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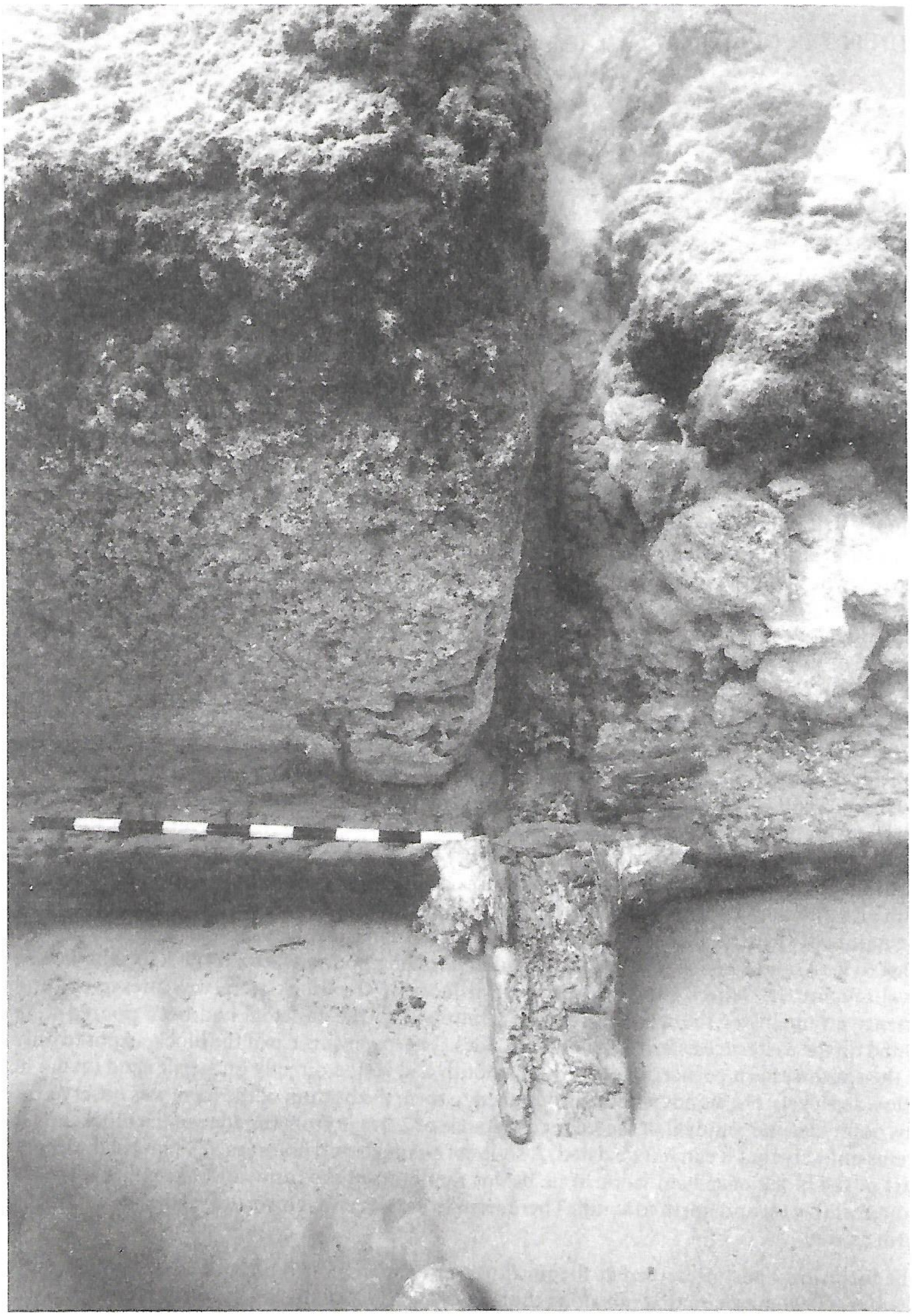
Herod and Vitruvius: Preliminary Thoughts on Harbour Engineering at Sebastos; the Harbour of Caesarea Maritima

