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Cements, Concrete, and Settling Barges at Sebastos: Comparisons with Other Roman Harbor Examples and the Descriptions of Vitruvius

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Sebastos, the harbor of Caesarea, was built on a coastline that had no natural feature such as a bay or headland, a fact common to a number of Roman harbors. The resulting need to create manmade harbors drove the Romans to conceive particular construction technologies that enabled them to build out into the open sea. The principal technology they developed was hydraulic concrete which, when formed into massive blocks that could withstand battering from the waves, provided foundations for seawalls, wharves, lighthouses, and warehouses.

The remains of concrete structures currently lying underwater at Caesarea Maritima exhibit prime examples of Roman concrete engineering skills. This chapter examines these remains and compares them with a few relevant examples from other Roman harbor sites and with the descriptions provided by Vitruvius. In particular, the new evidence that has been revealed from excavations in area K at Caesarea has enabled a reinterpretation to be made of Vitruvius' typology of construction techniques and also of previous studies on this, notably by Blackman, Oleson, and Yorke and Davidson.[1]

The innovative style of Roman imperial architecture was significantly due to the development of structural concrete, with its inherent ability to be shaped and to transfer loads, which owed its origins to the Greeks who had used it in a limited manner, for example, as a means of leveling courses of stone. The Romans realized the full potential of this material and used it for a variety of purposes including in foundations, within structural cores in walls, and in arches, vaults, and domes (such as in the 43 m. diameter concrete dome of the Pantheon in Rome built around 120 C.E. and still

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[1] Previous relevant discussions on Roman harbor technology are included in D. J. Blackman,"Ancient Harbours in the Mediterranean," *IJNA* 11 (1982), 79–104, 185–211; J. P. Oleson, "The Technology of Roman Harbours," *IJNA* 17 (1988), 147–57; J. P. Oleson and G. Branton, "The Technology of King Herod's Harbour," in *Caesarea Papers*, 49–67; and R. A. Yorke and D. P. Davidson, "Survey of Building Techniques at Roman Harbours of Carthage and Some Other North African Ports," in A. Raban, ed., *Harbour Archaeology: Proceedings of the First International Workshop on Ancient Mediterranean Harbours*, BAR Int. Ser. 257 (Oxford, 1985), 157–64.

standing today). However, it is the use of this material in its hydraulic form in submarine structures that is arguably the most intriguing aspect of Roman engineering technology.

Roman concrete differed from modern concrete not only in its chemical makeup but also in the manner in which it was placed. It was actually a lime and sand mortar, into which large lumps of aggregate, approximately 100–300 mm. in length, were individually placed by hand, building up its mass layer by layer. For increased strength and for hydraulic uses, volcanic sand (pozzolana) was added to the mix as well as crushed pottery or tiles.[2] Modern concrete, however, is a mixture of cement (an amalgamation of lime, clay, and metallic salts) combined with a fine aggregate, being usually a sharp sand, and a coarse aggregate comprising crushed stone, approximately 25 mm. in diameter. Unlike Roman concrete, the ingredients are all mixed together dry before water is added and the material poured into the formwork.[3]

It must have been in the vicinity of Puteoli that the large-scale use of pozzolana in underwater structures was conceived and perfected, probably by trial and error, during the construction of the early phases of one of the numerous ports and harbor facilities in that region. Vitruvius provides some of the only surviving descriptions of construction methods from the Roman era, and he includes references to the use of hydraulic concrete in the building of harbors. In book 2 he describes the raw materials for Roman concrete:[4]

> Chapter V, Lime.
>
> 1. . . . Lime made of close-grained stone of the harder sort will be good in structural parts . . . After slaking it, mix your mortar, if using pitsand, in the proportions of three parts of sand to one part of lime; if using river or sea-sand, mix two parts of sand with one of lime. These will be the right proportions for the composition of the mixture. Further, if using river or sea-sand, the addition of a third part composed of burnt brick, pounded up and sifted, will make your mortar of a better composition to use.
>
> Chapter VI, Pozzolana.
>
> 1. There is also a kind of powder which from natural causes produces astonishing results. It is found in the neighbourhood of Baiae and in the country belonging to the towns round about Mt. Vesuvius. This substance, when mixed with lime and rubble, not only lends strength to buildings of other kinds, but even when piers of it are constructed in the sea, they set hard under water . . . they set into a mass which neither the waves nor the force of the water can dissolve.

Roman engineers and builders tended to use a pure as possible limestone to make their lime for mortar. However, this lime, which had only between 0.1 to 1.0% of clay impurities, produced a non-hydraulic mortar, whereas if they had used limestone with 8 to 20% clay, an aluminum silicate, it would have actually made a hydraulic lime.

