



Reconstruction of the Slope Instability Conditions Before the 2016 Failure in an Urbanized District of Florence (Italy), a UNESCO World Heritage Site

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Abstract

On May 25th, 2016, following a massive water leakage from the city water supply pipeline a portion of the urbanized riverbank collapsed along the Arno River in the city centre of Florence (Italy), UNESCO World Heritage site. Understand the dynamics driving the landscape evolution (from the slope up to the riverbank) is useful to know the historical growth of such a territory and to plan a farsighted and sustainable urban development. Therefore, a historical characterization of the area surrounding the Arno riverbank collapse was made considering the interaction between the anthropic pressure and the local geological hazards or those factors that activate them. Based on this reconstruction, some advanced technologies (like satellite imaging), integrated with more traditional techniques, have been employed (a) to analyse the landscape condition almost up to the trigger moment, (b) to study the dynamics of the event, (c) to monitor the possible spatial evolution of the 2016 landslide, and (d) to characterize the damage condition of the involved structures. The results show very low deformation rates, indicating relatively stable ground conditions before the event.

Keywords

Riverbank landslide • Satellite imaging • Cultural heritage monitoring • Hazard assessment • Landslide awareness

Introduction

The southern extremity of the historic centre of Florence, on the hydrographical left side of the Arno River, is bordered by a belt of rolling hills which yield an evocative landscape of inestimable cultural, historic and artistic value where the beauty of nature blends harmoniously with the fervour of the human activity. However, because of materials nature below the walking surface this area is subjected to a certain geological fragility that, in history, has contrasted such great beauty with recurring damaging events. Earthquakes, floods, and mass movements are here the main natural hazards affecting the city, showing respectively a high relevance for the entire built-up area, a high impact for the plain (including the reshaped sub-flat areas close to the river), and confined heavy consequences for the urbanized hillsides up to the riverbank slopes. The latter type of events, which for the riverbanks occurred even during floods due to the action of strong flows, is analysed in this paper. Starting from a historical reconstruction of the city evolution, we initially report the failures, the collapses, and the landslides occurred in the past up to describe the collapse of the artificial structure of the modern riverbank occurred in 2016 just upstream the Oldest Bridge (Ponte Vecchio in Italian) of Firenze.

Without the contextualization of the complex historical evolution of the slope and its alterations, it is difficult to understand the last instability event and the risks that can be incurred during this kind of events. This aspect, here described, was taken into consideration during the 2016 event for the emergency management and the design choices in the subsequent securing and final restoration.

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The Study Area

The area affected by the 25th May landslide (red area in Fig. 1, named Lungarno Torrigiani) involves a portion of the left riverbank of the Arno River just upstream of the medieval stone closed-spandrel segmental arch bridge called Old Bridge (Ponte Vecchio in Italian). It is located in the naturally narrower section of the river and for this reason it was chosen as the first crossing point in history (Mariotti Lippi et al. 2013). This area also corresponds to the hill foot called “Poggi dei Magnoli” (slope inclination between 20 and 45%) and commonly recognized by the population as “Poggio delle Rovinate” (Rovinate hill) because of the succession of landslides in past times (“Rovinate” means landslides in ancient Italian language), involving sometimes even the riverside.

From a geological point of view (Fig. 1) this area is set on the formations belonging to the Monte Morello Unit that represents the solid bedrock on which most of the buildings in this part of the city are anchored. Upward there are the Villafranchian fluvio-lacustrine deposits and finally the Holocene fluvial deposits. In detail, the Unit of Monte Morello is represented by the Pietraforte Formation in the lower portion, with lithofacies consisting of calcareous sandstones, shaly limestone with clay and marl (Cretaceous late), and by the Sillano Formation in the upper portion with lithofacies consisting of shales with limestone and sandy-limestone layers (Upper Cret.—Lower Eoc.) (Fanti 2006). The fluvial-lacustrine sediments in sandy and gravelly facies with abundant clayey matrix are higher up,

followed on the top by the Holocene fluvial deposits constituted by pebbles and sands, with silts and clays.

The study area does not have a real aquifer. However, a degree of permeability is locally present such as to allow meteoric waters a relevant underground circulation. It is caused by altered and disrupted (also for the past gravitational events) clay layers and by intense fractured arenaceous-calcareous interlayers. At the end of June 2016, the water levels in local piezometers were found to be between -7.0 m and -7.5 m from the street level (Asioli et al. 2017).