Although my research is still in progress, I am happy to have the opportunity to present to this conference a preliminary analysis of the historical and technological significance of the wooden formwork discovered in the harbour of Caesarea in 1982[1]. This find has shown that Herod's engineers possessed a competence in hydraulic engineering and a knowledge of available construction materials that go far beyond the traditions of the region. The technology of Sebastos, like its scale and finish, was imperial in scope. After a brief description of the excavation and of the remains of the formwork, I will compare the archaeological material with a passage in Vitruvius that describes the use of concrete in harbour construction. A discussion of the procedures and materials known to Vitruvius provides information crucial to our knowledge of the technology used to build Sebastos.

DISCOVERY AND EXCAVATION OF THE FORMWORK

The eastern face of the channel leading into the harbour basin was built of immense *kurkar* (the local eolian carbonate cemented quartz sandstone) blocks (ca. 5.5 m x 1.0 m x 1.25 m) mortised into one another and held in place by iron clamps. In contrast, the northwestern tip of the northern breakwater, which in aerial photographs appears as a large, square projection at the western end of the northern face, was built of concrete. Even before excavation in 1982, the outlines of eroded concrete blocks could be seen, topped by the remains of what may have been limestone paving blocks. During the 1982 season, sand and rubble were removed by hand and with an airlift at the northwestern corner of this area (termed Area G) in an effort to determine the nature of the structure. Excavation ultimately revealed a concrete block ca. 11.50 m wide (east to west) and 15.0 m long, with an irregular, eroded upper surface ca. 4.0-5.10 m below sea level (Figure 1). Where exposed, the vertical faces of the block were well preserved, and extensive remains of the wooden formwork into which the concrete had been poured were found on the eastern, western and northern sides. The lower surface of the block, exposed only at the southwestern corner, was level and smooth and rested directly on sterile sand (at 6.4 m below sea level). No wooden flooring designed to form the bottom of the form was observed at this point, despite removal of the fill for a distance of 2.0 m in from the edge of the block, and it seems unlikely that it can have existed, A series of channels and holes (ca. 0.18 m^2) in the upper part of the block once held wooden tie beams that crossed the formwork at regular intervals from east to west and north to south. There seem to have been a few vertical supports within the form as well.

The formwork, best preserved at the northwestern corner, was built on massive pine sleeper beams ca. 0.29 m square that ran along the base of each face of the block and interlocked at the corners with simple lap joints (Figures 2-3). A series of fir uprights (ca. 0.12-0.15 m x 0.23 m), mortised into the horizontal beams at ca. 1.60 m intervals, carried an external and internal wall of horizontal pine and spruce planks 0.08 m thick and 0.14 m wide (Figure 4). The lowest of the planks on the inner face of the formwork is inset slightly into the upper surface of the large sleeper beam. The seams between the various planks and beams making up the formwork presently are filled with a sandy white mortar. This substance may be intentional packing, but it could also be cement that was forced into loose seams when the interior of the formwork and its