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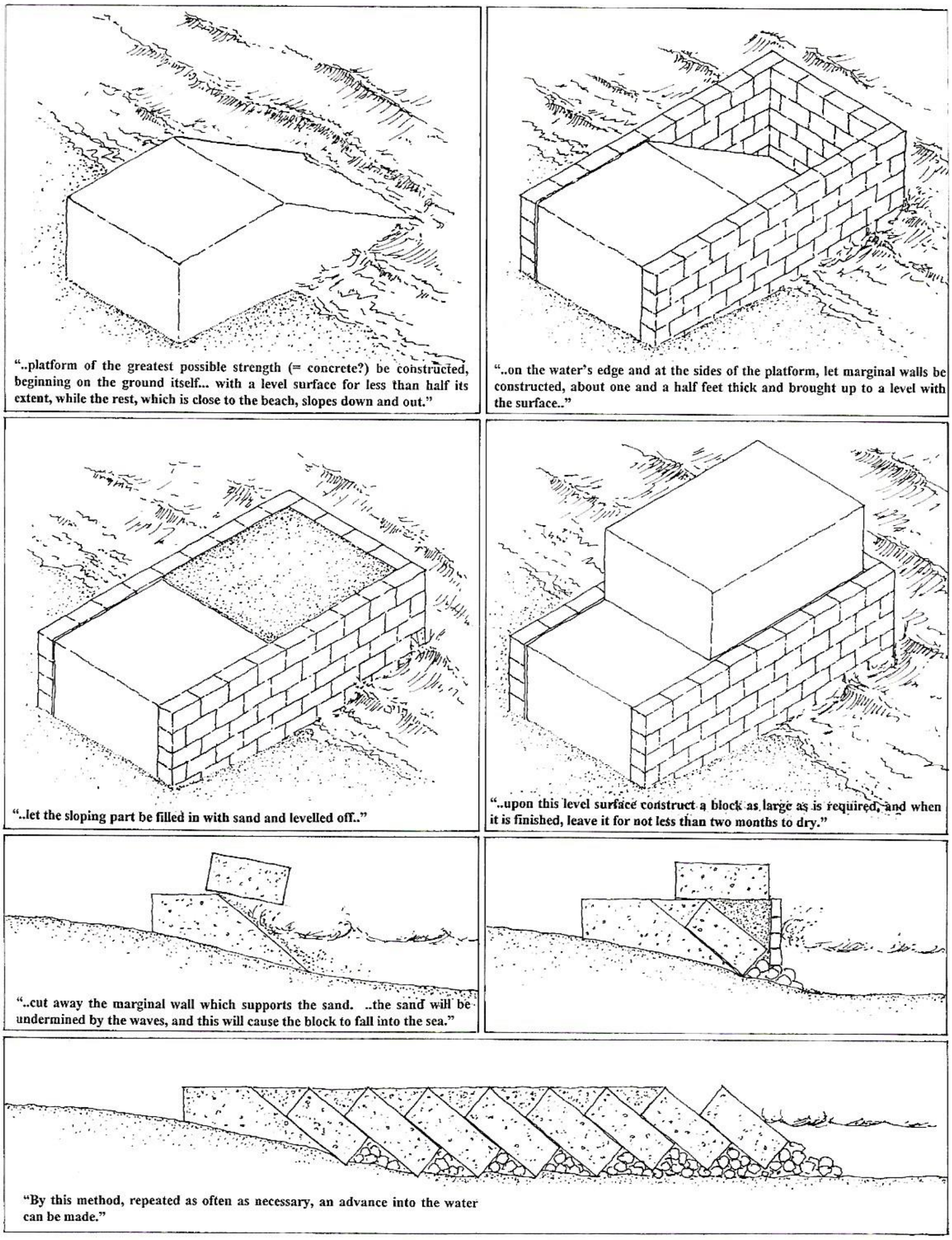
[2] For a description of Roman concrete construction, see Vitruvius, *The Ten Books on Architecture*, trans. M. H. Morgan (New York, 1960), 45–49.

[3] Comparisons between modern and Roman concrete are discussed in J-P. Adam, *Roman Building: Materials & Techniques*, trans. A. Mathews (London, 1994), 73–79.

[4] Vitruvius, trans. Morgan, 45–49.



"..platform of the greatest possible strength (= concrete?) be constructed, beginning on the ground itself... with a level surface for less than half its extent, while the rest, which is close to the beach, slopes down and out."

"..on the water's edge and at the sides of the platform, let marginal walls be constructed, about one and a half feet thick and brought up to a level with the surface.."

"..let the sloping part be filled in with sand and levelled off.."

"..upon this level surface construct a block as large as is required, and when it is finished, leave it for not less than two months to dry."

"..cut away the marginal wall which supports the sand. ..the sand will be undermined by the waves, and this will cause the block to fall into the sea."

"By this method, repeated as often as necessary, an advance into the water can be made."

Figure 1. Hypothetical reconstruction of the sequence of construction of a mole using Vitruvius' Type 2 technique. Except as noted, all illustrations are by the author.

The addition of pozzolana, with its high levels of silicate of alumina, to a non-hydraulic lime converts it to a hydraulic version. The same effect was achieved by adding crushed pottery, again due to its source as an aluminum silicate.[5]

Vitruvius is very specific that the pozzolana for hydraulic structures should be sourced from the region around Vesuvius. This is confirmed by the work of Oleson and Branton who have clearly shown that the pozzolana at Caesarea was shipped all the way from this region to what is now Israel, although there were suitable sources much closer.[6] Even later, during the construction of the Claudian harbor at Portus, the volcanic sand was also imported from Baiae (the region around Vesuvius), as described by Pliny (*NH* 36.70), despite the existence of exactly similar material in the vicinity of Rome. This conservatism shows how little they understood the chemistry of the process and how much they relied on experience.

The all-important aspect when working with concrete, either above or below water, is that it has to be contained within a formwork to mold it into the desired shape while it sets. It is the design of either the permanent or temporary containment systems, and how they evolved to suit the contextual variations in site conditions, that form the basis for understanding how Roman structures were built, and particularly those associated with harbors.

Yorke and Davidson have proposed a typology of formwork construction methods.[7] Method 1 was the construction of formwork around or on top of natural features such as reefs. Examples of this exist at Sabratha and possibly Thapsus. Method 2 consisted of the erection of pre-fabricated panels onto driven piles. Alternatively, complete box sections could be lowered into the water, into which the concrete was cast, either in a flooded state or partially pumped out. Method 3 comprised forms that were completely prefabricated on dry land before being floated into place and sunk.

Vitruvius' description of various designs of formwork used in the construction of piers and breakwaters is, however, more relevant and has been used here in the comparisons of the various construction techniques that have been revealed from the excavations at Caesarea and other sites.[8] In book 5, chapter 12, Vitruvius identifies three different types of construction, which can be summarized as follows: Type 1 was the placement of concrete within a flooded containment system; Type 2 was the casting of concrete blocks above water on the end of a pier and after they had set allowing them to settle into the sea so as to extend it; Type 3 was the placement of concrete within an evacuated watertight enclosure.

Type 1:

> 2. . . . . If there is no river in the neighbourhood, but if there can be a roadstead on one side, then, let the advances be made from the other side by means of walls or embank-

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[5] Adam, *Roman Building*, 73.

[6] Oleson and Branton, "Technology," 58–60.

[7] Yorke and Davidson, "Survey," 158.

[8] Vitruvius, trans. Morgan, 162–64.

> ments, and let the enclosing harbor be thus formed. Walls which are to be underwater should be constructed as follows. Take the powder which comes from the country extending from Cumae to the promontory of Minerva, and mix it in the mortar trough in the proportion of two to one.
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> 3. Then, in the place previously determined, a cofferdam, with its sides formed of oaken stakes with ties between them, is to be driven down into the water and firmly propped there; then, the lower surface inside, under the water, must be levelled off and dredged, working from beams laid across; and finally, concrete from the mortar trough . . . must be heaped up until the empty space which was within the cofferdam is filled up by the wall. This, however, is possessed as a gift of nature by such places as have been described above.

Type 2:

> 3. . . . But if by reason of currents or the assaults of the open sea the props cannot hold the cofferdam together, then, let a platform of the greatest possible strength be constructed, beginning on the ground itself or on a substructure; and let the platform be constructed with a level surface for less than half its extent, while the rest, which is close to the beach, slopes down and out.
>
> 4. Then, on the water's edge and at the sides of the platform, let marginal walls be constructed, about one and one half feet thick and brought up to a level with the surface above mentioned; next, let the sloping part be filled in with sand and levelled off with the marginal wall and the surface of the platform. Then, upon this level surface construct a block as large as is required, and when it is finished, leave it for not less than two months to dry. Then, cut away the marginal wall which supports the sand. Thus, the sand will be undermined by the waves, and this will cause the block to fall into the sea. By this method, repeated as often as necessary, an advance into the water can be made.

