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Ancient Mediterranean harbours: a heritage to preserve

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ABSTRACT

Management and protection in coastal areas mainly addresses the natural environment and rarely addresses cultural and technical resources. This paper represents a plea for diverting more attention to some valuable historical features which exist, abandoned, along the Mediterranean shores.

Along these shores a UN inventory identified some 1255 submerged archaeological coastal sites, many of which showed no signs of any protection from the attack of the sea and of growing coastal tourism. Many of them are remnants of harbour structures which are over 2000 years old.

A condensed overview is given of the historical evolution of ancient harbour engineering, particularly related to the Roman age, describing the most interesting and innovative technological aspects, which could still add a valuable insight to the design of modern coastal structures. This knowledge was initially derived from literary and pictorial evidence and is now greatly expanded by the recent discoveries of underwater archaeology and by the developments of remote sensing technology.

Co-operation between coastal engineers and archaeologists is encouraged, both for the preliminary surveys before the execution of new coastal works and for the interpretation, defence and revaluation of discovered maritime remains.

Finally, recommendations for the restoration and creation of major ancient port sites as museums, possibly within innovative 'coastal submarine archaeological parks', are given. Copyright © 1996 Published by Elsevier Science Ltd.

1. INTRODUCTION

The motivation for writing this paper arises not only from my personal curiosity of the historical background of my own technical discipline (harbour engineering), but also from the disappointing observation that ancient harbours and coastal works are so much neglected, especially in Italy and other Mediterranean countries which almost uniquely retain this valuable heritage from the 'classic world' and could take advantage of it for fruitful coastal management.

Within the United Nation's (UN) Mediterranean Action Plan some 1255 semi-submerged archaeological sites have been recently surveyed along the coasts of the world's largest closed continental sea. Many of them are remains of quay walls, breakwaters and other harbour structures which, if not covered by new constructions or reused as building stone etc., usually lie near the shore without any systematic recording, any protection and any explicative sign. Fencing is rarely provided, maybe only if the ruins of a coastal settlement are also present.

The ancient works are progressively deteriorated by the aggressive and more polluted marine environment, and especially by the growing pressure of coastal tourist crowds, fishermen and 'predator scuba-divers'. However, many old intact structures still show a surprisingly high durability, when compared with similar modern works nearby! The study of these monuments can give coastal engineers and managers a useful humanistic background and even some good hints for new projects.

Research on ancient harbours has been carried out by geographers, historians and then archaeologists, usually without any consultation with expert port engineers and without following actions to preserve the discovered remains from further deterioration. Their research approach is mainly aimed at the historical investigation, i.e. itemising and dating the ruins, identifying the geographical location and reconstructing the old topographical situation related to the predicted shoreline position.

In fact, the analysis of harbour remains is also helpful for assessing long-term sea level changes. There is some evidence that the sea level has risen by over 1.5 m in the last 2500 years and most remnants are in fact underwater. However, coastal tectonics in the geologically unstable Mediterranean area and erosion/deposition effects have locally altered the coastline position, so that ancient port sites can now be found even totally landlocked (Ostia) or deeply submerged (Miseno).

The basic source of information has been the classic literature and paintings (mosaics, coins, etc.). Further information was gained from

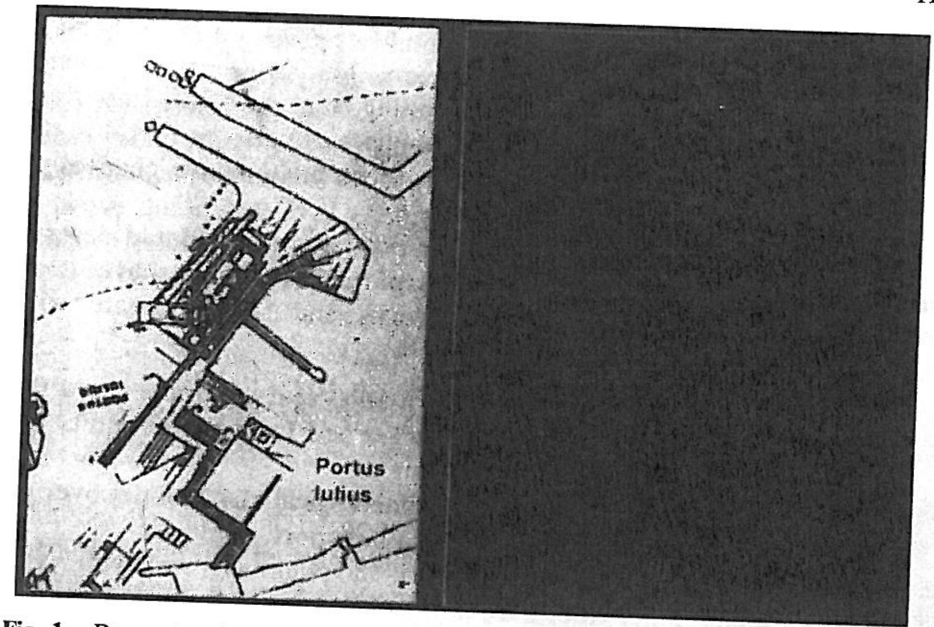

Fig. 1. Reconstruction of the Roman port of *Portus Iulius* from aerophotography of submerged remains.

the first systematic excavations of submerged port structures, carried out by G. Jondet at Alexandria in 1912. In latter years, a new powerful surveying technique has been used, namely aerial photography, even infra-red (Fig. 1). Low-cost aerial surveys can now be simply performed using paragliders or ultralight planes on clear calm days. Moreover, on-site resistivity analysis with mega-ohm-meters is useful to detect underground silted remains. However, the developments of the surveying techniques (e.g. tele-survey, underwater inspection) still need to be fully exploited to make new important discoveries.

The field of 'harbour archaeology' also needs to be developed and organized, as demonstrated by the scattered bibliography. Presently it represents a secondary study area within 'underwater archaeology', which is defined as a 'nascent discipline', probably due to the high costs and technology involved. In fact, it may be subdivided into three study areas: (1) submerged dry sites after climatic changes (e.g. cities submerged by earthquakes or bradyseism); (2) maritime structures (e.g. harbours and fishing ponds) once already in the water; and (c) shipwrecks.

The attention of submarine archaeology is especially concentrated on shipwrecks and their often precious cargo. It is estimated that some 30 000 shipwrecks lie on the Mediterranean seabed (with a uniform rate of 10 sinks year^{-1}, even today!). The *Mare Nostrum* ('Our Sea') is in fact an immense submarine museum, holding signs of several important civilizations, which are still waiting to be revealed. Important artifacts from sunken ships or port warehouses can also be found in the excavations of ancient harbours, where there are obvious chances to find shipwrecks.

Therefore, the numerous remnants of port structures should deserve more attention. Coastal engineers in particular should have good reasons to know about these old works and to co-operate with archaeologists—reasons such as:

- the fundamental background of a 3000-year experience and the useful lessons which can still be learned from the antiquity for present port design and management;
- a better knowledge of the 'archaeological risk' of discovering ruins during the construction of a new port;
- the potential technical support in planning, surveying and defending underwater excavations;
- a useful assistance for interpretation of the discovered ruins and identification of the design solutions and construction methods chosen by their ancient predecessors;
- the specific role for protection of the degraded structures and their eroding shores from sea attack.

For example, a large project of beach nourishment protected by groins and submerged barriers is under way at the Venetian Lidos, which will also defend the 250-year old monumental sea walls called 'murazzi'.[1] In fact, it may be envisaged that more and more efforts will be addressed for the conservation and rehabilitation of old coastal structures rather than for the construction of new ones.

In the development of a new coastal project, the archaeologist could help the engineer in planning and analysing the careful preliminary field surveys which should always be executed to prevent the risk of discovering ruins later during construction. The co-ordination of different specialists, such as marine geologists, biologists, archaeologists, geographers, architects and engineers, would be very useful to interpret, defend and develop the discovered remains and to enrich the skills of each expert learning the different approaches and views of the others.

This paper aims to underline the importance of the cultural–technical heritage of ancient harbours and the need to protect them and sometimes even make them accessible to the public within attractive maritime archaeological parks.

In order to highlight the interest of these structures, an overview of the historical evolution and technological innovations of ancient harbour engineering follows, with special reference to port planning and breakwater design. The review of the early 'gentle' port architecture, from the simple natural harbours to the larger artificial ones, may also improve the hydraulic efficiency and the environmental harmony of the modern harbour designs.

2. TECHNOLOGICAL EVOLUTION AND APPARENT FEATURES OF ANCIENT MEDITERRANEAN HARBOURS

The development of harbour engineering in ancient classic times is related to the different dominations and cultures which followed in the Mediterranean basin: Egyptians, Minoans, Phoenicians, Carthaginians, Greeks, Etruscans and Romans. In fact, after the Roman age almost no technical evolution took place until Napoleonic times. Brief resurgences in harbour technology only occurred during the Crusader times, when the Genoese and Venetians constructed some remarkable ports such as that at Heraklion, Crete, or in 1500 AD when Leonardo da Vinci made advanced hydraulic designs of a few harbours in Italy (e.g. Cesenatico). In a simple historical classification port designs might be defined as 'ancient-naturalistic' (2000 BC–500 AD), 'medieval-architectural' (500–1800 AD) and 'modern-technological' (present day).

Unfortunately, very few written reports on the ancient methods for harbour construction are available. The only technical handbook is the one of Vitruvius[2] (30 BC), which is mainly related to the Roman engineering experience. Further useful descriptions in the classic literature are given by Herodotus, Josephus, Suetonius, Pliny, Appian and others.

A general map of the main ancient harbour sites in the Mediterranean Sea, mostly with apparent remnants, is proposed in Fig. 2. This location map would become more complete after a more systematic inventory, hopefully leading to the publication of a specific atlas.

A first comprehensive review on pre-Roman harbours, also called proto-harbours, was given by Lehmann-Hartleben[3] (1923), though largely compiled based on literary evidence. An updated review including an extensive bibliography is given by Blackman[4] (1982). Reference is also made to De la Pena *et al.*[5] (1994).

Proto-harbours were mainly used for refuge, unloading of goods and

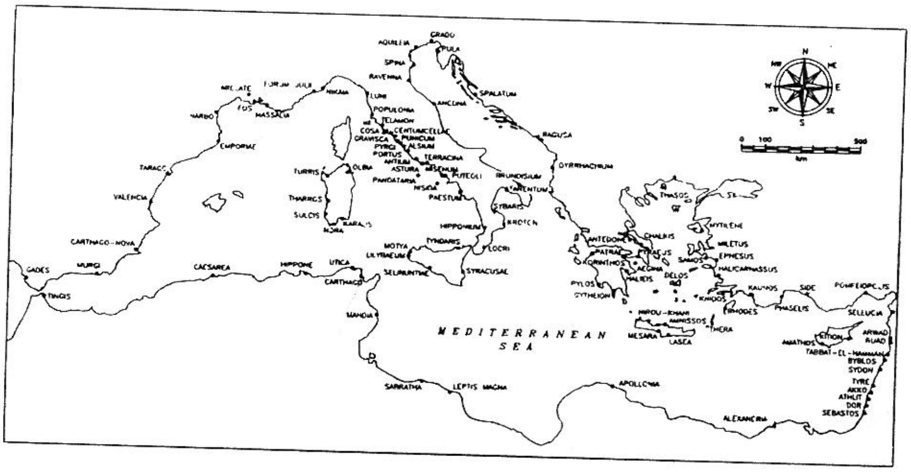

Fig. 2. Location map of main ancient Mediterranean harbours, generally labelled with their original names (mostly with visible remains).

freshwater supply for the shallow-draught wooden vessels cruising along the 'inside routes' of the Mediterranean Sea during the 'good' season. Early harbours were 'natural', typically located in favourable geographical conditions, such as sheltered bays near capes or peninsulas, at river mouths, inside lagoons or deep coves, where short breakwaters were often sufficient to supplement the natural protection. Harbours were generally close to high coastal mountains easily visible in the distance from the sea and they were possibly spaced at 40–50 km intervals (20–30 nautical miles) to allow safe day-by-day transfer to the vessels sailing coastwise at a speed of 3–5 knots. Simple anchorages were also frequent for temporary stopovers or for mooring smaller boats (which implies that many more remains could still be discovered in the Mediterranean Sea).

