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COMPRESSED-AIR FOUNDATIONS IN ITALY: HBIM-AIDED STUDY OF THE TIBER RIVER EMBANKMENTS (1876-1900)

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Ilaria Giannetti, Stefania Mornati

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Abstract

The paper focuses on using compressed-air foundations technology in Italy in the last three decades of the 19th century. The case study of the Tiber River embankments in Rome (1876-1900) reveals the significant application of the technique to construct retaining walls, exploiting iron caissons as excavation chambers. Furthermore, the case study discloses the transfer of knowledge in Italy and the innovative contribution of Italian construction companies and engineers to the international development of the technique. In this framework, applying the so-called 'demountable caissons' marked a significant step in perfecting the attempts conducted since the late 1850s to recover the iron used for constructing the caissons for future use. The study exploits the original design documents of the foundations of the Tiber retaining wall, conserved in the Archive of the Genio Civile of Rome, and an HBIM, functioning as an investigation tool and digital archive for educational purposes.

Keywords

Construction History, HBIM, Pneumatic foundations, Iron construction, Archival research.

Ilaria Giannetti*
DICII - Università degli Studi di Roma Tor Vergata, Dipartimento di Ingegneria Civile e Ingegneria Informatica, Roma (Italy)

Stefania Mornati
DICII - Università degli Studi di Roma Tor Vergata, Dipartimento di Ingegneria Civile e Ingegneria Informatica, Roma (Italy)

** Corresponding author:*
e-mail: ilaria.giannetti@uniroma2.it

1. INTRODUCTION

In the 19th century, the rapid development of the railway network and the improvement of urban river infrastructures brought widespread progress in foundation techniques. Using air pressure has been considered an efficient method for excavation below the groundwater level.

In the backward Italian building industry, the use of compressed air for foundations was introduced in the 1860s by French and English construction companies and further developed in the 1870s by Italian engineers and local contractors [1].

The national evolutions of air pressure-based foundation methods in the second half of the 19th century are still poorly addressed in the construction history literature [2, 3]. The topic can be significantly improved by analyzing the work site micro-histories via literature of the time and archival research. Furthermore, considering the complexity of the technique in terms of both the construction process and building details of the excavation devices, the use of digital tools for knowledge and graphic representation, such as HBIM, can support the investigations, providing a powered visual framework [4, 5].

Under these premises, the scope of the present paper is an insight into the application of the technology in Italy – via the case study of the design and construction of the Tiber River embankments (1876-1900) – combining archival surveys and philological HBIM approach, based on historical documents [6, 7]. Archival surveys were mainly conducted on the design documentation produced by the *Ufficio Speciale per la Sistemazione del Tevere* – "Special Office for the Tiber's settlement" –, today kept in the Archive of the Genio Civile of Rome [8]. The Special Office was the institution charged with the execution design and the direction of works of the river embankments since 1876: the archive, thus, collected execution drawings, technical reports, work site agendas, and construction site pictures, providing crucial data for insight on the excavation compressed air processes. The case study was framed in the coeval experimentation at the national and international level via the analysis of the technical literature of the time – manuals and journal papers – addressing the subject. The HBIM was first used as an investigation tool to acquire a robust knowledge of the construction details and the building processes and, thus, developed in terms of a digital archive for educational purposes [4–7].

The contribution presents the following contents: a general overview of the development of the use of air pressure for excavation works in the 19th is provided in Paragraph 2, retracing the introduction of the *pneumatic foundations* in Italy; in Paragraph 3, the historical analysis of the case study is presented, while the HBIM process and its outcomes are presented in Paragraph 4; conclusions, concerning knowledge increasing and methodological consideration, are given in Paragraph 5.

2. PIONEERING ON THE *VACUUM* AND *PLENUM* METHODS (1840-1850)

In addition to daring methods known from as far back as the 13th century [9], the first technological solution was the *diving bell*, comprised of a small chamber, open at the bottom and isolated from the water by overpressure.

The English engineer John Smeaton (1724-1792) was the first to use the diving bell for excavations below the groundwater level. Dry digging was only possible for a short time before oxygen was depleted, whereas the bell could reach a limited depth [9].

Between the 1840s and the 1850s, French and English engineers would excavate below groundwater level for mining and digging deep bridge piers' foundations [3]. Two alternative methods were developed: the so-called *vacuum* method based on the depressurization process for sinking hollow piles [10], and the so-called *plenum* method based on the overpressure of an excavation chamber [11]. Initially applied to mining shafts, the latter affirmed compressed-air caisson technology for excavating foundations.

In 1841, the French mining engineer Jacques Triger (1801-1867) submitted to the *Académie des Sciences* an account of using compressed air to successfully sink a colliery shaft through the alluvial deposits of the Loire [11]. In 1848, Triger proposed extending the use of the system, at first for shaft sinking and particularly for the foundations of bridge piers [3].

In the meantime, the experiments with excavation techniques based on air pressure advanced through an invention by the English physicist Laurence Holker Potts (1789-1850). In 1843, Potts filed a patent listing "certain improvements in the construction of piers, embankments, breakwaters, and other similar structures" [10]. The invention comprised the sinking of iron hollow piles, open at the lower end and closed at the top by a cap. Reversing the Triger process, a partial *vacuum* was formed within the tube by means of air pumps. Shingle and sand would flow upwards through the pile due to atmospheric pressure, and the rush of water from below would break up the soil and undermine the lower edges of the stack. Gravity enabled the pile to descend, assisted by the pressure of the air on its closed end, and when it was filled, the contents would be discharged by a pump. As Potts wrote in 1848, «In practice, a very partial *vacuum* is required; the descent of the tube is simultaneous with the commencement of the extraction of the air» [8].

That system soon gained the backing of the great engineers and companies of the time and was used for railway bridges (Tab. 1), such as the Black Potts Bridge over the Thames River (1849) and the Britannia Bridge (1849).

