Ancient Port Structures
An engineer's perspective

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Abstract

This paper aims to compare ancient and modern port structures hoping that the modern can help us in a better understanding of the ancient, with special focus on breakwaters and quay walls. Archaic shipping and the oldest known port structures are briefly presented. Vertical breakwaters and quays, large concrete blocks, pilae and arched breakwaters, piling walls, moulded structures, in-the-dry constructions, rubble mound breakwaters and training walls are described in the ancient and in the modern world. A few geomorphological aspects of coastal harbours are also reviewed.
It is concluded that most natural shelters were used in Roman times, but some major ports have been built in places without any natural shelter, for strategic or economic reasons.
Most of today's concepts for maritime structures were already existing in Roman times and it seems that little progress was made until the 18th c. when large maritime structures started to be built again. The combination of reinforced concrete and steel enables modern engineers to build higher, deeper and larger than Roman engineers could dream of, but some modern structures may not last as long as some Roman structures, especially in salt water …

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Introduction

The main structures of a port are its *breakwater(s)* to reduce wave action inside a protected *basin*, where *quays* and *jetties*[1], with some mooring devices, are available for loading/unloading ships. Hence, a breakwater and a quay have to be built using available construction materials and methods, and a basin has to be dredged and maintained at adequate depth.

Ancient port structures and construction methods were described mainly by Vitruvius and very few others, like Philo of Byzantium, Piny the Younger (Centumcellae), Flavius (Caesarea Maritima), Procopius (Hiereia) and a few more on Portus Claudius provided information.

Modern coastal engineers like to distinguish breakwaters[2] and quay walls, as the first are meant to protect the second from wave action. However, many combinations can be found, e.g., a quay wall on the lee side of a breakwater. The modern trend is motivated by the concept of "time is money", meaning that a ship must be loaded/unloaded as soon as possible upon arrival into the port. The ancients did probably not have such constraints as some quay walls are found without any breakwater protection, meaning that ships would sometimes have to wait for calm weather before being able to berth.
Another distinction modern coastal engineers like to make is between "vertical breakwaters" and sloping "rubble mound breakwaters": the former are made of large masses of concrete, and the latter are made of loose rock dumped into the water. Here again, combinations are found, e.g., a vertical structure placed on top of a rubble mound. The modern distinction is often based on the water depth: vertical breakwaters are preferred on larger water depths (say over 15 to 20 m) because of the large quantity of rock that would be required for a rubble mound. Ancient

[1] A quay allows berthing on one side, a jetty allows berthing on its two sides and both can be on piles or be a massive concrete or ashlar structure.
[2] Archaeologists use the word "mole", while engineers prefer "breakwater" in the sense of "wave-breaker". See also: https://en.wikipedia.org/wiki/Breakwater_(structure)

breakwaters and quay walls were often built on what we would call today 'very shallow water'[3], using vertical structures (ashlar[4]) where divers could work easily, and rubble mound structures on deeper water.

Figure 1 below shows the two main families of breakwaters: sloping rubble mound breakwaters, and vertical breakwaters with a definition of their elements.