Ports were necessarily built on the numerous islands and along the sea coast to serve a large hinterland and they were often closely linked with city sites. In fact, the harbour basin was often enclosed within fortifications, even closable from the sea, and separated from the city for reasons of security (military harbours) or for the control of goods and passengers.

First the **Egyptians** (3000–30 BC) mainly developed river ports along the Nile, such as Memphis and Thebes. The typical landing facilities included simple ramps or docks on wooden or stone piles. The only vestiges of a sea port (1900 BC) were discovered on the Red Sea coast, at the mouth of Wadi Gasus. However, a great achievement of Egyptian hydraulic engineering was the construction of a navigation channel between the Red Sea and the Nile delta—it had a width of 45 m and a depth of 5 m, with stepped rock slopes.

The **Minoans** were actually the first maritime power until their decline after the eruption of Santorini around 1500 BC. Today the best preserved Minoan harbours are the first port of Alexandria, the south port of Tyre and the port of Nirou Khani (Crete)—the former was built to the west of Pharos island around 1800 BC and it may be considered as the oldest man-made sea port. The main basin was 2340 m long, 300 m wide and 6–10 m deep to accomodate 400 ships of 35 m length; the numerous breakwaters and docks (14 m wide) were made with rock blocks (5 m long). The harbour of Nirou Khani (1500 BC) still shows two rectangular slips (43 × 6 m) cut into the dune rock and divided by a 0.8 m wide masonry rock wall.[6]

Similar and more sophisticated designs can be observed in the **Phoenician** harbours (7th–4th century BC) mainly located along the present coasts of Lebanon and Israel, often behind fragments of offshore reefs. The most complete and preserved remains are those of the two ports on the island of Tyre connected by a navigation channel, the early knowledge of which was enhanced by the pioneer exploration of Father Poidebard in 1939. Both vertical and rubble mound breakwaters were built with typical L-plan shaped roundheads and armoured with 15 tonne rock blocks (Fig. 3(a)).

The design of the early harbours was mainly dictated by nautical and military constraints, such as providing safe access even in hard weather through narrow entrances, which could be easily controlled and even closed with chains. Two or more entrances were sometimes provided to ease navigation under variable winds, to separate different port routes and traffic (commercial, military and fishery) and to favour water flow in the relatively tideless basins in order to keep silt in suspension and avoid harbour siltation.

Prevention of siltation was in fact a fundamental issue, since mechanical dredging was not feasible. Not only multiple port entrances were provided, but also underwater channels and tunnels through the moles—examples are found in Syracuse, Halicarnassus (Bodrum) and Mytilene. River flow, sometimes diverted in settling tanks, was also used to prevent siltation (Massalia–Marseille). The flushing channels, often controlled by sluice gates, would be open to the sea above MSL at the side where the seabed was rocky and shallow enough for the waves to break and release most suspended sediment before reaching the breakwater. Ramps were even constructed to allow the wave crests to sweep over and collect sand-free water in a tank at a higher elevation for periodical release into the harbour, as at Dor and Sidon (Fig.

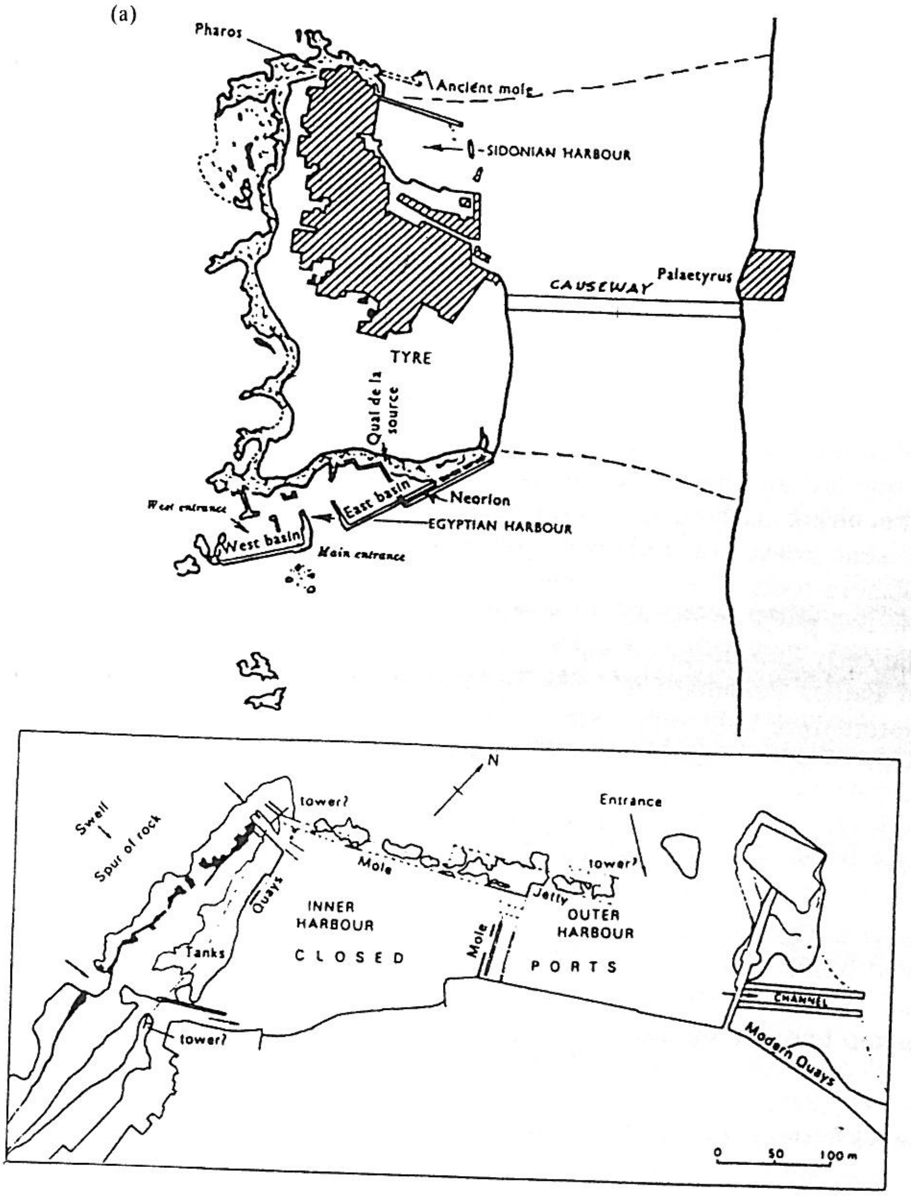

Fig. 3. Reconstruction of the Phoecian 'multiple' harbours of (a) Tyre and (b) Sidon (showing two flushing tanks on the west side) (after Poidebard and Lauffray, 1951[7]).

3(b)).[7] This 'wave pump' system is now proposed for flushing Mediterranean marinas, with the novel scope to improve water quality, and openings through the breakwaters (using pumps in addition) are already being created for this reason.[8]

In order to reduce large wave overtopping at the vertical rocky cliffs and breakwaters, the Phoenicians excavated hollows and trenches in the rock. These 'wave catchers' would channel and drain the water off back to the sea (as at Dor and Sidon) and were also used as an immediate source of building stone. This concept was later resumed by the Romans for the natural 'carved breakwater' of Pandataria (Ventotene) and a modern artificial version was recently patented under the name of 'Overspill Basin' breakwater and used at Fontviellie, Monaco.[8]

In fact, another characteristic of the earliest harbour works cut out of rock reefs or islands (Arwad, Byblos, Sidon, Tyre) was that the rock mass was flattened on its sheltered landward side to make a quay, leaving a protective rock wave-wall on the sea side.[9]

The Phoenicians achieved a high level of technology for submarine construction, as shown by the regular placement of small stones to build smooth walls, which are still in place today. An innovative technical feature was the use of ashlar header sea walls—the slim blocks were laid in tight courses with their long joints in a very close fit to give maximum drag and thus solving the problem of the vacuum effect of the retreating water from the vertical wall.[10] The Phoenician engineers were also able to prevent the undertrenching of walls laid on sand by paving it with a layer of large pebbles (e.g. Akko, Athlit).

The western Phoenician colonies later assumed naval prominence in the Mediterranean under the guide of Carthage (750–146 BC). The typical novel feature of **Carthaginian** port layouts was the so-called *cothon*, an internal artificial basin, excavated behind the coast and joined by one or more channels to the sea. The cothon could be used for the home fleet (leaving the outer harbour for foreign ships), or for the military fleet, or just for ship repair works.

Beautiful examples are still visible at Motya (Sicily) and Carthage (Tunisia). The famous harbour of Carthage, recently studied under a United Nations Educational, Scientific and Cultural Organization's (UNESCO) safeguard program, shows two large basins excavated inland, a rectangular one probably devoted to commercial traffic and an inner ring-shaped refuge basin for the navy, invisible behind a long high wall. Right in the centre of the inner basin, the 125 m wide circular Admiralty island was used as a shipyard for up to 200 warships and dominated by a control tower (Figs 4 and 5). It seems that radial wooden finger piers were also provided along the circular perimeter for an easier sideways berthing, as in modern marinas. Columns were also used as bollards instead of mooring rings. At Motya, the cothon might even have been closable and drainable to form a dry dock. Other Punic harbour ruins are visible at Apollonia, Utica, Cartago-Nova, Nora, Tharros and Lylibeum.

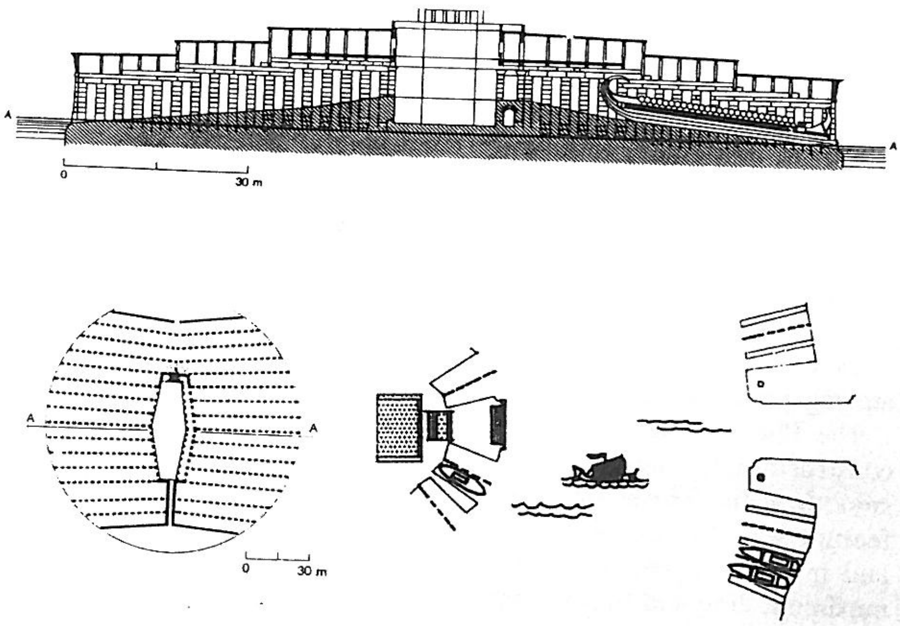

Fig. 4. Ancient harbour of Carthage: reconstruction of the slipways on Admiralty island at the centre of the circular inland basin—cross-section and plan (after De la Pena *et al.*, 1994[5]).

