The 3D virtual reconstruction of an engineering work of the past

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Abstract. The construction of artificial emissary of Lake Fucino’s represents one of the most significant engineering challenges that took place in antiquity. Unfortunately, the imposing structure of the Roman emissary was almost completely erased from the building of the late nineteenth century, constructed for the final drying of the lake. This article presents its virtual reconstruction, to understand the technological issues met by Romans and to visually offer reconstruction theories starting from interpreting of the few Roman remains. So that, engineering resources are used to try to understand unresolved issues in archaeology.

1. Introduction
The emissary of Lake Fucino in the Abruzzo region of Italy, build between 41 and 52 B.C. can be considered one of the most important hydraulic construction in antiquity. It operated until Middle Age when the tunnel collapsed. Its length, about 5650 m, is a record unmatched until the 19th century. The tunnel construction required to adopt new technologies in order to deal with unusual problems never faced before. This emissary was replaced in the 19th century, when the old Roman emissary was obliterated by the construction of a modern tunnel. The modern emissary was made using the old one as a track, but its section presents different shape and size, more suitable to cope with the different pressures of the soil, and capable to sustain of greater water flow. The result is a tunnel much larger than the Roman one that completely erased the Roman emissary.

The first detailed records about the Roman construction are written by Raffaele Fabretti [1] and Carlo Afan De Rivera [2]. The first reports some illustrations of the tunnel and its accessory structures. The second one proposes a complete work describing in detail the conditions of the Roman emissary at the beginning of 18th century. The most complete record is written by Alexandre Brisse and Léon De Rotrou [4]. This consists of two books and an Atlas, which report the Roman emissary's path and its sections. The analysis of these sources, taken individually, does not permit the complete comprehension of this hydraulic construction. Furthermore, a joint study of these sources, without adding engineering resources does not solve some open questions.

The aim of this paper is to understand the specific technologies used to plan and realize the emissary. It is useful, to fully comprehend this work and the technologies applied to its construction, to collect in a single representation all the documentary sources. These concern the territorial geography and the archaeological remains, such as wells and other auxiliary structures. The main goal is to evidence the complex functional connections among the wells, the tortuosity of the main tunnel’s path, the secondary tunnels network and the territory’s orography, and the subsoil. Together with these purposes, the
exteriority of the construction is shown. The 3D geometric relations that all these sources show, hold the technical reasons for such a complex work. Since a lot of the technologies used to realize the emissary apply geometry’s principles, a 3D virtual reconstruction of the Roman emissary gives the opportunity to achieve information about the methods Romans used to realize such a difficult task. Advanced techniques for 3D reconstruction can be used for specifically understanding several issues Romans met in realizing the emissary: surveying methods, hydraulic technologies, the constructive phases together.

3D reality-based technologies are typically used to reconstruct ancient monumental buildings, focusing on their aesthetic and historical value. The Fucino’s emissary can be an opportunity to evaluate how virtual reality technologies are able to support the archaeological research of scientific and technological aspects, through the analysis of measured data, combined with documentary and iconographic sources.

2. Historical events: a brief summary
Lake Fucino was an endorheic lake without any natural emissary, whose waters were affected by great variations, both in surface and depth. Therefore, the lake overflowed the lands surrounding its shores, causing several problems to the nearby towns. This was the main reason that brought local people asking to somehow regulate the Lake level.

The first idea of controlling Fucino’s waters and exploiting its territories was expressed by Roman administration. The drying project was conceived during the first century BC by Caesar. He wanted to make new arable land available, through the draining of the Pontine Marshes and the Fucino. Caesar’s death prevented the realization of this project, that was taken over a century later by Claudius. The emperor decided to build an artificial emissary to regulate the water’s level. Even if this wasn’t the first time that Romans build artificial emissaries and hydraulic construction, the Lake Fucino’s emissary represented a more difficult challenge. This work was complex and hard to achieve, demanded the best methods in tunnels building and innovative technologies. With no written records, it’s very difficult to retrace the several phases of the survey and the construction. The emissary was completed in AD 52 and its use continued with Claudius’ successors. Trajan and Hadrian took care of the restoration and maintenance of the emissary, as documented by historical and archaeological sources. As a result of indifference, and natural events such as earthquakes, the Roman tunnel lost, in the following centuries, its function as an emissary.

