Monitoring ground deformation using Sentinel-1 PSInSAR and RTS measurements in the context of the Grand Paris Express project

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ABSTRACT

The Grand Paris Express project consists in the construction of new tunnel sections, stations and additional structures. Like all underground works, this can cause ground movement around the construction sites, especially neighbouring buildings and surface transport network like roads and railways. To monitor the movements, an automatic monitoring system composed of a network of robotic total stations (RTS), control points and monitoring targets attached to neighbouring structures is designed and set up. The aim of this system is to provide the real-time coordinates and displacements of the targets in a three-dimensional system. Although the system provides the most reliable, height frequency and real-time measurements, which is required in this field, it presents some practical difficulties especially on construction sites located in a dense urban area like Paris. Inter-visibility limitations and lack of stable control points are the most encountered cases. This work reports in the context of the Grand Paris Express project the challenges of displacements monitoring and describes the RTS monitoring system installed by Cementys. The ground-motion monitoring is also investigated using the radar interferometry (InSAR) considered as a complementary survey technique. This study is using PSInSAR (Permanent Scatterer InSAR). Even if X-band data are currently available in this area, this first experiment focuses on the use of C-band Sentinel-1 images. The results show the limits and the advantages of such images in this context.

I. INTRODUCTION

In the context of Grand Paris Express project, we are involved in the hearth of tunnelling monitoring with Cementys Company. Actual topographic monitoring system (Emery, 2019) offers most reliable measurements required for structural health assess. But some limitations related to this technique, notably low spatial density and coverage of measurements, lead us to an interest in the PSInSAR technique. Indeed, we showed for instance the potentials of PSInSAR technique for ground deformation monitoring due to the tunnel excavation in the city of Rennes using Sentinel-1 data (Nahli et al., 2018).

We will present in this paper the context of Grand Paris Express Project, then we will describe the installed monitoring system followed by a short description of PsInSAR processing. Next, we will present the first results of both techniques followed by an analysis of the advantages and limitations of each technique separately based on presented results. Finally, we will discuss the interest of combining these techniques and show their complementarities in the context of tunnelling monitoring over dense urban area.

II. CONTEXT OF GRAND PARIS EXPRESS

Grand Paris Express (GPE) is currently the largest urban infrastructure project, not only in France but also over the whole Europe. It offers another dimension to the Parisian transport network through the creation of four new automatic metro lines (15, 16, 17, and 18) and two extensions of the existing line 14. It will be also connected to the existing metro network. One aim is to provide more transport fluidity by creating direct links inside the Île-de-France country avoiding passing through Paris centre. 200Km of the Grand Paris Express metro lines will be mostly underground tunnels. Additionally, 68 new stations will be created along the lines (Figure *1*) (SGP, 2018).

Construction works usually begin by the realization of the stations, which involves digging a box volume from the surface after building support foundations, and then the construction of the tunnels joining the stations (SGP, 2019a). Around 2000 tons of materials are extracted every day mostly by Tunnel Boring Machines (TBM). The residual comes from stations digging (SGP, 2019b).