In 1850, Potts' pneumatic piles were adopted for the foundations of a bridge across the River Medway at

Year	Bridge Name	System	Engineer
1849	Britannia bridge	vacuum piles	Stephenson
1849	Conwy bridge	vacuum piles	Stephenson
1849	Black Potts bridge	vacuum piles	Brunel
1849	Benha bridge	vacuum piles	Stephenson
1849	Neuville-sur-Sarthe bridge	vacuum piles	Fox
1850	Rochester bridge	water inflow	Huges

Tab. 1. *Main bridges with vacuum piles based on Potts' system (1849-50).*

Year	Bridge Name	System	Engineer
1850	Rochester bridge	pneumatic piles	Hughes
1855	Torino-Novara bridges	pneumatic piles	Murray
1859	Royal Albert bridge, Saltash	pneumatic piles	Brunel
1859	Kowno bridge	pneumatic piles	Cézanne
1859	Khel bridge	pneumatic caissons	Fleur Saint-Denis
1861	Argenteuil bridge	pneumatic piles	Castor
1863	Piacenza bridge	pneumatic caissons	Biadego
1864	Mezzanacorti bridge	pneumatic caissons	Cottrau

Tab. 2. *Main bridges with compressed air foundations based on Trigers' system (1850-65).*

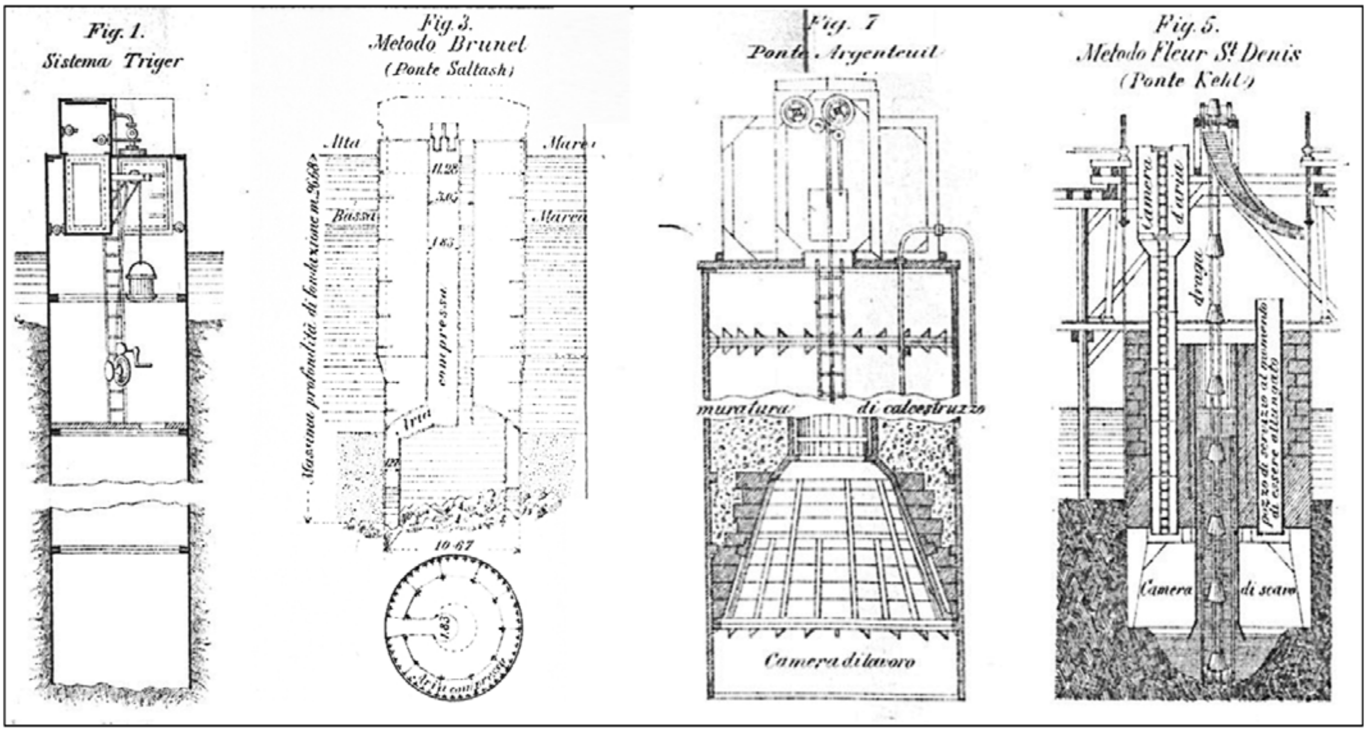


Fig. 1. *Triger's plenum system: main modifications of the excavation chamber (1850-70), reported in [10].*

Rochester, Kent, which the Fox & Henderson Company managed. The method proved to be a failure because it was found to be impossible to sink cylinders through the compact mass of Kentish ragstone, which encumbered the riverbed [3]. The contractor's engineer, John D'Urban Hughes (1807-1874), reversed the process to be very similar to that of Triger by giving each pile the characteristic of an overpressured excavation chamber. The Triger method, perfected by Hughes [12], was soon adopted as the standard for excavating the foundations of deep bridge piers (Tab. 2), while that of Potts, not suitable for excavation in consistent soils, was progressively abandoned [3]. In the 1850s, the Triger method was perfected through subsequent modifications concerning mainly the enlargement of the excavation chamber, using iron caissons: iron caissons were first used in 1859 by the engineer Fleur Saint Denis and, thus, became the standard solution in the 1860s and 1870s [13].

2.1. THE INTRODUCTION OF COMPRESSED AIR METHODS IN ITALY

In Italy, the technique was introduced by English and French contractors operating in the country since the 1850s; the first national treatise on the topic was published late, reporting on the knowledge transfer process to the local engineers and contractors [1, 3, 14–16].