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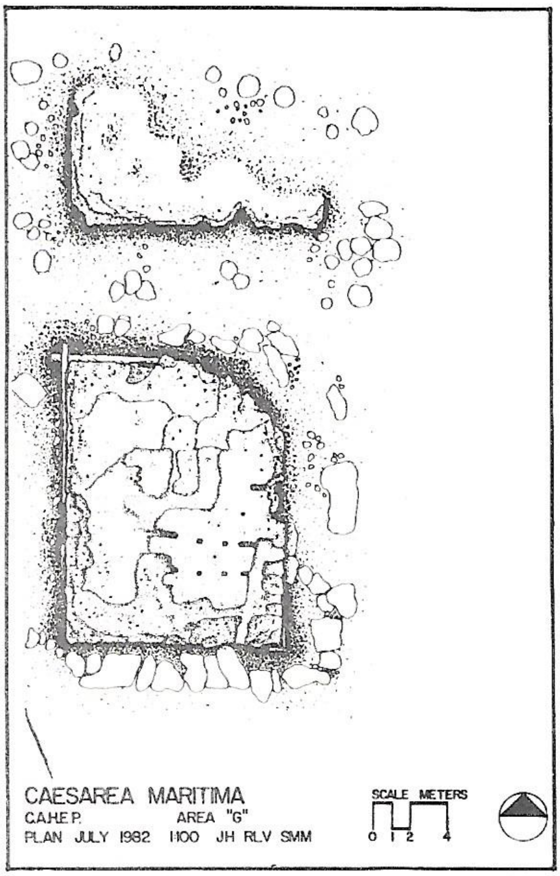
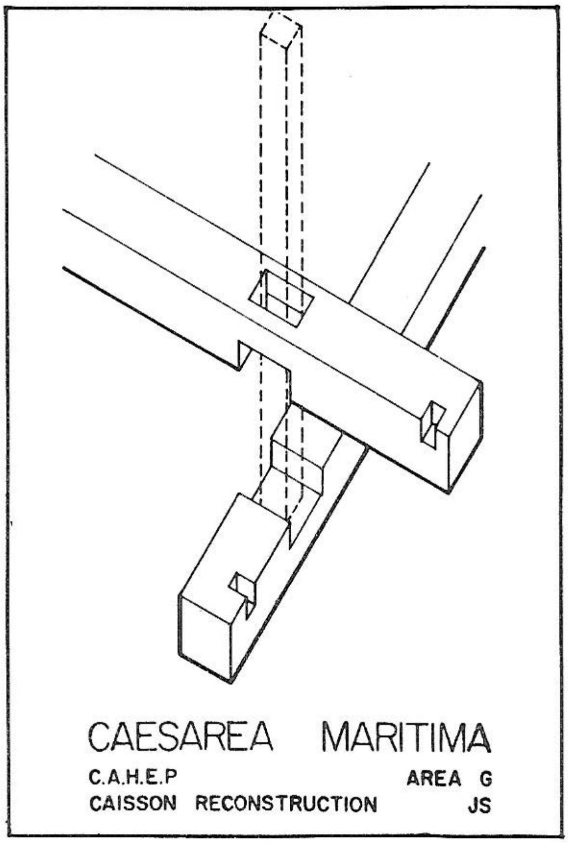
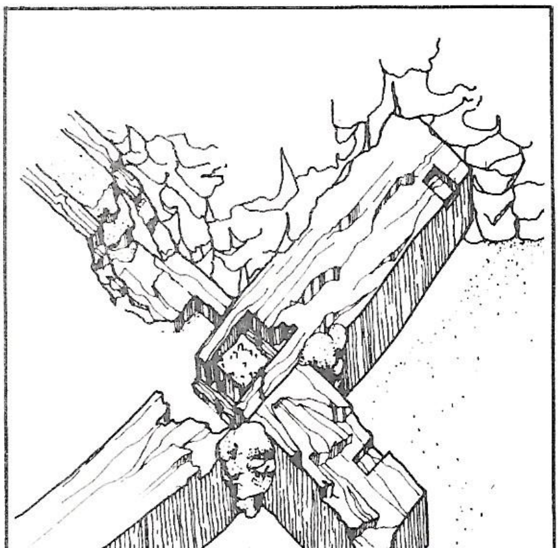


