# Arno Riverbed Survey in Florence 1935 - 2019: From the Integrated Survey to the Geomatic Monitoring

# Arno riverbed survey in Florence 1935 - 2019: from the integrated survey to the geomatic monitoring

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**Abstract.** On the 50th anniversary of the 1966 flood, the University of Florence, together with many other institutions, promoted the "Florence 2016 Project" by collecting materials, launching new research activities, supporting projects and events to obtain tangible results for the prevention of future disasters and identify good practices for the protection of people and of cultural, economic and environmental heritage. The paper aims to review how the Arno Hydrographic Office surveyed the river during World War Two by photogrammetry and classical topography and to compare the old surveys with the recent activities carried out as part of the Florence 2016 Project. By considering past and more recent surveys, it is possible to identify methodological approaches that retain their validity and to highlight the potentialities of innovative technologies that offer new perspectives for investigation and analysis.
In particular, GNSS (Global Navigation Satellite Systems) techniques offer an easy solution to survey georeferencing, with an evident advantage in repeatability and comparison of results, but a high precision survey needs a critical approach, so to aim at effective monitoring.

**Keywords:** Hydrographic Risk, Classical Topography, Aerial Photogrammetry, Mobile Mapping Systems, Bathymetric Survey, 3D Modelling, Geomatics, Monitoring

## 1 Introduction

On the 50th anniversary of the 1966 flood, the University of Florence, together with many other institutions, has promoted the "Florence 2016 Project" by collecting materials, launching new research activities, supporting projects and events in order to obtain tangible results for the prevention of future disasters and to identify good practices for the protection of people, and of cultural, economic and environmental heritage [1].

The project was founded by the Municipality of Florence, the Consorzio di Bonifica Medio Valdarno, the Autorità Idrica Toscana, and Publiacqua. Many researchers from the Department of Civil and Environmental Engineering were involved, each contributing with his/her specific background – as well-known complex problems benefit from multidisciplinary approaches [2].

One of the activities carried out as part of the project is the survey of a stretch of about 18 km of the Arno riverbed and its immediate surroundings, from Varlungo to the mouth of the Bisenzio River. A Mobile Mapping System (MMS), mounted on a rubber boat, integrates different sensors: a multi-beam echo sounder (MBES) for the riverbed documentation, a terrestrial laser scanner (TLS), in profiler mode, for the simultaneous survey of banks and architectural structures, and a series of valuable sensor for georeferencing 3D data acquired, contemporary, over and under the water.

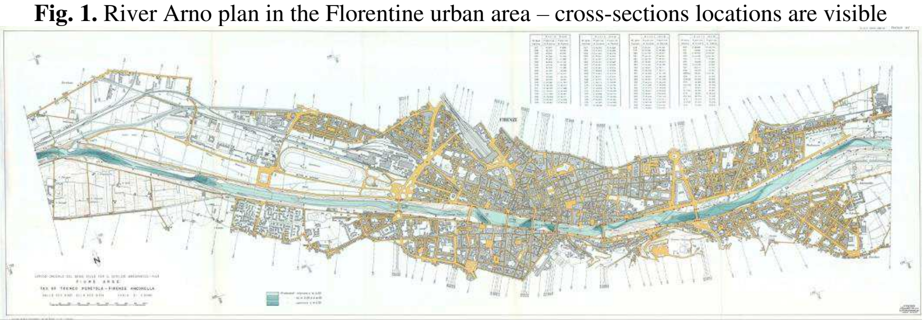
The paper reviews how the Arno River was surveyed in the past, then presents some cutting edge techniques offered by geomatics to acquire, manage, and examine spatial data, and describes the specific case of the section of Arno under investigation. Lastly, it concludes with some remarks and perspectives about new studies we carried out recently in the west branch of the Arno, in Signa and Lastra a Signa.

## 2 The Survey Campaign 1935-1961

In 1935 the Arno Hydrographic Office started to survey the river, but they did not complete the work due to the Second World War, which destroyed most of the documents already completed. In the '50s, the same Office started to survey the river, starting from its mouth.

The results were published in 1954 (the first section of about 42 km) [3] and 1956 (the second section of 40 km more) [4]. In 1960-61 the survey was further extended in the urban stretch of the river (see Fig. 1) [5], then proceeding towards the river mouth in the later years. The following section provides some details about how, at that time, data was acquired to better make a comparison later with the new surveys.

