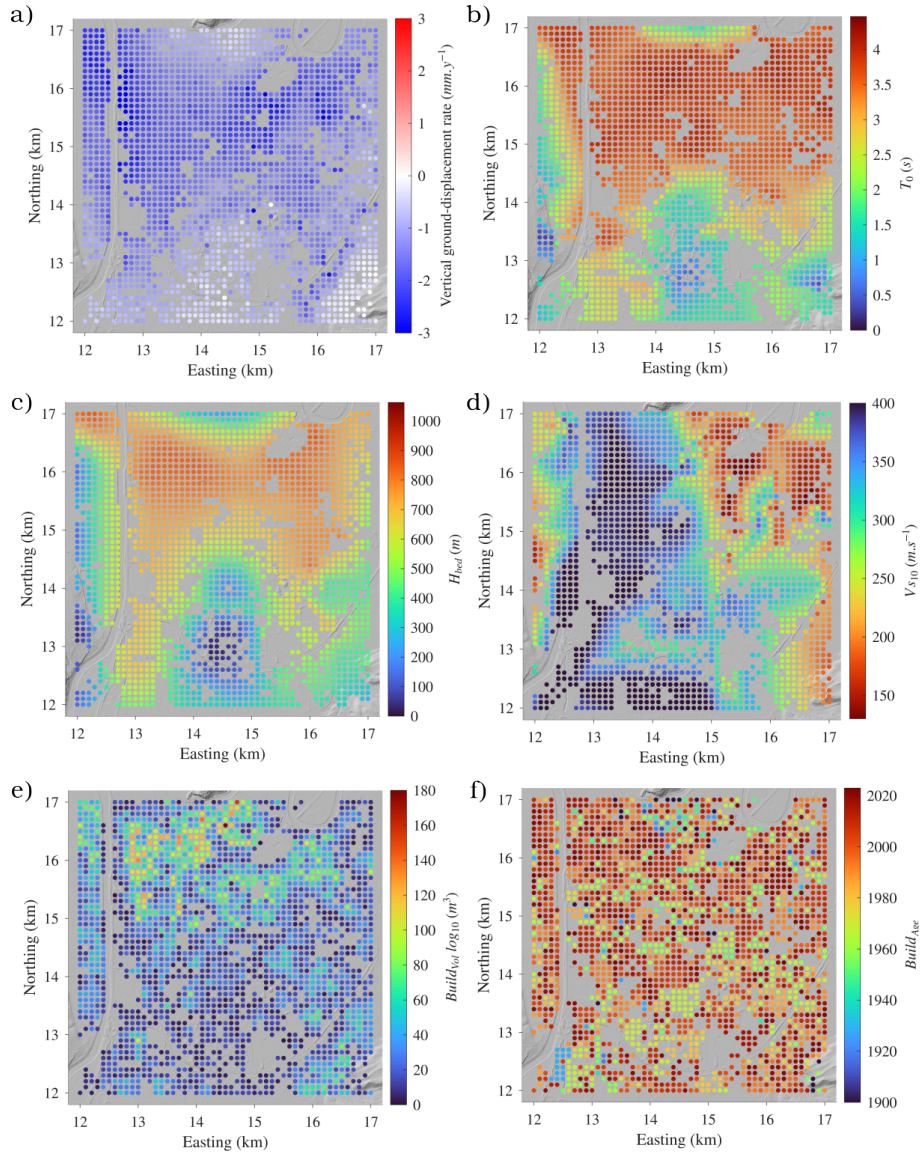


Figure 11. Maps of the parameters used as output (a) and inputs (b to f) in the Random-Forest analysis developed in Sect. 4.2. For the output in (a), the EGMS dataset selected for the ground-displacement rates is VER15. For the purposes of the calculation, all of these data are determined here on a regular but incomplete grid with values spaced 100 m apart. The combined inputs are T_0 (b), H_{bed} (c), V_{S10} (d), $Build_{Vol}$ (e) and $Build_{Age}$ (f). For (a), (b), (c) and (d), the data are linearly interpolated on the regular grid. For (e), at each cell of the grid, the value is the sum of the log of the building volumes within each cell. For (f), only the latest year of construction permit is considered for all the buildings that are included within each cell. If a value is missing for one of those six parameters, it is discarded for all others.

When the ground-displacement rates are used with V_{S10} as inputs to predict T_0 or H_{bed} (cases 3 and 4 in Table 4), V_{S10} still
 665 accounts for about 10 % of contribution and the ground-displacement rates for 90 %, with $R^2 \geq 0.61$. The performance of



the model is equivalent in both cases. These results show that adding the V_{S10} parameter in the model can lead to a slight but limited improvement of the R^2 , but the contribution of V_{S10} always remains moderate regardless of the configuration tested (around 10 %). This reflects that V_{S10} (Fig. 11d) does not show first-order correlation with the ground-displacement rate (Fig. 11a).