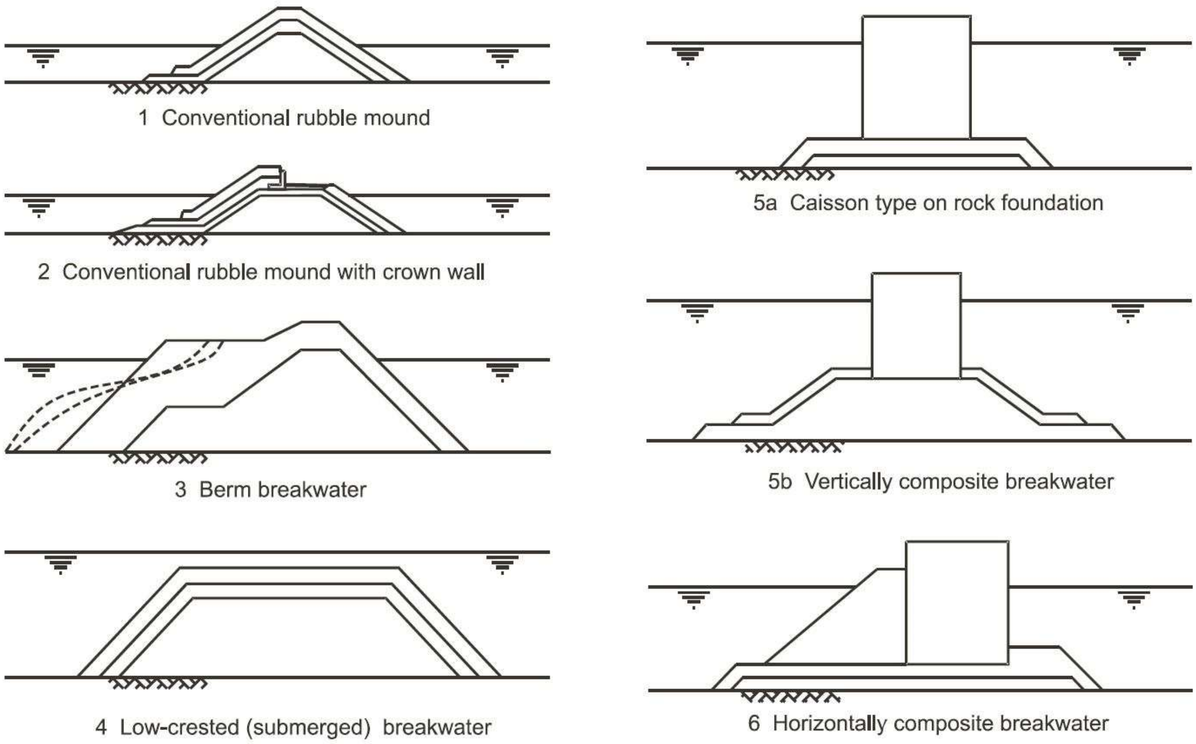

Fig. 1. Typical modern rubble mound (sloping) breakwaters and vertical breakwaters (Rock Manual, 2007)[5]

Brief historical overview

If you are not an expert historian, this may help you to start (Fig. 2) …

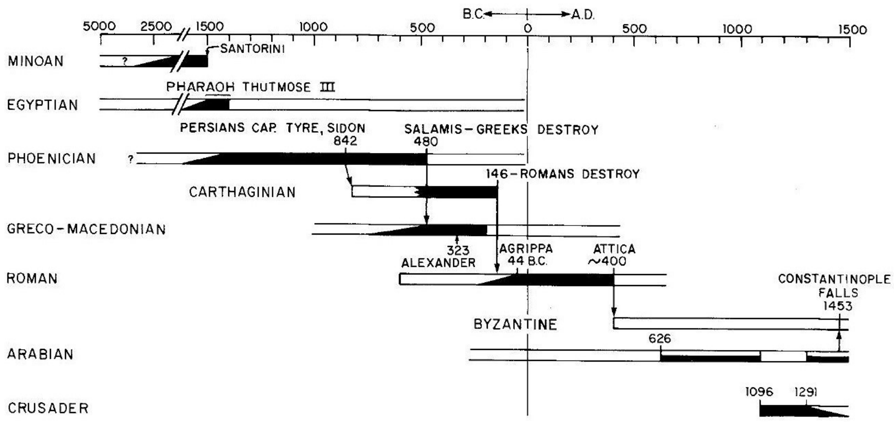

Fig. 2. Chronology of civilizations acc. to Inman[6]

[3] Ancient breakwaters were built on 2 to 5 m water depth used for ships with a draught of 1-4 m, while modern breakwaters are built on 5 to 50 m water depths for ships with a draught of 3-20 m (resp. sailing boats and Very Large Crude Carriers).

[4] Wikipedia : Ashlar is finely dressed (cut, worked) stone, either an individual stone that has been worked until squared or the structure built of it. Ashlar is the finest stone masonry unit, generally cuboid, mentioned by Vitruvius as opus isodomum, or less frequently trapezoidal. Precisely cut, ashlar is capable of very thin joints between blocks.

[5] CIRIA, CUR, CETMEF, 2007.

[6] INMAN, D., 1974.

As far as **archaic seagoing shipping** is concerned, Egyptian rulers have been sailing during the Early Bronze Age (ca. 3300-2100 BC), i.a. Pharaoh Khufu-Cheops importing copper from the Sinaï (ca. 2570 BC), Sneferu (ca. 2575 BC), Sahure (ca. 2450 BC) and Sesostris I (ca. 1950 BC) sending ships to Byblos for wood and to Puntland for exotic goods[7]. In the Gulf, Mesopotamians were sailing to the Indus valley and to East Africa via Dilmun (Bahrein) and Magan (Oman)[8].