**Fig. 1.** River Arno plan in the Florentine urban area – cross-sections locations are visible



### 2.1 Classical Survey Techniques: Topography and Photogrammetry

An aerial photogrammetry survey was performed, and data that was not derivable from the aerial images, as the ground under the vegetation, and the riverbed, were measured by tacheometry and bathymetry. A Wild RC5 camera was mounted on an airplane, taking several images on 230 x 230 mm high film slides. Thanks to the stereoscopic observations of photogrammetric models (Fig. 2), the operator plotted all the relevant details, including urban areas facing the river. Integration of so many different survey techniques and instruments (triangulation, traverses, tacheometry, levelling, aerial photogrammetry), induces to define this approach as "ante litteram" geomatic.

Several traverses connected benchmarks, some of those already used in the 1935-36 survey, and some trigonometric points from the Italian Geographic Military Institute (IGMI) and Cadaster. A precise levelling was performed on the left bank, that served as a base for the levelling lines on the right bank, connected to principal line benchmarks with loop circuits. Cross-sections have been surveyed using tacheometers so as floodplain areas in order to allow a 25 cm contouring.

Therefore, we can say that the "state of the art" in mapping was applied to document the river, and it sounds clear that it has been a demanding work, considering technologies, the required time, and costs.

**Fig. 2.** Analogue stereo plotter (Galileo-Santoni Stereosimplex III)

## 2.2 Traditional Graphical Outputs

Conventional rules were well established for plotting traditional surveys: e.g., the plan view represents the outline of the right and left riverbanks, with the river's length in a smaller graphical scale than its breadth. The maximum depth line, or Thalweg line, the tributary waterways, and the bridges are also plotted. The profile stresses the elevations on a scale of 1:200, whilst the length of the whole river is on a scale of 1:50.000 (Fig.3). In addition to the ground representation, the low-water and high-water levels are taken into account.

For the section of the Arno passing through Florence, 243 transversal sections describe bridges and weirs (Fig.4). They were measured by tacheometry and levelling.

Finally, contours lines, with a contour line distance of 25 cm, were plotted based on a tacheometric riverbanks survey with a resolution never lower than 10 points in a hectare.

**Fig. 3.** River Arno longitudinal profile – scales: 1:50.000 / 1:200

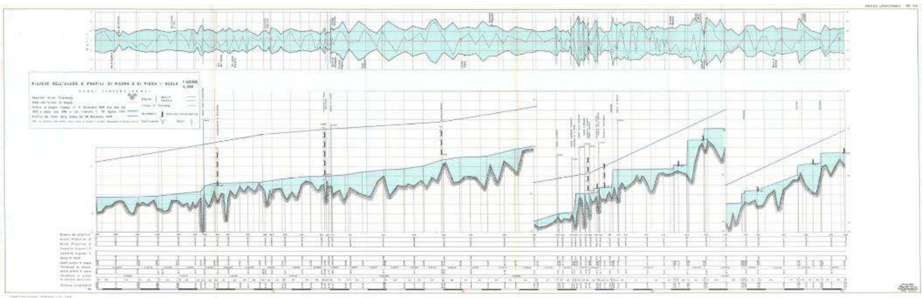
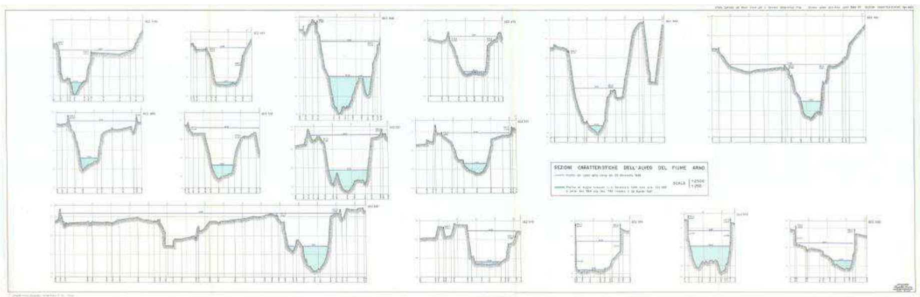


**Fig. 4.** River Arno cross-sections – scales: 1:2.500/1:250



### 2.3 Comments and Remarks

The report of the survey works done in the field at that time sounds fascinating to us, and we can appreciate the thorough description of the instruments and adopted methods, the precision declared, the admirable drawings. A massive amount of data was measured, computed, elaborated, and finally plotted to describe the river meticulously. Despite this, the river's description, with its banks, the bridges, the buildings close to it, is "discrete" or, as we would say nowadays, it has a "low resolution": in fact, the shape description of the riverbed is weak from the point of view of continuity, and only along cross-sections it is satisfactory.