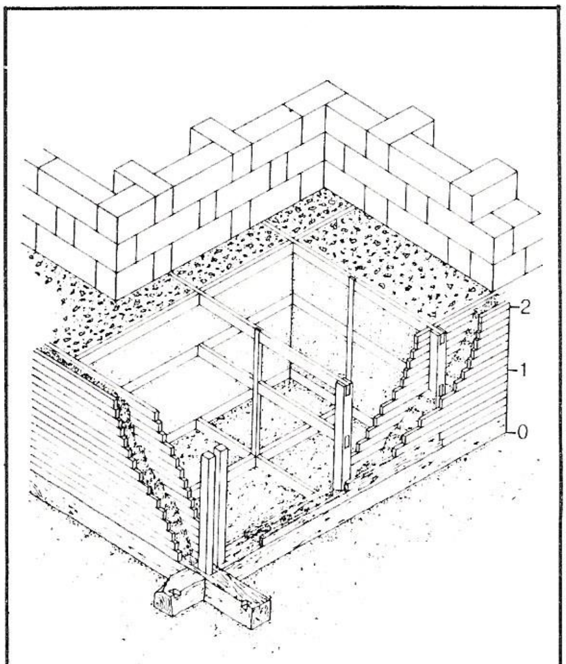
1. *Area G: plan of concrete blocks.*



2. *Area G: formwork.*
Actual state drawing of beam crossing.



3. *Area G: formwork.*
Exploded view of beam crossing.



4. *Area G: reconstruction of formwork.*

hollow walls were filled with concrete and mortar. A translucent, gypsum-like material has crystallized on some of the wooden surfaces through reaction with the sea water since the time of construction.

The hollow spaces formed by the lower beams, uprights, and double walls of planks were filled with a blue-green, sandy mortar containing large particles of tuff, pumice, and lime. Striations in the mortar show that the substance was poured in quickly in a semi-liquid state and puddled as it filled the cavities. The fabric of the block is composed of the same material, but with the addition of a high proportion of aggregate consisting of irregular chunks of *kurkar* and seaworn boulders of a harder limestone. A sample of concrete from the block itself was composed of SiO_2 (37.48%), CaO (6.3%), MgO (21.13%), Fe_2O_2 (2.07%), and Al_2O_3 (9.8%). A sample of mortar from within the walls of the form was composed of SiO_2 (13.98%), CaO (33.24%), MgO (9.3%), Fe_2O_2 (1.3%), and Al_2O_3 (4.4%). Chunks of the greenish, granular tuff (concreted volcanic ash), and fibrous pumice used in the mortar were recovered from the fill in the harbour channel. They currently are being subjected to analysis in Victoria in an attempt to determine their place of origin. The exact species of wood used in the formwork has been established only for some elements made of spruce (*Picea europea*), but it has been determined that the pine (*Pinus*), fir (*Abies*), and poplar (*Populus*), like the spruce, are of mid-European origin[2]. Since the range of these species is far to the north and west of the Levant, the timber must have been imported for use in the harbour. The volcanic material used in the mortar may also have been imported, most likely from central Italy or the Aegean. It would have been more difficult for Herod's engineers to transport construction materials in bulk by land from the nearby volcanic strata in the Galilee region than to ship them from seaside quarries in central Italy or the Aegean. Josephus himself reports (*Jewish Antiquities* 15.332): "But what was especially notable about this construction was that he got no material suitable for so great a work from the place itself but completed it with materials brought from outside at great expense".

The unique wooden formwork at Caesarea was protected from decay by a sloping rubble berm piled ca. 1.40 m up against each face of the form. To judge from modern harbour engineering practices, the berm was meant to prevent erosion of the sandy foundation of the finished block by wave action, and its consequent displacement and fracturing. Excavation may show that the body of the whole northern breakwater is composed of such large concrete blocks, originally overlaid by ashlar *kurkar* paving and a spray barrier. If this is the case, a berm would have been necessary only around the periphery of the structure.