Fig. 5. Aerial view of the two inland harbour basins of Carthage.

The **Greeks** (6th–3rd century BC) also took advantage of narrow peninsulas for building safe 'multiple harbours' (Cnidos had four, Phaselis three). The breakwaters were mostly built with cut rocks regularly placed without mortar on rubble mounds. Herodotus reports of a breakwater at Samos built around 530 BC in water depths up to 35 m! Large breakwater remains are well visible at Cnidos (Turkey).

The large Athenian harbour of Piraeus is famous for its 372 covered slipways ('shipsheds'). The best preserved remains are the rows of columns forming the partitions between the slips, which are 37 m long and 6 m wide with a slope of 1:10.

Alexandria was also a well known monumental Greek harbour, actually built by Alexander the Great in later Ellenistic times (3rd–1st century BC) behind the coastal island of Pharos. A 1.5 km long breakwater, with two openings, joined the island to the mainland dividing two basins with an area of 368 hectares and 15 km of quay front. The port also became famous for its impressive 130 m high lighthouse tower, built on the eastern end of Pharos to guide ships from a distance of about 50 km towards the port in a sea without landmarks. The multi-storey building, one of the Wonders of the Ancient World (Fig. 6), eventually collapsed due to earthquakes in the Middle Ages, though it was made with solid blocks cemented with melted lead and lined with white stones, which are just now (1995) finally being recovered underwater by a French expedition.

Another peculiar feature of the Graeco/Ellenistic harbours was the use of colossal statues to mark the entrance and a chain gate fixed to the breakwater roundheads in order to control ship entry. The most famous application reported by historians was the 30 m high Colossus of Rhodes, standing on top of the breakwater heads (but not yet discovered). It is interesting to observe that three ancient windmill towers are still surviving upon Rhodes breakwater, impressive precursors of today's wind turbines for energy production[11] (Fig. 7). Sculptures of lions guarding the harbour are still visible in Miletus (Anatolia).

The Greek ports were still part of the town (even closed within the walls like Delos), whereas in the Roman Empire they became an independent infrastructure, with their own buildings and warehouses (*horrea*). Other Greek harbours with existing remains, mainly in Greece, Turkey and southern Italy, are Delos, Nafplion, Thasos, Halieis, Korinthos, Ephesos, Miletus, Cnidos, Assos, Myndos, Side, Phaselis, Kaunos, Kroton and Tarentum. A more detailed description of the history and remnants of ancient harbours along the Turkish coast can be found in Kurtulus and Arisoy.[12]

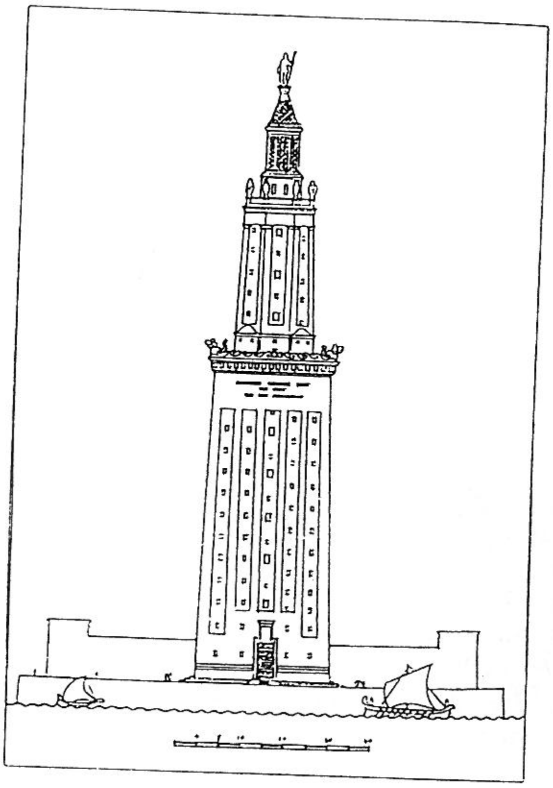

Fig. 6. The famous lighthouse of Alexandria port built by Sostrato of Cnidos, according to old paintings.

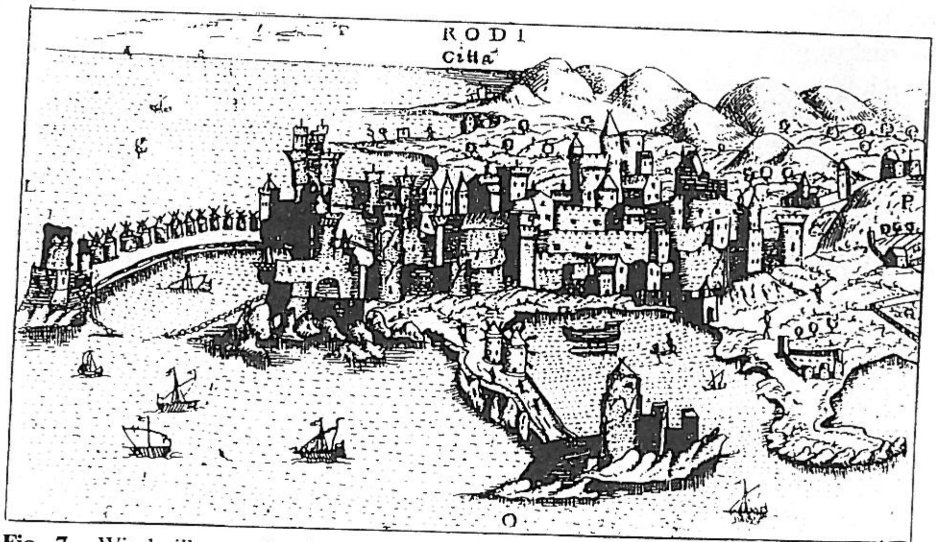

Fig. 7. Windmills on the breakwater at Rhodes; the port entrance chain is also depicted (an old print, probably 17th century) (after Gaudiosi and Cesari, 1993[11]).

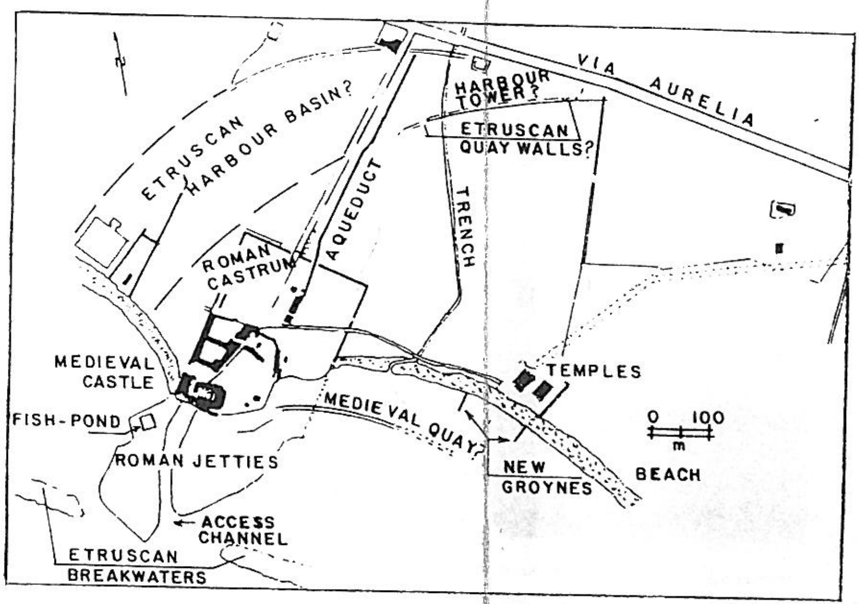

Fig. 8. Ancient harbour of Pyrgi (S. Severa): reconstruction of the Etruscan and Roman port layout (after Protani and Frau, 1989[13]).

At the same time, the western central part of the Italian peninsula was ruled by the **Etruscans**, who also constructed new harbours (often in coastal lagoons), later used and upgraded by the Romans. Several marks exist along the coast north of Rome, as shown in Fig. 2.

Shore protection works have recently been built at S. Severa (50 km north of Rome) to defend the excavations of the *colonia maritima* of Pyrgi and a superimposed medieval castle, deteriorated by the wave activity focused on the shallow promontory. A new breakwater protection partly covers the neglected semi-submerged harbour remains. Recent studies[13] seem to reveal an inland Etruscan basin and quay walls, and offshore detached rubble breakwaters at −5 m (Fig. 8). Aerial photography shows an interesting access channel dredged across the wide later Roman jetties and an emerging square fishing pond (Fig. 9).

One of the earliest **Roman** harbours was built at Cosa (now Ansedonia) in the formerly Etruscan region of southern Tuscany (2nd century BC)—worth mentioning due to its interesting engineering features, which are mostly visible today, despite the lack of protection and signs at this beautiful coastal site. Excavations have been carried out at Cosa by the American Academy in Rome since 1948.[14,15]

The harbour represents a transition between the natural anchorages of the early Etruscans and the elaborate artificial harbours of the later

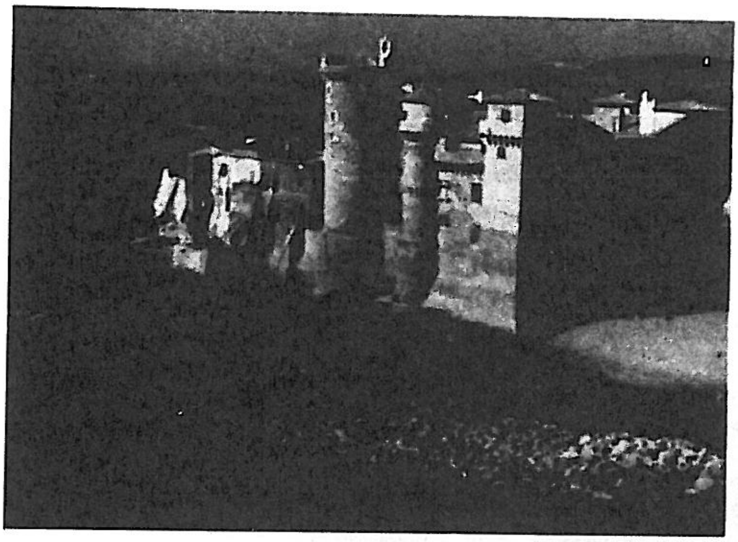

Fig. 9. Aerial view of the newly protected medieval castle of S. Severa and underwater remains of the Etruscan-Roman jetties of Pyrgi harbour with a square fishing pond.

Romans (Figs 10 and 11). It was composed of a lagoon and an outer basin sheltered by the limestone promontory and by breakwaters (now submerged) made with 2 tonne rock blocks directly quarried from the adjacent cliff, piled on the seabed and later cemented with natural sand concretion, hydraulic cement and the addition of broken pottery to increase the bond. The rocks are now worn to an oval shape and reduced in size due to sand abrasion and animal borings over 2000 years. A few tufa-and-mortar eroded piers (docks?) are still standing out of the water and some detached breakwater extensions are visible underwater near the 50 m wide entrance—their staggered arrangement was probably intended to provide the usual scouring de-silting currents. Existing spectacular features are the gigantic natural sluiceways.formed by two nearly parallel cuttings along the adjacent rocky cliff, the natural crevasse Spacco della Regina (260 m long, 30 m deep and 1–6 m wide, after suitable wall scarping and bed clearing) and the artificial Tagliata (70 m long and 4–5 m wide, partly tunnelled), which link the deep sea with the inner harbour and lagoon (Figs 10 and 11). Vertical rock-cut slots are clearly visible on opposite sides of the channel, which were surely used for sliding boards used as sluice-gates to control the water flow (probably also the fish flow to and from the lagoon) according to wind conditions and tidal cycle.

