Analysis of temporary deep landslide reactivation with interferometric monitoring technique

Enzo Fontanella[1] and Augusto Desideri[1]

[1] Department of Structural and Geotechnical Engineering, Sapienza University of Rome – via Eudossiana n.18 – 00187 Rome
Enzo.fontanella@uniroma1.it
Augusto.Desideri@uniroma1.it

Abstract. The paper presents the case of a slow landslide temporarily reactivated by the excavation of twin tunnels in the Tuscan-Emilian Apennines. After a description of the case study, the paper illustrates the most significant outcomes of the monitoring system characterized by a large quantity of data which yielded an important opportunity to study the interaction of tunnels along the slope.

The monitoring system consisting of traditional monitoring data, and satellite measurements (SAR interferometric technique) allowed analyzing the characteristics of the landslide movements before, during, and after tunnel reactivation.

Keywords: Landslide monitoring, Twin tunnels, SAR interferometry technique.

1 Introduction

This paper illustrates the locally well-known Ripoli—Santa Maria Maddalena (hereinafter, indicated as SSM, in brief) landslide, reactivated in 2011 during the excavation of twin tunnels for the new motorway crossing the Apennines between Bologna and Florence (Italy).

Over 70,000 landslides bodies have been identified in Emilia– Romagna region (Bertolini, 2010), most of which are complex landslides and involving structurally complex formations (Esu, 1977; D'Elia et al., 1998; Bandini et al., 2015).

In areas prone to instability, such as in the case here reported, the excavation of a tunnel can trigger or accelerate landslide movements, even on large scale (Desideri, 2021; D'Effremo and Fontanella, 2012; D'Effremo et al., 2016).

Due to particular significance of the project a constant surveillance of the evolution of movements has been performed. After describing the study site, the paper is basically aimed to show the importance of satellite measurements in the analysis of deep gravitational movements. The interferometric analysis is used, in particular, to evaluate the actual stability condition of landslide showing its usefulness in long-term monitoring of extremely slow landslides especially when combined with topographic measurements.

2 The study site

The Val di Sambro twin tunnels project concern the motorway crossing the Apennines between Bologna and Florence. Each tunnel, identified, in Fig. 1, as “North tunnel” (for the traffic towards Bologna) and “South tunnel” (for the traffic towards Florence) has a section of approximately 180 m^2 with a maximum span of 16 m and a distance between the tunnel axes of 14 m. The tunnels were driven with the full-face method using traditional techniques and with fiberglass dowel reinforcement of the face. The excavation in the area close to SMM toke place between May 2011 and July 2014.

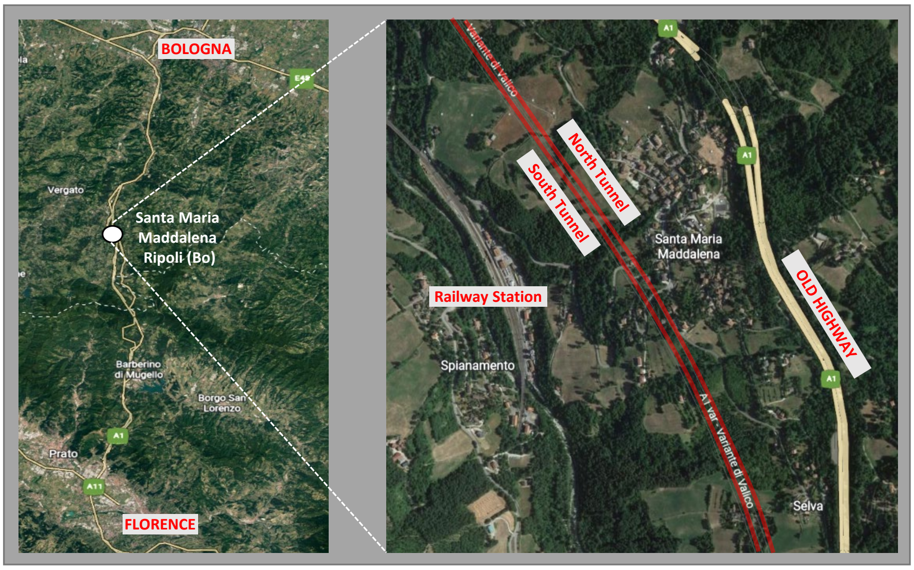


Fig. 1. Location of the “Valico Variant” project and of the Santa Maria Maddalena tunnels

