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The technology of Roman harbours

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Modern discussions of Roman harbours often fall into one of two very different categories: straightforward reports of the results of often very difficult field-work and historical studies of their social and economic significance. Particular regard is often paid to the specialized products exported and imported through harbours or manufactured within their confines for export. This paper will focus instead on the Roman harbours themselves as centres of technological activity and innovation, concentrating on several sites well known through excavation and on one or two special topics, but also with reference to some comparable sites and more general issues.[1]

In this context, the Roman harbour should be seen as a structure or group of related structures built at the interface of land and sea, a more demanding location than either the wet or dry environments alone. Along its margins, the sea most clearly reveals its enormous energy as it frets at the barrier of the land and the vulnerable structures built into it by man. Because of the demands of the situation, not only is the process of designing an effective harbour difficult, but also its very construction. Structures heavy enough to resist the pounding and sucking of the waves must at the same time often be founded on sand or mud. Currents work at them below the waterline and the sun above, which draws to the surface of the stone and mortar insidious chlorides that percolate through the fabric and weaken it.[2] The wind, made sharp with sand and salt, gnaws at every barrier, usually changing its direction 180 degrees within each day as the morning offshore breeze becomes an onshore breeze in the afternoon.

At the same time, harbour structures must offer commodious and convenient shelter to the largest and most complex machines known to the ancient world; ships, the hulls of which were strong and flexible when riding the sea but as fragile as eggshells when stressed at any one point by a reef, or by the quay of a poorly protected harbour.[3] Roman ships were really great units of floating architecture, shaped for the sea rather than for the prismatic forms of the structures that had to receive and protect them between voyages. But into the harbours they came, their great bulk and crushing mass guided and subdued with ropes fixed to the quay walls by means of carefully placed bollards or perforated stone blocks. Here, too, the harbour's function placed special demands on its design and materials. Stevedores swarmed up stout planks to carry out from the hold heavy sacks or baskets, large ceramic containers full of precious foodstuffs, or crates of delicate glass and ceramic tablewares. Somehow, enormous timbers and blocks of stone were removed as well, perhaps with quay-side cranes. All these goods had to be shifted across the busy platforms surrounding the harbour to open-air storage areas or conveniently located warehouses. Most often, the same ships were loaded up again with other, different goods brought to the port from its hinterland. Paved roads and transport canals fed such ports and constituted an essential part of a harbour's infrastructure.

But there were still other demands on a Roman harbour, with their own further technological ramifications. Ships due for repair or maintenance had to be careened, or pulled up on slips, or, in a few cases, possibly even accommodated in dry docks fitted with chocks, barrier walls and pumping installations.[4] The cleaning of ships' superstructures and cargo, victualling of their crews and the preparation of water stores for long sea voyages required the placement of fountain houses somewhere convenient to the quays, fed by pipelines or aqueducts[5]—ships' chandlers, too, and the bars and brothels that have always made harbour neighbourhoods so picturesque. Along some coasts, major Roman

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harbours were provided with lighthouses, the elevated beacon fires of which consumed significant quantities of wood. Furthermore, the harbour itself required maintenance; not just repair of the structures subject to such heavy use, but in many cases also dredging of the harbour basin or channel to preserve the depth required for navigation. There were *collegia* of workers who specialized in this unglamorous task, probably using scoops or baskets on ropes drawn by hand or windlass from special barge-like craft, although we have no archaeological evidence for the procedures involved.[6] Other groups of workers specialized as stevedores, or even as divers, the curiously named *urinatores* who assisted at submarine construction or recovered cargo dropped into the water (Oleson, 1976).

The topics of importance to Roman technology in Roman harbours, then, are numerous; design, management of streams and sediment, selection and preparation of materials, placement of materials during construction, maintenance or repair, and harbour facilities and services. In Roman harbours, we can see a wide variety of interrelated technologies responding to the need for economical bulk transport over long distances. It is the purpose of this paper to emphasize the high level of sophistication involved in Roman harbour technology and the need for careful research in a number of areas.