Type 3:

> 5. But in places where this powder is not found, the following method must be employed. A cofferdam with double sides, composed of charred stakes fastened together with ties, should be constructed in the appointed place, and clay in wicker baskets made of swamp rushes should be packed in among the props. After this has been well packed down and filled in as closely as possible, set up your water-screws, wheels, and drums, and let the space now bounded by the enclosure be emptied and dried. Then, dig out the bottom within the enclosure. If it proves to be of earth, it must be cleared out and dried till you come to solid bottom and for a space wider than the wall which is to be built upon it, and then filled in with masonry consisting of rubble, lime, and sand.
>
> 6. But if the place proves to be soft, the bottom must be staked with piles made of charred alder or olive wood, and then filled in with charcoal as has been prescribed in the case of foundations of theatres and the city walls. Finally, build the wall of dimension stone, with the bond stones as long as possible, so that particularly the stones in the middle may be held together by the joints. Then, fill the inside of the wall with broken stone or masonry. It will thus be possible for even a tower to be built upon it.

It is likely that Types 1 and 3, as described by Vitruvius, were limited to depths of up to 1.5 m. and possibly 2 m. Beyond these depths it would have been difficult to construct a formwork enclosure (Type 1) or a watertight cofferdam (Type 3) as he has described. It would also have been very difficult to hand lay concrete and aggregate in water deeper than 2 m. Type 2 could have been used to construct moles into relatively deeper water since the majority of the work was actually carried out on the surface. If the description is taken literally, then an interpretation can be made as described in figure 1, although there is no evidence from harbor sites that have been studied to date to suggest that this was ever done. There are examples of the use of Type 1 in a number of Roman harbors, notably Antium, Cosa, and Portus.

Cosa was one of the earliest harbors to have used hydraulic, pozzolana-based concrete in the construction of its breakwater, and has been dated to the first half of the second century B.C.E. It has been studied by the Cosa Port Excavations under the direction of Anna Marguerite McCann. The excavations revealed a series of irregularly spaced concrete piers, ranging in size from 6.3 x 12.6 m. to 6.8 x 10.5 m. on plan, which stretched out over a distance of 150 m. from the shoreline.[9] These piers were combined with mounded rubble to form the principal breakwater to the harbor in Antiquity, and the hypothetical reconstruction shows these concrete piers as foundations to a timber jetty as well as a lighthouse set into the end of the breakwater. The remains of the concrete piers retain the impressions of lapped vertical boarding and the negatives of horizontal tie-beams that pass through each block. It is apparent that these piers were cast within a flooded formwork similar to Vitruvius' Type 1. Thin narrow boards, approximately 15 cm. in width and probably with sharpened ends, were driven vertically into the seabed and overlapped one with another. The lap provided sufficient seal to retain the concrete but was not watertight. Horizontal tie-beams and external rails would have held the formwork together and provided the strength to resist the buffeting from swells (fig. 2).

It is unlikely, however, as suggested by McCann, that there was any prefabrication of the formwork, primarily because the purpose of lapping the boards was to enable a reasonable seal to be achieved between them when they were driven individually and not as a composite structure, and it is easier to drive in a board against the face of another rather than side by side. A prefabricated unit would have had the boards fixed to a frame, and they would have been flush joined side by side. It would have also been very difficult physically to manhandle large prefabricated panels into position, let alone fix them without subjecting them to severe racking stresses. The forms were cast in water that ranged in depth from 1.5 m. to 2 m. The silting up around the piers by as much as 2 m. as well as a change in sea level of 1 m. have resulted in the remains of the original piers being substantially buried. The distinct change in material at approximately 1 m. above the current sea level from a pozzolana-based material to a tile aggregate mix defines the original top of the piers, which would have been 2 m. above the ancient sea level. It can therefore be hypothesized that the original concrete piers were probably 4 m. in overall height. The seabed at that time was sand, as suggested by John David Lewis, and the concrete blocks subsequently settled into it due to tectonic liquefaction of the sand in a similar manner to parts of the breakwater at Caesarea.[10]

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[9] E. K. Gazda, "The Port and Fishery: Description of the Extant Remains and Sequence of Construction," in A. M. McCann et al., *The Roman Port and Fishery of Cosa* (Princeton, 1987), 74-79.

[10] E. K. Gazda and A. M. McCann, "Reconstruction and Function: Port, Fishery, and Villa," in McCann et al., *Cosa*, 137.