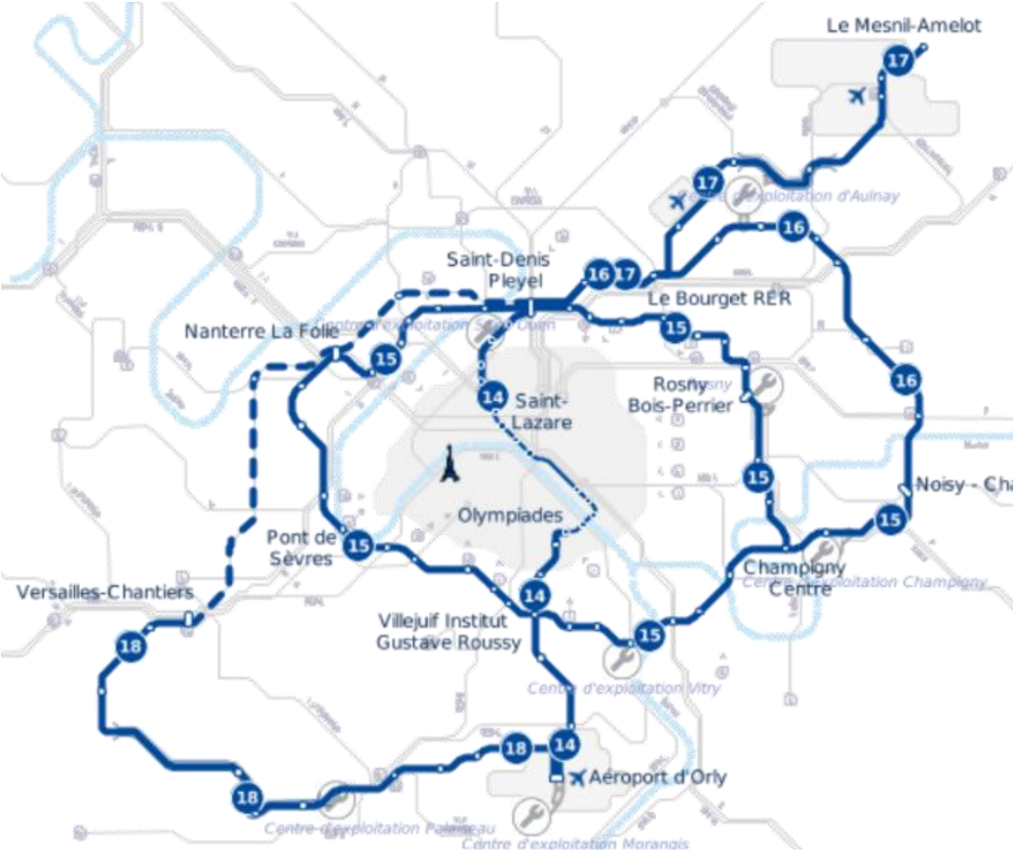

Figure 1. Grand Paris Express project: extended and new metro lines (www.societedugrandparis.fr)

Regarding the existence of cavities on historical exploitation areas and quarries, materials are sometimes injected first to backfill the cavities and reinforce the ground before the realization of stations or tunnels (SGP, 2016).

Injections, digging and excavation works can lead to ground deformations in depth but also on the surface, of several millimetres to several centimetres (Kavvadas, 2005; Kontogianni et al., 2005). Consequently, vital infrastructures within the geotechnical influence area of the works could be affected by these deformations. Especially buildings, roads, bridges, railway networks and sensitive networks.

Deformations over Paris were monitored using radar interferometry and explained in relation with the underground structure of the city and human exploitations. In (Le Mouélic et al., 2002; Fruneau et al., 2004), the authors studied vertical deformations around Haussman-Saint-Lazare Eole railway station between 1993 and 1998 using C-band images from ERS and linked it to water pumping and underground works on this site. (Koudogbo et al., 2018) carried on a study of historical deformations on Paris and presented the case of a settlement zone in the path of Grand Paris Express line 15 using C-band images from ERS and X-band images from TerraSAR-X. This site is located on underground exploitation area and shows an important settlement.

These examples show the complexity of the underground structure of the city, which is taken in consideration during excavations works. Monitoring structural movement is also essential to know and prevent potential risks. For this reason, in this work, potentially impacted structures are monitored using topographic targets, levelling, inclinometers etc.

III. ACTUAL AUTOMATIC MONITORING SYSTEM

As part of the underground works of GPE, Cementys is involved in the monitoring of deformations on the surface (works sites and neighbouring) and in the underground (tunnels, excavations) within the area of geotechnical influence. This monitoring is carried out by topographic measurements (levelling, robotic total stations) and geotechnical auscultation measurements (inclinometers, extensometers, piezometers, etc.). The company is responsible for the monitoring several lots of the GPE project (Figure *1*), namely:

- Line 14: One lot GC03 on line 14 south.
- Line 15: Two lots (T3A and T2C) on line 15 south.
- Line 16: Two lots (1 and 2) in the north.