The first applications were developed for railway viaducts in the early 1850s. These included the foundation of four railway bridges (1848-1853) – over the Stura, Orco, Malone, and Agogna Rivers – between Turin and Novara, managed by the English contractor Fox & Henderson Company [3]. In the early 1860s, the technique was first applied with the contribution of Italian engineers: the construction of the pneumatic foundation of the viaduct over the Po River in Piacenza was directed by the Italian engineer Giovanni Battista Biadego (1850-1925), exploiting the design of wrought-iron caissons [1]. In the following years, the *Impresa Industriale Italiana Costruzioni Metalliche* (IIICM), directed by the engineer Alfredo Cottrau (1839-1898), led the national development of compressed air foundations, becoming the national dealer of the technique [3].

3. THE TIBER RIVER EMBANKMENTS (1876-1900)

In the last three decades of the 19th century, the urban path of the Tiber River in Rome was channelized with new embankment structures featuring high retaining walls [17].

Since the very first work sites in the late 1870s, the ordinary excavation methods below groundwater level were considered unsuitable to reach the foundation depth required for the stability of the structures: the use of compressed air processes gradually established itself as the standard solution.

3.1. EXPERIMENTATION OF THE TECHNIQUE FOR DEEP FOUNDATIONS OF BRIDGES

The very first application of the system on the Tiber River was dated 1864: compressed air was used for the foundations of the two cylindric bridge piers in the riverbed of the railway bridge on the Rome-Civitavecchia line; works were led by foreign construction companies under the direction of the Italian engineer Romolo Burri [18].

In 1877, a system of tubular piers was applied for the foundation in the riverbed for the pedestrian Ripetta bridge, involving, for the first time, a local contractor: the Italian construction firm IIICM.

On 25 September 1876, the IIICM presented a memorandum, signed by Cottrau, that illustrated the advantages of an iron structure as an alternative to the wooden truss bridge project already approved by the local authorities [19]. The proposed solution guaranteed a smaller footprint in the riverbed and improved the structure's resistance against the impact of the river's flow. The iron truss bridge, with a total length of 94 m, presented four spans, three of which were 27 m long and 8 m wide. The two main girders, also to serve as parapets, rested on coupled cylindrical piers with an average height of 15-16 m and a diameter of 1.80 m. When proposing the iron structure, IIICM suggested using compressed air tubular foundations for the piers in the riverbed [19]. The tubular foundation system consisted of cylindrical piers functioning like excavation chambers: piers were formed by piling wrought-iron rings with a wall thickness of 8 mm; once sunk to the specified depth, they were filled by

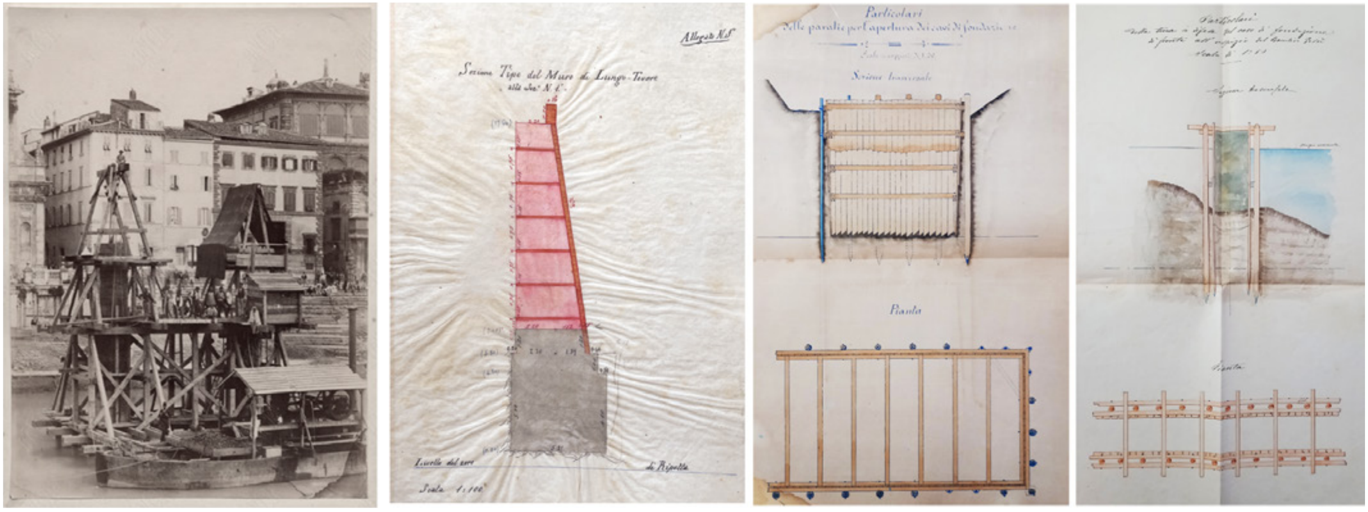


Fig. 2. *The compressed air tubular piles of the Ripetta bridge foundations: picture of the sinking of the tubular piles [14]; Special Office of the Tiber's settlement, execution drawing of the retaining wall and traditional excavation device for excavation below groundwater level, 1876 (courtesy of Rome State Archive, USTRA collection).*

a concrete cast. A wooden castle equipped with winches was designed to sink the piles (Fig. 2).

3.2. THE RETAINING WALLS FOUNDATIONS: COMPRESSED AIR CAISSONS

The design of retaining walls featured sub-vertical masonry structures and concrete foundation blocks (Fig. 2). The construction site started in 1876. Conventional excavation methods below groundwater level – wooden cofferdam (Fig. 2) – didn't allow to reach the design foundation depth, 6-9 m below the low water level, affecting the planned works in costs and times.

In 1878, the engineers of the Special Office considered the conventional excavation processes unsuitable, suggesting the application of compressed air methods. In particular, the use of pneumatic iron caissons, as excavation chambers, was proposed for the foundations of the retaining walls, in the Regola lot of land, assigned to the Campos construction firm [20]. The proposal relied on subcontracting the construction of the wrought iron caissons to IIICM, which had already been entrusted with the Ripetta bridge [20].