The subsoil in the SMM area is mainly characterized by shallow debris, 20 m thick, overlying the Monghidoro Formation (defined as MOH hereafter), which is represented by a turbidite succession dating from Upper Cretaceous to Paleocene.

In particular the MOH consists of arenaceous-pelitic turbidities with a ratio between sandstone and marl larger than 1. This formation includes a clayey-arenaceous lithozone (MOHa hereafter) defined by clayey/arenaceous facies with a ratio between sandstone and marl ranging from 1/3 to 1/2 (Fig. 2).

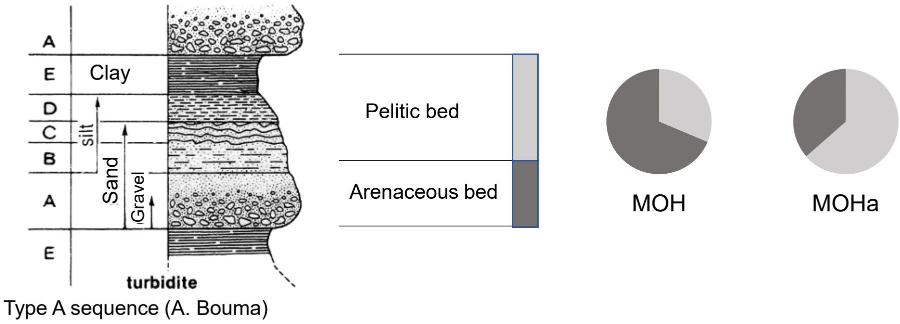


Fig. 2. Example of turbidity layer for Monghidoro geological formation (modified from Bosellini et al., 2021)

3 Slope monitoring

Fig. 3 shows the map of the area of SMM with location of twin tunnels and a part of the installed inclinometers just used to represent the slope movement of SMM.

As it can be observed in Fig. 4 the elaboration and interpretation of the integral inclinometer movements highlights the presence of a fully-developed sliding surface having a maximum depth of about 70 m b.g.l..

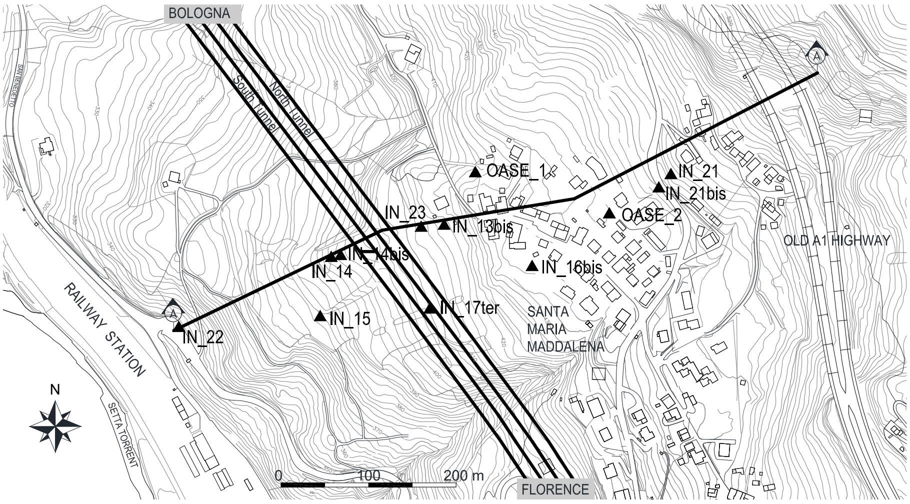


Fig. 3. Map of the area in proximity of Santa Maria Maddalena with the location of the inclinometers installed (modified from Desideri, 2021).

