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THE IMPACT OF VERY SLOW MOVING GRAVITATIVE SLOPE DEFORMATIONS ON INFRASTRUCTURES: THE CASE STUDY OF THE BRIDGE OF GINOSA

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EXTENDED ABSTRACT

I movimenti gravitativi a cinematica lenta sono fenomeni diffusi sul territorio italiano molto più di quanto normalmente si ritenga, ed interessano versanti sia di ambienti di catena o di recente sollevamento tettonico, ma anche ambienti più collinari apparentemente tranquilli. Questo tipo di fenomeni gravitativi sono caratterizzati da velocità di spostamento medie molto basse anche se a volte caratterizzati da movimenti con piccoli scatti, pertanto non sono sempre immediatamente evidenti. Tuttavia, i loro impatti sul costruito, come strutture ed infrastrutture, cumulati nel tempo, possono comprometterne la funzionalità e fruibilità; sono inoltre potenzialmente pericolosi perché possono nel lungo periodo portare a deformazioni eccessive e stati di coazione che possono portare a collassi. Fra le infrastrutture maggiormente esposte per la loro intrinseca vulnerabilità, oltre che per gli impatti potenziali per l'uomo, vi sono i ponti. Questi sono opere spesso strategiche, a servizio di reti stradali e ferroviarie, con una resilienza limitata nel tempo rispetto alle sollecitazioni indotte da masse di terreno soggette a movimenti gravitativi che coinvolgono l'opera o parte di essa. In Italia esistono numerosi casi di ponti definitivamente o parzialmente compromessi da movimenti franosi a cinematica lenta. Fra questi un caso sicuramente rilevante è quello del viadotto a servizio della linea ferroviaria dismessa Lagonegro (PZ) – Spezzano Albanese (CS) sul vallone Serra, in prossimità dell'abitato di Lagonegro (PZ) in Basilicata. Altro caso singolare è certamente quello del ponte sul fiume Magra presso la frazione di Caprigliola (MS) nel nord-ovest della Toscana crollato improvvisamente nel 2020. Il problema del danneggiamento dei ponti a causa di movimenti franosi a cinematica lenta è diventato di particolare interesse a seguito dell'invecchiamento delle infrastrutture, in relazione all'evoluzione dei movimenti franosi. Il numero di ponti interessati da stati di sollecitazioni dovuti a movimenti franosi, tali da generare danni osservabili e talvolta critici, è in costante aumento e può comportare rilevanti problemi di funzionalità delle reti infrastrutturali coinvolte, oltre che costi di intervento. È pertanto di fondamentale importanza identificare i ponti sollecitati da fenomeni gravitativi a cinematica lenta, prima che i danneggiamenti possano dar luogo a situazioni critiche, nonché analizzare e studiare le caratteristiche dei movimenti franosi che interagiscono con i predetti ponti.

Nel presente lavoro è descritto un particolare caso di studio di un ponte ubicato in Puglia, nell'estremo ovest della provincia di Taranto, nell'ambito del territorio del comune di Ginosa, sulla strada provinciale 1 (SP1). Si tratta di un ponte con ampie spalle in muratura ed una singola stretta arcata in calcestruzzo. È stato realizzato presumibilmente a metà degli anni 40 del XX secolo. L'opera si trova nella parte medio bassa di un versante in Argille Subappennine. Apparentemente, il versante non sembrerebbe interessato da movimenti in atto, tuttavia il ponte risulta gravemente danneggiato in corrispondenza della spalla destra con pesanti ripercussioni sull'arcata in calcestruzzo e sulla spalla sinistra, con profonde fessure aperte. Inoltre, è interessante osservare che nell'incisione morfologica superata da questo ponte, immediatamente a monte, sono presenti i resti di un vecchio ponte stradale, sostituito dall'attuale, a causa dei seri danneggiamenti che lo hanno reso inagibile. Il vecchio ponte, dismesso negli anni 40 del XX secolo, fu realizzato, presumibilmente, negli anni 80 del XIX secolo, essendo rimasto in servizio, probabilmente per circa 60 anni.