A renewed interest in Lake Fucino emerged in Medieval times. The first one, who took into consideration the idea of restoring the emissary, was Frederick II, in 1240 ca. However, his death cancelled any plan concerning Fucino and there are no reliable reports about practical intervention in this area. In the meantime, issues related to the endorheic nature of Fucino and the lack of any emissary occurred again. The level of water increased without interruption from 1787 to 1816 and the lake reached 35 m in depth.

The Kingdom of Naples, which in those days exercised its government in the Fucino area, considered to carry out such a project with Carlo Afan De Rivera. The military engineer was appointed Director of Public Works of the Kingdom of the Two Sicilies in 1824, but the lack of funding made more difficult the work continuation and then, the death of Afan De Rivera in 1845, temporarily put an end to the Bourbon efforts to figure out Fucino’s problem. The definitive solution came with the involvement of Prince Alessandro Torlonia, who thought of radical modifying the project by substituting the Roman emissary with a modern hydraulic construction. The new tunnel differentiates itself from the ancient one, being much larger and, due to its construction, the Roman emissary was almost completely erased.

3. Documentary and iconographic sources
Torlonia’s work helped to increase knowledge about Claudio’s emissary, together with all its pertaining structures. Nevertheless, this knowledge comes from its definitive and complete destruction. Moreover, even if this is one of the most challenging hydraulic work realized in antiquity, involving the application of new technologies, the Fucino’s emissary remains quite unknown throughout the centuries.
To research what is left about this construction and its functions, it is necessary to collect and pull together in a single representation, data that can be directly measured in site and the ones coming from sources and documentation.

The first documentation available comes from classical sources like Plinius, Tacitus and Cassius Dio, who mainly described only the emissary’s inauguration and the historical events involving Claudius and his court. These sources do not contain engineering information about the hydraulic constructions and used technologies. This kind of information can be found in the descriptions of the Roman emissary made by Raffaele Fabretti [1] and Carlo Afan De Rivera [2]. The first one briefly described the Roman construction, including plate and drawing in his work. The last one reported his works to recover the ancient construction in 1836, with the aim to use again the original Roman tunnel and outlet. A. De Rivera describes the methods he used for the underground excavation and the machines needed for it, together with the solutions adopted. These methods and techniques probably didn’t diverge too much from the ones used in antiquity. It gives also a very precise description about working environment and condition at beginning of 18th century.

The books published by A. Brisse and L. De Rotrou [4] are the most important and detailed document nowadays left. They supervised the building of the modern tunnel and can be considered as the last witnesses of the Roman emissary, before its final demolition. The ancient construction is described in two volumes and an illustrated Atlas, which also contains the technical description of the modern works to drain Lake Fucino (figure 1). Detailed plates describe the tunnel’s itinerary and its longitudinal section, together with wells and secondary tunnels (cunicola). Moreover, the Atlas presents a series of detailed charts with sections of the Roman gallery every ten meters. As regards the cunicola, sections and plans are reported in [7].

In the preparation of this work, other sources were used. One is the G. Agricola’s treaty, De re metallica [3], which is not a specific work about Fucino’s emissary, but it can be used as a frame of reference for wells and tunnels function, as well for working techniques and machinery. A further special evidence for the equipment used for the Roman works is a bas-relief found during the nineteenth-century Torlonia construction. Other elements were pointed out by studying the few remains of the tunnels and the other structures.

Figure 1. Drawings sections of the Roman emissary compared to the modern one as illustrated in [4].

The documentation above illustrated gives the possibility to offer a series of reconstruction hypothesis about the original method used to project such a difficult challenge, and about the use of suitable types of machinery for lifting and transporting construction materials.