The technology was firstly applied to the foundations of a 200 m long wall section (Fig. 3), with four rectangular masonry piers (6x6.50 m in plan), exploiting wrought-iron caissons with a constant depth of 6.60 m from the river level. The caissons were 3 m in height and featured the same plan dimensions as the piers. Each caisson, made of a wrought iron sheet joined by a flat

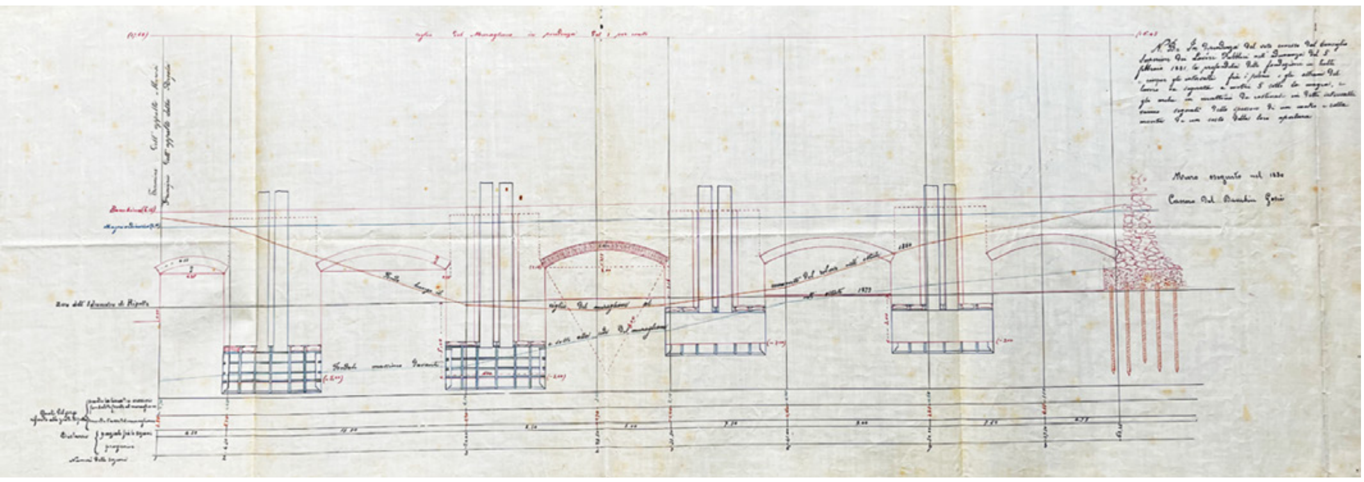


Fig. 3. *IIICM, wrought-iron caissons for the retaining walls' foundations, 1882 (courtesy of Rome State Archive, USTRA collection).*

iron, was equipped with a pair of iron tubes 90 cm in diameter, connecting the excavation chamber at the bottom to the airlocks and the outside.

At the design stage, the proposed building procedure consisted of excavation works in the caisson chamber to obtain the progressive sinking of the caisson and masonry works over the caisson's ceiling for the piers' elevation. The masonry piers, in tuff and pozzolanic mortar, were thus built in free air, functioning as an additional load for the sinking of the caisson.

The construction site opened in 1882 [21]. As reported in the technical treatizes of the time, the proposed building process was improved with the pioneering application of the so-called demountable caissons aiming to «minimize the considerable amount of iron that remains lost in the foundations» [1]. The caissons, designed by the IIICM, featured a demountable wrought-iron sheets elevation wall (in Italian *camicia*) for supporting the masonry built over the ceiling (Fig. 4).

The excavation chamber (20x4.80 m in plan and 3 m high) was comprised of wrought-iron sheets, strengthened and stabilized by vertical and horizontal elements in flat irons (Fig. 4): the ceiling was strengthened by a grid of truss in flat irons, while the vertical walls, composed of 7 mm-thick wrought-iron sheets, were reinforced with triangular-shape ribs; a set of tie rod was added at the base. The caissons were equipped with a pair of iron tubes, 90 cm in diameter (in Italian *camini*), which would connect the excavation chambers to the airlocks and the outside.

The elevation wall for supporting the masonry built over the excavation chamber ceiling (*camicia*) was composed of 7 mm-thick wrought-iron sheets jointed with flat irons that functioned as coulisses (sliding joints) (Fig. 4). During construction, the latter were weakly fixed to the wrought-iron sheets by only four small spikes. Once the masonry works were completed, the wrought-iron sheets were removed.

In 1882, the adoption of compressed air caissons became mandatory for constructing the foundation of the retaining walls, with a minimum depth of 6 m below the mean river level. As a direct consequence, the building details of the retaining wall section were updated by the Special Office (Fig. 5). The possibility of assigning a broad building lot to a single construction company – featuring technological skills and economic robustness to guarantee the extensive adoption of the compressed air foundation technology – was envisaged by the Special Office and approved by the national authorities (*Consiglio Superiore dei Lavori Pubblici*): Italian contractors didn't fit both the economic and technological requirements; thus, the Swiss firm Zschokke & Terrier was appointed for the works [21].