To be sure, the circumstances I have just reconstructed are those of a major Roman harbour, such as Leptis Magna, Caesarea Palestinae, Portus, Puteoli or Centumcellae. There were simple anchorages as well in the Roman world, and unprotected or poorly protected ports, small harbours of local importance with wooden quays, river harbours and Bronze Age Near Eastern or Classical Greek facilities that survived into the Empire, all the subject of a surprisingly rich Latin terminology.[7] Ancient harbour technology never followed a completely linear development; too much depended on local topography, available building materials and regional economic conditions. What we can see across time is the gradual evolution of a repertoire of techniques that gave each succeeding Mediterranean culture greater flexibility in design and a better chance of success. The earliest solutions were concentration of maritime activity around a bay or along a beach sheltered by an offshore island, or on one or the other side of an exposed headland, depending on the wind. Solid, ashlar-built quays appear already in the Late Bronze Age, at least in exceptionally sheltered spots, and by the 8th or 9th century BC the Phoenicians were modifying natural reefs to serve the needs of harbours and building breakwaters of ashlar blocks (Raban, 1985). Because of the greater depth of their coastal waters, the Greeks usually constructed rubble-mound breakwaters when such shelter was required, with ashlar quays on top or along adjacent shores. The totally enclosed, fortified harbour basin, the *limēn kleistos*, was a Hellenistic development, although the ill-defined Carthaginian *cothon* may constitute a precedent.[8]

The appearance of Roman lime-mortar and pozzolana-mortar concrete in the late 3rd or early 2nd century BC brought about a profound change in the patterns of harbour construction, but many old materials and procedures continued to be used alongside the new. Concrete splash walls or piers could be founded on rubble mounds, or ashlar walls on concrete foundations, and wooden quays based on the dredge-and-fill principle appear in imperial river harbours, even at important centres such as Londinium (Milne, 1985). Harbour layout, of course, depended on local topography and currents, and on the potential volume of traffic within the basin. Nevertheless, even the minor centres shared to some extent in the relevant technological advances. Because of its very function, to facilitate the movement of people and goods, innovations in Roman harbour technology spread rapidly as the better built and more successful harbour complexes attracted the ships and the careful scrutiny of technically competent visitors from other ports.

The crucial Roman contribution to harbour technology was in the area of materials and their placement, along with consequent changes in overall harbour design. This aspect of harbour technology will constitute the focus of my discussion. Many of the other techniques associated with ancillary services, such as lighthouses, canals, repair slips, dry docks and water-supply installations, can be found already in the Hellenistic period. The Roman contribution in this area was the perfection of the designs involved and their more general application. What the Romans developed on their own, of

Figure 1. Cosa: impression of vertical board shuttering on Pier 1. Photo: A. M. McCann.

course, was concrete, both lime-mortar concrete and hyraulic concrete made by adding to the mortar pozzolana, a powdery volcanic ash, and often characterized by volcanic tufa aggregate as well. The use of this material, which seems to have become customary in Roman structures in central Italy by the beginning of the 2nd century BC, carried with it a host of ancillary techniques and tools involved with preparation of formwork, mixing of the mortar and placement of the aggregate.[9] Hydraulic concrete had the benefit of extraordinary tenacity and longevity in terrestrial structures, but also the added attraction of an ability to set and cure while immersed in fresh or salt water. It is not certain when or where this discovery was made, but the suitability of this superb new material to structures connected with water—bridge footings, harbours and aqueducts, for example—must immediately have been obvious.

The earliest datable example so far known of pozzolana-mortar concrete used in an inundated structure has been found in the harbour of Cosa, which was laid out in the late 2nd or early 1st century BC (McCann, 1987).[10] The breakwater consists of a series of stout rectangular piers built of hydraulic concrete on top of a rubble-mound foundation. To modern eyes, this design seems to leave ships in the basin curiously vulnerable to the waves, but it was typical of early Roman harbours along the Italian coast, where the long-shore currents carry enormous amounts of sediment. Other examples of the design were built at Puteoli and Misenum, and possibly at Antium and Terracina as well (Blackman, 1982: 197 and n. 86). The *pilae,* as they were called, broke the brunt of the sea's force but at the same time allowed free enough circulation of water within the basin for the sand and silt to stay in suspension. Closed basins, such as that at Portus, quickly ran into difficulties with sediment. The most famous example of the *pilae* design was the harbour of Puteoli, where the upper surfaces of the piers were joined by low concrete arches supporting a long, broad walkway. At Cosa, this walkway may have been built of wood. The quality of the material used at Cosa and these other sites is clear from the very survival of the piers despite exposure to the full force of the sea for almost 2000 years. In some cases, even the marks of the wooden formwork into which the concrete was laid can still be seen (Fig. 1).