As regards to identify the evolution of slope movements at different phase of excavation (during excavation and after excavation), in Fig. 5 are reported the differential displacements on sliding surface with time.

The inclinometric measurements show that the displacements along the sliding surfaces have gradually ceased after the excavation was completed on December 2014.

The monitoring data presented mainly began after the start of tunnel excavation. In order to investigate the slope activity even before tunnelling, SAR interferometry analyses performed in the area through the SqueeSAR technique are also considered.

The satellite images datasets were processed to compute the displacements magnitude and rate of natural targets available on the ground surface. The algorithm provides the component of the displacement vector along the line of sight (LOS), i.e. the line joining the radar and the target. Positive displacement values indicate movements towards the satellite (shortening along the LOS), while negative displacements denote movements away from the sensor (lengthening along the LOS). In order to SSM case study, taking into account the maximum slope line (assumed as the preferential direction for sliding phenomena), and the direction of orbital geometry by the two satellite (RADARSAT and TERRASAR X), negative displacements denote downstream movements.

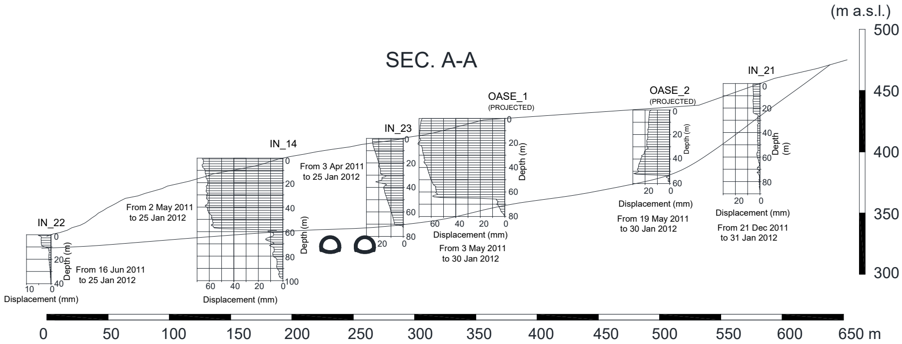


Fig. 4. Interpretation of the inclinometers along Section A-A of Fig.2 (Desideri, 2021).