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ABSTRACT

Slow and very slow-moving landslides are quite common in Italy and in zone of recent tectonic uplift, in particular in clayey or sandy-clayey slopes. These landslides are not easy to be detected, since their extremely slow movements do not apparently produce effects. However, whereas structures or infrastructures exist and are stressed by slow landslides, their impacts can damage the structures/infrastructures. Bridges are valuable infrastructures, potentially threatened by slow moving landslides. Bridges can warp if stressed, but their resilience is limited. Therefore, the progressive and constant increasing of the stress due to slow landslides can cause failures of the bridges, and potentially collapses. In Italy, a large part of the bridges was built or rebuilt just after the WWII. These infrastructures are now aged and whereas slow moving landslides exist, they are suffering potentially dangerous stresses. This work focuses on a peculiar case study of a little bridge built between 1940 and 1947, located in south Italy, stressed and damaged by a slow-moving landslide.

Keywords*: slow landslides, bridges, clay, remote sensing*

INTRODUCTION

Slow and very slow-moving landslides are quite common despite not immediately evident, particularly in those areas of recent uplift, where the increase of the effect of gravity forces induced by uplift starts its action. The attention on infrastructural monitoring and maintenance is a crucial topic for infrastructure, due to several important phenomena that may cause relevant damages to the infrastructure serving the territory. In Italy after the tragic failure of “Morandi Bridge” in 2018, National Guidelines for safety controls of bridges (Mit, 2020) were emanated. In these guidelines there is a special risk analysis related to the interaction between bridge and landslide. The interaction between infrastructures and gravitative phenomena may be among the most important and critical pressing problems, because sometimes not immediately evident. This issue becomes relevant for transport infrastructures, like roads and railways, crossing territories where the instability phenomena are a potential threat to their functionality and safety.

The most sensitive elements to instability phenomena are the man–made structures such as bridges, viaducts, and tunnels (Barla, 2018; Nappo *et alii*, 2019; Guerricchio, 2022).

Among the instability phenomena, the experience of analyzing the instability and degradation of large infrastructures built during the XX century, highlighted the relevance of giant, non-catastrophic landslides (Galeandro *et alii*, 2013; Agliardi *et alii*, 2013), With very slow dynamics, framed within the so-called Deep-Seated Gravitational Slope Deformations (DSGSDs). These represent major threats to people and infrastructures (Agliardi *et alii*, 2020; Discenza & Esposito, 2021). In fact, they often produce significant interference with anthropic environment leading a great potential risk factor. Recent experiences highlighted how these phenomena can cause important deformations on infrastructures over long time periods. This issue, despite its scientific and technical relevance, is not always been sufficiently investigated. This is likely due to the difficulty of monitoring very slow deformations over time and joining purely geological aspects with the pragmatism of the practical problems of artificial structures. Only since the end of 1970s the phenomena such as the DSGSDs were better understood and framed (Guerricchio & Melidoro, 1981), putting the attention on the associated hazard and risk.

In the last decades, the number of studies considerably increased, disclosing at global level that these phenomena are not uncommon. (Pánek & Klimeš, 2016; Lacroiz *et alii*, 2020; Moretto *et alii*, 2021; De Soldato *et alii*, 2021). In fact, they are quite widespread, especially in those areas of recent orogenesis such as Italy, being potentially more critical for the Italian infrastructure than for those of other European countries.

The increasing use of geodetic and remote sensing techniques such as spaceborne radar interferometry (Crippa *et alii*, 2020; Confuorto *et alii*, 2021) and the improvements of instrumental monitoring allowed to detect and describe the deformation behavior associated to these slow-moving phenomena. However, due to their limited displacements rates and their areal extension, these phenomena are difficult to be monitored and interpreted. This causes an underestimation of movement rates and then of the potential effects on infrastructures (Cignetti *et alii*, 2020).

This work focuses on a particular case study of a relatively small bridge, severely stressed and deformed by a very slow slope movement. It is located in south Italy, close to the town of Ginosa, near the bound between Apulia and Basilicata regions. A very slow-moving landslide, involve the clayey slope where the right bridge abutment is located continuously stressing this small bridge, inducing severe damages over a period of about 75 years. Here, the geological and morphological features of the slope are described, together with the interaction between the slope deformation and the bridge.