Placement of this material in an inundated marine site is not simple. None of the boards or beams have survived in the context of the breakwater structures at Cosa, but marks of the

Figure 2. Cosa: holes left by tie beams in Pier 2. Photo: A. M. McCann.

boards and the long horizontal holes left in the mass of several of the piers by timbers reveal that the concrete was laid in box-like forms with vertical shuttering along the sides held in place by exterior beams, reinforced by horizontal tie beams that ran across the interior (Fig. 2). The use of pozzolana mortar meant that the forms could be left full of sea water during construction, but securing of the forms in position for filling must have taxed the ingenuity of the engineers involved. Forms intended for submerged locations must have been floated into position, then somehow ballasted to sink upright on the prepared sand, rubble or ashlar block foundation. Vitruvius, in his famous, often-quoted passage concerned with harbour construction (5.12.3) unfortunately is ambiguous about the solutions to most of the practical problems of placement:[11]

Deinde tunc in eo loco, qui definitus erit, arcae stipitibus robusteis et catenis inclusae in aquam demittendae destinandaeque firmiter; deinde inter ea ex trastilis inferior pars sub aqua exaequanda et purganda, et caementis ex mortario materia mixta, quemadmodum supra scriptum est, ibi congerendum, donique conpleatur structurae spatium, quod fuerit inter arcas.

Next, in the designated spot, formwork enclosed by stout posts and tie beams is to be let down into the water and fixed firmly in position. Then the area within it at the bottom, below the water, is to be levelled and cleared out, [working] from a platform of small cross-beams. The building is to be carried on there with a mixture of aggregate and mortar, as described above, until the space left for the structure within the form has been filled.

In the subsequent paragraph (5.12.4), Vitruvius alludes to problems in setting up formwork in rough seas and proposes a method of preparing and curing concrete blocks on land for transport to the breakwater site by the natural forces of beach movement. Frankly, it does not sound very practical, but the context reveals that Vitruvius had at least heard of attempts to cope with sites on exposed coasts. He goes on to describe a type of double-walled form that could be drained for use with non-pozzolana mortar concrete (5.12.5):

. . . uti arcae duplices relatis tabulis et catenis conligatae in eo loco, qui finitus erit, constituantur, et inter destinas creta in eronibus ex ulva palustri factis calcetur. Cum ita bene calcatum et quam densissime fuerit, tunc cocleis rotis tympanis conlocatis locus qui ea septione finitus fuerit, exinaniatur sicceturque, et ibi inter septiones fundamenta fodiantur.

Let double-walled formwork be set up in the designated spot, held together by close set planks and tie beams, and between the anchoring supports have clay packed down in baskets made of swamp reeds. When it has been well stamped down in this manner, and is as compact as possible, then have the area bounded by the cofferdam emptied and dried out by means of water-screw installations and water-wheels with compartmented rims and bodies. The foundations are to be dug there, within the cofferdam.

One would like, of course, to know precisely how the forms were to be 'set up in the designated spot'. The terminology used, archaeological parallels and modern practices suggest that upright posts (*destinae*) were driven into the bottom at close intervals to support horizontal planks (*tabulae*), and the whole reinforced by means of transverse tie beams (*catenae*). The erection of isolated uprights implies the use of a pile-driver mounted on a raft. The addition of the planks would have required a team of large-lunged divers skilled in high-speed submarine carpentry. Alternatively, the whole form could have been built in shallow water with the sharp ends of the uprights projecting below the level of the planks, floated into position, up-ended, ballasted and the main supports carefully driven into the sea bottom with simultaneous blows. It would have been difficult to carry out this last operation on a completed box-like form without subjecting it to intolerable strains, so perhaps—although Vitruvius does not mention it—the four double-walled sides of the form were prefabricated separately, then floated into position and driven into place. Making the corners watertight and firm afterwards would have presented difficulties, but probably not insuperable ones.

Once the formwork was in position, pumping machinery might have to be transported out from shore and installed, depending on the type of form and mortar (Oleson, 1984: 108–9), and enormous amounts of mortar and aggregate prepared and laid according to a careful schedule. Presumably, specially designed boats were used (see note [6]). The placing of concrete is not at all straightforward in inundated formwork. Even modern marine concrete, which is much more homogenous in consistency than its ancient counterpart, cannot simply be dumped into inundated formwork from the surface of the water. It must be carried to the bottom of the form by means of a tube (called a *tremie*), or carefully released from the bottom of hoppers lowered to the floor (Reynolds, 1967: 226–7; van Loenen, 1973: 197–201; Taylor, 1977: 330, 543–6).[12]. Otherwise, in falling through the water the mortar and aggregate are sorted by size and density, and the result is a series of strata with little or no strength. Vitruvius, to our keen regret, says only that 'building is to be carried on there with a mixture of aggregate and mortar' (5.12.3).