Minoans from Crete were probably the first "professional seafarers" sailing internationally in the Mediterranean area. This spanned, in round figures, the period between 2000 BC and 1500 BC.

In the next period, from 1500 BC to 1200 BC, the Mycenaeans ruled the Aegean Sea and eastern Mediterranean as illustrated by Homer's later epic on Achaeans[9] fighting the Trojan War. The Egyptians have been sailing on the Nile and on the Red Sea, and we know of Hatshepsut's sailing from Myos Hormos (Quseir al-Qadim) on the Red Sea to the Land of Punt (ca. 1450 BC) and of Rameses III's naval battle near Pelusion on the Nile against foreign invaders (1178 BC).

The Bronze Age ended around 1200 BC, when the Iron Age started with long "Greek Dark Ages" in Greece (1200-800 BC) corresponding to a Phoenician climax (Carthage was founded in 814 BC, but Byblos was already a trade port in the 3rd millennium BC). This was followed by a Greek revival called "Greek Archaic Period" (800-500 BC). In this period, the Egyptian pharaoh Necho II sent an expedition to circumnavigate Africa (ca. 600 BC).

This period was followed by the better known "Greek Classical Period" (500-323 BC), the "Hellenistic Period" (323-31 BC) and the Roman period[10].

At the end of the Roman Empire (476 AD), it was western Europe that had its "Dark Ages", for say five centuries, during which everything had to be rebuilt in the western Mediterranean … while the Arabs were over-active in the Indian Ocean.

Finally, if you would like to read a recently published overview on ancient ports, I recommend Arnaud (2016), Morhange (2016) and Oleson (2015). For a complete overview on ancient seafaring, see Danny Lee Davis (2009).

The **oldest known seaport structure**[11] (in 2019**[12]**) is the wadi al-Jarf breakwater in the Gulf of Suez (ca. 2570 BC, Khufu-Cheops). This structure is ca. 325 m long and ca. 6 m wide[13]. The port of Byblos (Lebanon) is from the same period, but it is located in an estuary with no known port structures[14]. Between 2400 and 2000 BC, a 4 m deep dock of 215 x 35 m was built with fired mudbrick at Lothal (India) at the outlet of River Sabarmati, and the smaller basins of Ur were probably also built in this period[15].

The very large port on Pharos island might also date around 2000 BC and its more than 2 km long main breakwater might be seen as an ancestor of the typical Phoenician breakwater structure with two ashlar vertical walls with interspace filled with rubble[16].

A series of Minoan ports were found on the north coast of Crete: Kydonia (Chania), Knossos and Amnissos (near Iraklio), Mallia, Ag. Nikolaos, Istron, Pachia Ammos, Tholos, Pseira, Mochlos, which are usually quite small.

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[7] MARCUS, E., 2002 and TALLET, P., 2015. See also Wikipedia: https://en.wikipedia.org/wiki/Sahure

[8] POTTS, D., 2016.

[9] Achaeans from the Peloponnesus were also called Danaans or Argives by Homer, and possibly Ahhiyawans by the Hittites and Tanaju by the Egyptians; today they are called 'Mycenaeans'.

[10] For a superb overview of the Roman history, have a look at BADEL, C. and INGLEBERT, H., 2014.

[11] OLESON, J., 2015..

[12] A submerged probable seawall dated ca. 5500-5000 BC was found at Hreiz (Israel), GALILI, E., 2019.

[13] TALLET, P. and MAROUARD, G., 2016: Khufu-Cheops is therefore a precursor, not only for his Great Pyramid, but also for his maritime works.

[14] CARAYON, C., 2012a.

[15] BLACKMAN, D., 1982.

[16] JONDET, G., 1916; Leopold SAVILE, 1940; Raymond WEILL, 1916, Galina BELOVA, 2019.

Anchorages more or less sheltered by offshore ridges were used as natural shelters on the Levantine coast in the 2nd millennium BC: Arwad (Syria), Sidon, Sarepta, Tyre (Lebanon), Sdot Yam, Arsuf, Yavne Yam (Israel).