Another nice example of an early Roman harbour is the river port of Aquileia built in 181 BC. The landlocked remnants of the stone

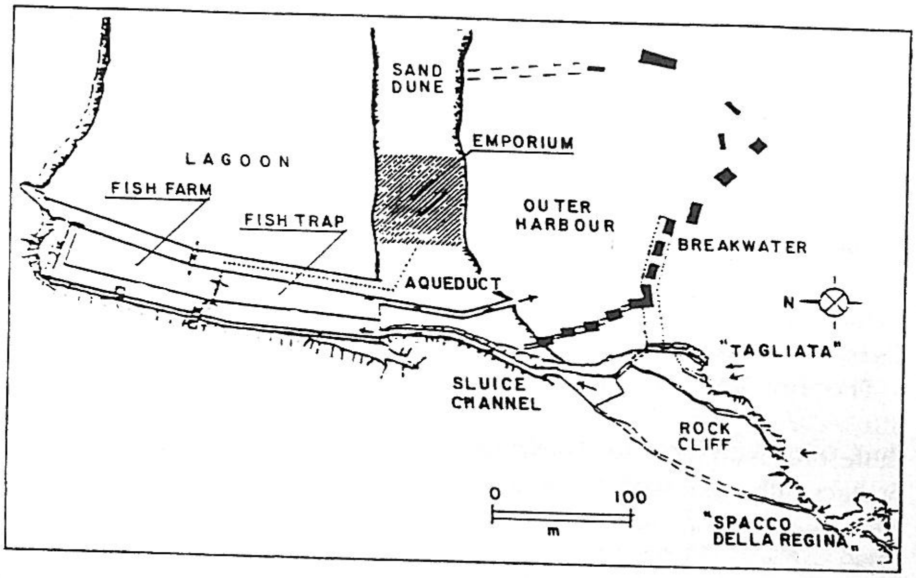

Fig. 10. Reconstruction of the Etruscan and Roman harbour layout at Cosa (after Brown, 1980[15]).

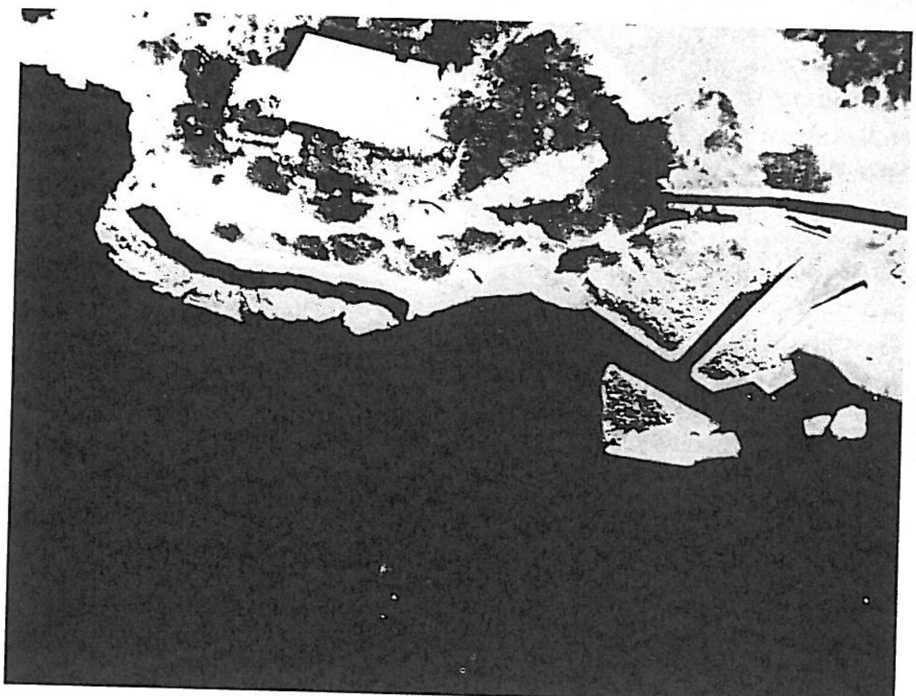

Fig. 11. View of the ruins of Cosa harbour from an ultralight plane, also showing the Etruscan artificial rock-cut channel named *Tagliata* (Source: L. Franco, 1991).

quay walls show two loading levels to cope with high and low water levels. Also visible, at 35 m spacing, are the mooring blocks made with three cut stones morticed together to form a round hole.[6]

The first harbours of the golden imperial times (since 1st century BC) are Forum Julii (Frejus), Mysenum (Miseno) and Puteoli (Pozzuoli). At the ancient naval base of Miseno near Naples, various remains of harbour deposits and tanks are visible. Other marks of well known Roman harbours are also found at Nisida, Terracina, Antium (Anzio), Portus (Roma), Ancona, Centumcellae (Civitavecchia), Astura and Caesarea, all of which have monolithic concrete breakwaters.

The revolutionary innovation in harbour engineering was really introduced by the Romans, who learned to build walls underwater and therefore managed to construct solid but compact breakwaters to protect fully 'external' harbours with free plan shape, even curvilinear. They learned the use of metal joints and clamps to fasten neighbouring blocks (Fig. 12) and discovered hydraulic cement made with pozzolana

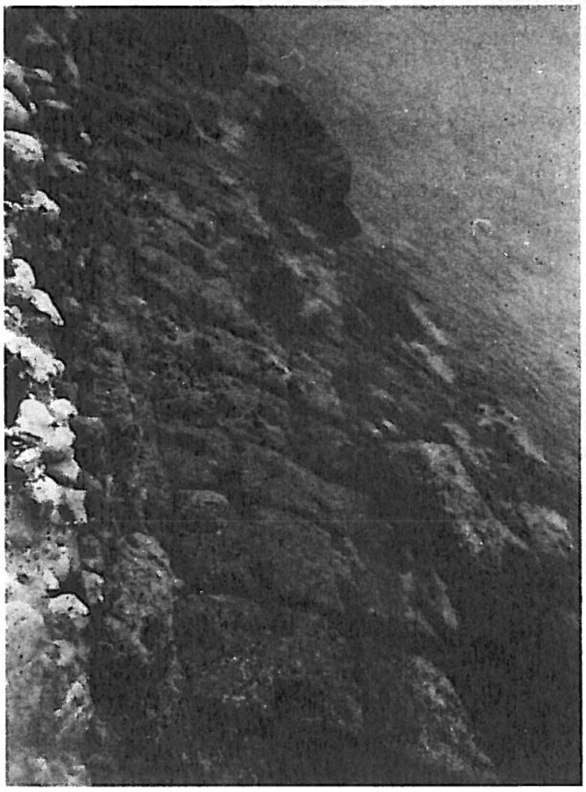

Fig. 12. Connection tracks on the rock blocks of a Roman quay in Pompeiopolis (Mersin, Turkey) (after Kurtulus and Arisoy, 1993[12]).

(from the volcanic region around Naples), which hardens underwater. Therefore, the Romans replaced the traditional Greek rubble mound breakwaters with vertical and composite concrete walls (*opus pilarum*). In fact, in deep seabeds they used to lay a rock foundation up to −6 or −7 m MSL and then construct the vertical structure. The durability of these monolithic concrete structures allowed their survival to sea attacks for over 2000 years.

It is interesting to note that this type of monolithic breakwater is still very popular in modern Italy[16] and it is presently receiving greater attention internationally on both scientific and practical grounds.

However, the Romans did not just follow a single codified tradition, but properly used a variety of design concepts and construction techniques at different coastal sites to suit the local hydraulic and geomorphological conditions and availability of materials.

Geotechnical conditions were analysed in order to choose a suitable foundation method. In hard bottom soils only a superficial layer was dredged to be replaced by a smooth rock bedding layer. If the bottom was sand, a trench wider than the wall was excavated (typically in the dry, as shown in Fig. 13) and then filled. In case of high layers of mud, according to Vitruvius,[2] the Romans used numerous short piles (0.45 m square section, made of wood from the olive tree, black poplar or holm-oak with scorched tips) with coal rock between the pile heads. In fact, the Romans developed the mechanical technology of cranes and piledrivers. For piledriving in water, the crane was placed on a raft or barge and guides, hoist and pile-hammer were used. The iron pile caps were covered with lead to protect them against corrosion.

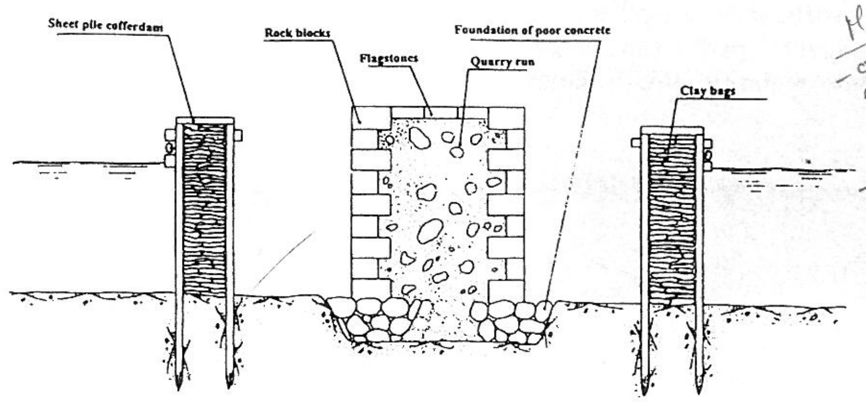

Fig. 13. Roman method of construction of a rock block vertical breakwater in good seabed conditions at exposed sites (after Prada and De la Pena, 1995,[17] according to Vitruvius[2]).

méthode 1 : béton coulé dans un coffrage en bois

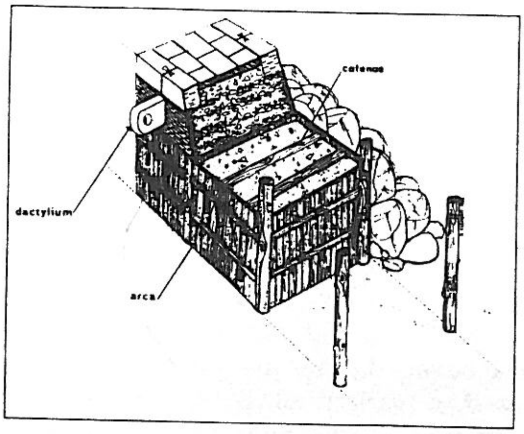

Fig. 14. Reconstruction of the Roman construction system of a cast-*in-situ* concrete vertical breakwater (after Clementi, 1981[18]).

Figure 13 also shows an interesting method for building a rock block structure after pumping out water within two 1.5 m wide coffer-dams, made with sheet-piles filled up with clay bags,[17] probably strengthened by cross tie-rods. However, the typical breakwater construction technique in sheltered sites consisted of pouring a mix of cement, pozzolana and brick pieces ('mass concrete') into immersed wooden forms (*arcae*) supported by driven piles and tie-rods (*catenae*), and later casting a concrete emerged superstructure, about 6 m wide, covered by bricks or joined squared rock slabs (Fig. 14).[18] This figure also shows the characteristic block with a hole (*dactylium*) used for ship mooring on the rear side (the hole axis could be either horizontal for mooring lines or vertical for tie-piles).