4. Virtual Reconstruction

In this virtual reconstruction, it is necessary to manage a considerable number and complex amount of information. Moreover, the available data here are mostly provided by written sources, especially the
Torlonia’s Atlas. Different tools have been used to provide a reliable virtual reconstruction of the ancient hydraulic construction.

The information about the territory’s topography are given by IGM cartography (1:25000) and aerial photographs. These were used as basis for the digital terrain reconstruction. The drawing of the tunnel described in the Torlonia Atlas [4] has been digitalized and added to the modern 2D representation, together with the acquisition of topographic points on site. An image processing software erased maps and digital image distortions. It was also necessary to use 2D drafting software, for providing dimensional relation among the different maps used as basis for this work (figure 2).

![Figure 2](image_url) 2D drafting of path emissary superimposed on aerial photographs (Google Maps®).

The 3D tunnel’s itinerary too has been modeled following the Torlonia’s engineers documentation [4]. In the Atlas, the emissary is well represented and described by plans, together with the heights of its bottom and 600 sections disposed every ten meters. Then, the secondary tunnels *cunicola* [7] and the wells were modeled. *Cunicola* entrances are the only parts of the original roman cladding still existing today. Resulting from detailed researches, textures and rendering tools were applied to 3D models, using a specific software for rendering and 3D animation. Textures related to wells and material construction has been determined based on the study and analyses of cladding in use at that time for similar construction. The textures of the geological strata are symbolic and representative, and they are taken from the Torlonia Atlas (figure 3). They help to understand the tunnel’s failure and problems.

4.1. The results

Claudio’s work consists in several constructions aimed to drain the Fucino’s Lake and functional to the tunnel construction:

- The incile, the artificial outlet;
- The emissary, the main tunnel;
- The cunicola, the secondary tunnels and the wells.

The first one is an opencast collecting canal for conveying Fucino’s waters towards a system of tanks: the so-called Incile (figure 4).
Then, there was the excavation of an underground tunnel, with a route that crossed Mount Salviano and Palentini Plain, ending in the Liri River. Probably original Roman plan didn’t consider the draining of all the lake’s waters, as happened centuries later with Torlonia’s works. Emperor Claudius wanted to regulate the water level of the lake maintaining, therefore, a part of the basin. The activity needed to be planned with a careful levelling, considering the level of Liri river lower than Fucino Lake. Once that the direction was decided, and the length measured, the outlets quotes were fixed, setting out the inclination necessary for the tunnel to be functional.

The main tunnel had to be built following a path far from straight, by setting both the starting and final points. This is illustrated by the reconstruction in figure 5, showing the topography of the area and the itinerary of the emissary (as a red line). Reconstructing and representing this itinerary in 3D allows to understand the technologies used to plan and execute the works, especially as regard the used topography technique [5].

The construction of the main emissary tunnel was difficult to pursue, especially where the path crossed Mount Salviano. To overcome several difficulties, a system of wells and secondary tunnels (cunicola) were realized. The system made of wells and secondary tunnels increased the spots where the horizontal tunnel excavation started. Once the well was dug to an appropriate depth, the tunnel excavation started, proceeding on the two opposite fronts (Figure 6).

Different functions can be assigned to these structures:
• They were used as start points for digging the main tunnel, sub-divided into several segments, simultaneously working as direction’s reference;
• Facilitated tunnel’s ventilation and air flow during excavation’s work;
• They were the fastest system to introduce building materials and to dispose of water and resulting material.

The excavation of the wells is located in areas of different soil consistency, so some could suffer unsustainable side pressures. It was therefore necessary to arm them with wooden or wall structures, and both systems were found and illustrated by the engineers involved in Torlonia's work (figure 6b).