Early Phoenicians gradually improved their natural shelters by adding breakwater structures on top of the offshore ridges, like at Sidon on the "Languette rocheuse" mentioned by Poidebard and Lauffray in 1951, and at other places (Arwad, Batroun, Zire)[17]. Corings show that Sidon's inner port was already existing in the 17-15th c. BC thanks to this artificially improved reef[18]. In Yavne-Yam (Israel) a 100 m x 50 m rubble mound was built on the reef possibly to improve the shelter[19].

At Kommos (Crete) a shipshed located at some distance from the coastline, and including 6 galleries of 37 x 5.60 m, is dated Late Minoan (ca. 1400 BC)[20]. A possible Minoan slipway with two galleries of ca. 5 x 40 m is located at Nirou Khani (Crete)[21]. Mycenaean ports on the Peloponnesus also date from this period: Epidauros, Egina, Asini, Tiryns, Gytheion, Pylos[22].

Next in time are the following port structures, all located in ancient Phoenicia:

- Dor (Israel, ca. 1000 BC) with a 35 m shallow water quay made of large ca. 0.7 x 0.5 x 2 m ashlar headers facing the sea[23],
- Tabbat el-Hammam (Syria, ca. 900 BC) breakwater 200 x 15 m[24],
- Sidon (Lebanon, ca. 800-600 BC) north breakwater 230 m long with headers up to 5 m[25],
- Tyre (Lebanon, ca. 800-600 BC) north breakwater 70 x 12 m with 0.5 x 0.4 x 2 m headers [26],
- Athlit breakwater (Israel, ca. 800 BC) 130 x 10 m, with 0.6 x 0.45 x 2 m headers[27].

These breakwaters were all made with ashlar headers ca. 0.5-1 x 0.5-1 x 1-5 m. These pioneering breakwaters consisted of two ashlar vertical walls with interspace filled with rubble. Moreover, this type of structure was still built much later in the 3rd c. BC (Amathus in Cyprus, 380 m with 3 m headers[28]) and in the 2nd c. AD (Leptiminus in Tunisia, 370 m with 1 m headers[29]) and even in the 4th c. AD (Seleucia Pieria, 120 m with 5 m headers[30]). They re-emerged in the 18th c. when international sea-borne trade asked for them again[31].

The first rubble mound breakwater was possibly built on Delos island in the 8th c. BC[32], but the Samos breakwater (ca. 530 BC) described by Herodotos (Hist, 3, 44-60) is more famous. This type of structure was widely used for breakwaters in water deeper than a few meters where positioning of ashlar headers by divers was difficult but dumping loose rock over board barges was easy. This construction method was described later on by Pliny the Younger at Centumcellae (103 AD). The largest ancient breakwater of this type is at Portus Claudius (ca 60 AD). This construction method is still used very often nowadays.

A major evolution was the introduction of 'Puteolanus pulvis' ('pozzolana') for hardening concrete under water. This enabled large blocks of hundreds of cubic meters of concrete to be constructed

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[17] VIRET, J., 2005. This paper is very informative, even if we do not completely agree with its conclusion.

[18] CARAYON, N., 2012b, and for further details on corings: MARRINER, N., 2009.

[19] GALILI, E., et al., 1993.

[20] BLACKMAN, D., and RANKOV, B., 2013, p 10.

[21] See : http://www.ancientportsantiques.com/a-few-ports/nirou-khani/

[22] MAURO, C., 2019.

[23] ARKIN SHALEV, E., 2019. Headers are long blocks placed with the smallest section towards the outer side of the wall. Stretchers are placed with their large side to the outer side.

[24] BRAIDWOOD, R., 1940, and FLEMMING, N., 1980.

[25] CARAYON, C., 2012b.

[26] NOUREDDINE, I., 2010. See also his 2018 & 2019 publications.

[27] HAGGI, A., 2005.

[28] EMPEREUR, J-Y., 2017.

[29] STONE, D., 2014 and 2016.

[30] PAMIR, H., 2014.

[31] ALLSOP, W., 2020 for breakwaters, and DE GIJT, J., 2010 for quay walls.

[32] FLEMMING, N., 1980. Note that accessing this island with northern Meltem wind in the narrow strait between the isles of Delos and Rheneia (Rinia) is difficult with a sailing boat.
See also: http://www.ancientportsantiques.com/a-few-ports/delos/

under water by pouring concrete into prefabricated timber caissons. The first known use for breakwaters is at Agrippa's naval base of Portus Iulius, near Pozzuoli, in 37 BC, and the most famous is at Caesarea Maritima (Israel) built between 21 and 10 BC[33]. Also this construction method is still used by modern engineers[34].