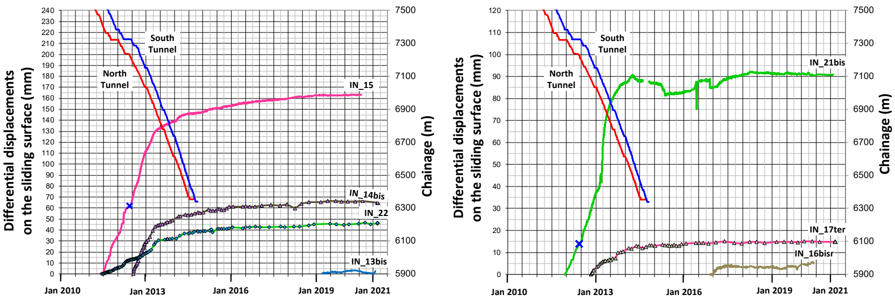


Fig. 5. Differential displacements on sliding surface

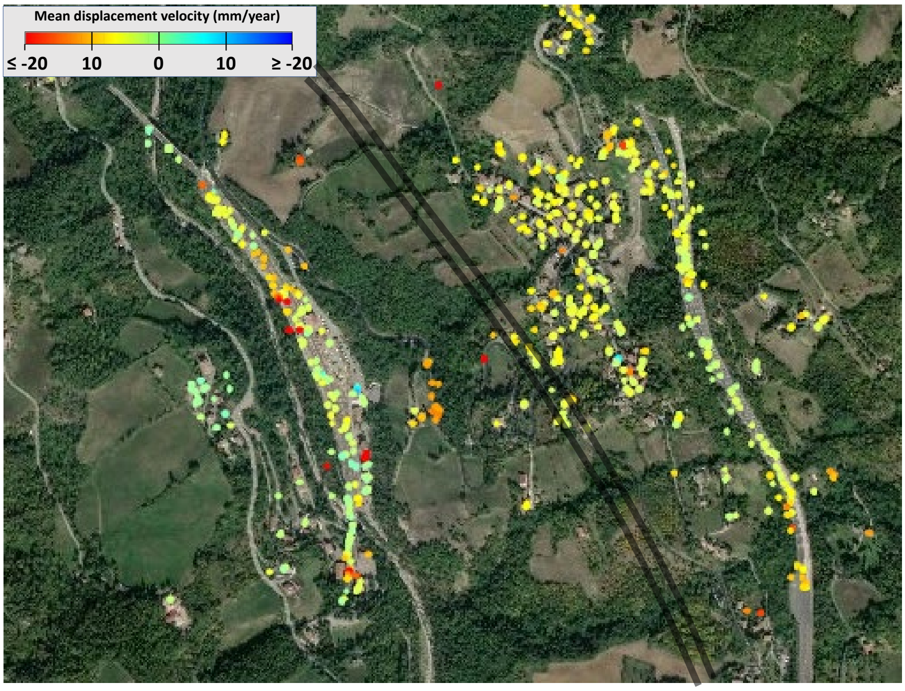
In Fig. 6 a,b,c are presented the measurements performed by satellite on the investigated area of SMM for three different period. The first one 2003-2009 is referred to the slope movements of slope before tunnelling excavation. The second one 2012-2013 is referred to the period of sliding reactivation of slope due to tunnel excavation. Finally the third one 2019-2020 shows the current condition of slope.

The colored dots in Fig. 6 represent the natural targets that the satellite can detect. They are concentrated mainly on the side of the old A1 highway, on SMM village, and SMM railway station.

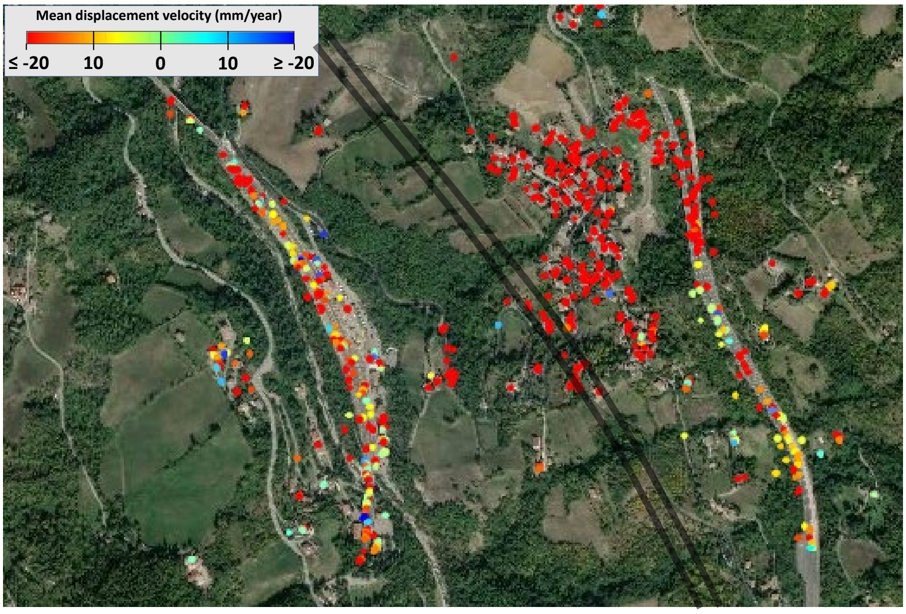
The repeated passages of the satellite over the same area allow to detect the movements undergone by the different points. The coloring of the points provides an indication of the displacements undergone in a year (the color scale of legend expressed in terms of mm/year is provided in the figure): the colors from green to red refer to downstream displacements, the colors from green to blue refer to upstream displacements.