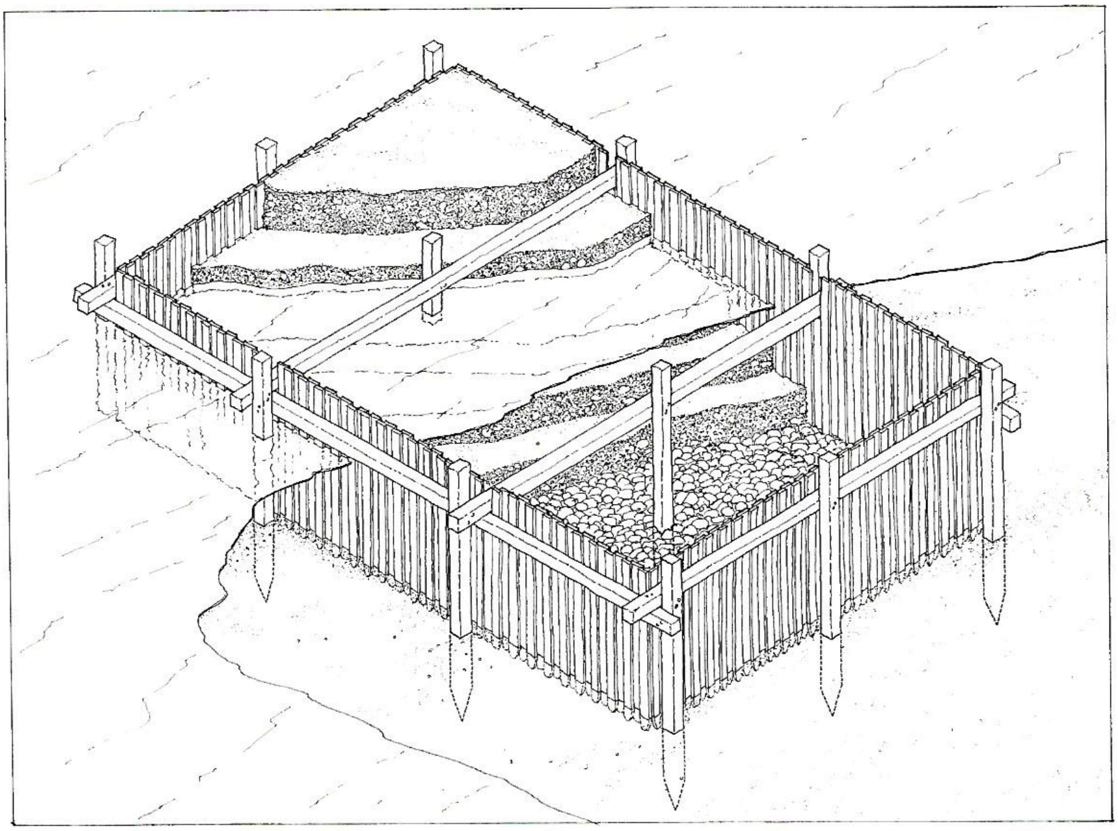

Figure 2. Hypothetical reconstruction of a Type 1 form as used at Cosa

There is evidence that this method of construction was also used at Antium and in parts of the Claudian harbor at Portus, as well as others.[11] Antium had an approximately semicircular harbor enclosure made up of two moles with the entrance probably to the east. There are well-preserved remains of the concrete which formed the eastern and western moles up to about 100 m. from the shoreline. Hydraulic concrete blocks were cast within a form comprised of lapped vertical boards driven into the seabed, secured by crosspieces and ties onto an internal structure of piles. These vertical piles perforate the interior of the moles in three or four rows at approximately 2.5 m. centers. The mole was originally continuous with a width of about 10 m.,

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[11] A description of the harbor construction at Antium is given in E. Felici, "Osservazioni sul porto neroniano di Anzio e sulla tecnica romana delle costruzioni portuali in calcestruzzo," *Archeologia subacquea* 1 (1993), 71–88, and the Claudian harbor at Portus in O. Testaguzza, *Portus* (Rome, 1970).

although it is now segmented, and in parts still retains elements of the overlying construction.[12]

The breakwaters of Portus were constructed with a variety of different methods, which include solid ashlar masonry, sunken hulls filled with concrete, and concrete formed within permanent timber shuttering that was subsequently faced with either brick or ashlar and ranged dramatically in width from 3 m. to 17 m. A stretch of the left mole was clearly constructed in the Vitruvius Type 1 method. This is a 5.5 m. wide concrete strip 3 m. high overall but cast onto a rubble foundation at a depth of 1.5–2 m.[13] Horizontal cross beams flush with the top surface, which tie into vertical posts at the edges, indicate the method by which the vertical formwork boarding was secured, as suggested by Enrico Felici.[14]

Yorke and Davidson describe several different designs of concrete shuttering, and the remains of some are well preserved *in situ*. However, they were mainly constructed in wet site conditions rather than underwater and are more closely related to terrestrial engineering techniques, although having similarities with the Type 1 design.[15]

It is clear that this Type 1 technique was only applicable in shallow sites, preferably with a sandy bottom which could take piles and boards being driven in, although, as can be seen at Cosa, Portus, and Thapsus, this method also can be used on top of a rubble foundation. It is likely that this type of concrete construction was also used in parts of the breakwater at Caesarea, although no clear evidence has been found to date. For example, it is possible that the concrete blocks on the southern breakwater recorded on survey line 3, which measure 4.7 x 3.6 m. on plan and are 1.7 m. high, were constructed using this method.[16] They still retain the impressions of horizontal beam casts within the top surface and lie in a tumbled line on a bed of kurkar rubble at a current depth of 5.5 m. (fig. 3), although it would have been shallower in Antiquity, probably 1.5 to 2 m. Whether the rubble was laid to reduce the depth of water onto which the blocks were to be cast, or whether it acted as a foundation cushion has yet to be established. It is likely, however, that these blocks were originally part of a continuous stretch of concrete, similar to that on the western mole at Portus, but when subjected to settlement due to tectonic activity, broke into segments along the lines of intermediate timber beams. Several other Roman harbor sites also contain the remains of concrete blocks which still retain the impressions of timber frames and cross beams, including Astura, Misenum, Puteoli, and Pyrgi.

What is especially interesting about Caesarea is the degree of sophistication in the formwork designs of some of the other underwater concrete structures. One of these, in area G, was a prefabricated version of Vitruvius' Type 1, which overcame the problems associated with trying to drive piles or boarding into a rocky seabed. Area G,

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[12] Felici, "Osservazioni," 71–81.

[13] Testaguzza, *Portus*, 69–81.

[14] Felici, "Osservazioni," 94.

[15] Yorke and Davidson, "Survey," 161–63.

[16] J. P. Oleson and A. N. Sherwood, in Raban, *Site*, 213–14.