Some of these breakwaters have been luckily preserved and survived two millennia of wave attack, but most of the ancient breakwaters were destroyed by wave action and remains are found under water as "submerged breakwaters". Careful examination of historical Google Earth images enables us to see quite a few breakwater remains in shallow waters[35].

It can be seen from the list above that most early maritime structures were vertical and made of ashlar in water depths not exceeding a few meters. This can be explained by the small draught of ancient ships (i.e., ca. 1-2 m for navy ships and up to 3-4 m for freighters) and the fact that breakwaters were used not only to reduce wave action inside a protected basin, but also to berth ships. Rubble mound breakwaters were built on deeper water and used exclusively for protection against wave action.

Vertical breakwaters, quays and jetties

Early vertical structures were often made with ashlar blocks. The north mole of the port of **Tyre** (Lebanon) is made of two parallel walls, 13 m apart and filled with rubble (Fig. 3). They are dated around 800 BC[36]. A similar but smaller structure was found at **Athlit**.
Ashlar headers of 0.7 x 0.7 x 3 m were found in **Amathus** (Cyprus) built around 300 BC.
In sheltered waters, headers were replaced by stretchers (Fig. 4).

Fig. 3. Tyre north mole built
with ashlar headers (0.5x0.5x2 m)
(Noureddine, 2010)

Fig. 4. Roman quay wall at Marseille,
built with ashlar stretchers
(Inrap, 2006)

Romans introduced the concept of timber caissons filled with marine concrete. Such caissons could be built directly on the sea bed by driving piles into the subsoil[37] (Fig. 5).
The north breakwater of **Portus** (ca. 50 AD) was built with caissons and the imprints of the transverse beams are still visible (Fig. 6).

[33] BRANDON, C., et al., 2014, and RABAN, A., 2009, and GALILI, 2021.

[34] FRANCO, L., 1996 and COULON, G., 2020.

[35] See: http://www.ancientportsantiques.com/ancient-port-structures/remains-of-ancient-breakwaters/

[36] NOUREDDINE, I., 2010.

[37] VITRUVIUS, ca. 20 BC, "de Architectura", 5, 12, provides a description of this construction method using marine concrete that hardens under water thanks to the use of pozzolana: "in the place selected, dams are formed in the water, of oaken piles tied together with chain pieces, which are driven firmly into the bottom. Between the ranges of piles, below the level of the water, the bed is dug out and levelled, and the work carried up with stones and mortar, compounded as above directed, till it fills the vacant space of the dam", transl. Lacus Curtius.
These caissons are also called "cofferdams", but a modern cofferdam is supposed to be watertight (see infra).

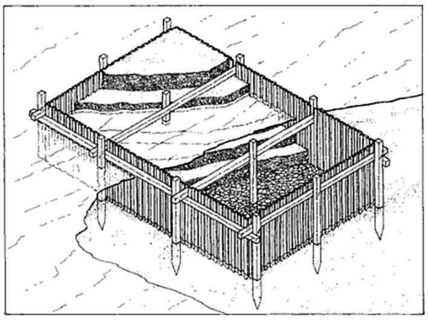

Fig. 5. Timber caisson acc. to Brandon (2014)

Fig. 6. Portus' north breakwater showing imprints of transverse caisson beams (de Graauw, 2011)

This type of structure was used also as a massive concrete jetty inside the harbour basin protected by a rubble mound breakwater at **Cosa**[38].

Timber caissons, with or without a bottom, could also be prefabricated elsewhere and floated to the final location where they would be filled with marine concrete to be lowered on top of a foundation layer[39] (Fig. 7). This construction method was used between 21 and 10 BC at **Caesarea Maritima** (Israel) where concrete blocks up to 14 x 7 x 4 m (that is around 1000 tons) were found by modern archaeology[40].