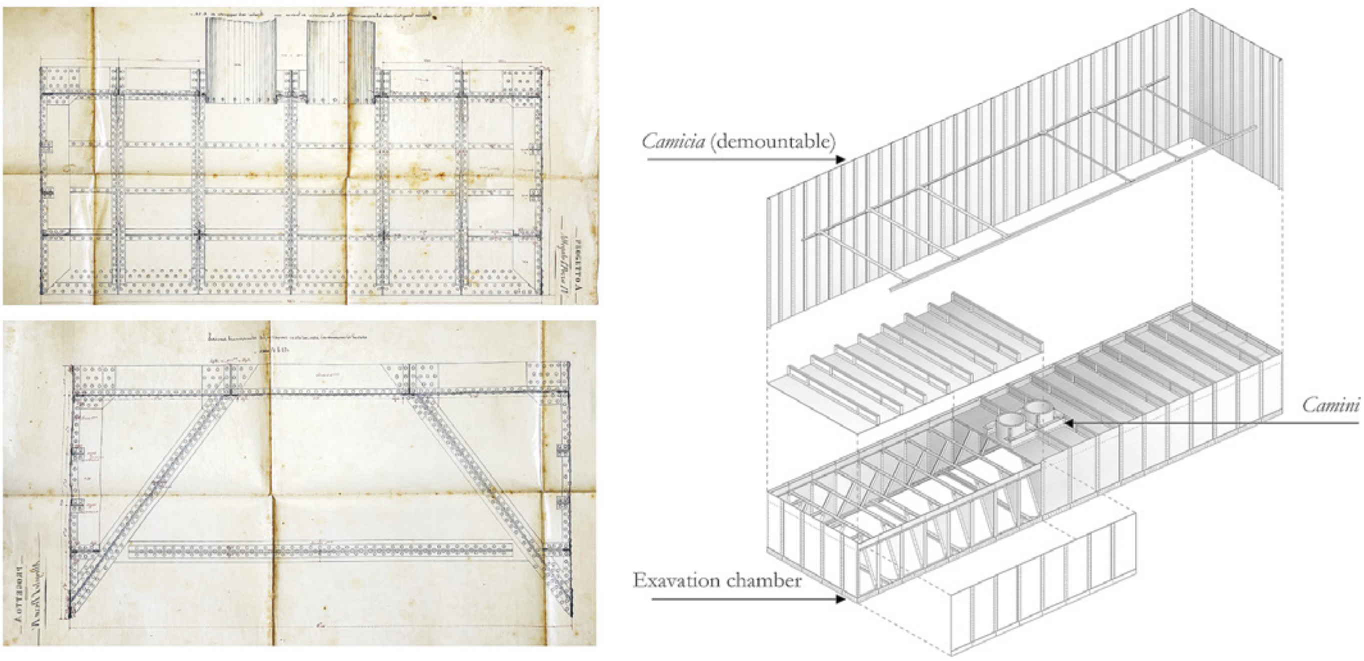


Fig. 4. *IIICM, construction details of the cassion, 1881 (courtesy of Rome State Archive, USTRA collection); 3D reconstruction of the caisson.*

Fig. 5. *Special Office for the Tiber's settlement, construction drawings of the retaining walls with wrought-iron caissons, 1885 (courtesy of Rome State Archive, USTRA collection).*

The foundations designed by Zschokke were approved in June 1884, and the construction sites opened in January 1885. While the Zschokke & Terrier established novel production plants in Rome, the Special Office for the Tiber's settlement soon standardized the technology, as proved by a new set of execution drawings of the caisson structures, signed in 1885 (Fig. 6).

The caissons were enlarged, with a maximal length of 30 m, a maximal width of 6 m, and a mean height of 3 m; the construction details were perfected with the new

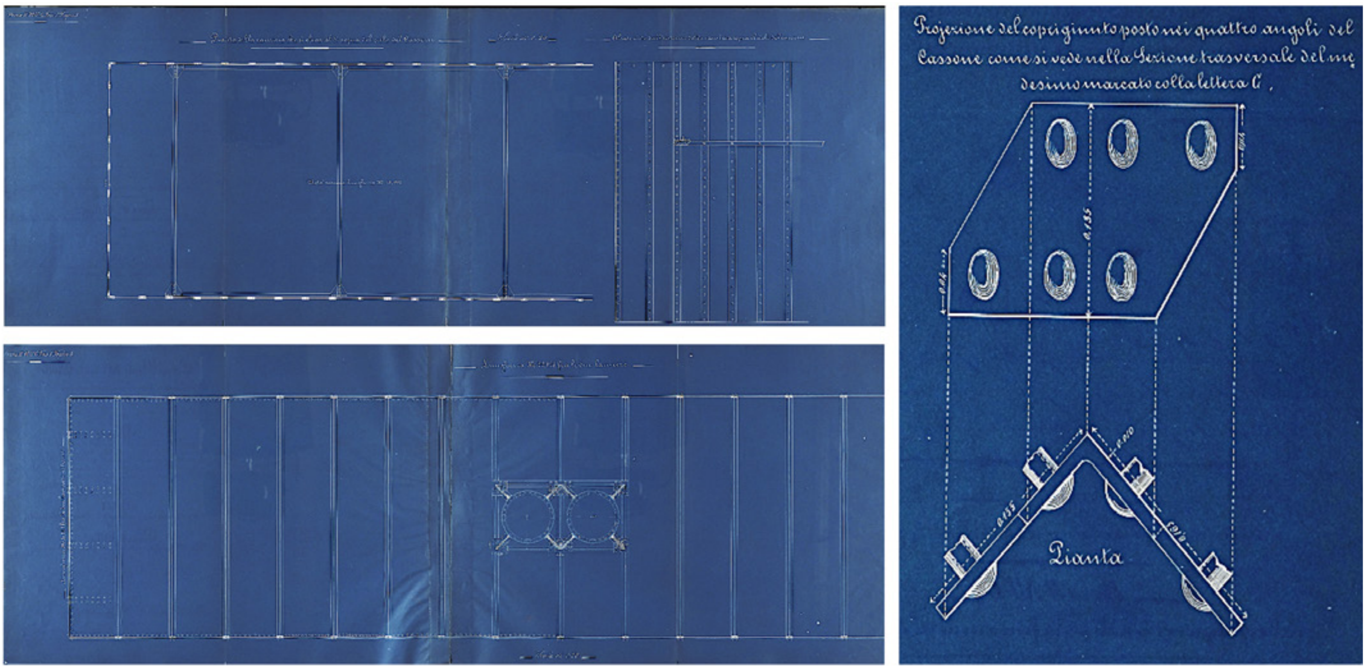


Fig. 6. *Special Office for the Tiber's settlement, construction drawings of the wrought-iron caissons, 1885 (courtesy of Rome State Archive, USTRA collection).*

Fig. 7. *Pneumatic foundations works on the Tiber's banks, picture by G. Primoli, 1888-90 (courtesy of Fondazione Primoli).*

design of the structural elements and the joints in flat irons. The execution drawing of the demountable *camicia* assumed the same building details of the 1881 project, standardizing the solution proposed by the IIICM (Fig. 6).