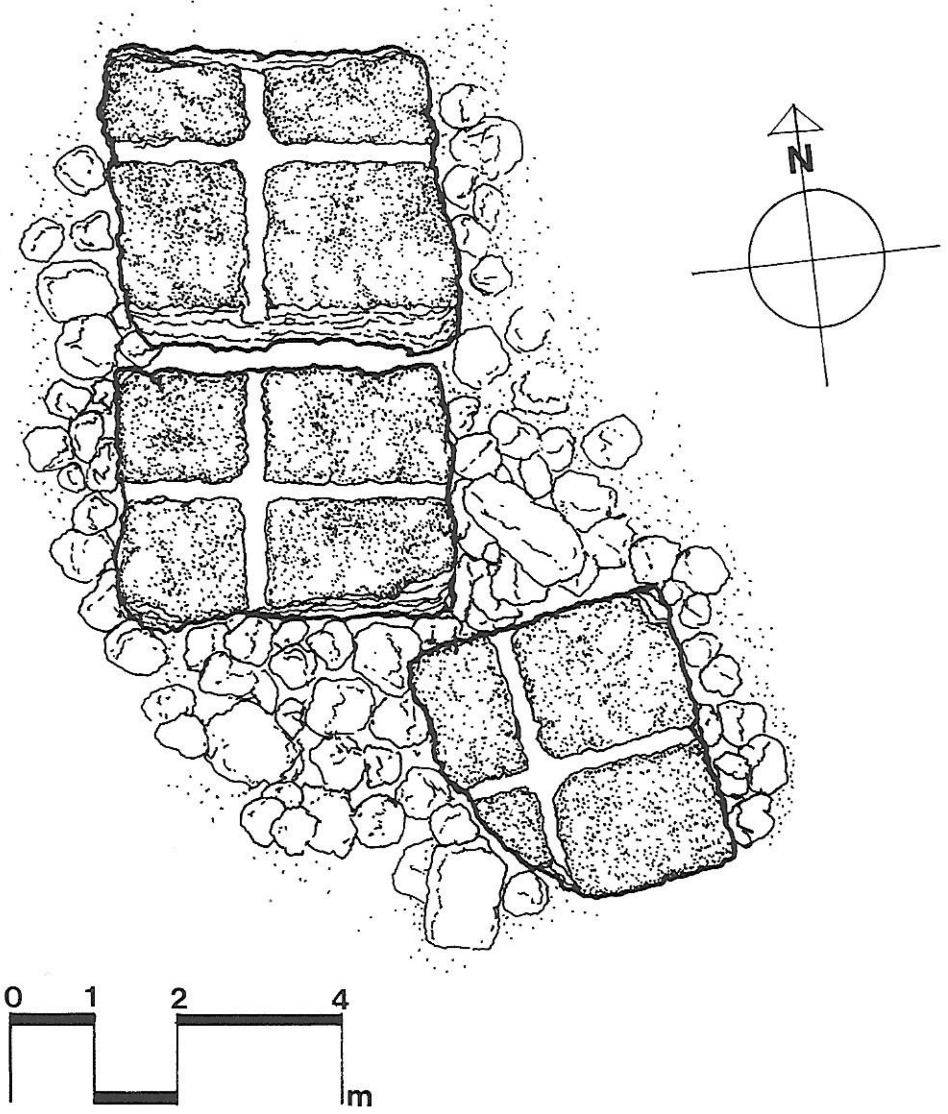

Figure 3. Type 1 constructed(?) concrete blocks on survey line 3 at Caesarea. Drawing by P. Dessauer and L. Reynafarje

which is at the western end of the northern breakwater, has the remains of concrete blocks 15 x 11.5 m. on plan and 2 m. high.[17] These blocks were cast within a form that comprised a double wall of planking with a 23 cm. gap between, mounted onto a 29 x 29 cm. sleeper beam (fig. 4). The interior of the structure was strengthened by timber ties and struts, but there was no bottom or floor to it. The watertight double wall was a novel method of providing buoyancy to enable the prefabricated form to be floated out to the site intact. The internal bracing provided rigidity and countered the racking forces as well as acting as platforms from which the enclosure could be filled. Floated out along the northern breakwater, the structure could be settled onto an already prepared rubble seabed by simply filling the void formed by the double wall with pozzolana concrete. Once it was on the bottom, rocks were piled against the sides to ensure that it remained in place. Divers working off the internal bracing filled the flooded structure layer.by layer with pozzolana-based mortar and stone and tufa aggregate. As it had no bottom, the concrete bonded to the rubble bedding, filling the voids and ensuring a solid bearing. The elegance of this design of formwork is only matched by another solution that was evolved to cast the concrete in area K.[18]

Herod more than likely put enormous pressure on the architect-engineers and contractors to complete the harbor within the shortest possible time. Avner Raban has suggested that one of the ways this was achieved was by building a number of construction islands at the outset at strategic locations around the perimeter of the harbor to serve as bases from which the breakwaters could be extended concurrently.[19] A key location was at the *terminus* of the main outer breakwater to the west of the entrance channel. However, since the depth of water in that area was approximately 3.5–4 m., it was too deep to use a Type 1 formwork. It would have required laying an enormous quantity of rubble to reduce it to a practical working depth, a solution that was adopted at Thapsus as well as for the outer piers at Cosa and at Portus.

Since the work in area K was not an extension of the breakwater but a starting point, Vitruvius' Type 2 was also not a possible option. The design that was adopted was a variant of Type 3, but instead of building a double-walled, waterproof cofferdam, which would have been difficult to construct in this depth of water, the architect-engineers chose to use ship construction techniques to achieve a watertight enclosure with a bottom. It was internally braced with a matrix of beams, posts, and diagonal props in addition to having the inherent strength of mortise and tenon jointed boarding. Since it was constructed like a boat, it could be prefabricated on the shoreline and floated out to the designated area. To date, three of these caissons, or single mission barges, have been studied and have been shown to have been made to the

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[17] Oleson, in Raban, *Site*, 127–30.

[18] C. J. Brandon, "The Concrete Filled Barges of King Herod's Harbour of Sebastos," conference proceedings, *RES Maritimae*, Nicosia, Cyprus, 1994.

[19] A. Raban, "Sebastos, the Herodian Harbor of Caesarea: How It Was Built and Operated," *CMS News, Report No. 19* (Haifa, 1992).

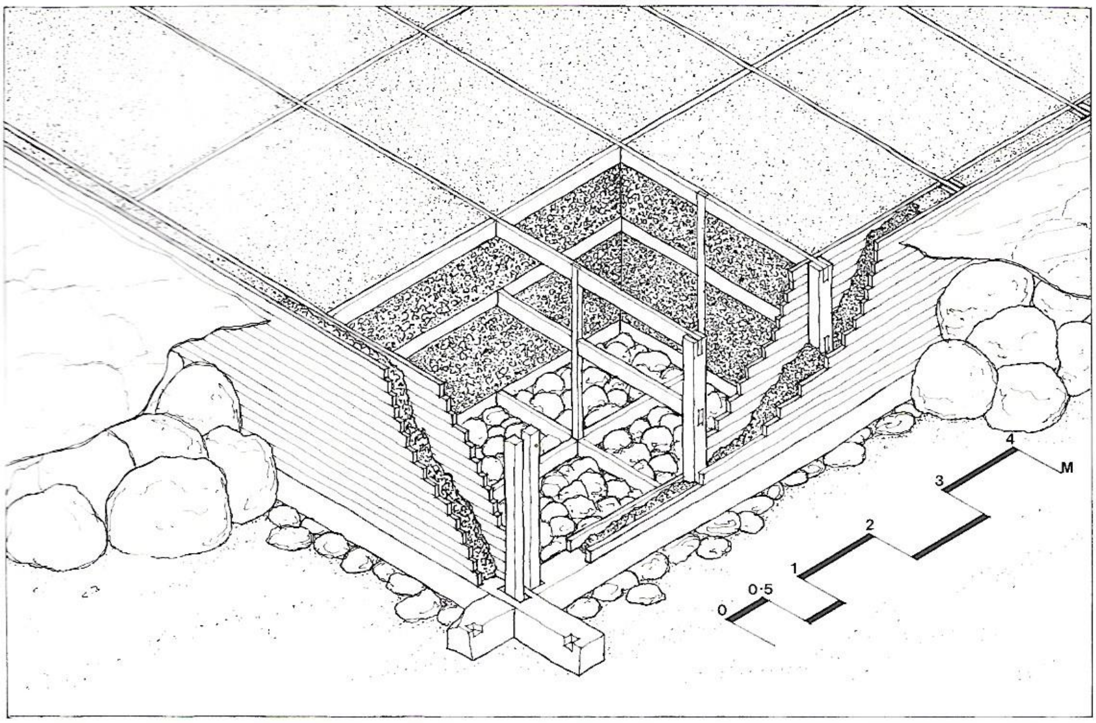

Figure 4. Caisson design as used in area G. Drawing by S. Talaat

same design.[20] They were 14 x 7 m. on plan and approximately 4 m. high, and one at least had an inner central compartment 2.5 m. wide and 6.5 m. long (fig. 5).