670 When building information $Build_{Vol}$ or $Build_{Age}$ (see Fig. 11e and 11f) are used in a combination of two input parameters, their relative contribution never exceeds 5 % and they tend to lead to models with lower values of R^2 , whatever is the other parameter used (not shown in Table 4). In the model with all possible inputs (T_0 , H_{bed} , V_{S10} , $Build_{Vol}$, $Build_{Age}$; case 5 in Table 4), the R^2 is not improved compared to simpler models, and the relative contributions are relatively unchanged (81 %; 9 %; 9 %; 0 %, 1 %). Hence, in these Random-Forest tests, we were unable to identify any configuration in which information
 675 on urbanization made a significant contribution to the model (*i.e.*, the contribution of urbanization never exceeds 5 %).

We conclude from this analysis that at the scale of the Grenoble basin, the impact of urbanization is not visible with the available parameters. This may be because the city consists largely of old buildings that have stopped settling (most of which are several decades old, if not older), while recently constructed buildings are in the minority within the area under consideration. We were able to observe the effect of the settlement at a few recent buildings in Grenoble on the vertical ground-displacement
 680 rates provided by EGMS, but this effect remains extremely localized to the building in question. Regarding the site-condition parameter V_{S10} that characterizes shallow Holocene sediments, in every case, its relative contribution is around 10 %, which can be considered as non-negligible. However, this impact remains too light in Grenoble's case to be clearly quantified by an empirical equation.

4.3 Application of the final models of T_0 and H_{bed} in Grenoble

685 The previous sections have allowed identifying optimized linear models that relate vertical ground-displacement rates of the soil to the two site-condition parameters T_0 and H_{bed} , with a good degree of reliability (R^2 ranging from 0.38 to 0.57), and in the Appendix A1, we described the referencing methodology to make those models fully independent of the initial EGMS dataset chosen as input. It is now possible to derive a single model that can be applied consistently to any EGMS dataset, even in future updates released by the Copernicus service. This section describes this single final model, how to apply it to estimate
 690 T_0 and H_{bed} at high spatial resolution in Grenoble, and related uncertainties.

In the final model, the slope in the linear equation is taken as the median value of the nine slopes determined previously (Table 2 for T_0 and Table 3 for H_{bed}). Regarding the null intercept implemented in the final model, the reader has to refer to the Appendix A1 for the detailed methodology to adjust the vertical ground-displacement rates accordingly. We recall also that the flowchart in Fig. 9 summarizes all these steps of application (right side of the flowchart).

695 Thus, the two final models, which apply to all the EGMS datasets tested, are as follows:

$$T_0(i) = -1.30 \cdot (GDR_V(i) - dx_{98.63^{th}}(GDR_V)) \quad (6)$$



$$H_{bed}(i) = -257 \cdot (GDR_V(i) - dx_{98.63^{th}}(GDR_V)) \quad (7)$$

where $T_0(i)$ and $H_{bed}(i)$ are the predicted values at each MP location i ; $GDR_V(i)$ the vertical ground-displacement rate of the considered MP without any spatial smoothing applied at this step, nor quality filtering, and $dx_{98.63^{th}}$ the 98.63th percentile value in the quality-filtered distribution of the full GDR_V dataset (basin and mountains) chosen as input (see Appendix A1 for the detailed computation of this parameter). Note that, after calculating these equations, further recommendations of processing must be considered, as described hereafter.

First, we recall that in order to retrieve the vertical ground-displacement rates (GDR_V , with negative values for downward motion), each value of ground-displacement rate in LOS (GDR_{LOS}) is beforehand divided by the corresponding value of cosine of the incidence angle α of the satellite, as follows:

$$GDR_V(i) = \frac{GDR_{LOS}(i)}{\cos(\alpha(i))} \quad (8)$$

The value of α is given for each MP in the EGMS products.

Second, as indicated by Eq. 6 and 7, the value at the 98.63th percentile (Appendix A1) is subtracted from all GDR_V values. This referencing step ensures that the predicted T_0 and H_{bed} are close to zero for the weakest displacement rates within the sedimentary basin. Third, despite the shift applied, it is necessary to delete all remaining positive values of ground-displacement rate, as they would result in negative predicted values of T_0 or H_{bed} , which is not a physical solution. These positive values, although few in number, occur simply because some MPs are affected by localized motions (for example, public works carried out on buildings during the satellite measurement period).

As one major interest is to exploit the high spatial density of the InSAR MPs as much as possible, and since the shift applied with the use of the 98.63th percentile allows comparing the ground-displacement rates of every dataset, it is now possible to merge the two ASC and DES datasets, for each time period (2015–2021; 2018–2022; 2019–2023). Indeed, due to their different acquisition geometry, the MPs of ASC and DES are not located at the same places, hence, merging them allows densifying the final predicted map of the site-condition parameters. Note that the methodology is also fully valid for the VER datasets, but to generate our final maps of predicted T_0 and H_{bed} , we deliberately decide to not use them, because the highest spatial resolution possible is fully achieved with the combination of the ASC and DES datasets.