Two additional tubes were added for the concrete filling. The caisson walls were built from 8 mm thick wrought-iron sheets and strengthened by a series of triangular-shaped vertical ribs with a 1.10 m step. The airlocks were 4 m high cylinders of 2.20 m in diameter that featured an additional smaller chamber of 2.20 m in height and 1.40 m in diameter and two conical appendixes to allow the extraction of excavation materials with buckets and winches (Fig. 7). Once the caisson reached the foundation's depth, the excavation chamber was entirely filled with concrete. The concrete cast was composed of superimposed layers by the workers in the chamber; the cast even filled the 40 cm space between two adjacent caissons, creating a monolithic foundation block.

Winches set up the entire caisson on a wooden castle, then used to demount and retrieve the wrought-iron sheet elevation wall (Fig. 7).

The Zschokke company remained the main contractor entrusted with the use of the technology until 1900 [22]. The complex risk of the technology due to the use of compressed air, in terms of workers' health, arose since the first application. In this regard, the 1882 contract, stipulated with the Zschokke company, introduced the mandatory presence of the doctor on the excavation work site and obliged the contractor to refund workers and their families in case of accidents [23].

4. THE WROUGHT-IRON CAISSONS HBIM

A document-based HBIM [4–7] was developed to verify the anatomy and building details of the caissons, exploiting a "Key set" of original design documents, ranging from execution drawings to technical reports.

4.1. METHODOLOGY AND PHASES

The HBIM processes featured five steps (Fig. 8): i) set up of a customized Common Data Environment (CDE); ii) crossing analysis of the historical documents to provide

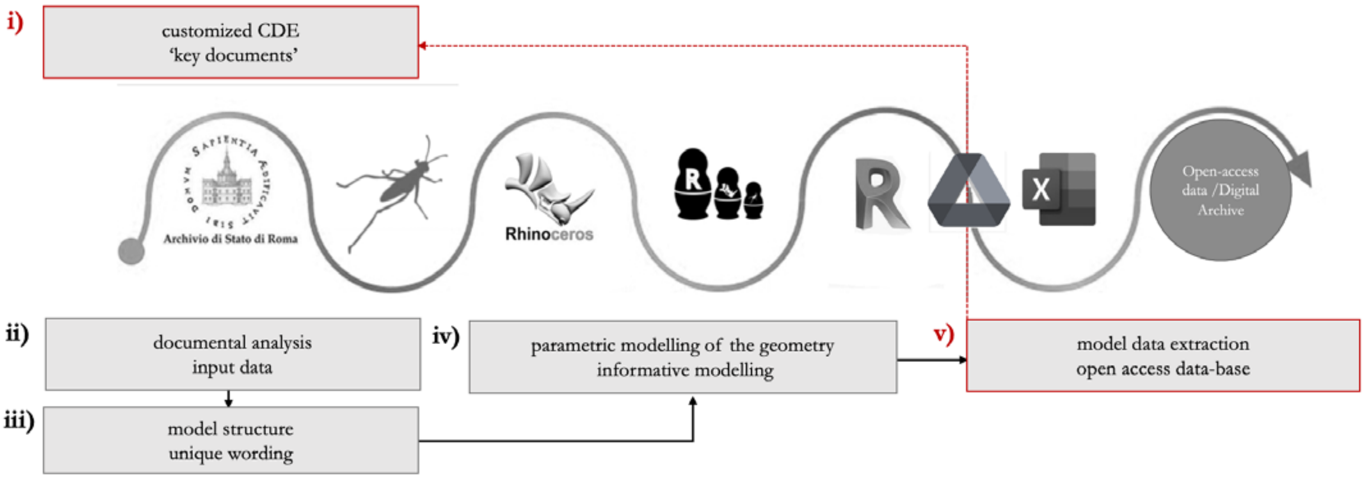


Fig. 8. *Workflow of the HBIM process.*

geometrical and informative input data of the model; iii) design of the model structure and wording of the model items (unique ID); iv) fully parametric geometric modeling, exploiting the data derived from historical documents; v) extraction of the graphic and informative data of the model in the open-access database.

The procedure's first step (step i) focuses on defining a customized CDE to support the subsequent modeling phases and assure data conservation. The standard areas of the CDE [24] were customized as follows: "Input" area, containing the listed and organized historical document and the input data tables (step ii); "Work in Progress" area, containing the models (step iii, iv); "Published" area, containing the open access database (step v), embedding hyperlink to the historical documents stored in the "Input" area.

Step ii) focused on categorizing information derived from the historical analysis and preparing the model input data (informative and geometric), referring to each building element of the caisson. A sample of the data workflow, known as the "Triangular-shape rib", is reported in Tab. 3.

Buiding Element	ID	Document Typology	Information Typology	Geometric Input Data	Informative Input Data
Triangular-shape rib	M-A_B -nXnY-0	Execution drawing	Geometric data	• Shape • Dimensions • Positioning	
			Data on building materials	• Connection systems • Industrialized elements dimensional standards	• Materials Typology
		Technical Reports	Construction system data	• Positioning (structural grids)	• Structural Typology
			Construction History		• Date
			Geometric data	• Shape • Dimensions • Position	
			Data on building materials	• Connection systems • Industrialized elements dimensional standards	• Materials Typology • Materials Properties

Tab. 3. *Modeling procedure step i): sample of the data workflow from the historical analysis to the input data.*

Step iii) focuses on defining the model structure, consistent with the anatomy of the caissons and the wording of the model objects. The unique ID of each model object was composed by combining the following: the building element "category" indicated with a letter; the building element "type" marked with a letter; and an alphanumeric code to identify the position of each element. The latter was composed of a numeric value corresponding to the position of each element on the X and Y axis of the structural grid of the caisson, followed by the numeric index of the two main levels of the caisson ("0" for the working chamber and "1" for the so-called *camicia* respectively). For example, for the triangular triangular-shaped vertical ribs, the standard ID code was composed of matching: "category" (indicated by the letter "M", "type" (indicated by the letter "A" or "B", numeric value, ranging from "0" to "n" of the position on the X and the Y axis respectively, numeric index of the working chamber level, "0" the resulting standard ID is "M-A-nXnY-0".