They were built with planking, edge fastened with mortises and tenons which were transfixed with treenails in the same manner as traditional shell-first ship construction. Built like barges, they were constructed on a nearby beach, and after being launched were loaded with a layer of pozzolana-based concrete to a depth of 0.5 m. and allowed to set before being towed out to the site. Anchored in place, lighters and barges transferred more concrete into them to settle them onto the seabed (fig. 6). It would have required only 1.5 m. of fill to sink them, and as with the "G" type forms, rubble was piled against the sides to secure them in place and to protect them from being undercut. When in place on the bottom, the caisson had a freeboard of between 0.5 m. and 1 m.

Analysis of the concrete in the second layer shows that it was actually not a hydraulic mix, but simply a lime sand mortar with a stone and tufa aggregate. This also confirms that it was a variant of Type 3, since Vitruvius designates it as a design suitable for situations where pozzolona is not available. It has been suggested that this short-

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[20] Brandon, "Concrete Filled Barges."

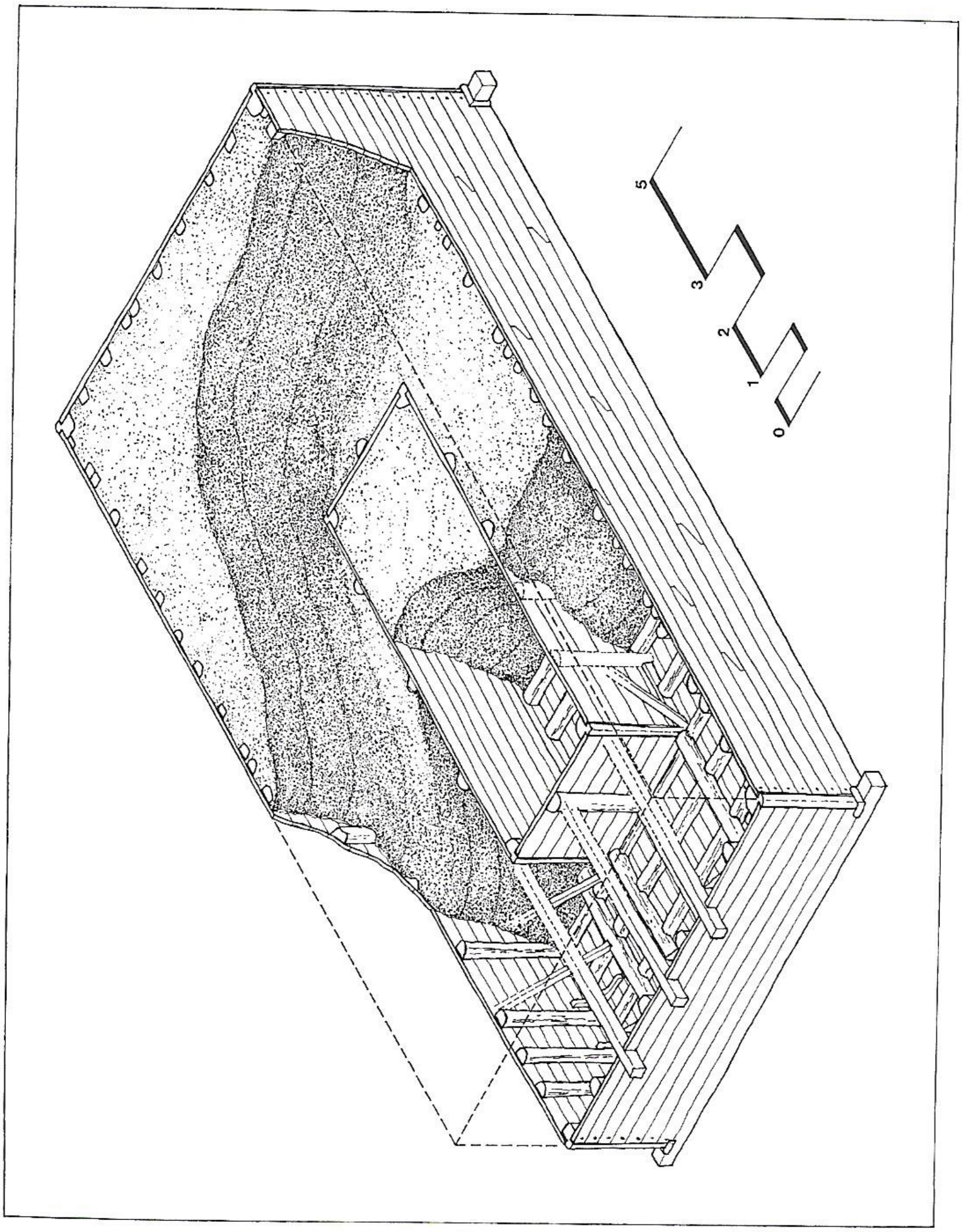


Figure 5. Caisson, or settling barge, as used in area K

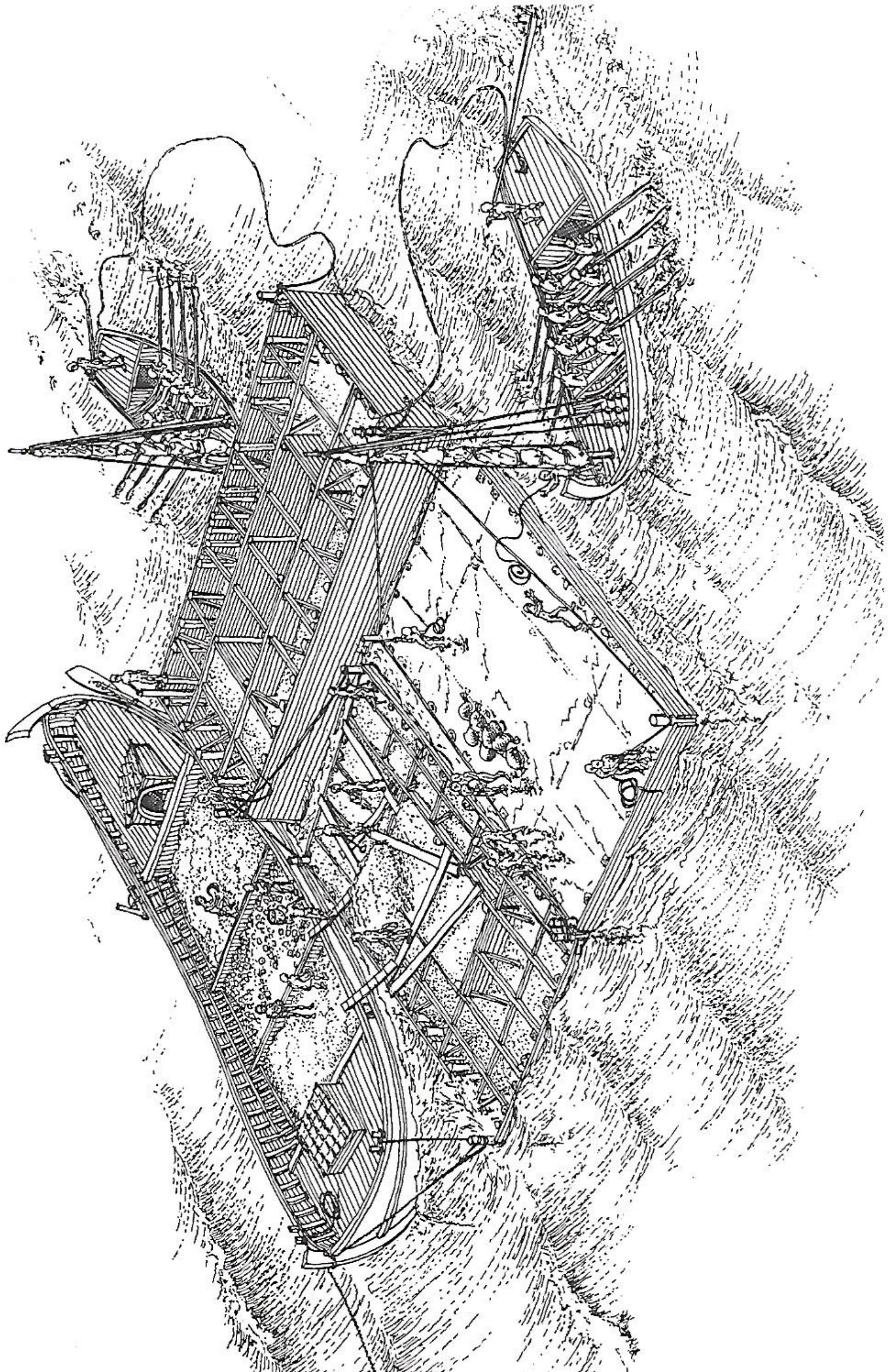
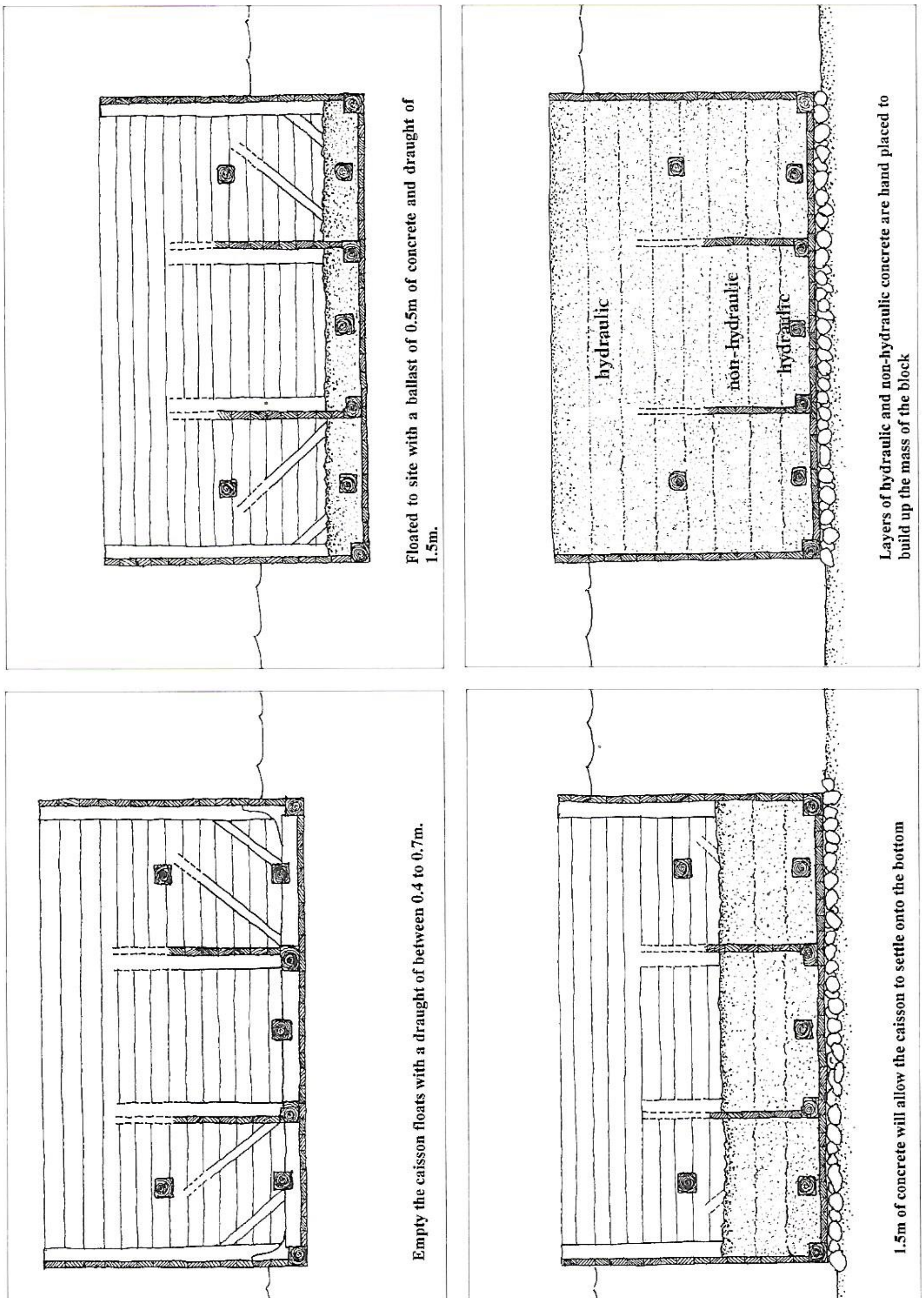


Figure 6. Hypothetical reconstruction of barges being sunk in area K



Empty the caisson floats with a draught of between 0.4 to 0.7m.