The current riverbank morphology (Fig. 2) is the product of a major urban restructuring and reorganization of the public spaces approved in 1866 and completed in 1872 in the overall framework of the modernization necessary to let Florence be the capital of Italy (1865–1871). Before these works, which have maintained almost the same resulting structure until today, the area still belonged to the river's meandering actions. It was in morphological continuity with the doorstep of the more proximal buildings whose main facades were facing the hill. Only the secondary facades were oriented towards the river with a direct access to it through vegetable or botanical gardens, exclusive spaces or private moorings. According to the project conserved in the Historical Archive of the Florence Municipality, the new riverbank (Fig. 2) was created by constructing a road several meters raised above the water level. In practical, it interrupted the direct usability of the river spaces and established a physical barrier between the elements that have lived together for centuries: the population and the watercourse.

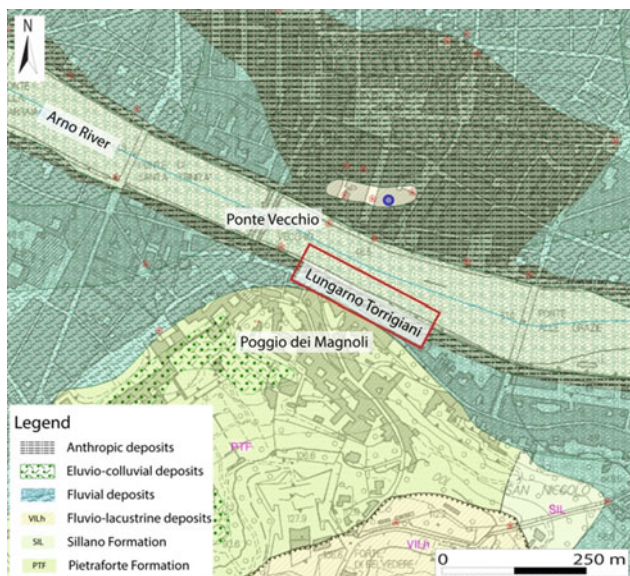


Fig. 1 Geological map of the zone surrounding the study area (red rectangle)

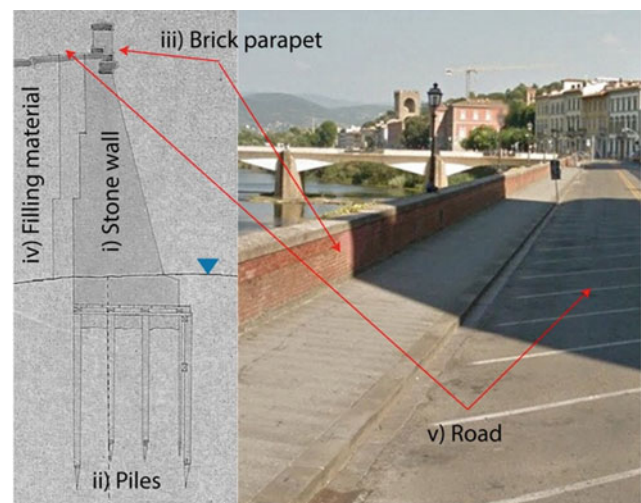


Fig. 2 The current riverbank morphology. (i) the vertical stone retaining wall; (ii) four rows of piles that anchor the wall directly to the substrate; (iii) the brick parapet; (iv) filling material with buried subservices; and (v) the paved road. Blue triangle is the water level

The riverbank new structure (Fig. 2) can be summarized with the following components: (i) a vertical stone retaining wall anchored directly to the substrate of the riverbed with four rows of piles; (ii) a brick parapet (about 1.20 m high); (iii) filling material and buried subservices between the stone wall and the original riverbank; (v) a paved road at the top. The filling operation was mainly managed with compacted landfill. Moreover, the riverbank was completed with the insertion of an arched vault culvert of metric dimensions just adjacent to the buildings' foundations, operating in junction with a lifting water station of a coeval aqueduct system that was built almost 600 m upstream.