Judging from the size and irregularity of the aggregate used in Roman marine structures, it is very unlikely that a mortar and aggregate mixture could have been poured into inundated forms through stiff leather tubes or wooden conduits. The mortar alone could have been poured through a wooden or leather tube, raked level to the required thickness around the form, a stratum of aggregate thrown in and raked and pressed into place, and the whole procedure repeated until the form was full. It seems strange, however, that the long, clumsy pipes necessary for this hypothetical procedure have totally escaped comment in Vitruvius.[13] Any such leather or wood pipe would have had to be manufactured in sections that could be disconnected one by one as the form filled, in order to allow raising of the pipe bit by bit to keep the outlet level with the rising upper surface of the mortar and at the same time to permit continued introduction of mortar and aggregate at the upper end. These sections would have had to be strong, flexible, tight-fitting, smooth on the interior and capable of being disassembled quickly and easily. Such specifications are unparalleled in surviving Roman pipes or hydraulic fittings. An open, U-shaped wooden gutter pipe could have functioned without joints, since it was not restricted to a single intake opening, and in consequence the slope could be adjusted more easily. Nevertheless, even this would have been very clumsy, and I doubt that the stiff mortar mix required for submarine construction would have slid down it quickly enough. Furthermore, even with this arrangement, the presence of aggregate could have caused jamming, and turbulence would have washed some mortar out of the open side. A more believable procedure is the use of numerous deep baskets with two stout handles at the upper rim for ropes to lower each container to the bottom of the form full or mortar, or of aggregate, or of both mixed together in the proper proportions, along with a handle at the bottom for a tip-rope used to spill the contents gently once the basket was at its proper position. Ancient representations of Roman construction projects show

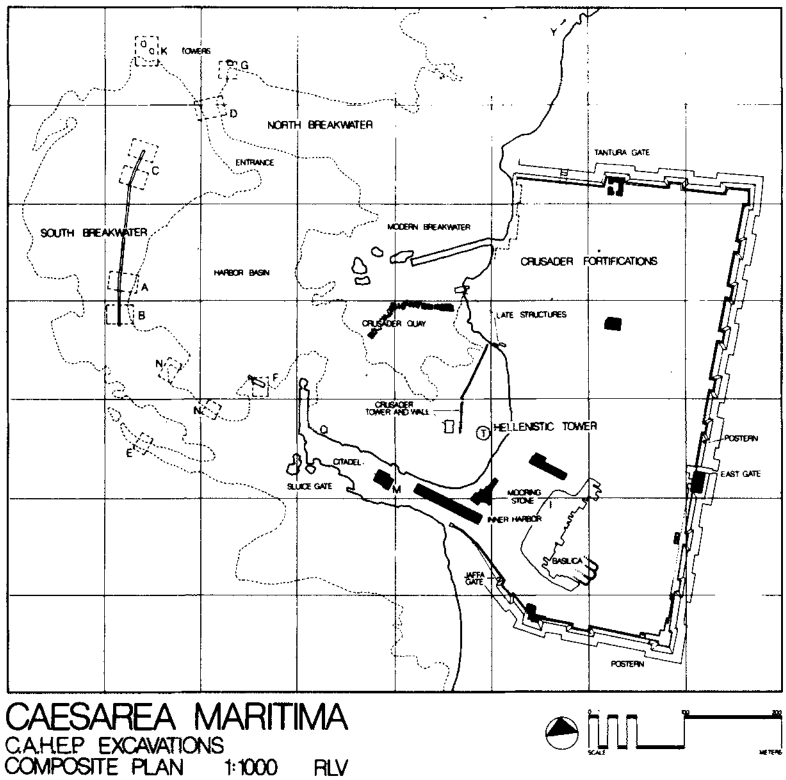

Figure 3. Caesarea: plan of Herodian harbour and excavation areas. Plan: R. L. Vann.

that baskets were the most common container for moving mortar and other building materials around construction sites (MacDonald, 1983: 158, pl. 127, 130b; Adam, 1984: 76–9, 87–90).