To limit the impact of the intrinsic small-scale variance of the ground-displacement rates (visible in Fig. 6c), we recommend applying as the final step a median spatial smoothing on the merged GDR_V . Figure 12 shows the impact of various half-widths of spatial smoothing on the predicted values of T_0 (same findings on H_{bed} , not shown) using both merged ASC19 and DES19: for no smoothing, half-width 30 m, half-width 80 m and half-width 120 m. From this figure, it is possible to observe that without smoothing (Fig. 12a) the predicted values are noisy, highly variable at small spatial scales (over less than tens of meters). However, when a smoothing is applied (Fig. 12.b to 12.d), the noise is filtered out, giving a more reliable estimate of the predicted site-condition map. Here, we recommend applying a smoothing over a half-width 120-m box (*i.e.*, the same size

used to derive the optimized model). Note that no smoothing should be applied before the value $dx_{98.63^{\text{th}}}$ has been retrieved (as it is recalled by the flowchart in Fig. 9), since smoothing alters the statistical referencing of the dataset. Another option to
 730 reduce the variance of the GDR_V dataset would have been to apply a quality filtering of the MPs, however, this would have led to a loss in spatial resolution.

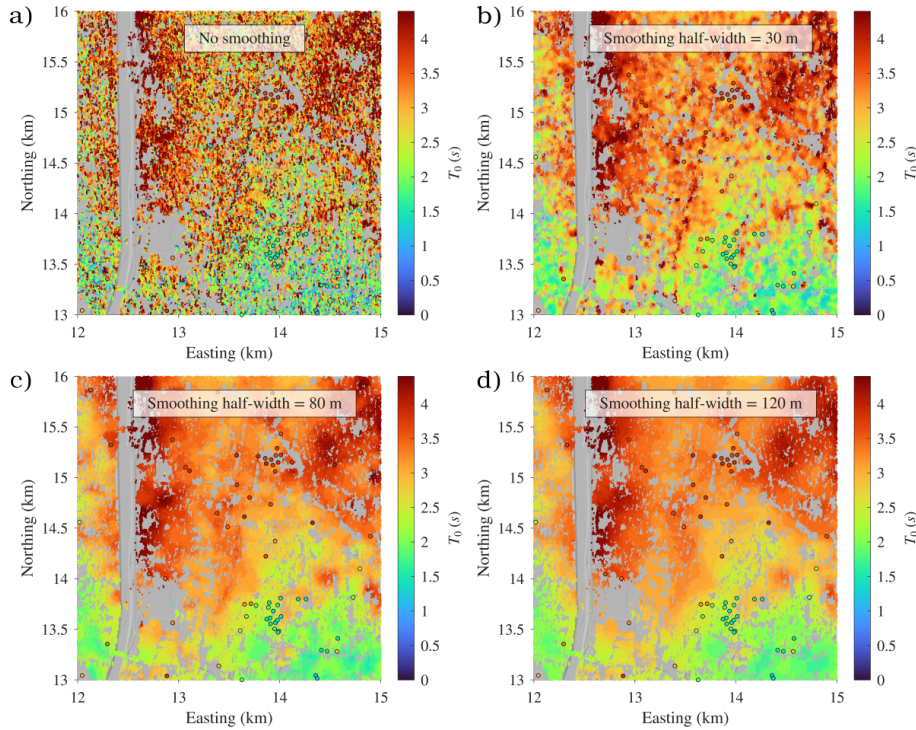


Figure 12. Maps of the predicted values of T_0 (color scale) in the center of the Grenoble basin as a function of the half-width of the smoothing window applied: (a) no smoothing, (b) smoothing of a half-width of 30 m, (c) 80 m and (d) 120 m. In these examples, the MPs used as inputs (*i.e.*, the rates of downward ground-displacement) are both the ASC19 and DES19 EGMS datasets. The initial T_0 estimates by the H/V method are shown as an overlay, represented by the dots encircled in black.

To estimate the uncertainties on the predicted values of T_0 and H_{bed} , we consider again the nine optimized models given in Table 2 for T_0 and Table 3 for H_{bed} . The highest uncertainty σ associated with each final value of T_0 (or H_{bed}) is half of the maximal one (obtained with the largest slope), minus the minimal one (obtained with the smallest slope) predicted by the
 735 nine optimized models. When related to the level of ground-displacement rate, we find that it is well fitted by two quadratic equations ($R^2 = 0.99$ for T_0 ; $R^2 = 0.95$ for H_{bed}):

$$\sigma T_0(i) = 0.015 \cdot GDR_V(i)^2 - 0.015 \cdot GDR_V(i) + 0.36 \quad (9)$$



$$\sigma H_{bed}(i) = 3.80 \cdot GDR_V(i)^2 - 0.096 \cdot GDR_V(i) + 62 \quad (10)$$

It should be noted that these equations show that the smallest uncertainties are 0.36 s for T_0 and 62 m for H_{bed} , but that they increase in proportion to the displacement rates. Those values of σ obtained are only slightly higher than the uncertainties associated with the initial and measured site-condition parameters used in the correlations, which is satisfactory. Despite the smoothing applied on GDR_V , a few predicted values of T_0 (or H_{bed}) are clearly overestimated, hence they are unlikely to be realistic predictions of the site-condition parameter value. Again, this may occur in specific areas where the displacement of a MP is not controlled primarily by the long-term motion of the natural ground. To remove those rare points, we advise to simply delete the 0.01 % of the maximal predicted values.

Figure 13 displays the final maps of the predicted values of T_0 and H_{bed} , e.g. for the 2018–2022 time period of the EGMS ASC and DES merged products, as well as the associated uncertainty. The maps of the predicted parameters are quite similar, so consistent, to the initial maps of the geophysical measurements (compare Fig. 13a with Fig. 1b, and Fig. 13c with Fig. 1c).