In the first decades of the '900, a more modern and functional aqueduct pipe was added few centimetres below the surface in connection to the whole city network. During the nineteenth century restyling also the facades of the aligned facing buildings were rearranged and embellished to become real main facades such as for "Palazzo Capponi alle Rovinate", whose name, thanks to the appellative "Rovinate", remembers once again the local land instability.

Space–Time Reconstruction of the Instability Framework

Past Riverbanks Failures

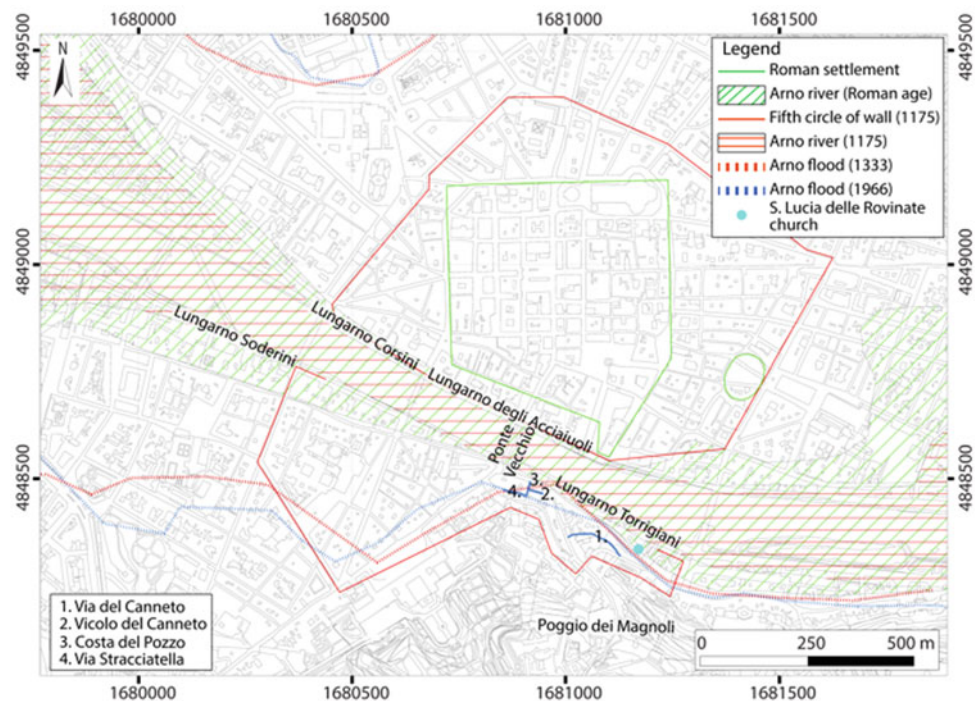
In 1175, the fifth circle of city walls was completed to encompass and defend some hamlets built on the Arno river left bank, tripling the urbanized area with a secure and stable fortification (Day Jr 2002). By means of this urban

reorganization, the city structure migrated its geographical barycentre closer to the Arno riverbed from a raised and ancient river terrace, which was occupied by the first Roman settlements (in 59 B.C.), and permanently inhabited for more than 11 centuries (Fig. 3). The two main consequences were: (a) the river was completely included in its natural narrowest stretch (Morelli et al. 2014) and (b) the inhabited area grew from a floodplain, less exposed to flooding and swamping, to a more floodable area. Thanks to renovations, integrations, and reconstructions of the old Roman walls in the north area of the city, the transition was very quick, and it was completed in just three years (Guidoboni and Ferrari 1995). From this moment onwards, all the natural riverbanks were progressively transformed into artificial urban morphologies thanks to slope reprofiling and accumulations of imported backfill (Schenk 2006).

Consequently, in this confined arrangement, the watercourse started to be a very active subject in the history of the city, both as indispensable support for the maintenance of the daily social-economic activities (especially those arisen to exploit directly the hydraulic power during ordinary flow conditions) and as a negative actor, during the most considerable flood events. In fact, as it is possible to read in many works published in Italian, (and here not cited) several damaging inundations were repeatedly observed over the centuries, and in some cases, riverbank collapses and/or damages to structures and buildings directly facing the riversides were induced by turbulent flows.