Recent excavations at the harbour of Caesarea Maritima, called in antiquity Caesarea Palestinae, Herod's great harbour in present-day Israel, have provided important new data on the technology of Roman hydraulic concrete.[14] The design and enormous scale alone of the harbour at Caesarea reveal a bold confidence in the relatively new material. Where there had been only an anchorage in the lee of natural reefs, and possibly a small Hellenistic *limēn kleistos,* Herod built between 21 and 9 BC two enormous breakwaters reaching out 600 and 300 m into the open sea to enclose an outer basin of 20 ha (Fig. 3). There were an intermediate and an inner basin as well, quays with broad landing areas, vaulted warehouses, probably a lighthouse, and everywhere gleaming marble and statuary. The breakwaters had a foundation of rubble on the sand bottom, but their strength consisted of enormous concrete blocks cast in place on the outer slope, supplemented by stone blocks of various sizes. Many of these concrete blocks still preserve the marks of the formwork into which they were poured (Fig. 4), and the mortar itself is rich with the volcanic sand and tufa that gave it its hydraulic properties. The source of this crucial additive is still under investigation, but visual inspection and trace-element analysis have already shown that it was imported from outside Palestine.[15] It would not be surprising if our final comparative analyses showed that the pozzolana was brought by ship from quarries in the Bay of Naples, near Puteoli. Vitruvius himself, writing more or less at the time the harbour was under construction, specifies the superiority of pozzolanic additives from that region (2.6.1, 4–6). He was not a pioneer, but he sums up much of the contemporary Roman practice in engin-

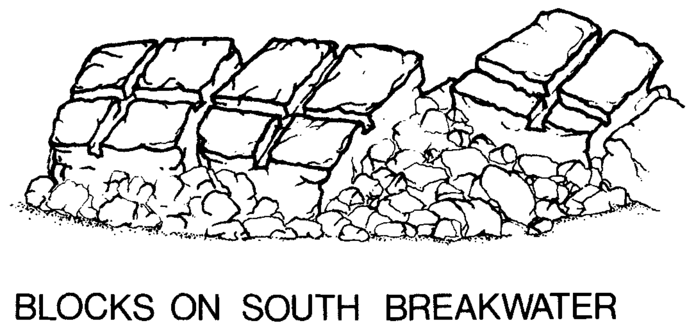

Figure 4. Caesarea: view of concrete blocks on southern breakwater. Drawing: R. L. Vann.

eering and design. So far, all that the preliminary analyses reveal is that a source near Puteoli is not impossible.

What can be seen at Caesarea is the transfer of technology on a grand scale. Herod, an enthusiastic builder very knowledgeable about Roman culture, imported Italian engineers skilled in the latest techniques of submarine construction. Their selection of the critical ingredient for the hydraulic concrete needed for the project would have reflected contemporary Italian practice and the general Roman concern with procuring the best possible raw materials—an attitude found throughout Vitruvius' handbook. Note, for example, 2.3–7, on the selection of bricks, sand, lime, pozzolana and stone to be used in construction. What Herod obtained with his wealth and foresight was a harbour without architectural precedent in the Eastern Mediterranean, imperial in character, on a scale even the Roman emperors did not attempt for another 60 years until Claudius built Portus.

Even apart from the need to import building materials on a large scale (alluded to in Josephus' famous description of the harbour: *AJ* 15.331–332), the task of pouring concrete blocks to the required size in the open sea must have been challenging. Many of the blocks still carry marks of simple box-like forms with horizontal tie beams such as we have already seen at Cosa and heard described by Vitruvius. But, in addition, in 1982 extensive physical remains were discovered of wooden forms of a new type.[16] Excavation showed that the structurally crucial tip of the northern breakwater (Fig. 3, area G) was built of enormous concrete blocks approximately 15 m long, 12 m wide and 2 m thick, laid directly on the sand of the original sea bottom (Fig. 5). One

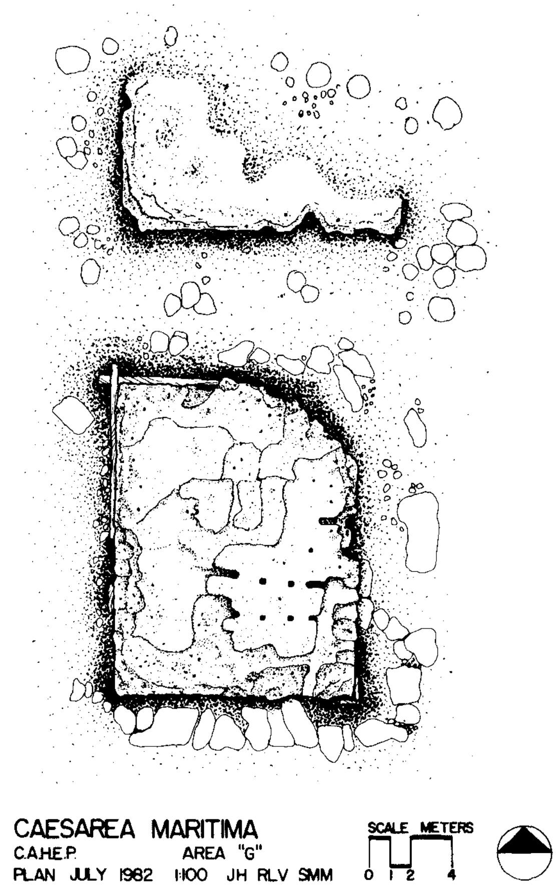

Figure 5. Caesarea: plan of area G. Drawing: R. L. Vann.