One key contribution lies in the number of estimation points for these two parameters, T_0 and H_{bed} , which has increased greatly with our methodology, without the need for additional field measurements: the initial number of T_0 from the H/V noise measurements is 924 (1747 for H_{bed} from the gravimetric measurements), while the amount of our predicted values is 307 159 (when using the 2018–2022 ASC-DES datasets). The spatial resolution achieved in the city centre of Grenoble reaches above 100 estimates in an area of 100 m by 100 m.

5 Discussion and interpretation of downward ground-displacement rates in the Grenoble urbanized basin

The causes of ground deformation of the Earth's surface rely on multiple processes and parameters, either purely natural or mixed with anthropogenic causes (Verberne et al., 2025). Natural compaction (or self-compaction) of the sediments due to isostatic sediment loading or consolidation of deposits is identified as one of the natural driving factors of downward and long-term ground displacements (Raspini et al., 2022). Indeed, many authors observed a link between the vertical displacement rates of the soil and the thickness of a so-called compressible layer of sediments, which is often found to be Holocene deposits (Törnqvist et al., 2008; Da Lio et al., 2018; Deng, 2025; Verberne et al., 2025). Observations around the world show that in this case, without anthropogenic causes, the downward displacement rates typically are of a few mm per year (Dixon et al., 2006; Meckel et al., 2006; Teatini et al., 2011; Chaussard et al., 2014), which is of the same order of magnitude as the rates measured by EGMS in the Grenoble sedimentary basin. For example, in Mexico City, because of the man-induced rapid subsidence ($> 30 \text{ cm yr}^{-1}$) due to water-pumping in very soft lacustrine sediments ($V_S < 100 \text{ m s}^{-1}$ from Olivares-Palomares et al. (2025)), Avilés and Pérez-Rocha (2010) use a power law to correlate the subsidence rates with the thicknesses of the topmost very compressible layer. Due to anthropogenic disruption, the rate at which the ground surface sinks is much larger than what is observed in natural-only conditions, hence, the non-linear model they obtain cannot be compared to the one derived in our study that shows a rather linear trend. However, in Grenoble, there are no such disruptions, which make it possible to study the long-term natural compaction of the sediments.

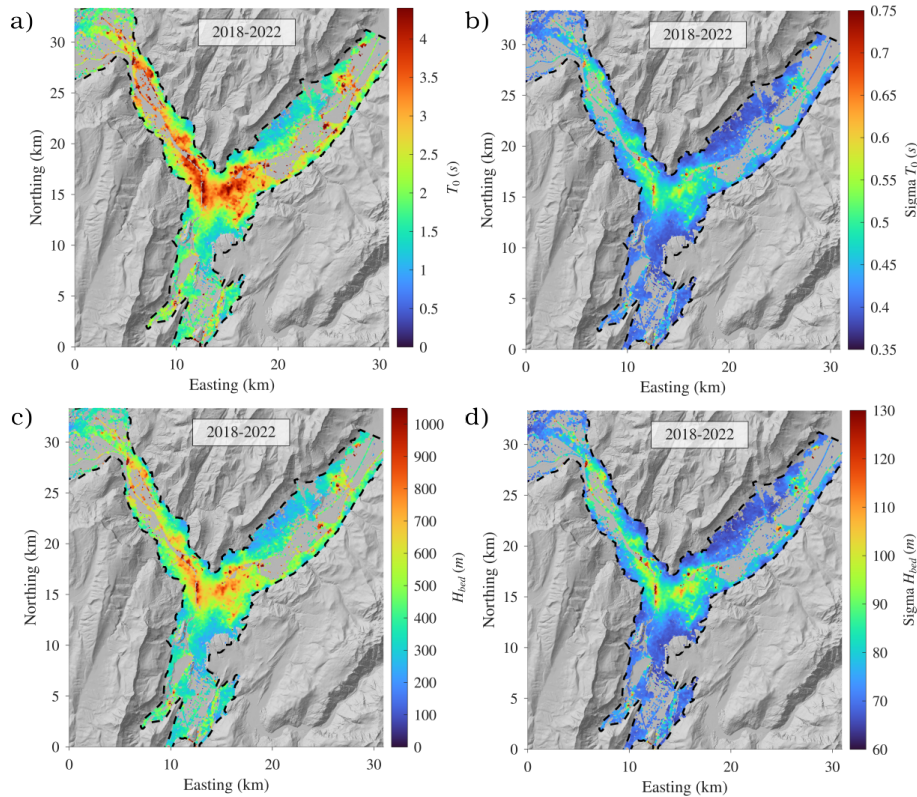


Figure 13. High-resolution maps of the predicted values of site-condition parameters in the Grenoble sedimentary basin using the final models developed in this study: for (a) the fundamental resonance period T_0 estimated by Eq. 6, with (b) its related uncertainty ($\pm$ sigma) estimated by Eq. 9, and (c) the bedrock depth H_{bed} estimated by Eq. 7, with (d) its related uncertainty ($\pm$ sigma) estimated by Eq. 10. The MPs used as input are both the ASC18 and DES18 datasets of vertical ground-displacement rates delivered by the Copernicus service EGMS, smoothed using a median filter with a half-width of 120 m.