However, tangible and nonphysical consequences were commensurate with the different urban development during

Fig. 3 The Florence city centre over the years



historical periods. The exposure to the river-related risks increased, from time to time, according to the gradually change of the general structure of the city until today. However, the memory of the most significant events has been lost caused by the age-old habit of the population to these episodes and the wide and systemic omission in the chronicles compared with the other types of calamitous events. During the history even the resonance of the events varied because of the momentary economic consequences and the fluctuation of attention and problems perception relating to river dynamics, with substantial and consolidated reduction in more recent times. In the contemporary age, the grow of the emotional emphasis in people's consciousness, resulting from an increasingly deep awareness of the high artistic and historical heritage value of the historical assets of the city (Guidoboni and Ferrari 1995), has been added to all this, in addition to the value of the human life quality.

In this context, as it is possible to read in the historical cornicles, on July 4th, 1965 a portion of the left riverbank, downstream out of the study area, rapidly collapsed within the Arno River after a leakage from the subterranean water supply network that hugely saturated the fill soil. Such occurrence engulfed the retaining wall, which was vertically built to protect the anthropic riverbank from high flood currents, and to sustain the above levee wall represented by a low masonry parapet. The resulting landslide was characterized by a volume of about 4000–5000 m³, a length and a width of 40 m and 6 m, respectively. Despite the central location of the event site, one person was killed and no one else was involved. The reconstruction works started immediately after the due checks and were so effectively executed that the disastrous flood of the following year (November 4th, 1966) did not cause any damages in this stretch. In the morning of the 1966 devastating event, also the studied riverbank did not suffer any failures or significant damages to the main structure (only to the street furniture or minor artefacts) from the rapid rise of the water level and the consequent flood spreading that began nearby around 7.00 am. At the contrary, a portion of the right riverbank (Lungarno degli Acciaiuoli and Lungarno Corsini embankments) suffered significant collapses for long stretches because of the erosive strength of the river flows.

Past Slope Instabilities

First reports of significant landslides on the behind hillside, south the study area (“Poggio dei Magnoli”, or Magnoli hill), date back to 1284. At that time, the urbanization had gone far beyond the plain next to Ponte Vecchio and it was consolidating on the surrounding hills. On April 2nd, 1284

after a very intense rainfall, a sudden mass movement collapsed into the riverbed. As mentioned in the historical chronicles, in that occasion, more than 50 buildings erected on the steepest hill collapsed killing many inhabitants. It was hypothesized that houses had been poorly built, without a proper terracing and retaining walls.

In 1373, 1490, and 1547 similar injurious events occurred in this area after prolonged rainfalls (Asioli et al. 2017). The latter landslide, composed by a big mixture of rocks and earth, had highly impacted the urban layout, and eighteen houses were completely devastated. The consequent human vicissitudes of this tragedy struck a chord in the whole population that it was necessary to find a practical solution for the future. Consequently, in 1565, the Duke of Florence tried to solve once for all the problem of the slope instability. Realizing that the structural works would not only be sufficient, he prohibited constructing new buildings in all the affected area and a plate with such ban was affixed on site for future memory. Substantially this ban was respected for a very long period and only some buildings in the most distal part were recovered with appropriate protection works like the old church of Santa Lucia dei Magnoli which was later popularly renamed church of “Santa Lucia delle Rovinate” (light blue dot in Fig. 3). The last damages to the remaining houses were documented in 1651. They were caused by incessant rains that, after a persistence of about four months, triggered local slope deformations and movements. This indicates that a large part of the problem was resolved (i.e., the human influence), but the issue of surface and groundwater circulation still existed.

Problems at the hydraulic draining system existed for a long time and with substantial evidences (continuous water rising, moisture surfaces, and stagnation along some impluvia) that some streets were renamed over time reflecting these characteristics. For example, “Via del Canneto” (assigned from the fifteenth century, 1. in Fig. 3) and “Vicolo del Canneto” (2. in Fig. 3) got their name from marsh with natural thickets of canes that once could be found in wetlands nearby the river. In the same area, also the abundant presence of not too deep underground waters is testified by the streets' toponyms, which are here dedicated to the existence of some public wells in past centuries. For example, there is “Costa del Pozzo” (meaning “Little Street - that runs along the slope—of the Well”) which was included in the past adjacent to the road currently renamed as “via Stracciatella” (3 and 4 in Fig. 3).