The mean displacements rate during the period of 2003-2009 is reported in Fig. 6.a. It can be noted that the area near the SSM village is interested by displacements rate of few mm per year before the tunnel excavation. A condition that is found similar in many areas of Apennines, not due to displacements of sliding surface but to surface deformations of slope.

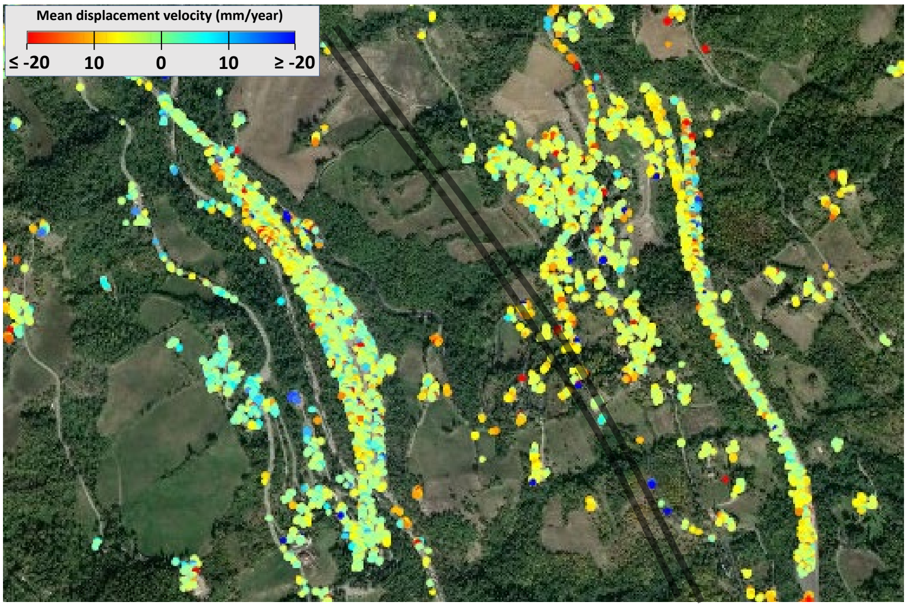
The image in Fig. 6.b clearly highlights the period (2012-2013) of reactivation of the movement with surface displacements rate equal or greater than 20 mm/year.



(a) RADARSAT satellite 2003 – 2009 (before tunnelling excavation)



(b) RADARSAT satellite 2012-2013 (during tunnelling excavation)



(c) TERRASAR X satellite 2019 – 2021 (after tunnelling excavation)

Fig. 6.a,b,c Spatial distribution and mean LOS displacement rate of the coherent targets in the area surrounding Santa Maria Maddalena

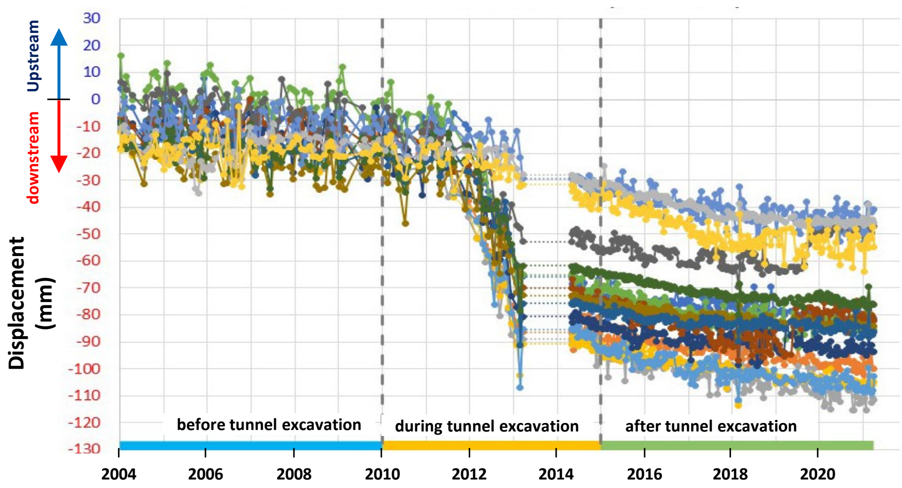


Fig. 7. – Evolution in time of the displacements of 15 targets near the village of Santa Maria Maddalena

The analysis of Fig. 6.c reveals how the current situation (2019-2021) is completely analogous to that in the period 2003-2009 (before tunnelling excavation) with downstream displacements rate less than 5 mm/year, moreover, the satellite measurements are congruent with the topographic measurements at the ground surface (Desideri, 2021, D'Effremo et al., 2016).