## 3 The Contemporary Survey

A survey, even the best-done survey, is something valid at the moment when it is performed. Moreover, a river changes over time, even without considering exceptional events, like floods. Therefore, the "Firenze 2016" project gave the chance to perform a new survey of the Arno river urban section. Each survey documents the land portion, the built heritage, or the river that is under study, and the technologies and the advances in the know-how of its time. In the broader project aimed at monitoring the Arno River and at building an updated and effective hydraulic modelling, a 3D survey was performed from Varlungo Bridge to the Bisenzio river mouth in Signa.

Compared to what happened in the past, the instruments used nowadays are more complex, and several sensors are frequently integrated to record information of different nature simultaneously [6]. The time required in the field has been greatly reduced, thanks to the instruments' operating speed and the possibility of adopting automatisms. On the other hand, the need to plan the survey in a rigorous way remains unchanged, as well the need to adopt measurement methods that allow to certify the quality of the collected data, and to document exhaustively all that is done, to guarantee the possibility to evaluate, to continue, and to integrate the work previously done.

Fluvial studies require high quality topographic and bathymetric data. While Section 2 represents state of the art at that time, subsequently tacheometric [7], satellite positioning [8], and aerial photogrammetry techniques [9] have been widely used to produce digital terrain models with increasing accuracy and resolution. In this field of studies, the increasing speed at which geometric data are recorded today seems to be, however, more favourable from an operational point of view - it allows the time spent in the field to be limited - than for exploiting the high resolution that can be obtained [10] [11]. In the case of the project presented here, the realisation of an integrated survey was also aimed at - at least preliminary - documentation of the bridges, whose state of conservation must be carefully inspected and monitored [12] [13]. The short time that needs to be devoted to on-site acquisition operations also makes it possible to carry out multitemporal surveys [14], thus providing valuable insights into fluvial morphodynamics. Detailed high-resolution maps of the river site can be rapidly and efficiently generated by boat-based MMS, which integrates various navigational and data acquisition sensors on a rigid and moving platform: GPS receivers and IMU (Inertial Measurement Unit) record the system trajectory, and laser scanners and digital cameras or videos record information from the surroundings of the river [15]. Integrating the MMS with a multi-beam echo sounder allows also reconstructing the submerged riverbed [16].

### 3.1 The Adopted Mobile Mapping System

The river survey was divided into seven areas, each characterised by shipping continuity and provided with a landing stage (see Fig. 5). An MMS was mounted on a rubber boat, integrating different sensors:

- a multi-beam echo sounder system,
- a 3D laser scanner, in profiler mode,
- moreover, a series of sensors for georeferencing 3D data acquired, contemporary, over and under the water.

During data acquisition, the onboard control system shows real-time info about the navigation and positioning, and data recorded by the multi-beam (underwater) and by the laser scanner (over the water). A subsampled view of 3D data is also visible on the screen. Fig. 6 shows an example of the data recorded in the sections 2 and 3 of the river, where the Arno crosses the city centre, and Fig. 7 highlights that 3D data has a very high resolution.

**Fig. 5.** The entire stretch of the river under consideration has been partitioned into continuously navigable segments