770 In the literature, it is common to find a relationship between the thickness of the uppermost sediments from the Holocene age layer (Törnqvist et al., 2008; Teatini et al., 2011; Gebremichael et al., 2018) or the urbanization (Stramondo et al., 2008; Van Der Horst et al., 2018; Parsons, 2021) and the vertical ground-displacement rates. A phenomenon of the primary consolidation process of an anthropogenic land is observed by Cavalié et al. (2023) using PS-InSAR over the Nice Airport (France), which is built on reclaimed land. They measure the decrease over 30 years of the vertical ground-displacement rates over the airport,
 775 from 16 mm yr^{-1} to 8 mm yr^{-1} . In the Grenoble basin we observe very locally (*i.e.*, over a few MPs) that very recent constructions impact the ground-displacement time series, with a fast downward displacement that slows down after some years due to the ground settlement below the buildings. However, such local downward displacement rate does not control the overall displacement rates measured in Grenoble (see Section 4). Regarding the impact of the uppermost sediments, we had to exclude a small area of anomalous strong subsidence that could be related to very soft and saturated superficial sediments
 780 (solid black polygon in Fig. 2, Sect. 2.4). In the rest of the Grenoble basin, the impact of the superficial soil layer is highlighted



by the small but non-negligible contribution that VS10 has in the Random-Forest regression done in Sect. 4.2. However, this contribution cannot be generalized at the scale of the whole basin, because it is not dominant enough compared to the main driving phenomenon that operates at the full thickness of the basin's sediments.

Indeed, the lithology of the Grenoble sedimentary basin mostly consists of lacustrine clay deposits, with some sand and clay inclusions, that were deposited around 30 000 years ago (Nicoud et al., 2002). The distinctive feature with many other valleys is the relatively large thickness of the sediment layers, which is up to 1000 m (Vallon, 1999). The sedimentary infill in the Grenoble basin is predominantly of Pleistocene age rather than Holocene age, with the thickness of the deposits from this more recent period not exceeding a few tens of metres at most. We recall that we were able to quantify the link between the vertical ground-displacement rates measured at the surface by EGMS and the site-condition parameters T_0 and H_{bed} (which are related to the total sedimentary column down to the bedrock), but that it was not possible to do so for the parameter V_{S10} (which is related only to the most superficial and most recent alluvial deposits). From this observation, we can interpret the overall downward ground motion occurring in the Grenoble basin (delimited by the dashed black line in Fig. 2) as the result of the compaction of the whole thick sediment layer, due to the long-term consolidation process. It is more likely that the ground-displacement rate resulting from this natural compaction can be measured by EGMS in Grenoble because the thickness of the sedimentary infill is rather large.

Audet (1995) gives a mathematical framework to compute the 1D compaction of sediments due to their own weight (gravitational compaction expressed as thickness reduction), as a function of time, permeability and thickness of the sediments. The results show that for a 4-km thick sediment layer (the author is interested in the depth at which smectite transforms to illite), the system is still in active compaction after 15 Ma. This simplified modeling with a uniform sediment layer is compatible with the assumption that the whole Grenoble basin itself should still undergo active compaction throughout its entire thickness (up to 1 km), even though it is predominantly of Pleistocene age (less than 30 000 years; Nicoud et al., 2002). Kooi and de Vries (1998) also propose another 1D mathematical framework to estimate the natural compaction rate of shales, as a function of the permeability and porosity of the sediments. In order to understand the causes of the ground subsidence observed in the Netherlands, they show that for an initial thickness of 200 m, the compaction of shales can last for more than 30 000 years. The compaction rates they model are lower ($< 1 \text{ mm yr}^{-1}$) than the ones we observe in Grenoble ($> 1 \text{ mm yr}^{-1}$), but the total sedimentary column is significantly thicker in Grenoble's basin. From their synthetic modelling, Kooi and de Vries (1998) also indicate that the duration of self-compaction of a sedimentary layer, depending on its lithology and its permeability, and even after sedimentation has ceased, can in theory reach millions of years if the layer's thickness reaches several kilometers. Regarding the theoretical models from Audet (1995) and Kooi and de Vries (1998), the vertical displacement of the ground surface versus time is non-linear and decreases with time. After a sufficient geological time (from centuries to million years, highly variable depending on the lithology, permeability and initial thickness of the deposit), the rate tends to a constant low value, hence, when considering a small time period of only a few years with the satellite measurements, the behaviour of the soil compaction can appear as linear.

If the methodology developed in this study is applied elsewhere, the parameters (slopes and intercepts) of the derived T_0 and H_{bed} models are not expected to be identical to those of the case of Grenoble, due to technical and physical reasons.