At least 40 wells were built in a square section together with the tunnels. 29 of these wells are positioned on the side where the town of Capistrello is located, and 11 beyond the mountain Salviano, on the eastern slope. The depth of the wells is variable from 19 m to the deepest well (number 22), the last on the side of Capistrello, which reaches 122 m in depth. The wells on the western side of Mount Salviano have a depth generally greater than 80m. The wells had wooden scaffolds like the ones represented in the virtual reconstruction in the figure 6a.

The *cunicola* were tunnels directed towards the main gallery, with the same function of the vertical wells, but placed on the two slopes of Mount Salviano. These passages found below Salviano’s slopes are seven and constitute the expedient used to deal with one of the most difficult segment of the project. So, they have a function similar to the wells, plus they were used to transport excavation materials and as an entrance for workers and means.

The analysis of 3D textured emissary model helps to understand the tunnel’s failure and problems. The section under Mount Salviano, where the tunnel is dug into the compact rock, it crosses a section of rocky debris mixed with pebbles. Here the Romans ran into great difficulties and needed to make a deviation from the preset path, probably because of landslides. The emissary then crosses a long stretch of clay and sand, where the Roman gallery suffered, in the centuries following its realization, the collapse of many tunnel’s parts.

![Figure 5](image-url)  
*Figure 5*. Virtual reproduction of the Palentini Plains territory overlapping the route of the Roman emissary.
The tunnels located on the side of the lake are Cunicolo Imperiale, Cunicolo del Ferraro, and Cunicolo Maggiore. The latter is the most monumental, with an entrance made on three arches in vertical succession. It is the last descender on the east side of Salviano and is connected, transversely, to the Ferraro's tunnel (figure 7). After the Mount Salviano, there are three descents, sequentially excavated and intercepting well 22, called Salviano 1, Salviano 2 and Salviano 3, or Calderaro tunnel. Not far away there is another tunnel, the Salviano 4, connected to the well no. 21 through a short deviation.

The final tunnel will result in an impressive work by the length of approximately 5,650 meters. The exit of the emissary is on a bend of the Liri River, in a narrow gorge in Capistrello town. It is a monumental exit surmounted by an arch of great height, made of masonry in opus incertum and in opus reticulatum.
5. Conclusion

The virtual reconstruction of the Fucino’s Roman emissary here presented aims to investigate and to study the Roman hydraulic work and the technologies applied in its realization. Virtual reality contributes to further understand the different steps in the emissary’s construction: how the surveying techniques were applied in such a complex construction project, the knowledge of digging technology, the realization of the main tunnel and the cunicola. The 3D modelled tunnels system shows a complex functionality, which the modern virtual reality systems enhanced, stressing for example the tunnels orientation in space. This allowed to revise the technical assessment made later by the Torlonia engineer, which believed the roman project and emissary construction affected by errors that cause several issues through the years.

The virtual reality in cultural heritage is usually applied architectural or landscape reconstruction contexts. In this case, the application is closer to the original use of 3D techniques (Computer Aided Design) used as a tool for functional analysis of artifacts rather than for their historical or artistic representation. The here presented work can be compared to a reverse engineering process, which extracts knowledge and design information from ancient sources, documentation, and drawings of the Roman emissary’s archaeological remains. In this work, virtual reality completes the missing data and it is used to reconstruct the model of an ancient hydraulic construction, illustrating its original functionality and giving hypothesis about the Roman organization of work and the building site.

The 3D geometric model could be used to investigate the hydraulic construction considering a different technical point of view. By using, for example, numerical fluid dynamic models, with regard to water flows, but also to study the cunicola and wells function analyzing the air flows necessary for the survival of the workers who built the construction. In this way, the engineering resource becomes the means for a deeper understanding of archaeological questions, combining the tools of engineering and archeology and thus promoting the development of the knowledge of ancient technology.

The result of this work was alongside with the production of a film documentary, which describes and summarizes the history of this construction, from the origin to present day. It has an educational purpose, and it is nowadays used to introduce visitors to site visits, but it’s still useful to fully understand the technologies behind this hydraulic construction.

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