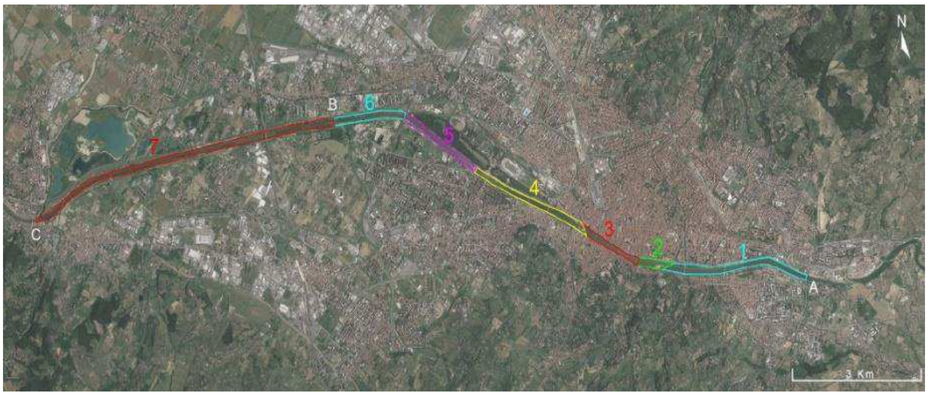



**Fig. 6.** 3D data recorded where the Arno crosses the city centre

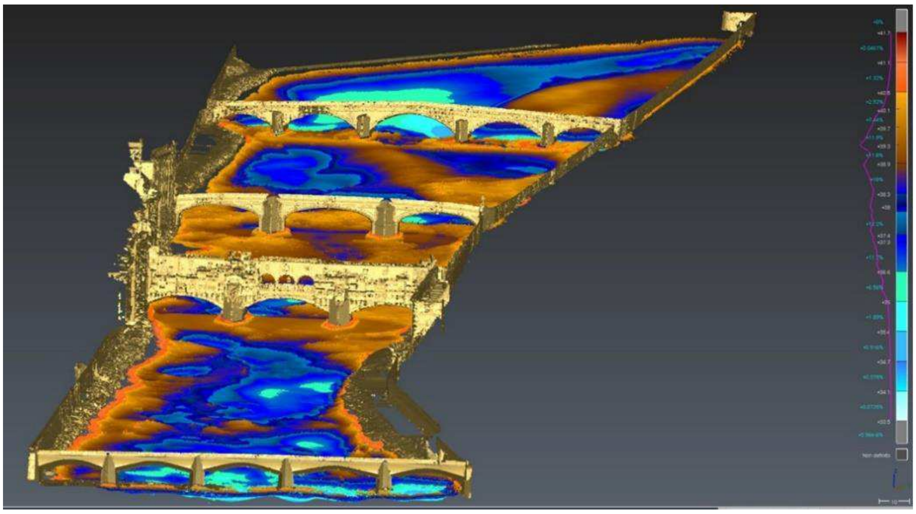
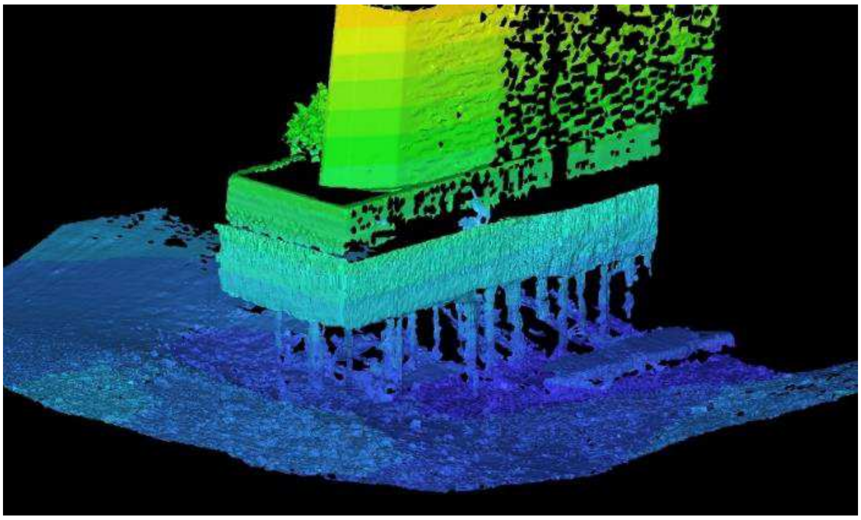


**Fig. 7.** 3D data has a very high resolution, which also allows to check and monitor the piers of bridges



## 3.2 3D Data Georeferencing

To correctly georeference 3D data, the control network plays a key role, consisting of fixed points measured with great accuracy and therefore positioned in a specific reference system. Reaching high accuracy is an expensive task; that is why it is essential to plan the control network carefully, balance the need to have available reference points all along the river, and that of limit the resources that have to be employed to do it.

**The Datum Choice.** The official geodetic datum in Italy is the European system ETRS89 - ETRF2000 updated to 2008.0. However, for technical purposes, a cartographic projection must be defined but still considering deformations - of course, if and when they are relevant concerning the expected accuracy. Given the extent of the survey, neglecting these deformations would lead to an error of about 50 cm, much higher than the one resulting from position measurements, both satellite and topographic. Therefore, a local system was explicitly defined to limit deformation effects and to compute and adjust topographic measurements. The orthometric height was considered to support the hydraulic modelling correctly for elevations.

In order to improve interoperability - that is a relevant aspect in such an interdisciplinary project - all the benchmark's coordinates are computed both in UTM32 and in Gauss Boaga cartographic reference systems.