Concerning the technical reasons, we observe that the slopes of the models are highly sensitive to (i) the variance of the EGMS dataset used as input, (ii) the potential outliers in the same dataset, (iii) the size of the smoothing window applied over it. As a comparison in the Grenoble basin, Michel et al. (2011) used a 150-m half-width smoothing box centered on the T_0 measurement points (a slightly larger size than the final one retained in our study), they exploited SAR data from satellites ESR-1 and ESR-2 (acquired between 1992 and 2000), and their other processing steps are significantly different from ours. As a consequence, the slope of their T_0 model is larger (-2.56) than the one presented here (-1.30), but it is not possible to interpret this difference. This remark is important, because if one wants to compare the slopes of models derived in different areas, the correlations must be applied on unified satellite data (processed by the same service), and the spatial smoothing of the ground-displacement rates must be of similar length. However, we acknowledge the fact that the adequate smoothing size should be proportional to the size of the target site. This issue should be assessed when testing our protocol on other valleys. For all these reasons, it is also not possible to directly compare the values of the slopes of other linear H_{bed} models available in the literature (e.g., from Deng, 2025; Verberne et al., 2025). However, the rather low slope values (-13.5 to -21.7, same unit as our study) obtained by Deng (2025) may be due to the fact that the sediments are much younger, hence compact faster than the ones observed by Verberne et al. (2025), who obtained a slope of -109, while our H_{bed} model gives a median slope of -257.

As for the physical reasons, the theoretical models (e.g., Audet, 1995; Kooi and de Vries, 1998) describe that the self-compaction rates depend on the thickness of the sediment layer, the lithology and the time since deposition of the sediments. Hence, the slopes of the site-condition models should also be controlled by those parameters. We expect to obtain different slope values for valleys with thinner or thicker sediment layers, with very different lithologies, and of more recent or older geological age than the Grenoble basin. For sediments recently deposited, the early and rapid stage of the compaction is not linear, but it can appear as such with the InSAR technique due to the short period of observation (a few years). On the contrary, sediments that compacted for a long time may not exhibit enough vertical displacement to be measured by EGMS, because displacement rates under a few mm yr^{-1} are not well constrained by PS-InSAR. It means that in order to be measurable by satellite, the magnitude of the natural compaction of the sediment has to be of the same order as the one observed in Grenoble. For areas where the natural compaction is less important (e.g. thinner or older soil layer), or on the contrary where large anthropic disruptions occur, the natural compaction of the sediments may not be as clearly observable.

6 Conclusions

In this study, we make use of the vertical ground-displacement rates delivered by the European Ground Motion Service (EGMS) to investigate their potential correlation with different site-condition parameters used to predict the seismic response of sedimentary basins to earthquakes (*i.e.*, the fundamental resonance period T_0 , the depth of the rock-to-sediment interface H_{bed} , and the time-averaged shear-wave velocity in the first ten meters of soil V_{S10}), as well as with parameters describing the urbanization (the volume for each building Build_{Vol} and the age of the last construction permits Build_{Age}). Our study focuses on the case of Grenoble, an Alpine urbanized sedimentary basin in France prone to a significant lithological site effect.



EGMS processes and yearly updates ground-displacement maps obtained by Persistent Scatterers Interferometry Synthetic Aperture Radar (PS-InSAR), at the European scale, and distributes in open-access different products with different levels of processing: here, we make use of the products from level 2 (Ascending and Descending satellite tracks) and from level 3 (vertical). This study investigates whether EGMS displacement rates could potentially serve as a proxy in Europe to determine, at a high spatial resolution, the fundamental resonance period in sedimentary basins.

Among the site-condition parameters tested, only those related to the full thickness of the sedimentary column and to the depth of the main impedance contrast (T_0 , H_{bed}) were found to have a linear correlation ($R^2 \geq 0.4$) with the vertical ground-displacement rates. To obtain this level of correlation, we developed a specific processing protocol to account for the high inherent noise in the satellite data, and to avoid the dependence of the final T_0 and H_{bed} models on the EGMS dataset used as input (whether for level 2 or 3 products, and regardless of their satellite acquisition time period). Indeed, despite the referencing applied by EGMS, we observed that the values delivered by the service are not yet fully absolute, at least not at the relatively low displacement rates ($< 5 \text{ mm yr}^{-1}$) we had to deal with in Grenoble. Resolving these technical issues was a mandatory step, now allowing the testing of our correlation protocol beyond the spatial limits of this study. The processing we developed to address these issues involves two main steps: (i) a control of the variance of the vertical ground-displacement rates through spatial median filtering and (ii) a quality filter of the measurement points to retrieve, from their statistical distribution, the required referencing shift to uniformize any available EGMS dataset.

We did not find that parameters related to the urbanization or the superficial sediment layer correlate with the ground-displacement rates in Grenoble ($R^2 \approx 0$). Instead, correlations were only observed with parameters related to the entire sedimentary thickness. We thus conclude that, in Grenoble, the PS-InSAR technique primarily measures the long-term natural compaction of Pleistocene-to-Holocene sediments responsible for the strong earthquake site effect. This result is compatible with theoretical compaction models and the limited observations available in the literature for similar contexts.

The final T_0 and H_{bed} models we developed are applicable in Grenoble at decametric spatial scale, using solely available ground-displacement rates from EGMS. We highlight that the initial datasets of measurements for those two site-condition parameters were obtained independently with two different geophysical techniques. Still the processing protocol for correlation that we have defined is just as effective for one dataset as it is for the other. This study demonstrates the large potential of remote-sensing techniques such as PS-InSAR for lithological site-effect assessment and for seismic microzonation purposes, complementing in-situ geophysical measurements. Another advantage of this technique is the large number of measurement points acquired, enabling dense coverage of urban areas. In Grenoble city, we obtain up to 100 points of predicted T_0 and H_{bed} in a 100 m by 100 m grid cell. This results in over 100 000 estimation points across the entire investigated basin area, a more than +1,000 % increase compared to the initial geophysical measurements. The approach developed in this work leverages the high-spatial resolution of the satellite measurement points to obtain very detailed and accurate maps of T_0 and H_{bed} .

