How Did the Romans form Concrete Underwater?

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Abstract The Roman’s ability to cast hydraulic concrete underwater relied on their skill in being able to construct temporary or permanent formwork in the open sea that could withstand the force of currents and survive being buffeted by waves. The design of the forms frequently followed the description provided by Vitruvius in De Architectura (5.12.3); however, there was a technique that he did not refer to, that being the use of prefabricated floating caissons. It is surprising that Vitruvius made no mention of them as they were widely used. Based on archaeological evidence a new categorisation of Roman formwork designs used in underwater or submerged concrete construction addresses this omission. Three categories are proposed; 1, for in-situ constructed inundated forms for use with hydraulic concrete; 2, in-situ constructed drained forms for use with non-hydraulic concrete; and 3, prefabricated floating forms for use with hydraulic and non-hydraulic concrete.

1 Introduction

The discovery of hydraulic concrete sometime in the 2nd century BC or possibly earlier was one of the most extraordinary inventions of the Roman era. It allowed the Romans to build structures in the open sea with greater freedom either as the substructures to breakwaters, moles and lighthouses, or as elaborate geometric designed fishponds.

As with modern concrete it has to be shaped or formed within a mould whilst it hardens. The key to the success in working with concrete is in the design and construction of the formwork, especially when working in the sea. Vitruvius’s text is the only contemporary source that describes how the material was sourced, mixed and laid. He also included a description of the construction of formwork. In De Architectura (5.12.2-6) which he wrote sometime around 25 BC he outlined three techniques of which two are supported by archaeological evidence. The
author is proposing an alternative third category based on extant remains that includes techniques not referred to in *De Architectura*.

2 Categories of Formwork

2.1 Category 1 – an in-situ constructed inundated form that includes the type described by Vitruvius (5.12.3)

Used in the hydraulic concrete construction of either extensions to harbour moles, jetties, isolated blocks (*pilae*) and walls to fishponds. The formwork was usually constructed in timber. Piles were driven into the sea bed and framed with horizontal beams against which vertical boards were set whilst being pounded in, see Fig. 1. The boards, which ranged in size from 9.5 cm to 50 cm wide with the majority being between 25 to 30 cm and 3 to 8 cm thick, were set reasonably closely together with gaps of not much more than 2 cm.

Evidence of this type of formwork can be found at Anzio (*Antium*) where the impressions of horizontal cross beams set at approximately 1m above sea level can be seen on the outer mole with evidence of vertical piles at 2.5 m centres [14], and also the remains of the ends of vertical planks 0.23 – 0.5 m wide by 0.07 – 0.08 m thick have been found imbedded in the seafloor adjacent to the inner quay structure [16]. At Astura there is evidence for vertical planking with horizontal tie beams secured to vertical piles on the harbour mole [14, 15]. At Baiae (*Baianus Lacus*) on the upper surface of the entrance channel jetties can be seen the impressions of horizontal cross beams, 60 – 70 cm in diameter set at 2 - 2.5 m centres, and 20 – 25 cm diameter vertical piles set at alternating sides of the horizontal tie beams and stiffened with 20 cm diameter raking braces. The continuous run of concrete was laid in sections with the end bulkhead of the

Fig. 1 Category 1 formwork - C Brandon
formwork removed after each casting [31]. In the harbour at Caesarea Maritima in Israel there are blocks of concrete on CAHEP survey line number 3 that have horizontal tie beam impressions, some with single beam and some with cross tie beams [27]. At Cosa (Portus Cosanus) there are vertical impressions 0.10-0.15 m wide and 0.15-0.20 m deep on the western face of pier 1, and two square beam holes 4 m apart approximately 0.26 x 0.25 m in pier 2 [17]. At Egnazia there is clear evidence of beam, pile and tie impressions on the concrete harbour mole [1]. At Marseille in the South of France random width horizontal planks have survived in situ fixed to vertical piles that formed the concrete foundation to quay F.120 [21, 22]. At Misenum there are beam and post impressions in several of the concrete pilae [18] and one shows evidence of a repair to the formwork [4]. At Paola (Circeii) there is evidence for a complex shaped formwork with impressions of vertical piles, planking and horizontal beam holes [14]. In the Claudian harbour of Portus on the northern concrete mole there is extensive evidence of vertical planking with horizontal tie beams and external collar beams [14, 33, 25]. At S. Marco di Castellabate there is evidence for forms that were 6 to 8 m long by 4.5 m wide used to caste concrete in a continuous pier. Each bulkhead section of shuttering was removed (for re-use?) to allow concrete to be cast up against concrete. Horizontal cross beams were set at 1.5 m centres with 15 cm diameter diagonal braces fixed at 22°. The vertical piles were 15 cm in diameter and some of which were in-bedded between 45 and 60 cm into the rocky seabed [3]. At the fishpond at Santa Severa there is evidence for vertical planking formwork 0.10 to 0.40 m wide and 0.03 to 0.045 m thick [29]. At Sapri, on the Roman harbour pier, there are 16-18 cm diameter horizontal and vertical post and beam impressions, and in one case a 10 cm diameter vertical pile hole and two 20 cm wide horizontal beams [32]. On the sides of the concrete mole at Side in Turkey there is, apparently, the impressions of horizontal planking fixed to vertical piles 0.3 x 0.15 m at 0.8 m intervals, although the author could find no evidence of the horizontal boarding that may have been mistaken for courses of aggregate [23]. The concrete harbour mole at Thapsus in Tunisia is now completely buried under a modern rubble mole. However, Dallas and Yorke made a record of it in their survey along the coast of North Africa and noted the marks of circular horizontal beams in the upper surface at 1.3 m centres that would have tied the side walls of the form together [12].