**The Control Network - GNSS.** In this case, a robust geodetic framework was defined by GNSS measurements, based on some permanent stations near the survey area: IGMI and PRAT (by EUREF network), CALA and EMNS (by ItalPoS network). Observations collected by high precision total station integrate the control network.

Control network vertices have been fixed on all bridges (except on Ponte Vecchio, where buildings blocked most of the satellites signals) and along the banks in obstacle-free zones to acquire satellite data with a strong geometry.

**The Control Network – TS.** TS measurements started from GNSS (static) determined fix points positioned on the bridges, banks, or both. Precision in benchmark (each suitable as station point) position is about ± 1-2 cm (planimetric). For height measurements, five IGMI high precision levelling network benchmarks were employed and tied to the local TS network; University-Military Geographical Institute synergy gave excellent results; in fact, the accuracy in local network fix points elevations was better than ± 1cm.

**Ground Control Points.** As ground control points, black and white targets were fixed on the riversides and measured by a total station (TS). They were later used to control the georeferencing of all the data acquired by TLS (out of the water) and MBES (underwater).

Through the same topographic instruments (TS Leica TCRP1201), 3D positions of about 100 ground control points (GCP) – targets placed along the river' section considered from time to time - were determined with a precision better than ± 1 dm.

The entire mobile mapping survey was, at first, directly geo-referenced based on the onboard sensor observations (GNSS and inertial navigation system). Accuracy checks provided satisfactory results, showing differences between points measured by topography and the same recorded on the point model of about ± 1-3 dm, compliant with the survey purposes.

**Considerations Concerning Accuracy and Resolution.** Some studies about the hydraulic model's sensitivity to different topographic inputs demonstrated that the watercourse geometry and the inundation area are crucial elements to hydraulic models [17]. Given this, in the sections passing through the historical city centre, 3D data georeferencing was improved: by forcing GCP to correspond to topographic coordinates, subsets of laser scanner data were considered, and an adjustment was performed to enhance the survey accuracy and reliability globally. After that, the GCP root mean square errors are about ± 4 cm (planimetry) and ± 1 cm in height. Random checks on the point model showed that the actual accuracy is always compliant with the requests since never planimetric errors are worse than 10 cm and 5 cm in height.

Therefore, the new survey of the Arno is an accurate «digital twin» of the natural river. Graphical representation such as Digital Elevation Models (DEM), vertical sections, surface models, can be extracted from the available database, depending on the project's need, focusing on a long section or a small detail on a bridge's pier as well. Multi-beam resolution ranges from 1 to 5 cm, depending on the water depth and on some sensor parameters. Laser scanning resolution varies according to the scanned surfaces' position for the instrument path, with average values comparable to that of the multi-beam system. If a higher resolution is needed – for structures out of the water, of course - a terrestrial laser scanner can profitably be applied, thus allowing to resolve about half a centimetre – as shown in Fig. 8, about the 3D survey of Ponte Vecchio GeCo Lab did in 2012.

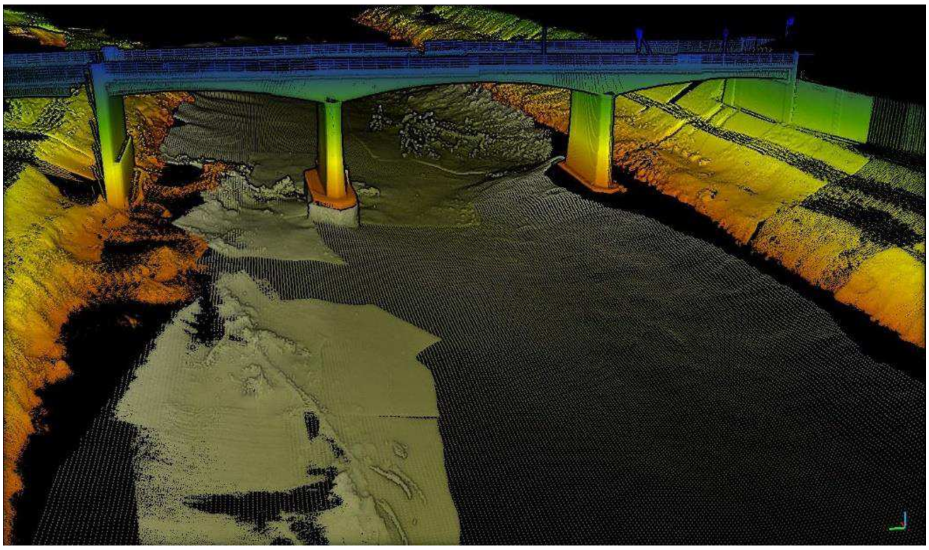
**Fig. 8.** Ponte Vecchio point model, TLS survey by GeCo Lab, 2012