Floated to site with a ballast of 0.5m of concrete and draught of 1.5m.

1.5m of concrete will allow the caisson to settle onto the bottom

Layers of hydraulic and non-hydraulic concrete are band placed to build up the mass of the block

Figure 7. Layers of concrete in the blocks in area K

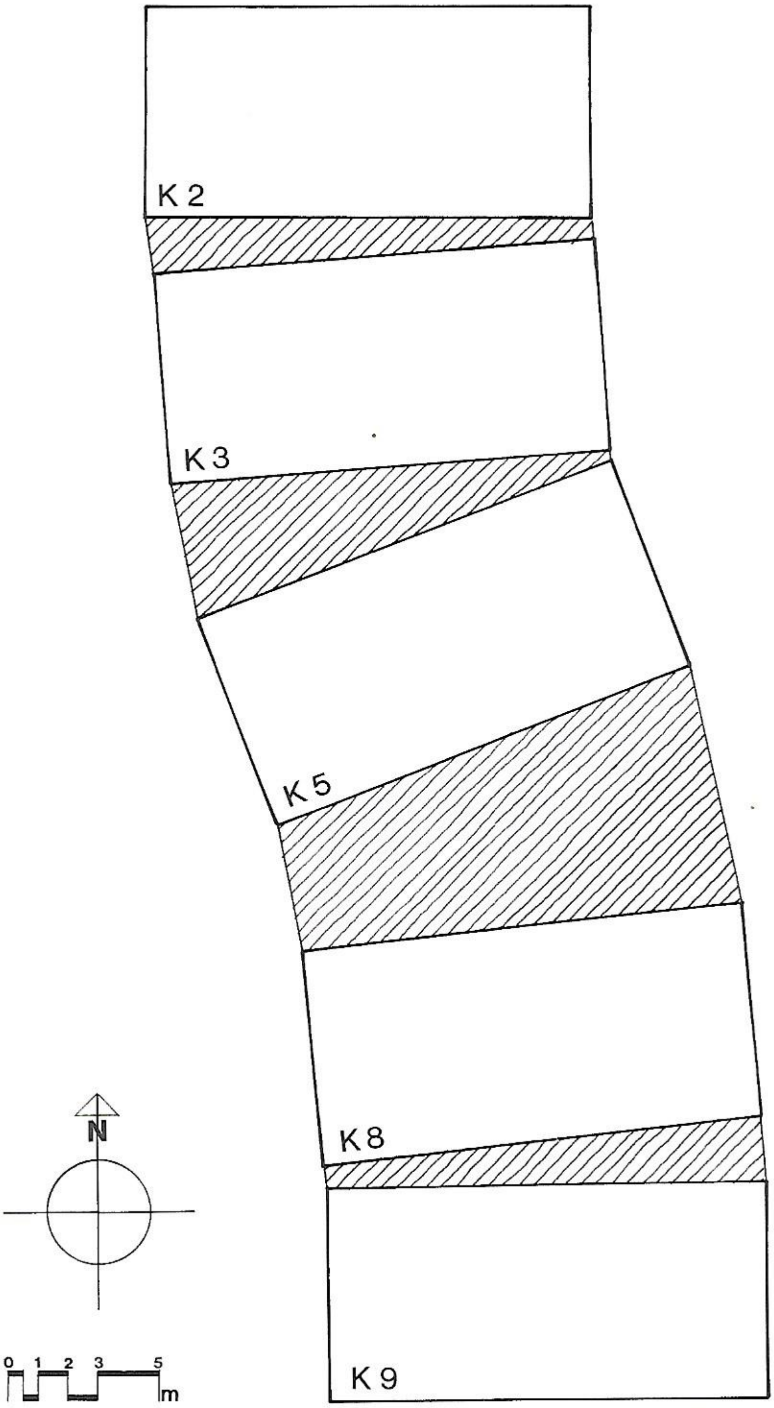


Figure 8. Infill sections between the blocks in area K

age of what was a key ingredient was due to there being insufficient time at the outset of the project to build up an adequate stock. Working off the interior framework, the caisson was filled layer by layer, with pozzolana added to the upper ones (fig. 7). The caissons were sunk next to each other in a loose header arrangement (fig. 8). Today the blocks appear in chaotic order lying at different depths and inclinations. As described by Yossi Mart, tectonic subsidence caused differential settlement local to the fault lines that ran adjacent to area K.[21] This movement disjointed the structures, opening gaps between the blocks and causing variations in settlement depth.

It is obvious that these techniques were incredibly labor intensive. They also required skilled resources to construct the "G" and "K" type caissons, which were by their very nature only temporary structures, to a very high standard. The logistics and manpower resources required to ship pozzolana and timber all the way from Italy to Israel and then to hand lay concrete, sometimes within flooded formwork, to construct a mole that extended more than 800 m. in length is a feat that is hard to comprehend today.

Although there are no other clear examples of these extraordinary designs of formwork from other sites, it is likely that they were not unique to Caesarea. Roman architect-engineers had a tradition of relying on previous experience, and in a sensitive situation such as the construction of an Imperial harbor at Caesarea, within a very tight schedule, it is unlikely that they would have departed from any tried and tested methods. Until further archaeological evidence is available from other Roman harbor sites, it is difficult to judge the extent of their use or of other variations in Vitruvius' typology.

The reuse of Caligula's barge that shipped the obelisk from Egypt to Rome as permanent formwork for concrete in the construction of part of the outer breakwater at Portus, and the caisson at Les Laurons, although not for concrete, do suggest that the "K" type caisson was used later elsewhere.[22]

The rapid demise and settlement below the sea of Caesarea's outer harbor provides a unique opportunity to study in detail a largely untouched Roman Imperial harbor. Like Portus, the harbor was constructed using numerous different methods. Further excavations along the breakwater will inevitably expand our knowledge of Roman harbor technology.

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[21] See the chapter by Yossi Mart and Ilana Perecman in this volume.

[22] S. Ximenes and M. Moerman, "The Roman Harbor of Laurons: Buildings and Structures," in A. Raban, ed., *Archaeology of Coastal Changes*, BAR Int. Ser. 404 (Oxford, 1988), 229–52.