A second concrete block was discovered projecting from the sand 6.60 m north of the first block in Area G, separate from the rest of the breakwater mass (Figure 1). Excavation revealed that the second block was built of the same materials and in the same manner as the first one investigated, that the blocks had approximately the same orientation, and that their western faces were aligned. At its west corner, where it is best preserved, the irregular upper surface of the block stands at 5.77 m below sea level, and the smooth, flat lower surface at 7.7 m below sea level. Although traces of a rubble berm survive around the block, only a few pieces of wooden formwork have been preserved, and the concrete mass itself was fractured and incomplete. The lower edge of the southern face of the block, which rests on a stratum of sterile gray sand, slopes upward slightly from west to east, from 7.70 m to ca. 7.20 m below sea level, and is interrupted by several major fissures 6.87 m and 8.0 m from its southwestern corner. The block tapers to a thickness of only 0.17 m before ending abruptly in a small heap of rubble 12.0 m east of the southwestern corner, possibly at or near the original southeastern corner. The western face of the block was excavated for 6.0 m to the north, uncovering several holes left by horizontal tie beams, but no corner appeared here, and a probe 2.0 m deep on the line of the western face and 12.0 m north of the southwestern corner did not encounter any structural remains. It seems likely that the block, whose dimensions will be determined by further excavation, was tipped and fractured by the fault slippage which seems to have destroyed much of the outer harbour sometime during the Empire. This block probably served as the foundation for the single tower supporting statuary mentioned by Josephus as standing to the port side of a ship entering the harbour (*Jewish Antiquities* 15.338; *Jewish Wars* 1.413). The two towers he mentions on the starboard side were examined in 1981.

LITERARY EVIDENCE FOR ROMAN HAROUR TECHNOLOGY

It is unfortunate that Josephus' otherwise detailed description of Sebastos (*JA* 15.331-339; *JW* 1.408-414) only hints at the construction procedures used by Herod's engineers.

> Having calculated the relative size of the harbour (*limēn*) as we have stated, he let down stone blocks (*lithous*) into the sea to a depth of 20 fathoms (ca. 37 m). Most of them were 50 feet long, 9 high, and 10 wide (15.25 m x 2.7 m x 3.05 m), some even larger. When the submarine foundation (*to hyphalon*) was finished, he then laid out the mole (*teichos*) above sea level, 200 feet across (61.0 m). Of this, a 100 foot portion was built out to break the forces of the waves, and consequently was called the breakwater (*prokumia*). The rest supported the stone wall (*teichos*) that encircled the harbour. At intervals along it were great towers (*pyrgoi*), the tallest and most magnificent of which was named Drusion, after the stepson of Caesar.
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> There were numerous vaulted chambers (*psalides*) for the reception (*katagogē*) of those entering the harbour, and the whole curving structure in front of them was a wide promenade for those who disembarked. The entrance channel faced north, for in this region the north wind always brings the clearest skies. At the harbour entrance were colossal statues, three on either side, set up on columns. A massively-built tower (*pyrgos*) supported the columns on the port side of boats entering harbour, those on the starboard side, two upright blocks of stone yoked together, higher than the tower on the other side.
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> (*JW* I.411-413)
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> To correct this drawback in the topography, he laid out a circular harbour (*limēn*) on a scale sufficient to allow large fleets to lie at anchor close to shore, and let down enormous blocks or stone (*lithous*) to a depth of 20 fathoms (ca. 37 m). Most were 50 feet long, not less than 18 feet wide and 9 feet high (15.25 m x 5.49 m x 2.7 m). The structure which he threw up as a barrier against the sea was 200 feet (wide). Half of this opposed the breaking waves, warding off the surge breaking there on all sides. Consequently it was called a breakwater (*prokumia*). The rest comprised a stone wall (*teichos*) set at intervals with towers (*pyrgoi*), the tallest of which, quite a beautiful thing, was called Drusus, taking its name from Drusus, the stepson of Caesar who died young. A series of vaulted chambers (*psalides*) was built into it for the reception (*katagōgai*) of sailors, and in front of them, a wide, curving quay (*apobasis*)encircled the whole harbour, very pleasant for those who wished to stroll around. The entrance (*eisplous*) or mouth (*stoma*) was built towards the north, for this wind brings the clearest skies. The foundation (*basis*) of the whole encircling wall on the port side of those sailing into the harbour was a tower (*pyrgos*) built up on a broad base to withstand the water firmly, while on the starboard side were two great stone blocks (*lithous*), taller than the tower on the opposite side, upright and yoked together.
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> (*JA* XV.334-338)