block was riddled with holes left by the horizontal tie beams and vertical interior supports necessary for the huge wooden form in which the concrete was laid. In addition, massive lower

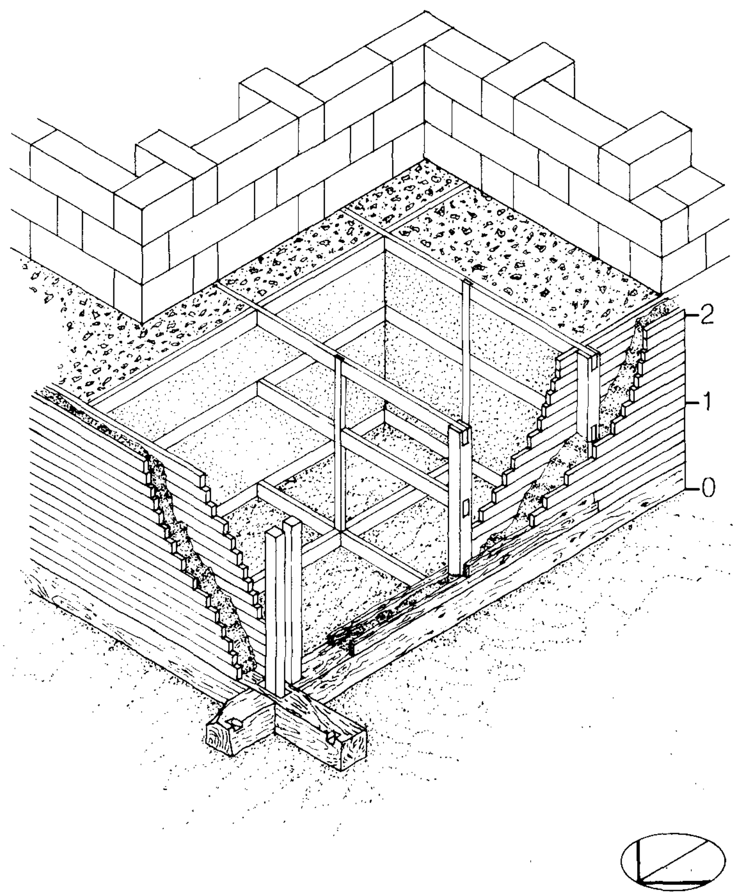

Figure 6. Caesarea: reconstruction of formwork in area G. Drawing: R. L. Vann.

sleeper beams and portions of the upright walls were preserved below a layer of rubble and sand.

The forms were double-walled, like the design specified by Vitruvius for use with non-pozzolana mortar concrete, which had to be poured in a dry environment (Fig. 6). Remember that the double walls in Vitruvius were to be packed with clay to allow pumping out of the interior. This concrete, however, had in fact been made with volcanic additives, and the wall compartments were filled with puddled mortar, which is permeable to water until hard. Furthermore, the interior could never have been pumped dry, because the heavy beams along the base of the form simply rest on the sand surface; any water removed from the interior of the form would have been immediately replaced by water bubbling up into it from below, through the sand under the walls. To be watertight, such forms must have a floor or be surrounded by upright beams that have been pounded deep into the bottom.

If the mortar-packed double wall of the Caesarea formwork was not meant to make it waterproof, then what purpose did it serve? I believe that we see here a conflation of two major types of formwork described by Vitruvius, in an adaptation of the basic principles involved to a third type of situation. The engineer knew from the start that he was working with an hydraulic concrete that could be poured directly in sea water, but either the exposure of the site to the open sea or the character of the sandy sea bottom and rubble breakwater foundation (or both) made it difficult to fix prefabricated forms in place by means of pilings. In consequence, bottomless, double-walled wooden forms were constructed on shore and floated to their final positions. Once the footings had been cleared and levelled by divers, mortar was poured into the sections of the hollow wall, with careful attention to balance, until the buoyancy of the wood was overcome and the form settled into position on the prepared surface. While the inundated form was being filled with cement and aggregate, rubble was also dumped around the periphery to prevent shifting of the formwork prior to the curing of the concrete, or undermining of the final block. The presence of tie beams passing through the mass of the concrete would have prevented salvage of the formwork intact, but portions may well have been pulled free for reuse; no traces of the double wall or its mortar packing were found, for example, along the north face of the block. Mortar would have been preferable to stones as ballast because it was uniform in weight, easily handled and would fill completely the sections into which it was poured.