The monitoring of 3D movements before, during, and after the execution of the works is a necessary procedure to ensure the durability of the structure in the short and long terms, to verify the impact of the work on the environment and the concerned buildings and alert in case of abnormal evolution or questioning of security.

The specifications prescribe the monitoring of infrastructures in the area of geotechnical influence at a certain frequency, varying typically between one and two times per hour. This measurement frequency is determined according to the sensitivity and vulnerability of the structure.

Before the start of the project, it is essential to identify the structures located in the influenced area and assess their sensitivity to settlements and vibrations. Then, plans of auscultation are established describing the devices of auscultation which will be set upon the field. These devices incorporate various surveying techniques: topographic, geotechnical and optical. Then, as soon as the sensors are installed on the surrounding structures, we carry out initial measurements to evaluate its state of health before the beginning of the works. During the progress of stations and tunnel excavations, the sensors continuously measure 3D displacements. The interpretation of the measurements is important since it will allow us to warn if the alarm thresholds are exceeded.

A topographic survey network is generally composed of the following elements:

1. ***Robotic Total Station (RTS):*** piloted automatically by an integrated software that instructs the total station to turn, target a prism and take an observation of angles and distance.
2. ***Reference points:*** considered to be fixed and whose coordinates are known. These points are used to locate the RTS during measurements;
3. ***Monitored points:*** they consist in prisms that are located in the influenced area and those coordinates are to be determined. Their calculated coordinates are compared with the initial coordinates in order to evaluate the displacement of the monitored structure.

Figure 2. Robotic Total Station for monitoring buildings on line 15

The RTS performs a measurement cycle in which it targets all the points to be monitored. The acquired data are transferred to the Cementys server via a data logger. The sent file is then processed to calculate the position of the station and the relative displacement with respect to the initial coordinates. The processing chain ends with the visualization of the measurements on a platform allowing the analysis and the interpretation of the measurements.

IV. INSAR DATA AND METHODS

We exploited PSInSAR technique (Ferretti, 2001; Hooper, 2006) with Sentinel-1 radar images[1] to study structural movements before and during excavation works on GPE.

61 Sentinel-1 images were chosen on the descending orbit 8. The images are acquired in IW mode and cover Paris city area during a time span of almost 2.5 years from 01/17/2016 to 08/10/2018. Only 3 bursts on the second Swath cover the city and environs including all the sites monitored using topography.

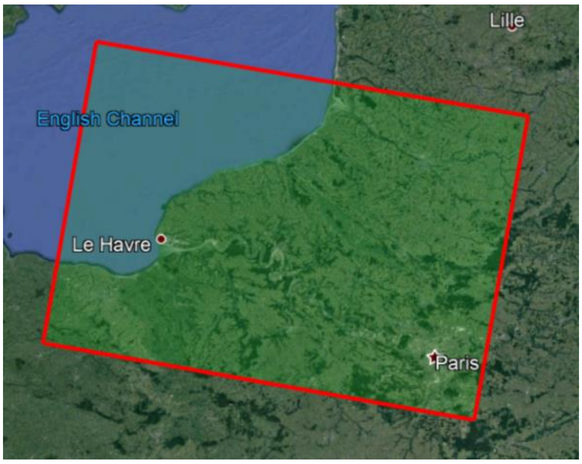

Figure 3. The footprint of the Sentinel-1 image used in this study from the descending orbit number 8.

We exploited this dataset using SNAP v6.0 with Sentinel-1 Toolbox (S1TBX)[2], which is a software from ESA and Stanford Method for PS (StaMPS) v4.1b (Hooper, 2006). The processing chain consists of three steps: interferograms generation using S1TBX, data export for StaMPS format and PSInSAR processing using StaMPS. Full processing chain is described in details for instance in (Nahli et. al, 2018). The two first parts are fully automated owing to the informatic developments proposed in (Foumelis et al., 2018). The third step mainly consists in Matlab functions. The results contain the detected PS location, their mean displacement velocity over the period and the times series of the total displacement. The displacement are indicated in the line-of-sight of the radar sensor.