The materials imported at such great expense from far-off sources are described only as *lithoi* ("stones") of various colossal dimensions "let down" (*kathienai*) into the sea to form a submarine foundation (*to hyphalon* is the only substantive used) for impressive "towers" or "superstructures" (*pyrgoi*). The mention of a depth of 20 fathoms (ca. 37 m) in an area presently no deeper than 15 m clearly is an error, but the specification of "stones" as large as 9 ft. x 18 ft. x 50 ft. (ca. 2.7 m x 5.49 m x 15.25 m) does not exceed the dimensions of the concrete blocks on the north breakwater. Josephus does not differentiate between stone and concrete blocks in the harbour, possibly because the concrete was all hidden below water level or clad in the white marble (*leukē petra, leukos lithos*) he mentions as a feature of the harbour area (*JA* 15.331; *JW* 1.408, 414). Josephus or his source may not have been aware of the variety of materials employed by Herod or may not even have fully understood the distinction between concrete and natural stone.

Although no ancient handbooks of harbour construction have survived, there is an account of breakwater construction in Vitruvius's *De architectura* (5.12.2-6) which complements Josephus's description of Sebastos. This passage, probably published around 25 B.C., just before construction began at Caesarea (ca. 22 B.C.), describes procedures and materials very similar to those for which we found evidence in 1982. A careful consideration of this contemporary technical document is of immense assistance in reconstructing the procedures used by Herod's engineers.

(2) However, if we have no natural harbour situation suitable for protecting ships from storms, we must proceed as follows. If there is an anchorage on one side and no river mouth interferes, then a mole composed of concrete structures (*structurae*) or rubble mounds (*aggeres*) is to be built on either side and the harbour enclosure constructed in this manner. Those concrete structures which are to be in the water must be made in the following fashion. Earth (*pulvis*) is to be brought from that region which runs from Cumae to the promontory of Minerva and mixed in the mortar used in these structures, in the proportions of two parts earth to one of lime. (3) Next, in the designated spot, formwork (*arcae*) enclosed by stout posts and tie beams (*stipitibus robusteis et catenis inclusae*; literally "made of stout posts and braced around the circumference with chains") 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 crossbeams (? *ex transtilis*). The building is to be carried on there with a mixture of aggregate and mortar (*caementis ex mortario materia mixta*), as described above, until the space left for the structure within the form has been filled. The places which we have described above, then, have this natural advantage.

But if on account of waves or the force of the open sea the anchoring supports (*destinae*) cannot hold down the forms, then a platform (*pulvinus*) is to be built out as firmly as possible from the shore itself or from the foundations of the mole (*crepido*). This platform is to be built out with a level upper surface over less than half its area. The section toward the shore is to have a sloping side. (4) Next retaining walls (*margines*) one and one half feet wide are to be built towards the sea and on either side of the platform equal in height to the level surface described above. Then the sloping section is to be filled in with sand and brought up to the level of the retaining walls and platform surface. Next a pier (*pila*) of the appointed size is to be built there, on this levelled surface, and when it has been poured is left at least two months to dry. Then the retaining wall which holds in the sand is cut away, and in this manner erosion of the sand by the waves causes the pier to fall into the sea. By this procedure, repeated as often as necessary, the breakwater (*progressus*) can be carried seaward.

(5) However, in locations where the earth does not occur naturally, one must use the following procedure. Let double-walled formwork (i.e. cofferdams; *arcae duplices*) be set up in the designated spot, held together by close set planks and tie beams (*relatis tabulis et catenis conligatae*), and between the anchoring supports (*destinae*) have clay packed down in baskets made of swamp reeds. When it has been well tamped down in this manner, and is as compact as possible, then have the area bounded by the cofferdam (*saeptio*) emptied and dried out by means of water-screw installations and water-wheels with compartmented rims and bodies. The foundations (*fundamenta*) are to be dug there, within the cofferdam. If the foundations are to be on a rocky, solid bottom, the area to be excavated and drained is to be larger than the wall (*murus*) which will stand above, and then filled in with a concrete of aggregate, lime and sand (*structura ex caementis calce et harena*). (6) But if the bottom is soft, the foundations are to be covered with charred alder or olive wood pilings and filled in with charcoal, as described for the foundations of threaters and city walls. Then the wall is to be raised of squared stone (*sa*[illegible]*m*) with joints as long as possible, so that the middle stones (*medii lapides*) may be well tied together by the joints. The space inside the wall is to be filled with rubble packing or concrete. Thus it may be possible to build a tower upon it.