After defining the structure, the geometric and informative modeling was performed in step iv), within two subsequent actions. First, the fully parametric geometrical modeling of the building elements of the caissons, referring to "category" and "type" (Fig. 9), was performed via a Grasshopper algorithmic code for Rhinoceros [25]. Second, the set up of "custom families" referring to the "category" and "type" of the building elements, and the association of informative data to each digital item of the model was conducted by exploiting the BIM software Revit 2022 [26] via the plug-in Rhino Inside Revit [27].

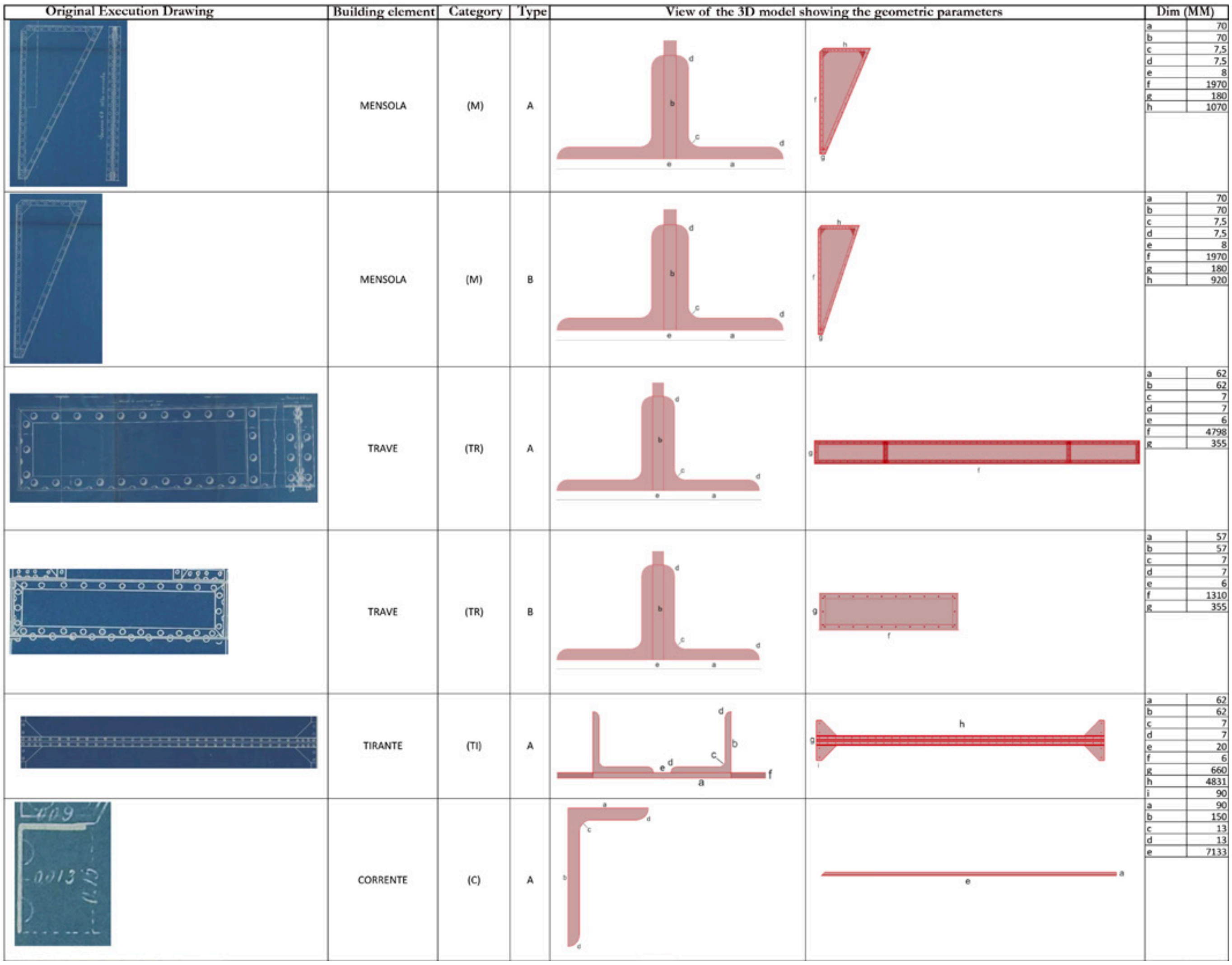
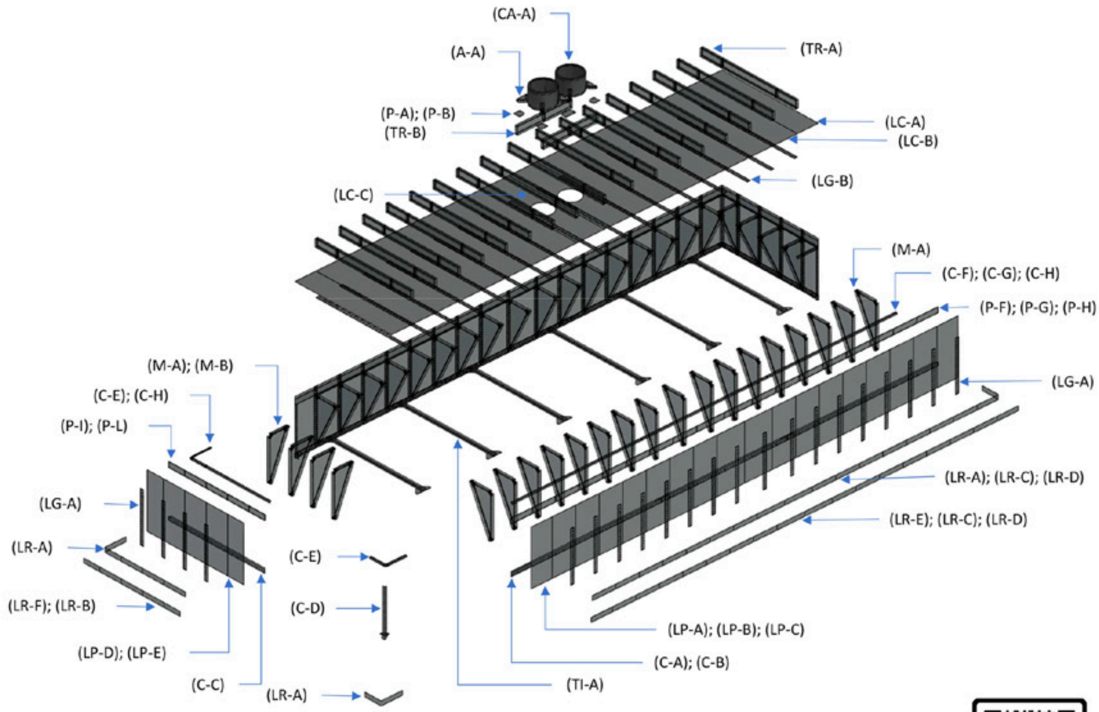