The slow-moving deformations, often not immediately evident, may impact on infrastructures and bridges, which are quite stiff with respect to slope deformations. Therefore, they may suffer the consequences of these slow phenomena over long periods. Their effects are not always properly evaluated, since difficult to be identified and modelled. This work, starting from a specific case history, aims at emphasizing such events and their consequences on the performance and safety of infrastructures. Therefore, this work intends to be representative of a category of problems affecting manifold infrastructures and bridges.

THE INVESTIGATED SITES

The west side of central Apulia is characterized by the passage from the Apulian foreland to the Bradanic foredeep

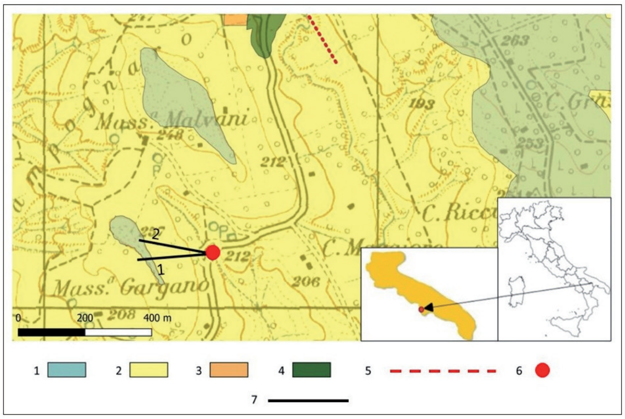

Fig. 1 - Geological maps of the studied area. (Excerpt of the Geological map of Italy 1:100.000, Fg. 201, modified); 1 - Sandy silt and gravel, regressive deposit (Pleistocene); 2 - Subappenine Clays ((Pleistocene); 3 - Sandstone, Gravina calcarenites (Pleistocene); 4 - Altamura Limestone (Cretaeous); 5 – Uncertain faults; 6 – Location of the studied bridge; 7 - Cross section

domain. In particular, the area close to the bound with Basilicata is part of river Bradano catchment, belonging to the western side of the foredeep domain of the Bradanic Trough. Sub Apennine clays of mid Pleistocene diffusively outcrop in this area, sometimes topped by thin strata of marine deposits of poorly cemented calcareous sands.

The investigated bridge (fig. 1) is in this geological environment, along a secondary road going from Ginosa to Montescaglioso, between the progressive distances 2+300 and 2+335 km of the road classified as SP1.

From a morphological point of view, the bridge crosses a small and quite deep valley, oriented along NW to SE direction. The landscape around the site is made by smooth clayey hills alternated to small valleys, with really small alluvial deposits. Elevations decrease going from E to W, towards the valley of river Bradano. The stream network is ephemeral, draining only the runoff generated by severe rainfall events. The slope of the bottom of the valley is about 10%, the slope of the right flank of the valley has a slope of about 12° (20%) (fig. 2). It is evident the deformation of the ground profile at the base slope upward the bridge abutment, like if the slope is involved in a sort of confined landslide, even if, fig. 2 shows a sort of infinite slope landslide.

The area around the bridge, even if is not characterized by the presence of evident landslides, shows several evidence of land instabilities: the side walls are visibly deformed, a small house, close to the road, is severely damaged, and the pavement of the road is diffusely fissured, see fig. 3. These could be considered as signs of shallow deformation phenomena that cannot be separately considered from each other. Indeed, they are consequences of a general extended instability affecting all the slope, moving towards the bottom of the valley in SE direction.