Evolution in time of the displacements of 15 targets near the village of SSM is presented in fig. 7. The dashed lines in the graph, during 2013, are due to a variation of the satellite from which the measurements were taken. It can also be noted a reduced data scatter for measurements of the new satellite (TERRASAR X) than the previous one (RADARSAT).

In the period 2003-2009 the displacements rate of the target is about 5 mm/year, and significantly increase during tunnelling excavation in 2012-2013. After 2015, is registered a progressive reduction in the ground movement rate with mean values in 2019-2021 of few mm/year.

4 Discussion and final remarks

The paper presented the case study of the Santa Maria Maddalena characterized by excavation of twin tunnels in an area affected by deep landslide.

Temporary reactivation of deep landslide is investigated with the large amount of traditional monitoring data and the interferometric technique INSar. The INSar technique is used in particular to analyze the behavior of the slope before excavation and after excavation (long term).

The results of interferometric analysis indicate that very slow landslide movements, with a mean displacement rate of 5 mm/year, were recorded before the tunnel excavation. The tunnelling caused a displacement acceleration along the sliding surfaces, reaching a maximum movement rate of about 20 mm/month.

The slope surface movements continued in time after tunnel faces excavation with a mean displacement rate similar to that registered before excavation.

The inclinometric measurements show the absence of movements along the sliding surface. Confirming that the slope is no longer affected by in-stability phenomena.

Finally, the slope of Santa Maria Maddalena has returned to its *ante operam* behavior, and the very slow rate of surface movement (a few mm/year) measured in the period 2019-2021 are typical of the slopes of the Tuscan-Emilian Apennines. Other stable areas of this Apennines are characterized by similar rate of movement (Desideri, 2021). It is therefore reasonable to believe that these displacements are not related to instability phenomena.

References

1. Bandini, A., Berry, P., Boldini, D.: Tunnelling-induced landslides: The Val di Sambro tunnel case study. *Engineering Geology*, 196, pp. 71-87. (2015)
2. Bosellini A., Mutti E., Ricci Lucchi F.: Rocce e successioni sedimentarie. UTET Torino (1989).
3. D'Effremo, M.E., Desideri, A., García Martínez, M.F., Gottardi, G., Ricceri, G., Selleri, A., Simonini, P., Torsello, P. : Analysis and monitoring of a tunnelling-induced deep landslide reactivation. In: Landslides and Engineered Slopes. Experience, Theory and Practice*, 2*, pp. 735-742. (2016).
4. D'Effremo, M.E., Fontanella, E.: The use of advanced remote sensing techniques for monitoring of slopes affected by slow movements. In: Life-Cycle and Sustainability of Civil Infrastructure Systems - Proceedings of the 3rd International Symposium on Life-Cycle Civil Engineering, IALCCE 2012*, pp*. 2008-2014. (2012).
5. D'Elia, B., Picarelli, L., Leroueil, S., Vaunat, J. : Geotechnical characterization of slope movements in structurally complex clay soils and stiff jointed clays. Rivista Italiana di Geotecnica 32 (3), pp. 5–47. (1998)
6. Desideri A.: Gallerie e movimenti di versante. Rivista Italiana di Geotecnica (1), 5-41 (2021).
7. Esu F.: Behavior of slopes in structurally complex formations. In: Int. Symp. The Geotechnics of Structurally Complex Formations, vol. II, pp. 157–169. Capri (Italy) (1977)