From the great landslide of 1547 to the beginning of the twentieth century no further news of slope instabilities were recorded. Nevertheless, as it is possible to read in the chronicles, modest gravitational movements were reactivated in the area of the Bardini Garden in 1916, and in

1925–1926 some slope deformations caused the shift of the Bardini Garden road by about 3 m towards the river. From 1926 to today no relevant movements occurred.

The 2016 Pre-collapse Condition

Following the failure of 25th May 2016, four datasets of very high-resolution X-band (wavelength of 3.1 cm) satellite images were acquired and processed to retrieve information about pre-event surface displacement phenomena. The purpose of the radar data analysis was to detect and record any pre-event deformation along and around the study area, through the use of advanced InSAR (Interferometric Synthetic Aperture Radar) techniques, suitable for mapping slow deformation phenomena (from mm up to a few cm per year).

Ground displacement data were obtained using the SqueeSAR technique (Ferretti et al. 2011), a second-generation PSI (Persistent Scatterer Interferometry) algorithm. Methods belonging to this family are based on the processing of long temporal series of co-registered, multi-temporal SAR images acquired over the same target area from the same acquisition geometry. The main idea behind these methods is to identify pixels and groups of pixels sharing similar radar returns during the entire observation period, via proper statistical analyses. Using this sparse grid of radar targets, PSI techniques are able to statistically identify, quantify and remove atmospheric noise from SAR phase data and to create a history of motion for each target with millimetre accuracy. Images acquired, along ascending and descending orbits, by the Italian Constellation COSMO-SkyMed and by the German satellite TerraSAR-X (both with 3×3 m of ground resolution) were processed with the SqueeSAR approach. Obtained results provided valuable information on ground movements before the event and are reported in Fig. 4, where measurements points are classified according to their average velocities. Positive values correspond to motion toward the satellite; negative values correspond to motion away from the satellite (in mm/year). Both COSMO-SkyMed and TerraSAR-X datasets show, for the area of the Lungarno Torrigiani, very low deformation rates, ranging between -1.5 and 1.5 mm/yr, indicating relatively stable ground conditions (green points). All the information included in Fig. 4 agree that no significant movements before the 25th May 2016 event can be observed. High-resolution multi-interferometric results highlight the absence of movements in this sector and exclude the presence of active slope instability before the 25th May 2016 failure.

The 2016 Riverbank Failure

At 6:00 a.m. of May 25th, 2016 part of the Lungarno Torrigiani road collapsed with a partial slide of the terrigenous layer towards the riverbed. This failure was approximately 4 m in high and 150 m in length (cavity volume: about 1300 m^3) and the retaining wall was deformed but did not collapse. Late in the night of May 24th, 2016 a large amount of water observed over the street, despite the absence of rainfalls, and the decrease in the water pressure within a ND 600 pipeline gave advance of this event. Remote sensing technologies like laser scanner, total station, camera for close-range photogrammetry together with in situ analysis (boreholes, electrical resistivity topographies, downhole, and seismic noise) and laboratory tests were employed to characterize the riverbank landslide and the wall cracks (Morelli et al. 2020). To forecast any possible extension of the failure, a monitoring system was set up. It involved a high-resolution ground-based interferometric radar, located on the right riverbank, three seismic stations, placed on the riverbank wall, four crackmeters and nine biaxial tiltmeters laid on the facades of the buildings and remotely controlled. A detailed analysis of the failure was performed to identify the damage condition of the involved structures, to define the causes of the failure, and to mitigate and preserve the cultural heritage site. This analysis followed the strategy of developing a reasoned incremental observational capacity, progressively focusing on the most significant points on a smaller scale with increasingly specific devices after understanding the investigated scenarios. The management of these instruments, especially the more sophisticated ones, has produced a large amount of data that have been used only partially for the contingent purposes of rapid monitoring. Many of the unused stored data were subsequently reorganized for characterizing the event and, thanks to small additions of appropriate data acquisitions, understanding the residual risk in the area. Such analyses are not the focus of this paper.