Several prints (and even some remains) of a more complex reinforcing 'skeleton' of oak pillars and crossbars can be observed in the moles of the Neronian port of Antium. The pillars inside the formwork (*destinae*) could have worked as anchors, while the horizontal crossbars (at +1 m MSL) could have also usefully supported a working floor. The modular frames are repeated with 2.5 m spacings. The joints show that half mole width (6 m) was probably cast against the quickly hardened solid wall edge of the other half. The 'staggered' construction sequence thus allowed saving the forms for the adjoining portions. The perimetral wooden forms could also be 'sunk' in a first fresh cast of mortar to increase the frame stability.

Sometimes, instead of the forms, old ships were sunk and filled with concrete, saving time and material. A well known example is the main west breakwater of Portus (Rome) built under Claudius (around 50

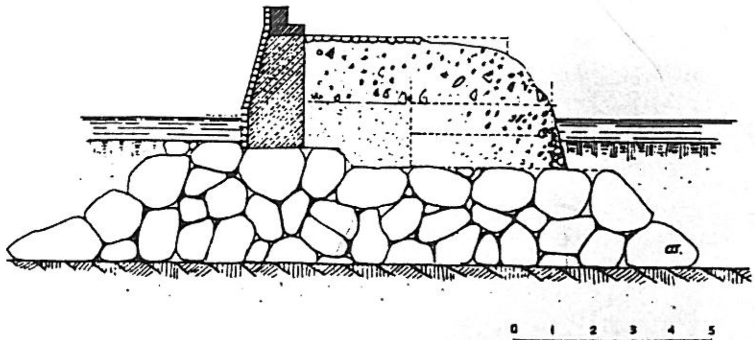

Fig. 15. Cross-section of the composite main breakwater of Claudius Port (Rome): the concrete superstructure (with seaward wave-wall and top slabs) was cast *in-situ* after sinking ship hulls for use as lost forms (after Testaguzza, 1970[19]).

AD) partly by sinking Caligula's 7400 tonne DWT, 104 m long ship (probably the largest wooden hull ever), which had transported the Vatican obelisk from Egypt, in order to create a solid foundation for the big lighthouse (Figs 15 and 16).

In wave-exposed locations a different construction method could be used. Work progressed from shoreland by dumping a submerged rubble mound. A perimetral sheet-piling was then filled with sand and topped with concrete. After the opening of little doors in the coffer-dam, the natural removal of sand allowed the concrete block to settle (a sketch

3

≠ Vitruve qui laisse faire l'érosion naturelle ↳ inefficace ?

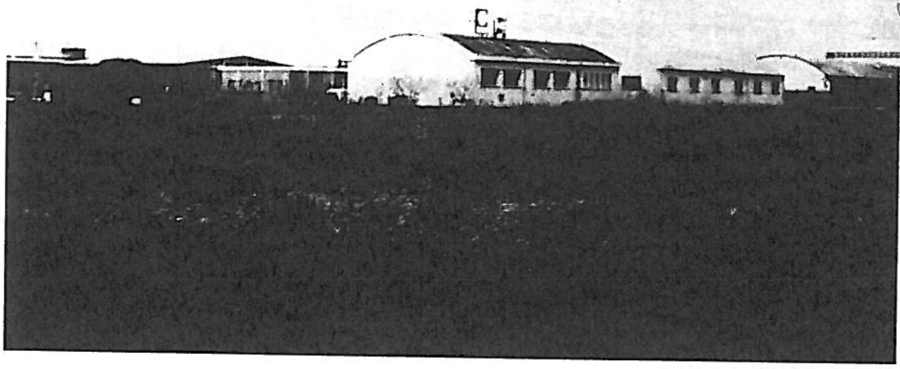

Fig. 16. The main west breakwater of Claudius Port, now covered by vegetation and abandoned without signs, within the grounds of Fiumicino airport (Rome). The holes mark the cross beams along the hull of Caligula's large ship, which was used as a lost form for cast-*in-situ* concrete (Source: L. Franco, 1995).

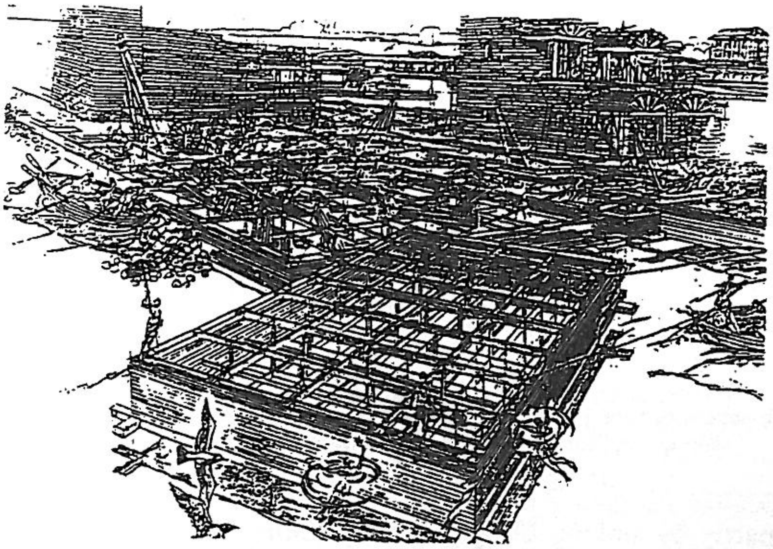

Fig. 17. Conceptual reconstruction drawing of breakwater construction at Sebastos-Caesarea Maritima (after Hohlfelder, 1987[20]).

can be found in Prada and De la Pena (1995)[17] reconstructed after Vitruvius).

In deeper waters wooden cellular floating caissons were used, as for the 60 m wide breakwaters of Sebastos (Caesarea) harbour built by Herod the Great's engineers in 18 BC.[10,20] Double-walled wood forms constructed nearshore were towed into position over a foundation of boulders on a sandy bottom and waterproof mortar was packed between the double walls to sink the form. Concrete was poured into the water-filled frames by lowering baskets and a rubble toe protection was also provided (Fig. 17). The large excavation project at Caesarea (CAHEP) also revealed a subsidiary parallel breakwater to reduce wave impacts onto the main walls (Fig. 18). The crest of this small 'tandem' rubble barrier was probably at the sea level, some 15–30 m seaward of the main breakwater. It was interrupted with gaps to provide an exit for rip currents and prevent the wave setup piling up in the 'stilling basin'.[10] Another unique feature of the main breakwater at Caesarea is the 'natural' construction technique used for building up the wide core—the block walls or caissons on the rubble foundation were framing hollow 'trap' compartments, which would be filled by the wave-carried sand within 2–3 years and then paved and built on above the water level. The large width of the imperial port breakwaters could allow the innovative construction of various installations (e.g. warehouses) on the crown (Fig. 19).

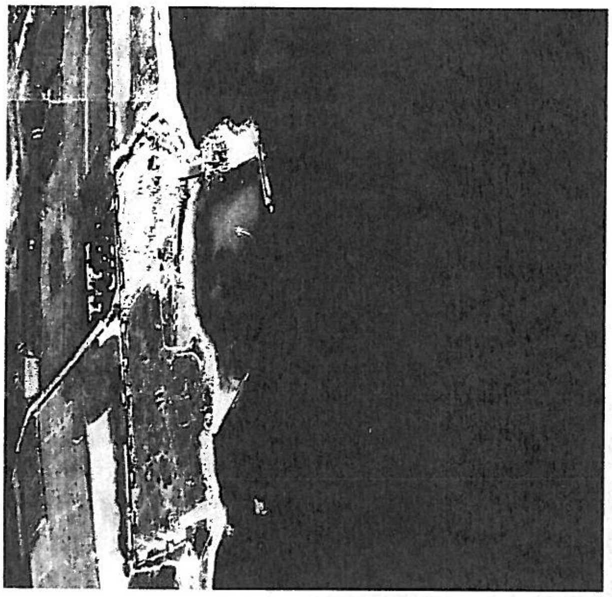

Fig. 18. Aerial view of the submerged breakwaters of Sebastos harbour (after Hohlfelder, 1987[20]).

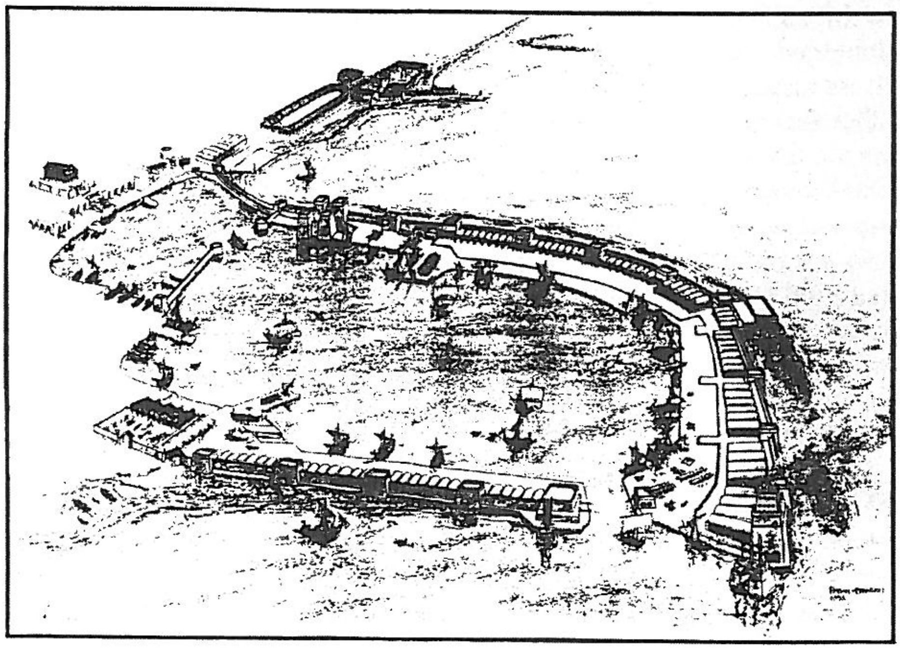

Fig. 19. Conceptual depiction of the ancient harbour of Sebastos based on recent archaeological data (courtesy of Center for Maritime Studies, University of Haifa, Israel).

An original vertical wall breakwater was built at Thapsus (today Rass Dimas, Tunisia), the 259 m long and 12 m wide impressive remains of which were still surviving in 1869. The peculiar feature of this monolithic mole was the presence of vents through the structure to reduce wave impact forces. This idea has been recently resumed by Jarlan to provide absorbing chambers in perforated caisson breakwaters and has numerous modern applications in Italy.

Another particular version of the Roman vertical-type breakwaters was the system of detached piers joined by arches. Remains of 'arched moles' have been found in Nisida, Mysenum and Puteoli (all in the Naples Gulf). As depicted in a famous fresco of Stabiae, the ancient monumental superstructure of Pozzuoli's mole was adorned with arches and columns to be an important social walkway. It was 372 m long and rested on 15 piers, each 16 m square (now incorporated in the modern breakwater), as shown in the surveys of De Fazio in 1814. The large water depth at the last pier (−16 m) can be surprising due to the shallow draught of the ships at that time—it demonstrates that not only nautical but also hydrographic reasons (wave disturbance, port siltation) were taken into account in the design of harbour protection structures. At Mysenum the breakwater was even made with a double row of arches in an offset position to reduce wave penetration. The submerged remnants of the supporting columns of the outer row can still be inspected by divers.

The technical reasons for these unconventional arched breakwaters may be to: control water circulation and toe scour against siltation; reduce wave reflection which affects coastal navigation; save material in deep water; borrow the successful construction techniques and aesthetic views of the Roman aqueducts and bridges. The arcades could have been equipped with sliding gates for temporary closure during storms. These large openings across breakwaters are found in other Roman harbours, despite their ineffectiveness due to the actual sedimentation and unacceptable wave disturbance in the sheltered basin (at Astura they appear partially closed at a later stage).