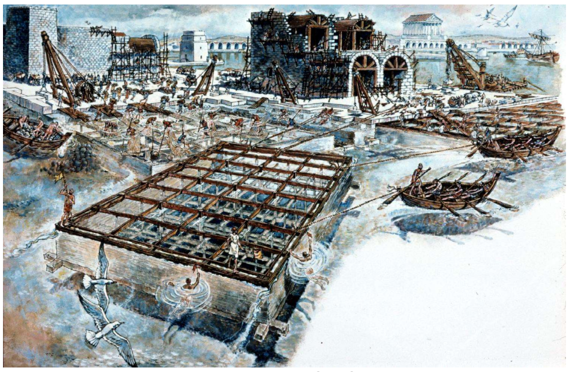

Fig. 7. Reconstruction of a floating caisson being positioned. (J. Robert Teringo, 1987)

In the 6th c. AD, Procopius' description of the Byzantine **Hiereia**[41] breakwaters (Fenerbahçe, Istanbul) seems to correspond to timber boxes filled with rock (or marine concrete?) and placed in line and on top of each other. It must be noted that such timber boxes placed under water may be eaten away by worms, leaving just a pile of loose stones. Nevertheless, recent Danish underwater excavations at the Byzantine port of **Lechaion** (Corinth) seem to confirm the remains of timber caissons (up to 5x10 m) filled with rock which have probably survived thanks to exceptional local sedimentological and biological conditions[42] (Fig. 8).

Fig. 8. Caissons filled with loose rock at Lechaion (P. Barthélémy, Le Monde, 2018)

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38 McCANN, A-M., et al., 1987.

39 VOTRUBA, G., 2007. A 40-cm thick layer of rounded cobbles (up to 35 cm diameter) was found underneath a large concrete block of the Caesarea western breakwater. This foundation method allows a strong flow within the foundation layer, e.g., with a wave having its crest outside and its trough inside the port. Such an alternate flow will erode sand underneath and thus undermine the whole structure (DE GRAAUW, A., 1984 and GALILI, 2021).

40 BRANDON, C., et al., 2014.

41 PROCOPIUS, 6th c. AD, Buildings, 1, 11, speaking about Justinian's harbour works at Hiereia, Eutropius and at Jucundiana in the 6th c. : "He prepared great numbers of what are called "chests" or cribs, of huge size, and threw them out for a great distance from the shore along oblique lines on either side of the harbour, and by constantly setting a layer of other chests in regular courses upon those underneath he erected two very long walls, which lay at an angle to each other on the opposite sides of the harbour, rising from their foundations deep in the water up to the surface on which the ships float", transl. H. B. Dewing, 1940. See also DAIM, F., et al., 2016.

42 BARTHELEMY, P., 2018. The initial port of Corinth at Lechaion was built by Greeks in the 5th c. BC and was used nearly continuously during the Greek, Roman and Byzantine periods.

Phoenicians seem to have initiated the concept of a double wall of ashlar headers filled with loose material such as cheap quarry run. This concept was taken over much later, around 150 AD, by Romans using marine concrete as a filling material between the lateral retaining walls made of ashlar for the breakwaters of **Pompeiopolis** (Mezitli, Turkey) (Fig. 9) and **San Cataldo** (Italy).

Fig. 9. Marginal ashlar wall (centre) containing marine concrete (left) at Pompeiopolis (Brandon, 2014)

The **Wadi al-Jarf** breakwater (Gulf of Suez, Egypt) mentioned above as the oldest known breakwater consists of cobbles and some kind of lime and clay mortar that resisted 4500 years of salt intrusion (Fig. 10). It is not yet clear how this structure was built, but it was possibly cast into some kind of formwork made of timber or ashlar blocks that might have been taken away at a later stage.

Fig. 10. Wadi al-Jarf breakwater (Tallet, 2016)

An overview of various types of modern vertical breakwaters is presented in Fig. 1 (5a, 5b).

Small quay walls (up to say 10 m water depth) often consist of separate blocks of massive concrete placed on several tiers by a crane[43]. Nearly-vertical blockwork walls with rubble infill placed on an underwater rubble mound were built in tidal areas in the 19th c. (e.g., **Jersey,** one of the Anglo-Norman Islands, Fig. 11)[44].