At a number of these sites surviving timber planking suggest that the formwork was left in place and not removed after the concrete had set. It is apparent that permanent or semi permanent cladding was often part of the finished structure. It is known that Roman concrete gains strength very slowly, over a matter of years [28]. The builders may have opted to leave the timber formwork in place to protect the concrete from potential erosion. In cases where a mole or pier was cast in a continuous line then the bulkhead sections of formwork appear to have been removed, and even possibly re-used.

Stone blocks were used as a permanent facing in addition to being used to form the enclosure within which the concrete was cast. At Pompeiopolis [35] and Kyme
in Turkey [13] and S. Cataldo near Lecce [2] ashlar marginal walls were built out into the sea to form inundated cells that were in filled with hydraulic concrete in a similar manner to the timber variant. The blocks were heavily clamped to bind the stones together particularly at the time when they were most vulnerable to damage from the sea, before the concrete core had been placed.

### 2.2 Category 2 – an in-situ constructed, de-watered, cofferdam formwork described by Vitruvius (12.5.5–6)

Vitruvius (12.5.5–6) describes the construction of a double walled cofferdam form that was pumped dry for casting non-hydraulic concrete. This category includes formwork with watertight enclosures that were constructed with single and double walls. In addition to being used for casting non-hydraulic concretes they were used also for revetments, bridge footings and other applications where an underwater dry working environment was required.

The simplest type of cofferdam was that described by Vitruvius; piles were driven vertically into the seabed (or lake or riverbed) at regular spaces around the area to be enclosed and drained, either as a single line or double row. Horizontal timber planks were then secured to the piles on both faces, internal and external, see Fig. 2. The void in-between the boarding and the piles was packed with puddled clay. The Romans developed rebated or grooved piles into which boards could be slotted making it considerably easier to set them underwater. Elaborate interlocking piles were also developed, some with continuous dovetails where additional strength was required, as found at Lake Nemi [34].

Evidence for Category 2 formwork construction can be seen at Marseille in France where a permanent double walled cofferdam to quay F.28 was built with 149 pine piles 12-14 cm in diameter and between 5.5 and 6 m long. Parts of 5 different vessels were also used in the sides of the cofferdam [21]. A cofferdam was also used as temporary works associated with the construction of quay F. 120

![Fig. 2 Category 2 Cofferdam – C Brandon](image)
[22], at Minturnae on the river embankment are the remains of a revetment structure comprising vertical oak posts onto which horizontal planks edge fixed with mortice and tenon joints were fitted [30]. Around the lakeside at Nemi were found the remains of cofferdams formed with a double wall spaced 0.75 m apart built with 30 x 20 cm interlocking piles and the void filled with clay. Also a double wall set 0.75 m apart formed with 5 cm thick planks fitted to close piled timbers 52 x 25 cm in section with the second wall built with 40 x 20 cm piles at 90 cm centres fitted with oak panels in between [34]. In Rome the bridge piers of Pons Cestius [5] and Ponte Elio [8] and at Tier in Germany [11] were constructed behind cofferdams and as was also the case for quayside structures along the River Tiber in Rome [24, 10].

Category 2 forms might well have been used to build opus reticulatum or brick faced structures deep underwater. At Ponza there appears to be evidence of a second line of timber sheet piles set off from the face of the wall, but inside the modern over-cladding, to provide the dry working space needed to lay the quasi opus reticulatum faced concrete [19]. How the Roman engineers resolved the practical problems associated with creating watertight enclosures and manually pumping out large deep water cofferdams, such as the one needed to construct the outer pilae at Nisida (circa 15 m x 9 m by 9 m deep) with its reticulatum faced sides, are difficult to comprehend [18].