The natural de-silting concept was still in use in the imperial harbour of Caesarea Maritima. The recent discovery of a dump off the entrance also seems to show that the outflowing current not only prevented the sand from entering the port, but even kept the floor of the closed basin free of jettisoned garbage. Moreover, the funnel-like topography of the entrance would channel the outgoing current through the whole opening, leaving no free space for an inflowing current.[10]

In antiquity the largest artificial harbour complex (1.3 Mm^2) was the imperial port of Rome—the maritime town at the Tiber mouth was in

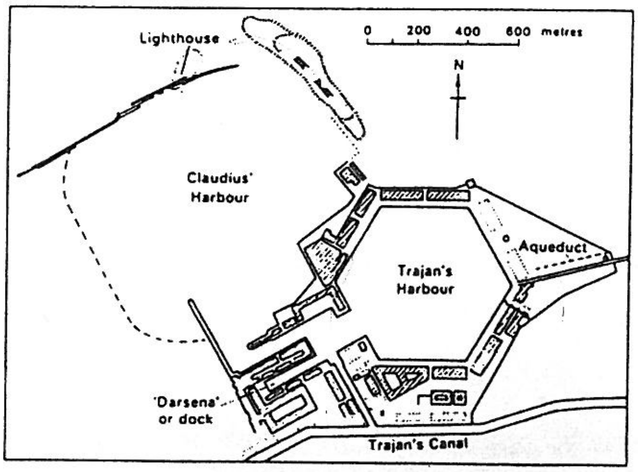

Fig. 20. The layout of Portus, the great port of Rome near Ostia (after Lugli and Filibeck, 1935[21]).

fact named Portus (*The* Port).[19,21] It is now some 4 km from the sea, partly buried under Rome's Fiumicino airport (the outer port of Claudius) and partly within a private estate (the inner port with the hexagonal basin later built by Trajan) (Fig. 20). Despite its importance for the supply to the empire capital (over 300 000 tonnes year^{-1} of wheat from Egypt and France) the port always suffered from river siltation, but this is also the reason for its conservation in modern times. Unfortunately, the remains of Claudius' port structures are hidden among the airport hangars and offices (Figs 16 and 21) and the beautiful water-filled basin of Trajan (six sides of about 360 m for an area of 33 hectares with a depth of 5 m, Fig. 22) is not yet fully accessible to the public and probably covers a huge underground cemetery of Roman ships. Numbered columns have been found set back from the edge on the quays of Trajan harbour, which were used to identify each berth. Large warehouses and other onshore port installations are covered by vegetation and can only be seen with special permits.

The near port of Antium was also developed in the 1st century AD by the emperor Nero and the ruins of the 850 m long main breakwater are still visible beside the modern harbour (Fig. 23). Trajan (around 100 AD) also built the ports of Terracina and Centumcellae (Civitavecchia). The former port was excavated at a river mouth and the mooring quays and columns are well visible along the nice circular perimeter.[22] The harbour of Centumcellae was built just to serve his villa, but after the decline of Portus it became (and still is today) the port of Rome

Fig. 21. The travertine block main breakwater of Claudius Port after excavations of Fiumicino airport (Source: Testaguzza 1972).

and remained unchanged for over 1000 years. The inner Roman Basin, presently in use, was dredged and the rock (200 000 m^3) which was used for the construction of an offshore mild-sloping rubble mound is now only partly visible under the modern port structures.

The new Roman habit of creating a harbour just near an important seaside villa can also be seen at Astura point near Antium, where Cicero had stayed. All the breakwaters are well visible underwater, together with some shipwrecks, columns, fishing ponds and the whole villa, connected to shore by an arched jetty (Figs 24 and 25). This small port is preserved due to difficult access and military constraints.

Well preserved monumental structures also exist at Leptis Magna (Lybia), partly covered by red quicksands. Here, early Punicum and Neronian harbours created at the mouth of a wadi had rapidly silted up. A new basin of 400 m diameter was later excavated in the dry behind

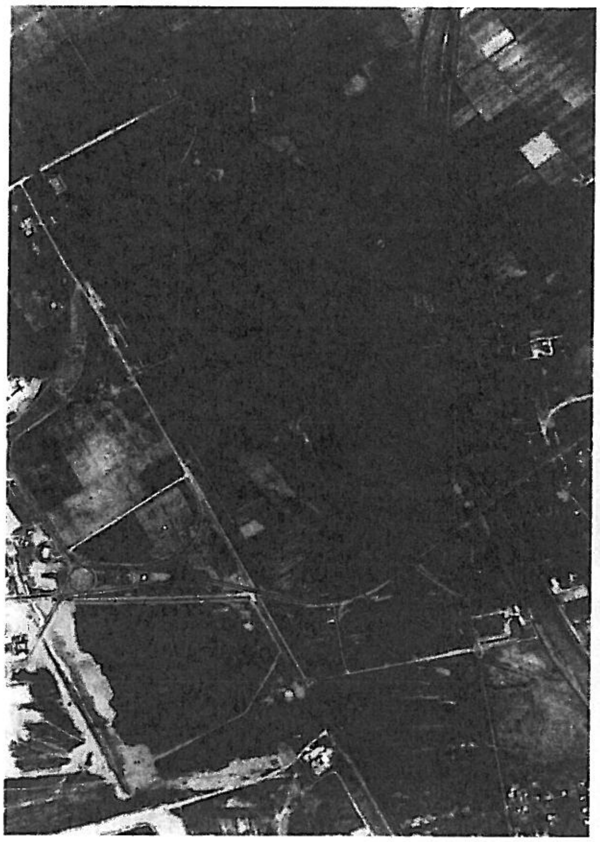

Fig. 22. Aerial view of the Trajan harbour basin and the east breakwater of Claudius Port (bottom left) near Fiumicino airport (Source: Testaguzza, 1972).

breakwaters under the emperor S. Severo (210–216 AD) and the river was diverted upstream with a dam to avoid siltation, which occurred anyway due to the littoral drift. Leptis is one of the few sites where port remains are not simply preserved at the foundation level and it is now becoming accessible to tourists.

However, the best preserved and fascinating Roman harbour is probably the one built under Augustus in the exposed prison island of Pandataria (now Ventotene), still in use in its original form and preferred to the modern port by the fishing and tourist fleet. It is infact a colossal sculpture, fully excavated into the dark tufa-rock (60 000 m^3 with an average cut depth of 9 m) to artificially create a 'natural' basin of 7000 m^2 with 3 m depth, a breakwater, quays and grotto storerooms (carved within deteriorated attractive arcades resembling petrified

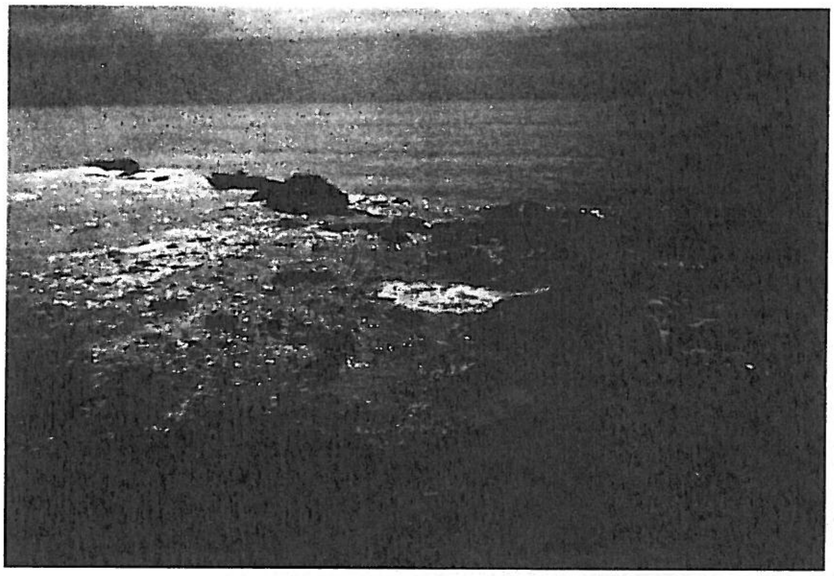

Fig. 23. Remains of the main monolithic breakwater of the Neronian harbour at Antium (Source: L. Franco, 1996).

elephants).[23] The breakwater in particular is ingeniously cut from the bedrock creating an effective wave absorbing seaward profile and an overtopping channel (Fig. 26) which follows the Phoenician tradition. Other apparent ancient port facilities are two aqueduct outlets, a number of large rock-cut bollards and a cave at the roundhead to contain the chain for closing the entrance. Again, a small secondary opening was still documented by drawings of the 18th century, but is now obstructed despite the need of harbour flushing. The general harbour plan shape of a bay with spending beach (used as a slipway) just after the entrance and with a lateral mooring basin is considered as one of the most modern and efficient (Figs 27 and 28).

However, as far as layout is concerned a characteristic innovation of Roman harbours was the construction of island breakwaters (not connected to the shore), which typically supplemented the two main converging arms in order to reduce wave penetration through the gap, providing a double entrance for manoeuvrable vessels and often supporting a large fire-lighthouse. The classic example of this (now declined) port scheme was Centumcellae, which was considered in the Renaissance (also by Leonardo) as the reference model of the 'ideal city-port'. It is even suggested that the round plan shape of its converging arms influenced Michelangelo's design of the famous

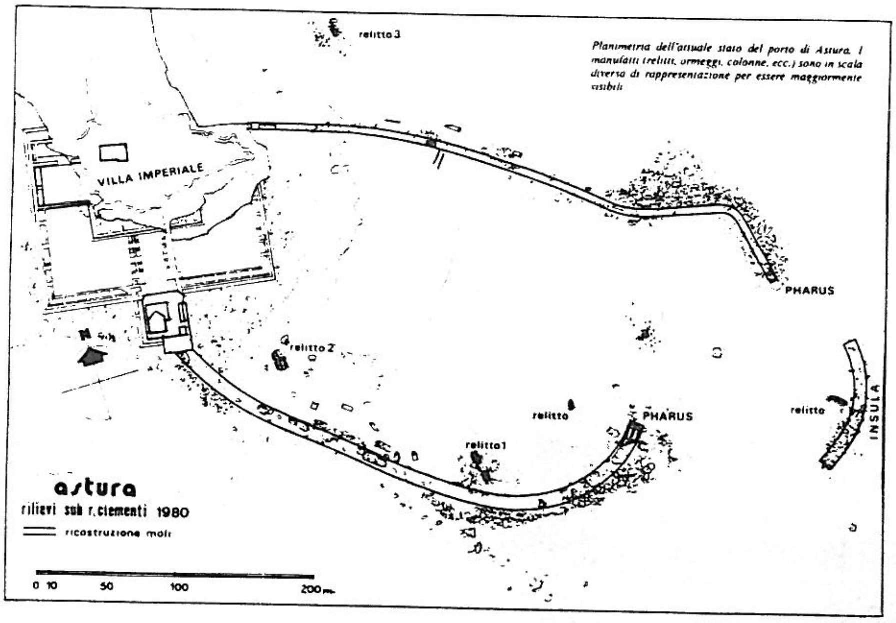

Fig. 24. Present remains of Astura harbour and imperial villa with location of shipwrecks (after Clementi, 1981[18]).