Discussion and Conclusion

The Duke of Florence's ban in 1565 was the first example of a farsighted and sustainable urban development. In the following centuries, the manipulation of the territory was concentrated on the riverbanks, reaching its maximum pressure in the last decades. The maintenance of these lowland areas however did not sufficiently take into account the natural features of the territory and its relations with the

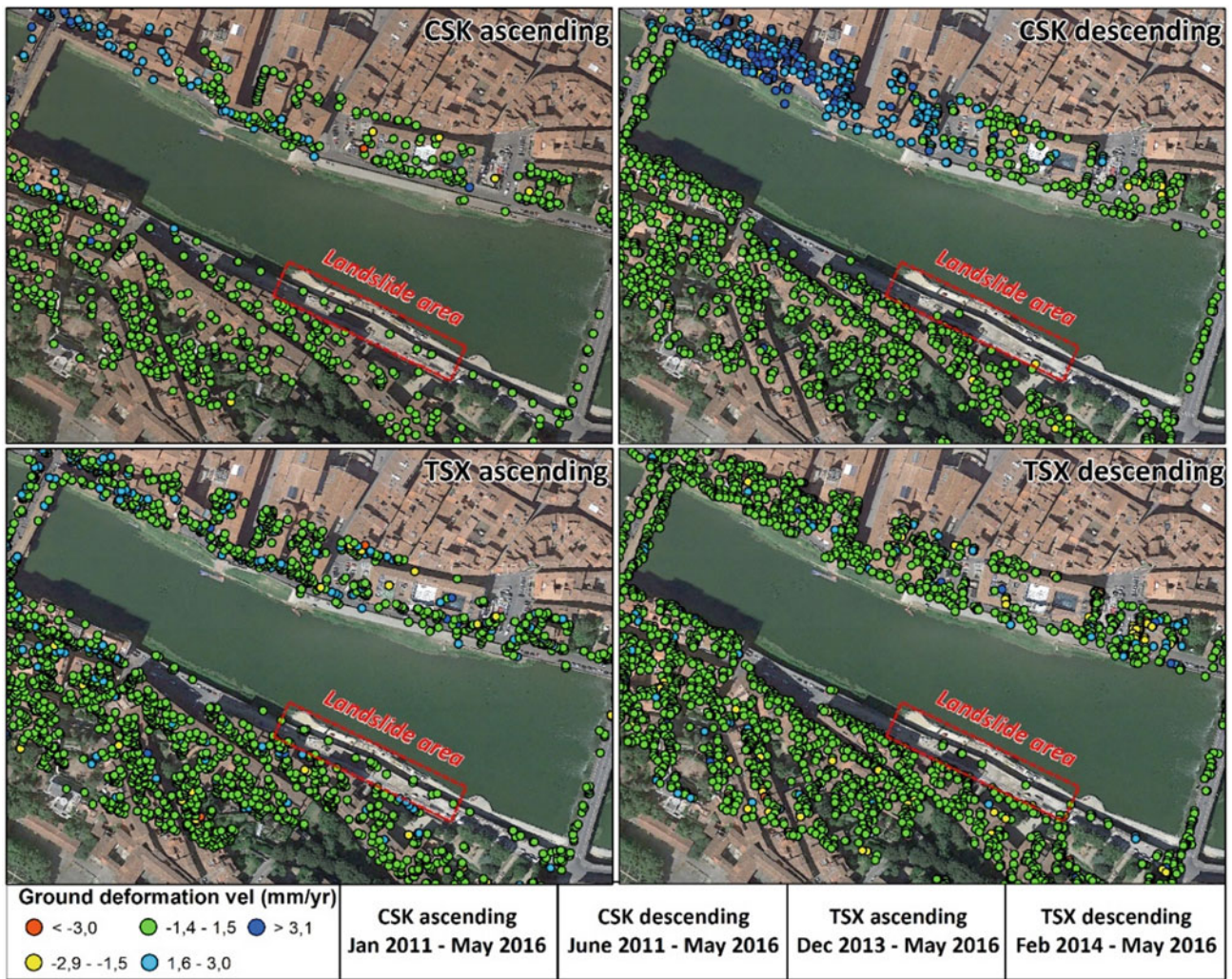


Fig. 4 Pre-event ground deformation for the area affected by the May 25th riverbank landslide obtained processing very high-resolution COSMO-SkyMed (CSK) and TerraSAR-x (TSX) satellite acquisitions

slope instabilities. Then, the last disastrous flood of 1966 completely shifted the focus on the riverbank preservation due to high waters levels in the river, developing specific plans only for inundations. The 2016 collapse, due to an atypical circulation of underground water, hit unexpectedly, but with few damages that it was possible to study, preparing the community to face again these ancient problems.

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