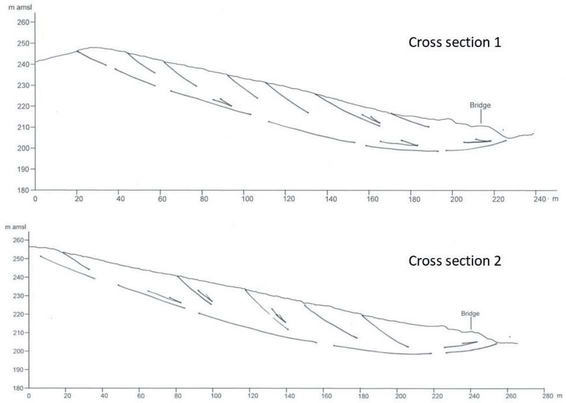

Fig. 2 - Cross sections of the slow-moving instability phenomena based on 1m-resolution LiDAR of the area around the bridge

Fig. 3 - Images of the damages evidencing the displacement of the landslide: a) damages of the side wall; b) reinforcement of the house; c) damages on the road pavement

THE DAMAGED BRIDGE

The damaged bridge is a single arch masonry structure, 50 m long and 8 m large. The arch is 4.8 m tall from the ground above the keystone, the springer line is at 3.8 m from the ground, the span of the arch is about 2.4 m large. Most of the structure is made by its abutments. Fig. 4a shows the SE side of the bridge. The bridge was presumably built between 1940 and 1947, replacing and older bridge, seriously damaged by the movements of the slope and still visible on the NW side of the bridge see fig. 4b. The bridge was recently closed to vehicular traffic for safety reason.

There is no documentation about the evolution of the cracks of the bridge, which were documented for the first time during an inspection on the bridge in 2005. Restrictions to vehicular traffic were introduced in 2005, after the aforementioned survey, reducing the width of the carriageway. Looking at the four pictures available from Google Street View, dated April 2009, August 2012, March 2021 and June 2022, it is noteworthy that in every picture the pavement of the road was replaced and there are new fissures and cracks. This implies a constant stress on the road, causing small deformations, which crack the pavement.

As showed by fig. 4a, the right abutment was displaced toward the bottom of the valley and slightly uplifted, thus causing the first fissure above the arch. The central section slipped down, causing the deformations, and fissuring on the barriers. The movement of the central part of the bridge caused the failure on the left abutment of the bridge.

The damage of the new bridge seems to be the same of the older, see fig. 4b, which was damaged by compression caused by the deformation induced by the right-side slope, this is consistent with the slow movement of the slope and the damages on both the bridges.

Fig. 4 - a) View of the SE side of the damaged bridge. b) Old, damaged bridge

DESCRIPTION OF THE PHENOMENON AND DISCUSSION

As already pointed out, the slow gravitative deformation involving the right abutment is neither known and investigated. There are sparse evidences of its activity, but no monitoring or specific surveys were ever done on this site. For this reason, a first general reconstruction of the phenomenon will be attempted, looking at the interferometric data available through the cloud-based geoinformation service platform Rheticus® (https://www.rheticus.eu/). These are based on Synthetic Aperture Radar (SAR) images collected by Sentinel-1A/B satellites. Data are processed by the SPINUA multi-temporal interferometry technique (Bovenga *et alii*, 2005) that is based on the processing of a stack of full-resolution differential interferograms in order to mitigate atmospheric and orbital artifacts and derive displacement time series for point or distributed scatterers (also known as Measurement Points, MP) that exhibit a good temporal coherence during the whole observation period. Since this study is mainly focused on the damaged bridge, the analysis is hereafter restricted to point scatterers.

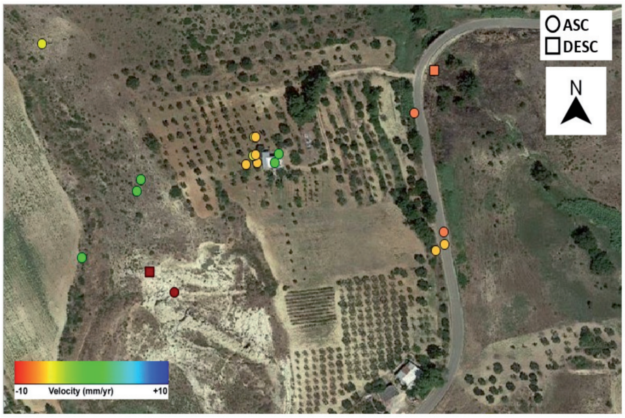

Fig. 5 - Positions of the MPs identified close to the bridge and upstream on the slope, along ascending (circles) and descending (squares) passes

Two Sentinel-1 interferometric stacks have been processed, one along ascending passes (relative orbit: 146; sub-swath: IW2; polarization: VV) and one along descending passes (relative orbit: 124; sub-swath: IW1; polarization: VV), by including all SAR acquisitions between April 2015 and February 2022. The detected MPs are shown in fig. 5.