Much of Vitruvius's technical information on various topics was based on Hellenistic Greek handbooks, and he certainly must have been familiar with Philo of Byzantium's *Limēnopoiika* (*Harbour Construction*), Book 3 of the *Mēchanikē Syntaxis*, published in the late third century B.C. He cites Philo as an authority (7 preface, 14) and had read the works of his teacher Ctesibius carefully (see 1.1.7; 7 preface, 14; 9.8.2-6; 10.7.1-4). Nevertheless, only the first and last paragraphs of Vitruvius's section on harbours (5.12.1 and 7; not quoted here) can have come from a Hellenistic handbook. They deal with natural harbour situations, their fortification, and shipyard design, while 5.12.2-6 describe typically Roman procedures of construction with concrete[3].

ARCHAEOLOGICAL EVIDENCE FOR ROMAN HARBOUR TECHNOLOGY

Helmut Schläger has already discussed Vitruvius 5.12.2-6 in the context of the remains of a concrete breakwater at Side[4]. He points out quite correctly that three procedures are described: 1) the construction of submarine piers with hydraulic concrete poured in a single-walled form (5.12.2-3); 2) the prefabrication of blocks of hydraulic (?) concrete above water (5.12.3-4); and 3) the construction of submarine piers of ordinary concrete within cofferdams that are pumped dry. The secret of Roman hydraulic concrete is the addition of pozzolana, a volcanic earth first identified around Puteoli (hence *pulvis puteolanus*), probably in the course of the third century B.C. By the late second century it had been used to construct piers and breakwaters at Puteoli

Portus Julius

and Cosa, but the first application on a truly imperial scale was at Caesarea[5]. Vitruvius describes this material in an earlier section of his work (2.6.1-6):

> There is also a type of earth which by its nature produces marvellous results. It occurs in the region around Baiae and the area of the municipalities around Mt. Vesuvius. When this has been mixed with lime and aggregate it furnishes strength to various types of buildings, and even when piers are built of it in the sea, they harden underwater. (2.6.1)

The procedures outlined by Vitruvius for the use of concrete formwork in harbour construction are logical, although his prose is not always clear. The first type of form is prefabricated of uprights held together by *catenae*, then floated out to position and driven into the bottom. In common with Schläger, I interpret the *catenae*, literally "chains", as tie beams which cross the formwork to provide necessary rigidity and resist the outward push of the mortar. The marks of such crossbeams are visible in the concrete blocks at Cosa, Caesarea, Side, Leptis Magna, and probably most other Roman harbours[6]. A circumferential brace of chains would have been much more difficult to arrange and would not have afforded protection against any propensity to buckle inward. The Caesarea formwork, in any case, does not correspond to Vitruvius's first category, since it has double walls. It also differs from the second Vitruvian procedure, where blocks are poured on a platform of sand, cured, and allowed to wash into the sea. In this situation the formwork almost surely would have been salvaged, and blocks the size of those in Area G probably would have fractured or come to rest in a tipped position.