V. FIRST RESULTS FROM TOPOGRAPHY AND PSINSAR

Among other sections, Cementys is responsible of the monitoring of two lots of line 15 South (Figure 1) excavation works. This section extends over a length of 12 km from the Ile de Monsieur to Villejuif Louis Aragon train station. Entirely underground, it integrates 3 underwater passages (Seine). We are interested her in the lot T3A including two new stations, four ancillary works and the tunnel that connect them.

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[1] www.sentinel.esa.int/web/sentinel/technical-guides/sentinel-1-sar

[2] www.step.esa.int/main/toolboxes/sentinel-1-toolbox/

Construction works already began on the stations Pont De Sèvre (PDS) and Issy-RER (Issy) in 2018. The tunnel will be inserted from Ile de Monsieur ancillary work by august 2019. It will excavate 3937m to join Fort d'Issy-Vanves-Clamart station passing by Pont de Sèvre, Issy-RER stations and the ancillary structures.

Construction sites and surrounding structures are instrumented. Robotic total stations monitor hundreds of targets installed on buildings, railways and roads. We present two cases where important displacements where measured around stations. The first one is a building on the edge of the excavations works of Issy-RER station and the second example is a dock alongside the Seine River where Pont de Sèvre station is under construction.

A. *Topographic monitoring results*

Issy-RER station is constructed in a high-density area of buildings and infrastructures. We choose to deal with a building near to the station where prisms are installed on the fronts of two floors. Collected data on a time span of one-year shows that this building suffers from important movements in vertical direction. It reaches more than -7mm from the beginning of 2019 (Figure 4). These displacements began in April 2018 to reach -5mm in Jun 2018. A steady period is observed until December, then the subsidence resumes. Besides, these displacements remain below the fixed thresholds.

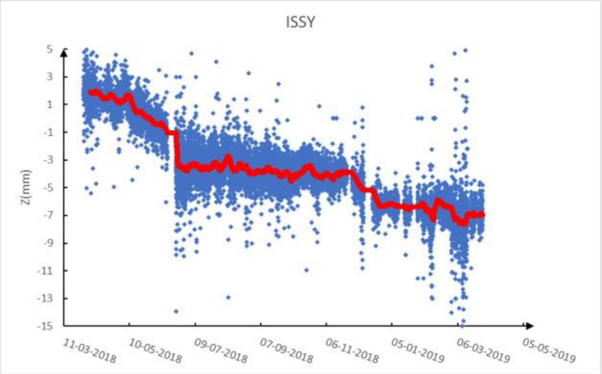

Figure 4. Vertical displacements time series of an optical target installed on a building in Issy-RER

Pont de Sèvre station is constructed under a dock of the Seine River where a range of 13 prisms were installed alongside with a spacing of 10m. Measurements show that the dock has undergone a rapid settlement between mid-July of 2018 and mid-August (Figure 5). It reaches 10cm on middle of the subway station. Referring to the works scheduled, the dock was demolished to be reconstructed again.

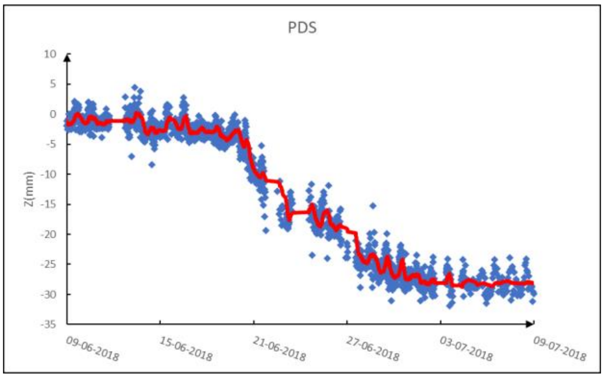

Figure 5. Vertical displacements time series of an optical target installed on Pont de Sèvre dock.