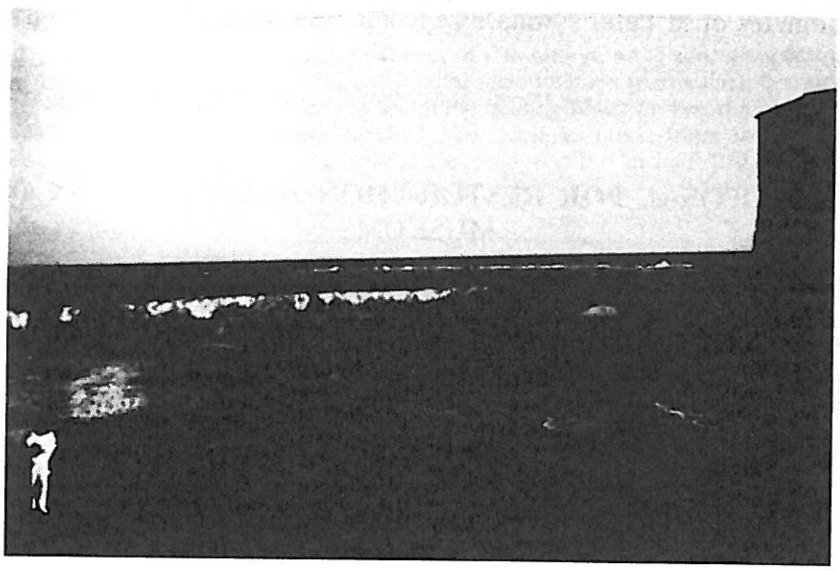

Fig. 25. Remains of the Roman harbour of Astura with submerged breakwaters (far end), the seaside villa connected to shore via an arched jetty and large fishing ponds (Source: L. Franco, 1993).

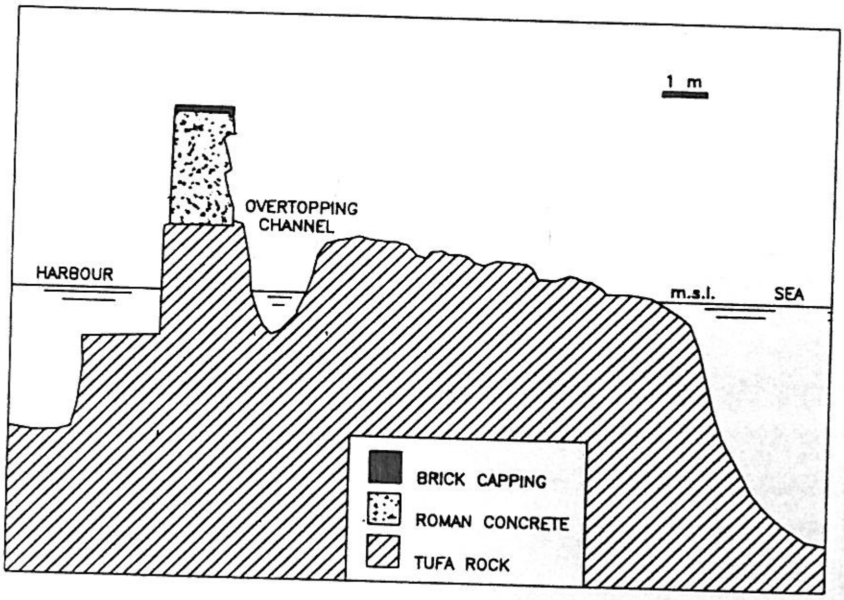

Fig. 26. Cross-section of the Roman 'carved rock breakwater' at Ventotene with sloping-parabolic seaward profile and overspill stilling channel (after a survey by Iacono).

columnates of St Peter's Square in Rome, as a safe refuge for pilgrims[24] (Fig. 29).

3. PROPOSAL FOR RESTORATION AND CREATION OF MUSEUMS

Very little is reported about the conservation and restoration of ancient maritime works, since attention is mainly paid to shipwrecks and artifacts from the seabed. Suitable techniques for the consolidation and protection of old submerged structures are to be developed and applied.[25]

In Turkey, there are now plans for restoring ancient harbours and bringing them back to life for yachting use.[12] For example, the old swampy harbour of Ephesus may be connected to the sea by means of a channel and used by tourist boats, whereas a modern marina is planned at the end of this channel.

In general, the objective is to spread the word to the public of these

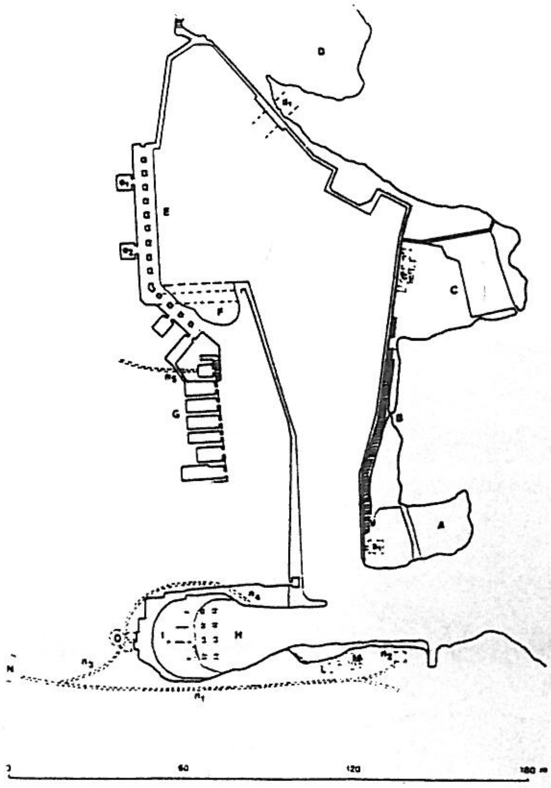

Fig. 27. Layout of the Roman imperial port of Pandataria, now Ventotene (after De Rossi, 1993[23]). Legend: A,C,D = natural coastal rock outcrops (partly cut); B = modern wall; E = rock-cut arcades worn out by wind; F = hauling basin; G = storerooms (still in use); H,I = slipways and spending beach; L,M = rock-cut boxes (near tufa bollards); N,O = water tanks; a = cave for 'closure chain' recovery; d = ancient flushing channel; n = ducts.

scientific and historical achievements and let the visitors combine their usual beach or boating activities with a rewarding 'cultural bath'. A minimal option should be to sign the coastal archaeological sites by means of simple illustrated panels with historical technical descriptions.

However, many coastal sites with remnants of ancient harbours or other civil structures built by the sea could satisfy the requirements for an 'open-air/water' museum, which are: (1) concentration of points of interest in a relatively small area; (2) combination of historical events and monumental remains; and (3) beautiful natural attractions and surroundings.

Good examples for a potential application in the vicinity of Rome are Astura, Pyrgi (S. Severa) and Cosa (Ansedonia). These neglected

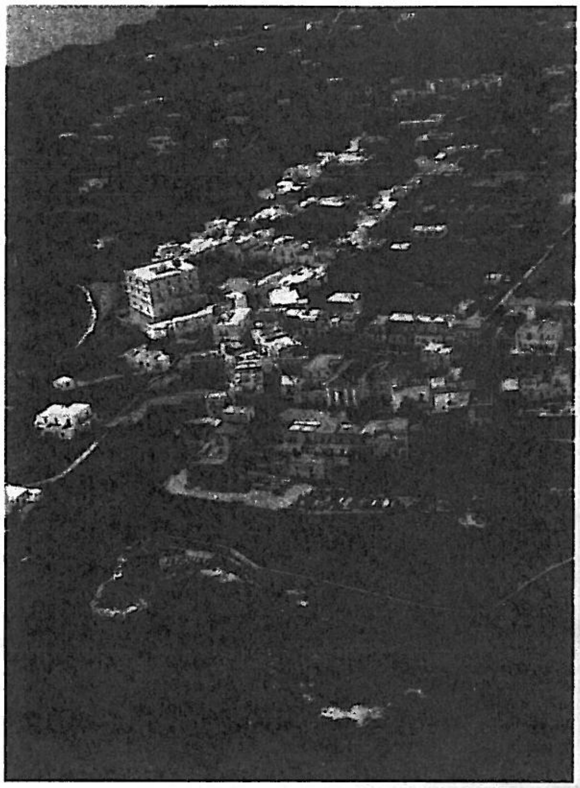

Fig. 28. Aerial view of the beautiful rock-carved Roman harbour at Ventotene island.

coastal archaeological sites appear suitable for a successful creation of an 'ancient harbour park', including modern (but not intrusive) facilities for underwater visual and didactical exhibitions onshore, for example within the adjacent Roman villa (Astura), the medieval castle (S. Severa), or the ruins of Cosa village (on top of Ansedonia hill). At this latter site a spectacular observation path could be created underground along the rock-cut channels, leading the visitors to the open sea and along the cliff overlooking the harbour remains near/on the beach.

A much larger and impressive 'inland' park has long since been proposed for the revival of the largest imperial harbour of Portus near Fiumicino airport (Rome), even allowing short visits during flight transits, but no concrete action has yet been taken.

In general, one possible option for excavation and creation of museums in shallow-water conditions might be the drainage of the harbour basin by means of permanent dykes and a pumping system, thus allowing easier protection and access. A more attractive, advanced

Fig. 29. T

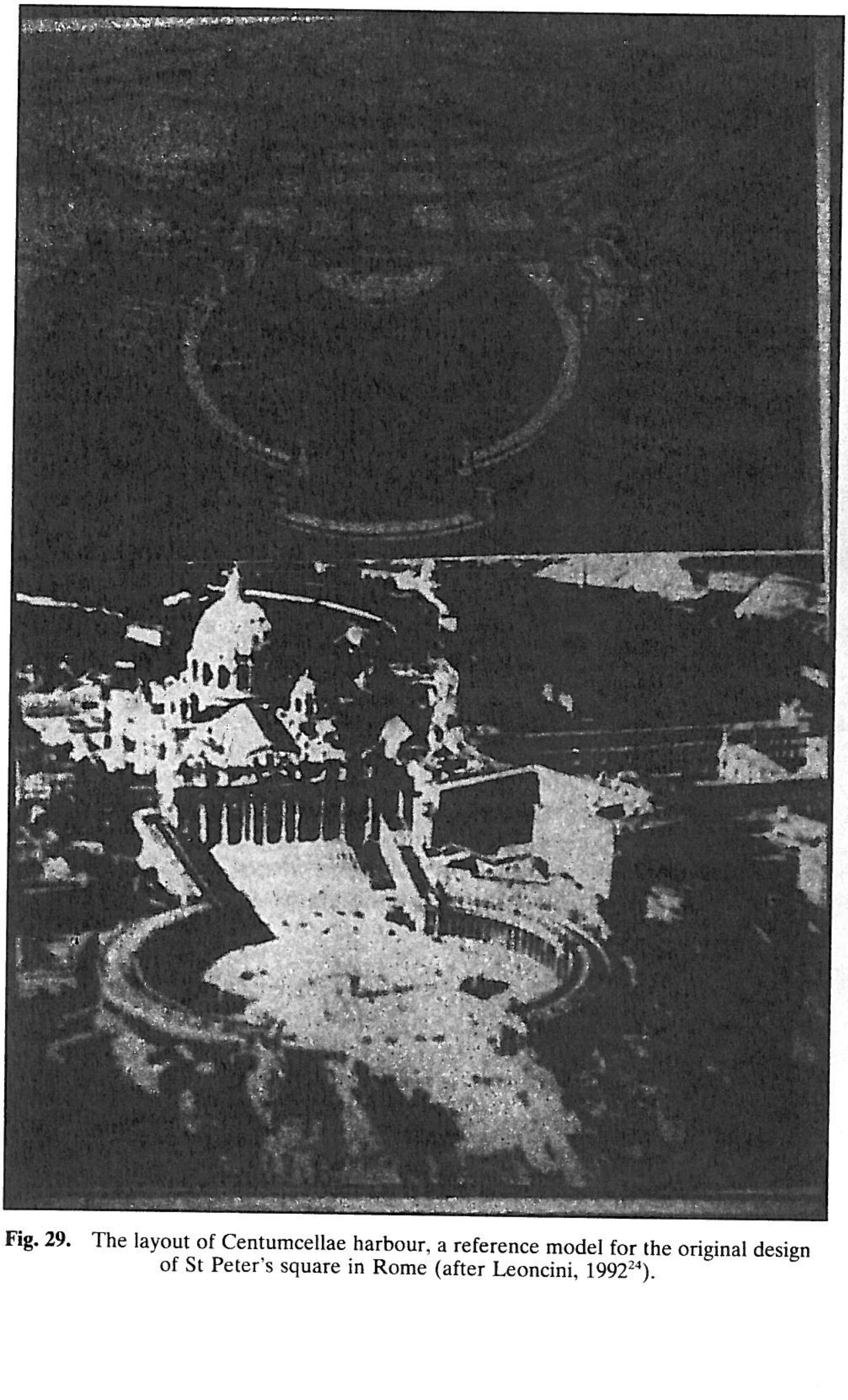

Fig. 29. The layout of Centumcellae harbour, a reference model for the original design of St Peter's square in Rome (after Leoncini, 1992[24]).

solution is to provide submarine footpaths within glass tunnels in a confined sea area. This option appears particularly feasible around shipwrecks or sunken cities. A promising site in Italy lies on the north side of the Naples Gulf where, beside the port of Miseno, the submerged remnants of the Roman town of Baia are well preserved. The water might need to be filtered and cooled to avoid marine growth and improve visibility. Fixed underwater observatories are already used for aquaria, however, the developing technology of submerged tunnels may well be applied to these historical sites and may even allow the observation of underwater archaeological operations.