However, the models obtained in this study are only valid for the Grenoble basin, and for the EGMS datasets used, although we designed our final models to ensure compatibility with future EGMS updates. The protocol developed in this study shows that it is possible to become independent of the EGMS dataset used as input, although it is advised to still use multiple datasets to ensure a correct estimation of the ground-displacement rates. The generalization of such site-condition models beyond our



testing area would require extensive testing in other types of sedimentary valleys or alluvial contexts, for example with thinner sediment thicknesses, different lithological facies and ages, and different types of urbanization.

885 Furthermore, as the regulations of the Eurocode 8 seismic design codes are evolving and now recommend the use of the fundamental resonance frequency of the soil (f_0 , the inverse of T_0) when the regulatory parameter H_{800} is not available for adjusting building design spectra to the soil conditions, this study opens the possibility to use a new data source: the vertical ground-displacement rate caused by the natural compaction of the soil, as a proxy to generate highly detailed maps of T_0 and H_{bed} in urban centers and across wide spatial areas.

890 *Data availability.* This publication has been prepared using European Union's Copernicus Land Monitoring Service information; European Ground Motion Service: Calibrated Baseline, 2018–2022, 2019–2023 datasets, <https://doi.org/10.2909/4137af9a-e3b6-405b-b714-e0cb5e9ca7d5>; Ortho Baseline, 2018–2022, 2019–2023 datasets, Vertical <https://doi.org/10.2909/4a14a29b-7db7-40e4-81ad-df3aa8dfbc6f> and East-West <https://doi.org/10.2909/4778163b-23bb-4403-af70-7accbc56e7d3>.

Appendix A

895 A1 Methodology for statistical referencing of the vertical ground-displacement rates

As demonstrated in Sect. 2.4.2, the intercept in the linear models linking the vertical ground-displacement rates with the site-condition parameters depends on the calibrating process done by EGMS, and therefore on the dataset retrieved from the service, as their calibration varies depending on the product's level and on the time period of satellite acquisition considered. Indeed we obtain positive intercepts that vary significantly among the nine EGMS datasets tested in this study, for both models
 900 of T_0 (Table 2) and H_{bed} (Table 3). Without appropriate referencing of the ground-displacement rates, the prediction map of the site-condition parameter inevitably depends on which EGMS dataset is used as input. For example, this complexifies the application of the results of our study to future EGMS products.

The intercept is equivalent to the value taken by the predicted site-condition parameter at a null value of vertical ground-displacement rate. We expect to observe the smallest values of predicted T_0 or H_{bed} where the bedrock is reaching the surface
 905 (*i.e.*, close to the dashed black line in Fig. 2), like it is the case for their measurements (Fig. 1b and 1c). In order to shift the used dataset of vertical ground-displacement rates so it exhibits null values of rates where the bedrock is reaching the surface, we recommend a statistical referencing based solely on the distribution of this dataset. Another method would have been to use a so-called stable area outside the basin as a reference, but the definition of a stable area may change according to different users of this method. Furthermore, Fig. 2 illustrates that, outside the area delimited by the dashed black line, the ground-displacement
 910 rates measured on mountains are quite unstable in many places, with rates at the same location on rock that are either lower or higher than those in the basin depending on the EGMS dataset. Figure 6f also shows that the MPs are not of the highest quality outside the urbanized area. The initial distribution of the ASC and DES datasets of the whole area (*i.e.*, in the whole square area shown in Fig. 2, including basin and mountains) are represented in Fig. A1a. Before any processing, the six distributions



are not identical (note the differences in variance as pointed out by the horizontal black arrow), and the upper percentiles are of different levels, ranging from 2 to 4 mm yr⁻¹).

We recall that dx is the shift (in mm yr⁻¹) that should be applied to the ground-displacement rates to correct for the nonzero intercept in the resulting linear model (Sect. 3.4). Likewise, we denote % dx the percentile corresponding to the dx value in the initial and full distribution of the ground-displacement rates in the whole area (basin and mountains). In Sect. 3.4, and in Fig. 7e and 7f for T_0 and H_{bed} respectively, we also noticed that it is possible to minimize the delta % dx with mainly the quality filtering of the MPs (for the highest levels of quality filter QF 1 to 3, the spatial smoothing only has a weak impact in reducing delta % dx). Using this observation, the median value of the nine % dx is retrieved from Table 2 for T_0 and Table 3 for H_{bed} to constitute the final models in Eq. 6 and 7. We obtain the 98.63th percentile for both T_0 and H_{bed} , to this degree of accuracy. We also observe that this is the exact value of % dx for the latest dataset VER19 in both Tables 2 and 3. That value is denoted $dx_{98.63th}$ in Eq. 6 and 7.