B. *PSInSAR monitoring results*

Regarding the observed displacements measured by topographic method, we choose to study the same two structures.

For the Issy-RER station, we have detected a dozen of PS on buildings in the surrounding, while no point were detected on the surface of excavations site. PS on the middle of a neighbour building have the most important velocity, which reaches more than -6mm/year (Figure *6*). PS time series show that the building has undergone a settlement since 2017 that has gone faster from 2018 after a period of stability between August of 2017 and April of 2018.

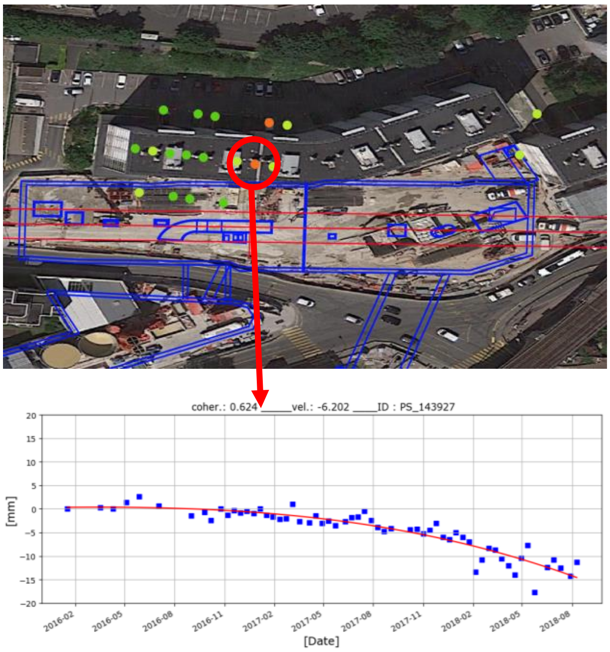

Figure 6. Top: Dectected PS (colored points) around the Issy-RER Station, overlayed on 6/26/2018 view in Google EARTH. We also represent the construction project in blue and red lines (origine de la donnée). The colors of the points represents their velocity in mm/year. Bottom: time series of the total displacement of a PS on a building in mm.

On Pont de Sèvre station, no PS were detected on the surface of excavation site neither on the dock. This shall be due to the loss of coherence after changes on surface and the important movement of the dock. PS located on the building are stable. Moreover, some of PS located on the north roads present a small subsidence, which reaches almost -3mm/year. The time series of the nearest PS to the station show that a continuous subsidence at this point began on March 2018. It reaches -15mm as maximum value.

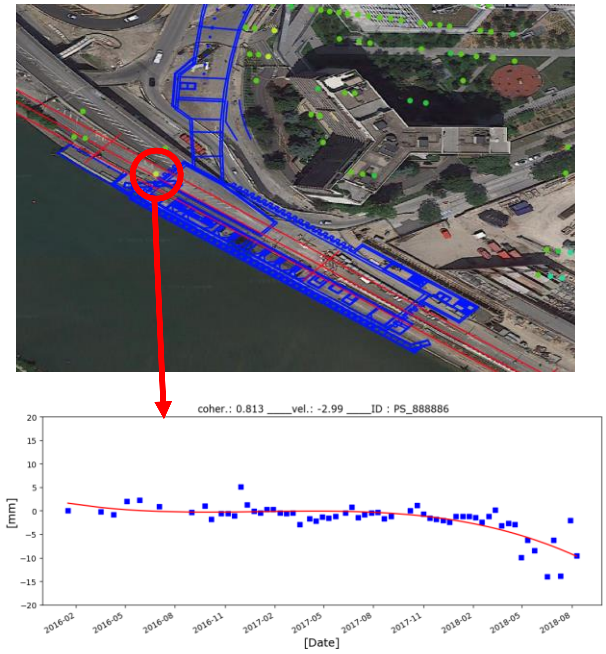

Figure 7. Top: Dectected PS (colored points) around the Issy-RER Station, overlayed on 6/26/2018 view in Google EARTH. We also represent the construction project in blue and red lines (origine de la donnée). The colors of the points represents their velocity in mm/year. Bottom: time series of the total displacement of a PS on Pont de Sèvre dock in mm.