Two MPs have been identified in proximity of the bridge (one for each satellite pass direction); their average velocities of displacement are -6.6 ± 0.2σ mm/year and -7.4 ± 0.2σ mm/year, measured along the satellite Line-Of-Sights (LOS) with a quite low temporal coherence (0.52 and 0.49, respectively), thus showing a relatively poor stability of the backscattering properties of these targets.

Another cluster of MPs is located along the road, close to the position of the damaged side wall reported in fig. 3. They are all detected along ascending passes and are moving away from the satellite, with LOS velocities ranging from -5.7 ± 0.2σ mm/year and -6.2 ± 0.2σ mm/year. All these movements are consistent with the slow movements of the slope described in the previous section.

Further MPs have been identified on the side of the hill; they are located at elevations about 24 m higher than those on the road, in the order 232 m a.s.l. and 208 m a.s.l. exhibit velocities ranging between -1.6 mm/year and -10.1 mm/year.

The measured displacements are consistent with the observed movements of the slope (i.e., towards lower elevations of the valley), but the investigation is still ongoing because of the complexity of the phenomenon. The use of high-resolution satellite data, like those acquired by the COSMO-SkyMed constellation, may be useful to increase the spatial density of the coherent targets on the bridge, or close to it.

The bridge seems to be compressed from W-NW by the slow displacements of the flank. This is consistent with the cracks of the bridge, as well as with the damages observed on the old, abandoned bridge (Fig. 4b). Fig. 2 shows cross sections with the reconstructed slow moving landslide phenomena affecting the right side of the bridge. Finally, it is noteworthy that the masonry abutment adsorbs part of deformation, instead the concrete vault of the arch shows major failures, repaired after the fissuring.

CONCLUSION

The presented case study focuses on the effect of very slow moving gravitative slope deformation involving a strategic infrastructure like a bridge, and it is representative of the effects of these kind of movements on infrastructure. The investigated bridge was severely damaged by cumulative stress effects, evolved over a long time, by slow deforming slope. However, the damages became evident only during the last decades. In addition, the morphology of the slope did not immediately shows any evident landslide, even if the cross sections of the slope show a sort of bulge at the base of the slope, immediately upward of the bridge flank. Thus, it can be the evidence of a sort of landslide as shown in fig. 2, mainly in a phase of confined landslide, that affect the slope. A plausible reconstruction of the displacements was attempted using SAR multi-temporal interferometry, which has the advantage of providing the monitoring of MPs over several years, with a millimetric accuracy. In this particular case, a very limited number of MPs were available in proximity of the bridge, but there were some MPs upstream the slope. All the MPs are not stable and allow to identify a very slow landslide involving a long front on a relatively small slope. It shows how this displacement compressed the bridge displacing and uplifting its right side, causing the damages that can be observed.

The investigated case study is quite complex, and the damaged infrastructure is small and located on a secondary road. However, this is a typical case study representative of several similar scenarios spread across Italy. These cases need for an accurate investigation, since, given the average age of the infrastructures in Italy, potential critical situations can occur. A simple first stage approach can be attempted using remote sensing techniques, like SAR-based interferometry, where MPs are available. These are low-cost and permit a mapping of those infrastructures, which are stressed by slow landslides. This early-stage mapping can be followed, if needed, by further investigations, in order to prevent the infrastructures from irreversibly deteriorate. Such pro-active management strategy of infrastructures would help saving money as well as avoiding service interruptions due to failures and dangerous accidents.

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REFERENCES

Agliardi F., Crosta G.B., Frattini P. & Malusà M.G (2013) - *Giant non-catastrophic landslides and the long-term exhumation of the european Alps*. Earth & Planet. Sci. Lett., **365**: 263-274. Doi: 10.1016/J.Epsl.2013.01.030.