The flowchart depicted in Fig. 9 summarizes the different steps that we followed to build the final T_0 and H_{bed} models given by Eq. 6 and 7 (left side of the flowchart), and that we recommend to apply those models to compute the final maps of predicted site-condition parameter (right side of the flowchart). For the application of the models, our recommendation is to use both the merged ASC and DES datasets of a single time period, after their appropriate statistical referencing, in order to exploit the maximum spatial resolution of the PS-InSAR method. Note that to retrieve the adequate $dx_{98.63th}$ value in each EGMS dataset, it is mandatory to use the full distribution (basin and mountains) after applying a quality filter on the MPs (we recommend the quality filter n°2: $TC \geq 0.825$ and $RMSE \leq 2.75$). This manner is strictly required to consistently remove the most extreme outliers beyond the 99th percentile, which vary greatly from one dataset to another. Finally, each dataset of ground-displacement rates is subtracted with its corresponding $dx_{98.63th}$ value (Eq. 6 and 7), in order to obtain an unified reference level. Then after exclusion of the remaining positive values of vertical ground-displacement rate, and exclusion of MPs outside the basin, it is possible to merge the ASC and DES datasets, and to multiply the merged dataset by the slope value (see Eq. 6 and 7). As the last step to reduce the intrinsic variance of the vertical ground-displacement rates, especially at the small spatial scales, we recommend applying a median spatial smoothing with a 120 m half-width (see Fig. 12 for a comparison of the effects of different smoothing half-widths). When applying the models, spatial smoothing is performed at the end of the procedure because it must be applied to the merged ASC-DES dataset.

The final distributions of the six ASC and DES processed datasets are shown in Fig. A1b, to illustrate the efficiency of the whole procedure in order to uniformize the different datasets. As shown by the black arrows, the variance of all datasets is greatly reduced, and their upper percentiles are all almost identical and close to zero. This referencing method, which relies solely on the statistical properties of the distribution of displacement rates, is suitable for areas exhibiting low displacement rates, such as the Grenoble basin, where ground deformation is of the same order of magnitude as that of rock masses considered stable (a few mm yr⁻¹).

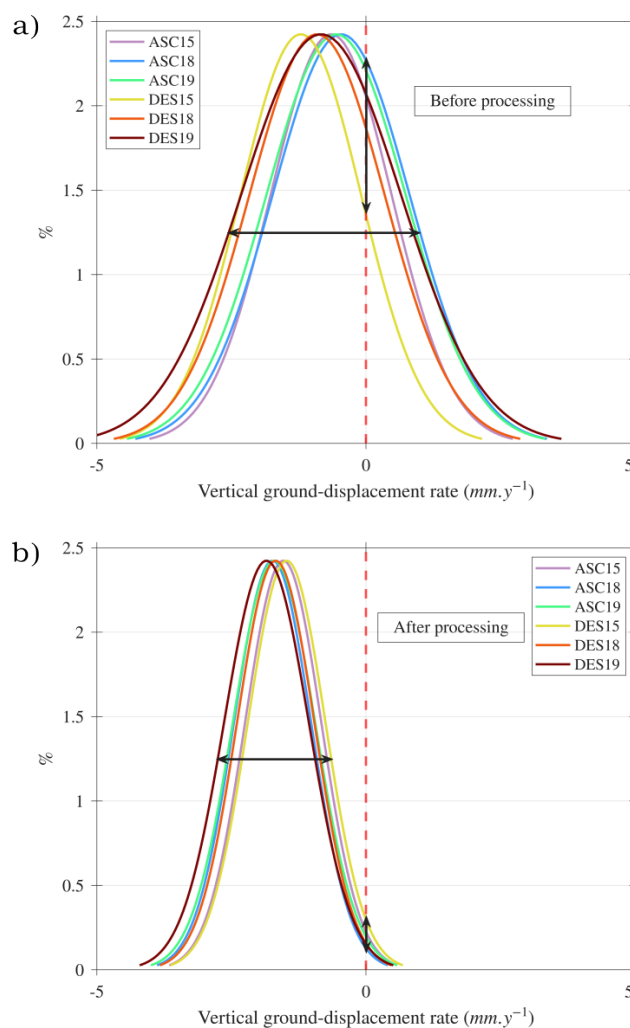


Figure A1. Distribution curves of the vertical ground-displacement rates from the six ASC and DES datasets used in this study, obtained (a) before any processing and (b) after the full processing that we developed for this study. Note how the dispersion of the datasets is reduced after the processing, as denoted by the black arrows.

Author contributions. VS: Conceptualization, Methodology, Writing (original draft preparation), Visualization, Investigation. EM: Conceptualization, Supervision, Writing (review and editing), Funding acquisition, Investigation. CC: Conceptualization, Supervision, Writing (review and editing), Investigation. AC: Visualization, Data curation, Writing (review and editing). EP: Conceptualization, Writing (review and editing)

950 *Competing interests.* The authors declare that they have no conflict of interest.



Acknowledgements. This work has been mainly supported by the ANR (Agence Nationale de la Recherche) project SASHA under the grant n° ANR-CE04-0013. Additional support was provided by the French strong-motion network from the French infrastructure Epos-France (rap.epos-france.fr). The authors also want to thank Marie-Pierre Doin and Oriol Monserrat for discussions about the InSAR processing, Jafar Karashi for his help with the Random-Forest algorithms, Stephane Schwartz and Yann Rolland for insights on Alpine geology, and

955 Christophe Dano for helping with the soil-mechanic theoretical background.



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