The formwork at Caesarea corresponds most closely with the third type of Vitruvian construction, in which a double-walled caisson is set up on the spot and pumped out to provide a dry situation for the use of a non-hydraulic concrete mixture. In this section (5.12.5) Vitruvius seems to be describing large uprights driven into the sea bottom, anchoring and providing a frame for two walls of planks and tie beams (*catenae* again). The uprights must be on the inside of the double wall, since he specifies that the baskets of clay are to be packed in between them. The enclosed area then is pumped out and cleared for construction. The Caesarea caisson has rigid uprights which held double walls of planks, and horizontal tie beams, but its relation to the sea bottom is very different. The uprights (*destinae*) are not pounded into the bottom, as both the term itself and Vitruvius's description of the first type of caisson implies, but are instead mortised into the upper surface of heavy sleeper beams. Like both Vitruvian designs, the Caesarea formwork seems to lack a floor, and the concrete was poured on a prepared sea bottom surface. But unlike the Vitruvian caisson, the double-walled Caesarea form could not have been pumped dry: in the absence of a floor or a barrier of upright pilings, sea water would have filtered through the sand under the sleeper beams and boiled up through the enclosed area as fast as it was removed. Another anomaly is the use at Caesarea of the double-walled forms Vitruvius designated as appropriate to concrete lacking pozzolana earth for concrete including a rich admixture of volcanic earth and aggregate.

If the mortar-packed double wall of the Caesarea formwork was not meant to make it waterproof, what purpose did it serve? I believe that at Caesarea we see a conflation of the two types of formwork described by Vitruvius, in a special adaptation for a third type of situation. The engineer knew from the start that he was working with a 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 (or both) made it difficult to fix prefabricated forms to the bottom 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 leveled, 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 in position on the prepared surface. While the inundated form was being filled with the 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 at Caesarea. 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 formwork, 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 fit 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. As the weather and the preparation of materials for the concrete allowed, forms could have been towed to various parts of the harbour and put in place by a few trained workers. Even Vitruvius's single walled, prefabricated forms (15.12.2-3) had to be pounded into the bottom, undoubtedly a tricky and time-consuming business. As long as the four massive sleeper beams of the Caesarea formwork had settled firmly on a level surface of sand, little concrete would have leaked out as the form was filled. This procedure conforms more closely with Josephus's assertion that Herod "let down enormous blocks of stone" into the sea than the alternative, construction of caissons on the spot by pile driving or submarine assembly.

In the next two seasons part of the C.A.H.E.P. excavation programme will focus on an examination of the construction techniques and materials used at Sebastos. Both breakwaters are made up largely of huge blocks, most of which still preserve marks of their formwork. Further evidence for the procedures used by Herod's engineers may yet appear. In any case, it is already evident that Herod had at his disposal harbour engineers skilled in the techniques of concrete construction and sophisticated in their choice of materials. This technology had developed in central Italy over the preceding century, and Herod almost certainly obtained his engineers from that region.

NOTES

1. I am grateful to Dr. Avner Raban, overall director of the C.A.H.E.P. project, for the opportunity to present the results of my research here. I am now preparing a more extensive study which will treat the technical and historical questions concerning the formwork in more detail. The translation of Vitruvius given below is my own, based on the Latin text in F. Grange, *Vitruvius, De Architectura* (Cambridge, 1931). The translation of Josephus is adapted from H. St. J. Thackery, *Josephus, Jewish Antiquities* (Cambridge, 1930), and *The Jewish Wars* (Cambridge, 1927).
2. The mortar and wood analysis was carried out by Professor Lupo of Tel Aviv University.
3. The modern bibliography on ancient harbours is now nicely summarized by D.J. Blackman, *International Journal of Nautical Archaeology* 11 (1983) 79-104, 185-211. For Philo's handbook, see K. Lehmann-Hartleben, "Limēn," in *RE* XIII.I (1926) 548; K. Orinsky, "Philon (48)", *RE* XX.1 (1941) 53.
4. H. Schläger, "Die Texte Vitruvs im Lichte der Untersuchungen am Hafen von Side," *Bonner Jahrbücher* 171 (1971) 150-61.
5. The Cosa piers, of the late second or early first century B.C., will be published by Elaine Gazda in A.M. McCann (ed.), *The Roman Port and Fishery of Cosa* (Princeton University Press). For Puteoli, see Blackman, *op. cit.*, pp. 195, 197, note 85-86.
6. Blackmann, *op. cit.*, p. 197, note 85.