Fig. 9. *Modelling procedure step iv): the parametric model of the building elements geometry, based on the historical documents data and referred to as "categories" and "types".*

Lastly, step v) focused on the extraction of geometric and informative data of the model in an open-access database, exploiting the automatically generated tables function in Revit 2022 [28]: the buildings elements (model items marked with ID) were listed in textual tables, accompanied by descriptions fields – e.g. main geometrical dimensions, building materials, year of construction –, and by the hyperlink to historical documentation and graphic representation, stored in the Google Drive-based CDE (Fig. 10).

Wording of the model objects (ID)

Category	Type
Mensola (M)	M-A M-B
Trave (TR)	TR-A TR-B
Tirante (TI)	TI-A
Corrente (C)	C-A C-B C-C C-D C-E C-F C-H
Lamiera di parete (LP)	LP-A LP-B LP-C LP-D LP-E
Lamiera di rinforzo (LR)	LR-A LR-B LR-C LR-D LR-E LR-F
Lamiera del cielo (LC)	LC-A LC-B LC-C
Lamiera di giunzione (LG)	LG-A LG-B
Piastra (P)	P-A P-B P-C P-D P-E P-F P-G P-H P-I P-F
Angolare dei camini (A)	A-A
Camino (CA)	CA-A



SCAN ME
Access to the full data-base

Open-access database of the model objects (caisson building elements) and digital archive of historical documents

Object ID	Category	Type	b (mm)	h (mm)	s (mm)	material	Technical drawing	Historical document (input source)
MA-1x3y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-1x4y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-2x1y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-2x6y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-3x1y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-3x6y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-4x1y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif

Fig. 10. *3D view of the model items and access link to the open-access database (Google Drive).*

4.2. DISCUSSION

Steps iii) and iv) – the heaviest actions of the process, in terms of conceptual design and geometrical modeling times – allowed us to achieve the crucial goals of the proposed methodology: the scalability of the modeling procedure and the interoperability of the model data, via the production of an open-access database.

The fully parametric modeling of the geometry, performed in step iv), exploiting algorithmic code, allowed, from the one hand, to adapt the 3D model to minimal dimensional variation (e.g., the different dimensions of the foundations of each retaining walls sector); from the other hand, to fill the lack of standardized digital object libraries, concerning historical building elements, with customized digital "families" of iron building elements, to be used in further models [7].

In step iii), the setup of a robust hierarchic structure of the model supported by a detailed wording of the model objects allowed the production of an open-access database featured by a strong connection with the anatomy of the represented structure. The categorization of the building elements and the unique wording of each "item" supported the production of easy-to-read tables, embedding informative and geometric data of each model object at the same time. Tables are, thus, enriched by the direct association (hyperlink) between the historical document and the model object, providing at the same a "proof" of the philological modeling approach and a tool to simplify the consultation of the historical records (i.g. execution drawings), exploiting the direct relation with the building elements data. A diagram of the organization and the functionality of the open-access database is shown in Fig. 10; the QR code provides access to the complete database of the building elements of the caisson as an insight into the cited functionality, even in terms of a digital archive of the historical documents.

5. CONCLUSIONS

The contribution focused on the use of compressed-air caisson foundations technology in Italy in the last three decades of the 19th century. From a methodological point of view, the study was supported by a historical-document-based HBIM, functioning as the same as both research and digital archives.

In the second half of the 19th century, alongside the main application of deep foundations for bridges, the deployment of pneumatic foundations was crucial in designing and constructing river embankments, especially in densely inhabited urban areas. The historical-documents-based analysis of the Tiber River embankment construction disclosed the fruitful knowledge transfer of the compressed-air foundations methods to Italian engineers and contractors, highlighting their innovative contribution to the international evolution of the technique. In this perspective, the study remarked on the following issues: the crucial role of the application of the pneumatic foundations for the construction of the Tiber River embankments; the innovative contributions in the standardization of the design of iron caissons, introducing demountable parts – the so-called *demountable caissons* which marked a significant step in perfecting the attempts, conducted since the late 1850s, to recover the iron and had a beneficial impact on the construction costs.

From a methodological point of view, the conjunction of the archival investigation and the HBIM supported both the investigation phase of the construction history analysis and the dissemination of the results. On the one hand, the document-based HBIM provided a powerful visual framework to understand the geometry, building details, and construction process of the analyzed structures and supported the cataloging of historical documents, facilitating their analysis in the digital environment. On the other hand, the production of the HBIM-related open-access database, embedding the digital collection of historical documents, expands the capacity of the model in terms of an open-access digital archive, providing an effective educational tool to disseminate knowledge of historical structures.

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Authors contribution

The Authors contribute in equal parts to the present paper.

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