## 4 Forthcoming Studies

In 2019, the Arno River survey extended for about 400 m towards the West (in the town of Signa and Lastra a Signa) in a research project aimed at the structural analysis of two bridges located in this area (Fig. 9). Accuracy requirements were stricter than those needed for the previous survey because of the new study's different purposes, mainly related to the structural analysis of bridges. Therefore, a laser scanning survey complemented the mobile mapping survey; a control network was designed to reach a precision of ± 1-2 mm and have GCP 3D positions defined in a ± 5-10 mm range. All the vertices were permanently fixed on stones on top of banks; temporary black and white targets were distributed along riverbanks to be used as GCP.

The control network was defined by combining GNSS and TS measurements, thus requiring a pre-calibrated mounting for the antenna to refer all the observations to the same point, both planimetrically and altimetrically. Apart from the increase in accuracy required by the new survey, the instruments and methods are the same as those used in 2015-2016, as is the reference system; by doing so, it will be possible to carry out new measurements that are entirely comparable with the current ones, even in the future.

**Fig. 9.** The road bridge crossing the Arno between the towns of Lastra and Lastra a Signa



## 5 Conclusions

The diachronic analysis of river Arno surveys executed along the last century highlights the evolution of instruments and methods for survey and representation of reality, also allowing to identify the aspects of continuity concerning the past:

- the relevance of the preliminary design of the field operations,
- the approach based on the integration of different techniques,
- the methodological rigour with which measurements and computations are carried out,
- the research of effective ways to represent the river and its surrounding area as exhaustively as possible.

Considering the survey activities concerning the time when they were carried out also allows to highlight which changes may have occurred in the area and to assess their entity: Fig. 10 shows a blue profile acquired in 2015 - during the survey campaign described above - and a red profile, recorded immediately after the collapse of the wall supporting the left bank in April 2016 in Lungarno Torrigiani, in the Florence city centre [18].

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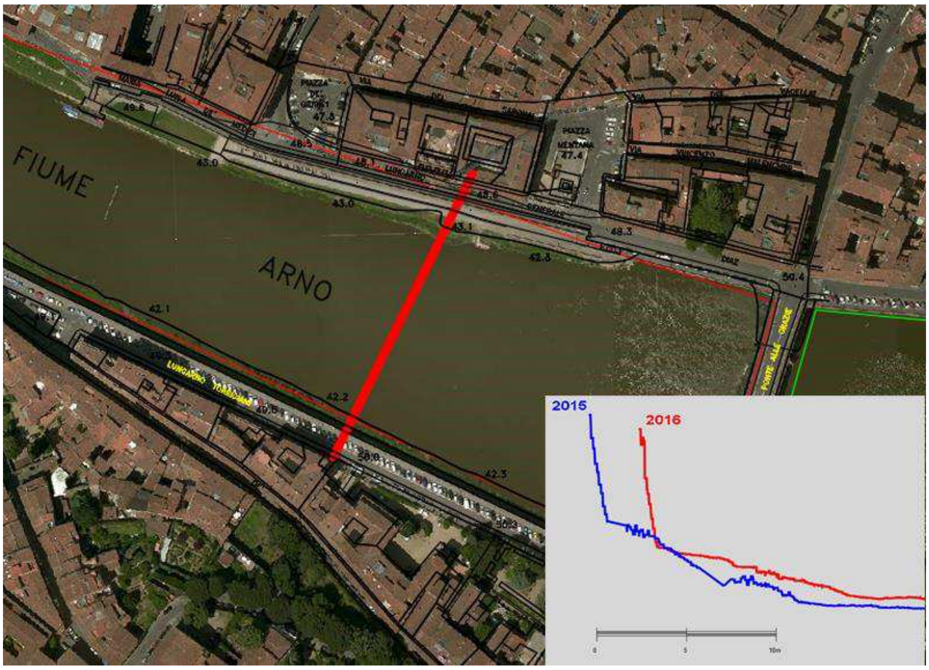
**Fig. 10.** Cross-sections in Lungarno Torrigiani before and after the wall collapse

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