Agliardi F., Scuderi M.M., Fusi N. & Collettini C. (2020) - *Slow-to-fast transition of giant creeping rockslides modulated by undrained loading in basal shear zones.* Nat. Commun., **11**: 1352. Doi: 10.1038/S41467-020-15093-3.

Barla G. (2018) - *Numerical Modeling Of Deep-Seated Landslides Interacting With Man-Made Structures.* J. Rock Mech. Geotech. Eng., **10**: 1020–1036. Doi: 10.1016/J.Jrmge.2018.08.006.

Bovenga F., Nutricato R., Refice A., Guerriero L. & Chiaradia M. T. (2005) - *SPINUA: A flexible processing chain for ERS / ENVISAT long term interferometry.* European Space Agency, (Special Publication) ESA SP, 572.

Cignetti M., Godone D., Zucca F., Bertolo D. & Giordan, D. (2020) - *Impact of deep-seated gravitational slope deformation on urban areas and large infrastructures in the italian western Alps.* Sci. Total Environ., **740**: 140360. Doi: 10.1016/J.Scitotenv.2020.140360

Confuorto P., Del Soldato M., Solari L., Festa D., Bianchini S.,.Raspini F. & Casagli N. (2021) - *Sentinel-1-based monitoring services at regional scale in Italy: State of the art and main findings.* International Journal of Applied Earth Observation and Geoinformation. **102**: 102448.

Crippa C., Valbuzzi E., Frattini P., Crosta G. B., Spreafico M. C. & Agliardi F. (2021) - *Semi-automated regional classification of the style of activity of slow rock-slope deformations using ps insar and squeesar velocity data.* Landslides, **18**: 2445-2463. Doi: 10.1007/S10346-021-01654-0

Del Soldato M., Confuorto P., Bianchini S., Sbarra P. & Casagli N. (2021) - *Review of works combining GNSS and insar in Europe*. Remote Sensing, **13**(9): 1684.

Discenza M.E. & Esposito C. (2021) - *State-of-art and remarks on some open questions about DSGSDs: Hints from a review of the scientific literature on related topics*. Italian Journal of Engineering Geology and Environment, **1**: 31-59.

Galeandro A, Doglioni A., Guerricchio A. & Simeone V. (2013) - *Hydraulic stream network conditioning by a tectonically induced, giant, deep-*

seated landslide along the front of the Apennine chain (south Italy). Natural Hazards And Earth System Science. **13**(5): 1269 – 1283. Doi: 10.5194/Nhess-13-1269-2013.

Guerricchio A. & Melidoro G. (1981) - *Movimenti di massa pseudo-tettonici nell'Appennino dell'Italia meridionale*. Geol. Appl. E Idrogeol., **XVI**: 251–294.

Guerricchio A., Melidoro G. & Simeone V. (1996) - *Le grandi frane di Petacciato sul versante costiero adriatico (Molise)* - Mem. Soc. Geol. It., **51**: 607-632.

Guerricchio A. (2022) - *Convivere con i grandi movimenti di massa*. Rivista Italiana di Geotecnica, **3-4**: 3-186.

Lacroix P., Handwerger A.L. & Bièvre, G. (2020) - *Life and death of slow-moving landslides*. Nat. Rev. Earth Environ. **1**: 404–419. https://doi.org/10.1038/S43017-020-0072-8

Ministero delle Infrastrutture e dei Trasporti (2020) - *Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti.* Decreto Ministeriale N. 578 del 17/12/2020.

Moretto S., Bozzano F. & Mazzanti P. (2021)- *The role of satellite insar for landslide forecasting: Limitations and openings.* Remote Sensing, **13**(18): 3735

Nappo N., Peduto D., Mavrouli O., Van Westen C. J. & Gullà G. (2019) - *Slow-moving landslides interacting with the road network: analysis of damage using ancillary data, in situ surveys and multi-source monitoring data.* Eng. Geol., **260**: 105244.

Pánek T. & Klimeš J. (2016) - *Temporal behavior of deep-seated gravitational slope deformations: a review*. Earth-Science Rev., **156**: 14–38. Doi:10.1016/J.Earscirev.2016.02.007

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