VI. DISCUSSION

We showed through this paper the first results of topographic and PSInSAR monitoring in the context of Grand Paris Express.

The topographic monitoring system makes it possible to continuously measure 3D displacements in real time with a precision in the millimetre order and a high frequency. However, this system is limited by the constraints of low spatial density of measurement points, target visibility and the cost of installation. This makes it difficult to ensure a monitoring of all surrounding structures in a dense urban site like Paris. Besides, the installation of the RTS and optical targets needs many interventions on the monitored site. Concerning the neighbouring buildings, an authorisation is required to install optical targets. Furthermore, measurements are relative to some reference points and it is not always easy to identify references outside the influenced area. In the either case we cannot detect whether they are suffering from a regional deformation. Moreover, historical measurements cannot be obtained using this technique. Usually, the period of initial measurements is limited to only one month before works because of the cost of additional time of monitoring.

PSInSAR technique with a high-density measurement points, wide coverage and also a long time coverage can overcome most of these limitations. Knowing that Sentinel-1 data are available from 2014, an historical study of structures along at least 3 years will allow to detect any seasonal behaviour or potential movements like continuous subsidence or uplift which should be taken in consideration before constructions works. It could also help to define vulnerable structures.

Another key point is the spatial density of PsInSAR measurements, which reaches few thousands of points per km² in an urban area like Paris. Giving that almost PS are naturally located on building and raised structures like bridges, which behaves like a corner reflector, we can monitor these structures within the influenced area notably those which are not visible in topographic monitoring. In addition, several PS being detected on structure's fronts, especially in case of high raising and slender structures, will allow to calculate some derived deformation parameters like structure's global and differential settlement which are essential to assess the structural health.

PSInsar technique has also some limitations in the context of tunnel excavations. First, measurements frequency is limited to 6 days (with Sentinel-1 images) which is not enough to survey in real time the construction works but the global trends of deformations. It allows also to cover non visible structures in topography at least once a week. Notably that non visible structures are usually located far away from the construction sites and monitoring prescriptions are less imposing in term of measurements frequency in that case.

A second limitation is the distribution of PS. Indeed, the density is high but the location of these points is critical in some cases. Especially for vulnerable structures like railways and roads, where detected PS using Sentinel-1 data are not enough to assess the structure stability. Even for buildings, the number and the distribution of PS are determined by the building geometry and its orientation relatively to satellite line of-sight. Surface around stations construction sites changes after earth works, causing a temporal decorrelation. For this reason, it is rare to detect PS on construction sites surface. In this case, ground movements cannot be measured directly, only its effect on neighbouring structures is measured.

We can also mention a limitation related to the technique. Real movement is underestimated when it is projected to the line-of-sight of the satellite especially if the horizontal component of the movement is significant. 3D movement retrieval using descending and ascending orbits data can be a solution also.

Finally, the position of PS is in some way "random" and one PS cannot be easily associated to an optical target. So to carry on a precise and punctual comparison of PSInSAR and topographic measurements, references and monitored points of both techniques must be collocated. This is achieved by identifying the physical nature of PS points during the historical study and materializing them with optical targets during monitoring. A second interesting solution is "to choose" the position of the PS point by installing a corner reflector and equip it with an optical target. Regarding the size and the cost of a C-band corner reflector, this can be possible only for a limited number of PS points. Reference points for example, can be equipped with integrated optical target and corner reflector.