Such a procedure would have allowed a rapid and flexible schedule of construction. The most complex part of the job, preparation of the form, could have been carried out conveniently on shore or in shallow water, without the danger of damage to partially completed formwork by storms. It is difficult to see how the Caesarea formwork could have been fitted together underwater without enormous effort. In the absence of pilings there would have been no firm anchor for any of the uprights or planks, and none of the heavy work could have been executed from the surface. In contrast, as the weather and preparation of materials for the concrete allowed, prefabricated forms could have been assembled and towed to various parts of the harbour and put in place by a few trained workers. Although Vitruvius' single-walled forms were prefabricated, pounding their uprights into the harbour floor would have been a tricky and time-consuming business. As long as the four massive sleeper beams of the Caesarea formwork had settled firmly on a level sand surface, little concrete would have leaked out as the form was filled. This procedure conforms more closely with Josephus' assertion that Herod 'let down enormous blocks of stone into the sea' (*BJ* 1.411; *AJ* 15.334) than the alternative—construction of caissons on the spot by pile driving or submarine assembly.

Conclusions

Ports depend on complex structures that must be capable of resisting the stress of two environments at once, while accommodating ships, the heaviest and most complex machines of the ancient world. The invention of hydraulic concrete in Italy during the 3rd or 2nd century BC made possible revolutionary changes in harbour design, but some of the same techniques and materials that appeared in Archaic and Classical Greek harbours continued in use throughout the Empire. The placement of materials during construction required innovative procedures and devices too; floating cranes and pile drivers, prefabricated caissons, pumps and professional divers. As artificial harbour basins grew in size, the analysis and management of river flow, ocean currents and the associated sedimentation became critical, and dredging was an expensive remedy for misjudgement. Ancillary structures such as lighthouses, warehouses, dry docks or repair slips, and the infrastructure of support services, such as cranes, water supply and associated transport canals or roads, demanded further technological expertise. In Roman ports, we can see a wide variety of interrelated technologies responding to the need for economical bulk transport over long distances.

Many of the suggestions presented above are hypothetical, since considerable research must still be carried out both in the field and through examination of the surviving ancient texts. But this discussion of one aspect of Roman harbour technology should provide an introduction to the complexity and sophistication of the techniques involved, and to the accomplishments of past excavation and surveys.

Notes

[1] This paper has been adapted from an oral report presented to a colloquium on 'Ports, technology, and trade in the Ancient Roman world' that took place on 29 December 1985 at the annual meeting of the Archaeological Institute of America in Washington D.C. I would like to thank Dr Anna Marguerite McCann for the invitation to

participate in the colloquium. The bibliography on ancient harbours is large and quite scattered, but the most important articles and books are collected in Blackman (1982). For an annotated bibliography, see Oleson (1986: 395–405). The best overall discussion is still that in Lehmann-Hartleben (1923).

[2] The bibliography on concrete in marine environments is enormous and highly specialized. For a summary of the major problems affecting the material and recent advances in the technology, see Cornick, 1962: 105–38; Mindess & Young, 1981: 114–5, 287, 551–2; Taylor, 1977: 327–33, 543–6; Tibbetts, 1968: 159–80; van Loenen, 1973: 197–201.

[3] The shell-first construction and technique of edge-joining strakes with numerous mortise and tenon joints, typical of Mediterranean ships built before the 7th century AD, meant that the intact hulls were very strong. Once the integrity of this resilient skin was breached, however, by the collapse of some planks, the frames were less well suited to absorb the added load than those of ships built in the frame-first fashion typical of the Medieval and modern period. For a brief, useful review of ancient ship construction, see Casson (1985). Further bibliography can be found in Oleson (1986: 364–95).

[4] The question of the existence of dry docks in the Greco-Roman world is a tantalizing one. A makeshift dry dock is mentioned by Callixenus in the late 3rd century BC (Jacoby, 1926–58: IIIC no. 627 frag. 1). See the discussion in Oleson (1984: 33, 326, 388, 394). There is, however, no concrete evidence that the Romans knew and used the principle of the pound lock, necessary for a convenient, permanent dry dock. This problem is discussed in Smith (1978); Blackman (1982: 207).