With this 'archaeological' purpose, a futuristic design of an observatory and a floating museum with underwater windows has been recently presented for installation in the Bolsena lake near Rome[26] (Fig. 30).

In clean shallow waters, cheaper glass-bottom boats can also be used, while in deep waters a solution is represented by semi-submerged mobile systems, such as the French Acquascope. A closed-circuit television could also enable the display of more remote underwater remains and show excavations under way. The onshore exhibition can easily include other explicative panels, shows and displays of objects excavated from the seabed.

A good solution would be a combination of the above systems, as

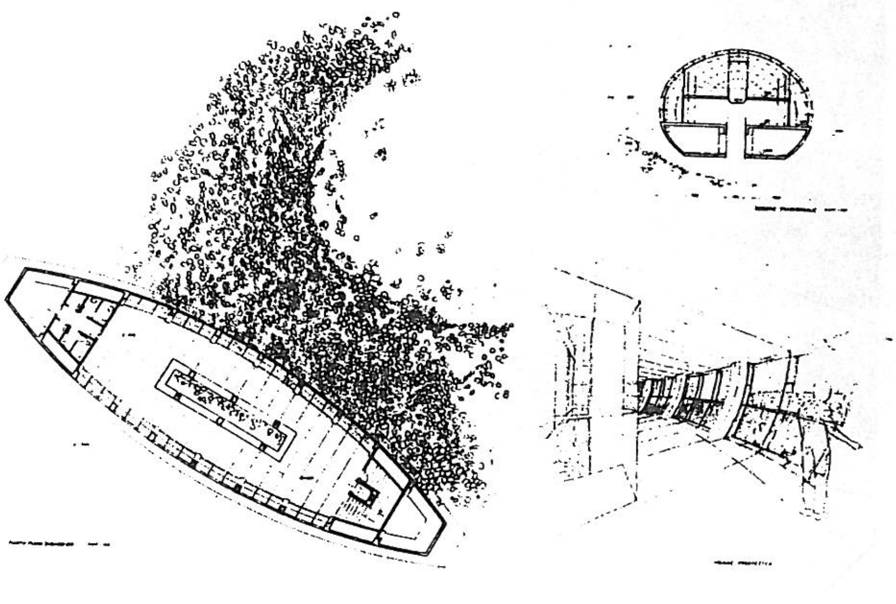

Fig. 30. A floating museum designed for underwater observation at Bolsena (after Postiglioni and Scocca, 1994[26]).

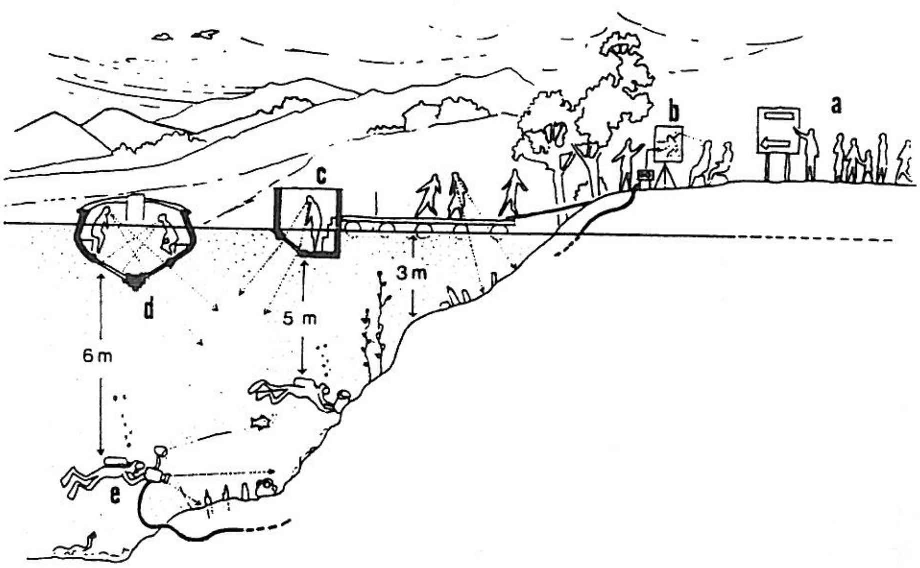

Fig. 31. Proposal for the creation of an 'open-air/water' museum for Mezzano lake (after Mitchell, 1988[27]).

shown in Fig. 31, proposed for the creation of the submerged remains of a prehistoric settlement found in the Mezzano lake (again near Rome) as a museum.[27]

The exhibition might include harbour structures and facilities, buildings, ships and artifacts, perhaps even a detailed artificial reconstruction to display technical and social features of the important ancient maritime trade. The high costs would easily be recovered by admission fees. It may be worth observing that such costly operations are sometimes afforded for quite different purposes—the site of Astura was temporarily renovated to reconstruct the port of Alexandria for the movie 'Cleopatra'!

In actual fact, an archaeological park (for divers only) already exists in the Mediterranean waters at Caesarea.[28] Following clearly marked cable guidelines, fixed to metal posts along the seafloor at about −6 m MSL, the visitors can explore the large submerged remnants of Herod the Great's port of Sebastos (Fig. 32). Equipped with plastic illustrated guidebooks the divers can follow four underwater courses, each about 400 m long, enjoying the view of old concrete walls, lead pipes, marble columns, wooden forms and hulls, iron and stone anchors. No admission fee is charged for these self-guided tours, although diving equipment, instructors and guides can be hired locally.

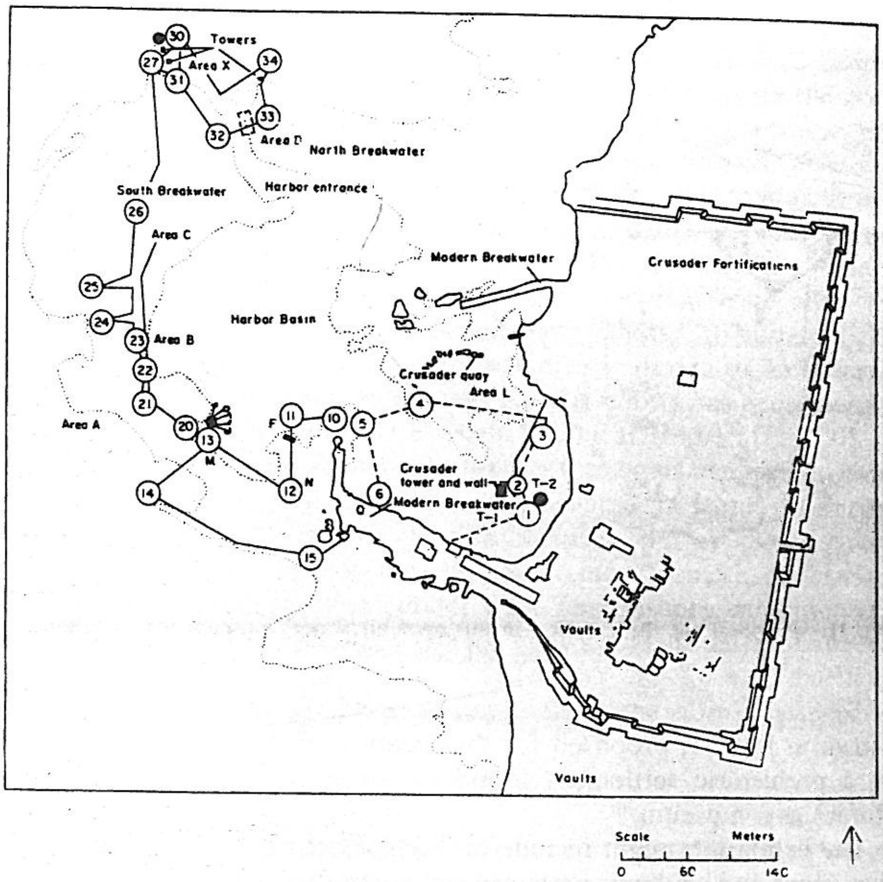

Fig. 32. Underwater archaeological park at Caesarea (after Raban, 1992[28]).

A proposal for a submarine park is now also being put forward for the famous harbour and lighthouse just discovered at Alexandria (Egypt).

4. CONCLUSIONS

The survey and excavation of ancient port sites is shedding new light on the historical evolution of harbour technology, reviewed in this paper. In particular, as far as port planning is concerned, it is shown that the early natural harbours, often equipped with ingenious de-silting systems, were followed by larger artificial ones. Similarly the port structures, such as breakwaters and quays, were built first with natural rock-cuts and rubble mounds, then with regular ashlar stone blocks and later with concrete blocks or mass concrete caissons, after the revolutionary Roman discovery of hydraulic cement. The natural but sophisticated solutions of ancient coastal engineers can still provide useful hints for today's designs.

However, wet coastal site archaeological resources are still under-represented, if not totally unknown, in many Mediterranean regions, despite the fact that they do exist and represent a highly valuable cultural heritage. An urgent task is the systematic survey of all visible remains, followed by their careful protection and management, given the threat of increasing tourist development in the coastal zone. In particular, not just shipwrecks but also the remains of impressive works of ancient harbour engineering need to be discovered, studied, preserved and exhibited. To this end, the co-operation between archaeologists and scientists from other disciplines, particularly coastal engineers and 'restoration' architects, is recommended. An excellent example of this fruitful co-operation is given by the valuable archaeological work conducted by the engineer Testaguzza[19] during the excavations of Fiumicino airport.

The fundamental tasks for the fruitful management of these coastal historical resources are: improved detection skills (remote sensing techniques); preventive site investigations where new works are planned; coastal protection; control of public access; conservation and consolidation; creation of 'on-the-water' museums.

The creation of coastal 'maritime-archaeological parks' or museums would certainly qualify the touristic offer of many Mediterranean areas, also improving the cultural asset and reducing unemployment. Promising sites on the Italian and Turkish shores have been pointed out. The park revenues could also finance new large underwater excavation projects, which should produce exciting finds and hopefully improve our knowledge of ancient port engineering.

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