VII. CONCLUSION

PSInSAR technique has several promising advantages in the monitoring field, but it presents also some constraints making it difficult to rely as single technique for tunnelling works monitoring. Combining PSInSAR with topography may improve the monitoring system by benefiting from the advantages of both techniques. We forecast in next studies to implement an integral monitoring system based on the complementarity of PSInSAR and topography. In a first time, using Sentinel-1 images, we will improve our results by integrating more images for the historical analysis; Combining ascending and descending orbits data for 3D movement retrieval when it is possible (for comparable PS detected in both dataset); Using TRAIN toolbox for reducing atmospheric noise; Investigating a way to improve PS detection on individual structures in particular on railways and roads. In a second time, we will move to X-band to be able to carry on more detailed analysis on infrastructures and in order to retrieve more precise PS location. We think in installing optical targets and GNSS antenna on PS locations or some radar corner reflectors on a limited number of structures. We will exploit these systems not only for techniques comparison but for combining these techniques.

VIII. ACKNOWLEDGEMENTS

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References

Chris Emery (2019). Building under Paris. Retrieved 30 March, 2019, from: https://www.geoconnexion.com/publications/geo-international/issue/march-april-2019-international-issue/article/building-under-paris

Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent scatterers in SAR interferometry. IEEE Transactions on geoscience and remote sensing, 39(1), 8-20.

Foumelis, M., Blasco, J. M. D., Desnos, Y. L., Engdahl, M., Fernández, D., Veci, L., ... & Wong, C. (2018). ESA SNAP-StaMPS Integrated Processing for Sentinel-1 Persistent Scatterer Interferometry. In IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium (pp. 1364-1367). IEEE.

Fruneau, B., Rudant, J. P., Deffontaines, B., & Prunier-Leparmentier, A. M. (2004). Suivi des déplacements verticaux par interférométrie radar: exemple de la gare Haussmann-Saint-Lazare (Paris). Revue française de géotechnique, (106-107), 103-110.

Hooper, A. J. (2006). Persistent scatter radar interferometry for crustal deformation studies and modeling of volcanic deformation. Ph. D. Thesis.

Kavvadas, M. J. (2005). Monitoring ground deformation in tunnelling: current practice in transportation tunnels. Engineering Geology, 79(1-2), 93-113.

Kontogianni, V. A., & Stiros, S. C. (2005). Induced deformation during tunnel excavation: evidence from geodetic monitoring. Engineering geology, 79(1-2), 115-126.

Koudogbo, F., Urdiroz, A., Robles, J. G., Chapron, G., Lebon, G., Fluteaux, V., & Priol, G. (2018). Radar interferometry as an innovative solution for monitoring the construction of the Grand Paris Express metro network–First results. In World Tunnel Conference.

Le Mouélic, S., Raucoules, D., Carnec, C., King, C., & Adragna, F. (2002). A ground uplift in the city of Paris (France) detected by satellite radar interferometry. Geophysical research letters, 29(17), 34-1.

Nahli, A., Simonetto, E., Merrien-Soukatchoff, V., Durand, F., & Rangeard, D. (2018). Sentinel-1 for monitoring tunnel excavations in Rennes, France. Procedia computer science, 138, 393-400.

Société du Grand Paris [SGP] (2016). Combler les carrières pour creuser en toute sécurité. Retrieved 30 March, 2019 from: https://www.societedugrandparis.fr/gpe/actualite/combler-les-carrieres-pour-creuser-en-toute-securite-621

Société du Grand Paris [SGP] (2018). Le Grand Paris Express en résumé. Retrieved 30 March, 2019 from: https://www.societedugrandparis.fr/gpe/le-grand-paris-express-en-resume

Société du Grand Paris [SGP] (2019a). La construction et la mise en service. Retrieved 30 March, 2019 from: https://www.societedugrandparis.fr/gpe/comprendre/les-techniques-de-construction-177

Société du Grand Paris [SGP] (2019b). Le chantier dans la ville. Retrieved 30 March, 2019 from: https://www.societedugrandparis.fr/gpe/comprendre/le-chantier-dans-la-ville-176