2.3 Category 3 – Prefabricated Forms

Vitruvius failed to include in his De Architectura (5.12. 2-6) any mention of the use of prefabricated forms. However, he does describe how pre-cast blocks could be constructed above sea level and only when they had cured and set solid were they tipped into the sea by a method that sounds particularly impractical and for which there is no archaeological evidence. Vitruvius suggests that this technique was intended for sites where the seas were too rough for in-situ construction of formwork (Vitruvius 5.12.3-4). One could question whether what he was actually describing was a prefabricated form that could be launched from the shore rather than a pre-cast block and somehow over time it has been lost in translation or it was simply misunderstood by Vitruvius in the first place.

Driving piles into a seabed in an exposed site offshore and keeping the pile driving barge on station without the benefit of modern powered winches and anchors must sometimes have been challenging. Also fixing beams and planks underwater in situations with strong currents or rough seas would have been very difficult. It would have been impossible to pump dry a category 2 evacuated cofferdam enclosure where the sea or river bed consisted of gravel or had an equally porous substratum.

The remains of a series of rectangular wooden forms, 14m x 7m on plan and 4m high were found in Area K to the west of the entrance to the harbour Sebastos at Caesarea Maritima in Israel [7]. Comprising carefully built watertight floating
box caissons, fabricated along the shoreline and towed out to the site of the northern end of the main southern mole, see Fig. 3. When they reached their final position they were filled with a mixture of hydraulic and non-hydraulic concrete and sunk in a line to form the foundations to the mole and warehouses described by Josephus. These caissons built using ship construction techniques; were in fact rectangular barges that had a single mission. Edge jointed boards set with mortice and tenon joints formed a watertight enclosure. Floor timbers or frames were let into chine beams that also took side-wall frames. The side-wall and floor planking were attached to the floor and wall frames by treenails and to the chine beam with tenons, in addition the joint was stiffened with knees. Internal bracing provided additional strength when it was subjected to hydraulic loads as it settled onto the seabed with a part fill of concrete and held it together while the concrete set.

A similar caisson design was discovered in the harbour of Alexandria [20]. The forms were originally about 10 to 15m long, 5 to 8m wide and 1 to 3m high. Watertight and constructed with a floor they were used to cast blocks of hydraulic concrete as part of foundations to the harbour esplanade. The caissons were made of 3 to 4 cm thick boards edge fixed with mortice and tenon joints and strengthened with frames and transversal beams. Unfortunately, at present, there is very little information available about these important structures. Although dated by carbon 14 tests to around 250 BC the concrete material and the formwork design studied by ROMACONS in 2007 suggest a much later date and one contemporary with the Caesarea forms, between the 1st century BC and 1st century AD.

The remains of a wooden caisson, 22.9m long by 2.2m wide was found on the northern edge of the Roman harbour of Laurons in the South of France [36]. This rectangular structure had a floor made up of wide planks fitted to a frame or chine...
beam from below. The upper surface of the chine beams had deep grooves that originally held the ends of vertical boards making up the sides of the caisson. Vertical elements were also let into the floor frames and chine beams. Unlike the caissons at Alexandria and Caesarea the method of construction used appears not to bear any relationship with ship building techniques. The jointing details were similar to those used in terrestrial based structures rather than ship construction, however, the unit was watertight and floated. It was constructed on the edge of the shore and then towed or pulled into place with ropes and the sunk with rubble to form the jetty.

An unusual cofferdam was used to build the Roman Bridge footings at Chalon-sur-Saône in France dated to the beginning of the 3rd century [6]. Unlike the design described by Vitruvius, the piers for the bridge at Chalon were constructed within watertight caissons each with a floor. They were built using ship construction techniques and the boards were secured with mortice and tenon joints fixed to frames. The caisson or bridge barge pier was at least 12m long by 6m wide and was built on the riverbank; this is evident from the fixings in the chine that were fitted from below.

One of the most innovative designs used by the Romans was the type of form used in the construction of the East side of the harbour entrance at Caesarea. Built as a floating open bottomed enclosure with a double walled perimeter that acted as the flotation collar, and allowed it to be positioned and sunk in a controlled manner by gradually infilling the void between the two walls. By not having a floor it could cope with an uneven seabed although it would be liable to raking and might only have been used in relatively sheltered waters [26]. These forms seem to be unique to Caesarea and may have proved too difficult to manoeuvre to have been used elsewhere.

Redundant ship hulls also fall into this category; although not purpose built they achieved the same objective. The most renowned example was the hull of a very large ship that was used to transport an obelisk to Rome and subsequently used in the construction of the outer breakwater of the Claudian harbour of Portus (Pliny, *Natural History*, 16.201-2, Suetonius, *Claudius*, 20.3). Rubble filled abandoned hulks were used to form part of the harbour mole at Toulon [9].

Vitruvius made no mention of these floating caissons maybe because they were not commonly used or that he simply was not aware of them. If it was necessary to build moles or breakwaters in deep or rough water then a more usual approach would be to dump large stone blocks from barges to form rubble breakwaters as witnessed by Pliny the Younger at Civitavecchia (*Centum Cellae*).

### 3 References

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