[5] Examples of spring houses or fountains immediately adjacent to harbour basins have been found at Leptis Magna and Sarepta; see Bartoccini (1958: 96–7, 100, pl. 41–2); Pritchard (1978: 55–9).

[6] This group may have been identical or associated with the *saburrarii*, literally 'sandmen' or 'gravelmen', who handled ballast for ships at Portus, since sand removed from the harbour basin would often have been suitable for ballast. The epigraphical sources are cited in Cason (1971: 370 n. 46) and Meiggs (1973: 324). Cf. also Laures (1986: 167). There is a short discussion of dredging in Blackman (1982: 199–202). Special boats or barges for carrying rubble to the site of a breakwater are implied by a phrase in Pliny's description of the construction of Trajan's harbour at Centumcellae: 'ingentia saxa latissima navis provehit' (*Ep.* 6.31.6). Dredgers may have used similar craft.

[7] References to the general bibliography on ancient harbours are provided in note [1]. The best treatment of the Latin terminology for harbours can be found in Uggeri (1968).

[8] The general Greco-Roman development is discussed in Lehmann-Hartleben (see note [1]).

[9] The scholarly literature concerned with the origins and technology of Roman concrete is enormous. Some excellent general discussions with full documentation and bibliography can be found in Lugli (1957: 363–444; MacDonald, 1983: 3–19, 143–66; Ward Perkins, 1981: 97–120). The most graphic reconstruction of the ancillary techniques and tools appears in Adam (1984).

[10] The excavation of this harbour was directed by Dr Anna Marguerite McCann, to whose generosity I owe two of the illustrations used here. I would like to thank Dr Elaine K. Gazda of the University of Michigan for sharing with me her research on the materials used in this harbour. The two of us are collaborating on a monograph concerned with the development and technology of Roman concrete used in inundated sites, and some of the ideas presented here have grown out of our discussions.

[11] The edition quoted in this and the following passage is that of Granger (1931: 312); essentially the same as Krohn (1912: 118–9). The translation is the author's.

[12] A famous early French edition of Vitruvius contains an engraving incorrectly showing workers pouring the concrete mix directly from a trough carried by a boat into the water-filled form (Perrault, 1673: pl. following p. 162).

[13] Grenier (1960) 35 asserts that Vitruvius 8.6.8 ff. extols the virtues of pipelines made of leather. Compare also De Magistris (1898: 96). This is an error based on a mistranslation of the phrase *crasso corio*. As the context makes clear, Vitruvius has eathenware pipes in mind. Only a few passages in ancient Greek and Latin authors mention the use of leather pipelines, and these concern only water. In Herodotus 3.9, an Arab king uses a long leather pipeline to carry water across 'ten days journey' of desert to fill several reservoirs with drinking water from a river. Even Herodotus does not believe the story. A passage in Strabo 16.2.13.753–4, describes an ingenious device designed to collect the water of a submarine fresh water spring near Arados, an island off the Syrian coast. The water was captured beneath a heavy, inverted lead funnel lowered to the sea floor and was conveyed to the surface through a leather pipe for delivery to waiting boats. Strabo obviously considers the arrangement remarkable and provides a clear description of all its parts. The same operation is mentioned by Pliny *HN* 5.34.128. Water, of course, is well suited to conveyance in such pipes. Wooden water conduits (*canales ligneae*) are mentioned by Virgil G 3.330, Cetius Faventinus 6 and Palladius 9.11, and wooden pipes are commonly found at Roman sites in northern Europe (Bonnin, 1985: 151–2).

[14] Dr Avner Raban of the University of Haifa is overall project director of the Caesarea Ancient Harbour Excavation Project (C.A.H.E.P.). The author co-directed these excavations between 1981 and 1985 along with Professor Robert Hohlfelder of the University of Colorado and Dr Robert L. Vann of the University of Maryland. My participation was made possible by generous funding provided by the Social Sciences and Humanities Research Council of Canada and by the University of Victoria. For an interim report, see Oleson *et al.* (1984).

[15] I would like to thank Dr Graham Branton of the University of Victoria for collaborating with me in the scientific

analysis of trace elements in the pozzolanic additives in the concrete from this and other Roman harbour sites and quarries. We will be publishing the results of this investigation in the near future.

[16] Oleson *et al.* (1984: 291–4, 297–9). The technique of pouring the concrete is discussed in Oleson (1985: 165–72).

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