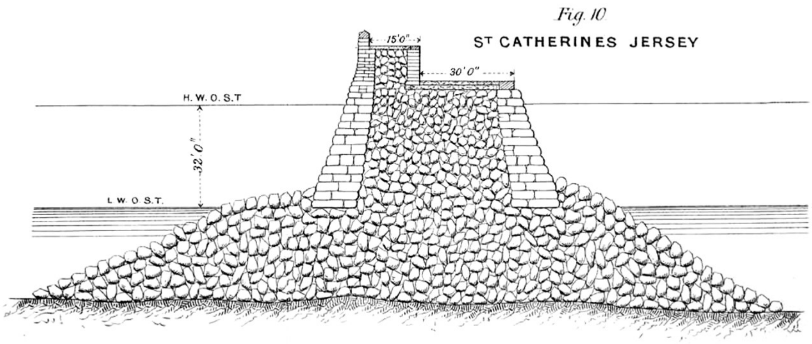

Fig. 11. Vertical breakwater at St Catherine's, Jersey (Vernon-Harcourt, 1885)

However, most modern vertical breakwaters on deeper water (say 15 to 50 m) are built by means of monolithic reinforced concrete[45] structures called "caissons".
Caissons are usually built in a drydock or on a specially designed platform, and consequently floated to their final location where they are filled with sand or quarry run to be lowered onto a

[43] https://www.youtube.com/watch?v=lnYIGAnx1mY
[44] ALLSOP, W., 2020.
[45] Marine concrete was rediscovered by John Smeaton (1756) and was followed by the invention of reinforced concrete by Joseph Monier (1867).
See also: http://www.ancientportsantiques.com/ancient-port-structures/reinforced-concrete/

foundation layer[46] made of a granular filter[47]. Their cap superstructure is usually designed to reduce wave overtopping and to provide access on top of the breakwater (Fig. 12-13).
Caisson stability is provided by gravity, but it can be moved by sliding and/or overturning by wave forces. It must be noted also that when a caisson is displaced during a storm, its repair is difficult and very expensive. The design of vertical breakwaters requires an estimate of the wave forces on the vertical front-wall. Wave impacts depend on the breaking of the waves in front of the structure, which in turn depend on the wave- and seabed conditions. Wave forces on the caisson are therefore usually measured by means of fairly complex small-scale modelling[48].

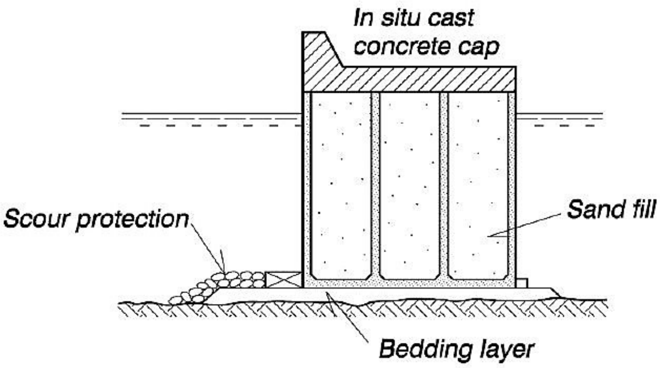

Fig. 12. Typical cross-section of a caisson breakwater
(Coastal Engineering Manual, 2012[49])

Fig. 13. 45x24x18 m caisson floated into position at Açu (Brazil) (The Corner, 2013)

An additional rubble mound is sometimes placed in front of the vertical structure in order to absorb wave energy and thus reduce wave reflection and horizontal wave pressure on the vertical wall (Fig. 1, 6). Such a design provides additional protection on the sea side and a quay wall on the inner side of the breakwater, but it can enhance wave overtopping[50].

A similar but more sophisticated concept is a wave-absorbing caisson, including various types of perforation in the front wall (Fig. 14-15).
Such structures have been used successfully in the offshore oil-industry, but also on coastal projects requiring rather low-crested structures, e.g., on an urban promenade where the sea view is an important aspect like in **Beirut** and **Monaco.** In the latter, a project is presently ongoing at the Anse du Portier including 17 wave-absorbing 27 m high caissons placed at 20 m water depth on a rubble foundation mound.

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46 https://www.youtube.com/watch?v=iKeGKYBOK50
47 DE GRAAUW, A., 1984.
48 TAKAHASHI, S, 2002.
49 US ARMY CORPS of ENGINEERS, 2012.
50 EUROTOP, 2016. Such a design was used on the south breakwater at Amathus, Cyprus (EMPEREUR, 2017).

Fig. 14. Jarlan-type wave absorbing caisson

Fig. 15. 17 wave-absorbing caissons
at Monaco Anse du Portier (Bouygues TP, 2019)

Prestressed concrete was invented by Eugène Freyssinet (1928) and used for even larger offshore oil platforms placed on 100 to 300 m water depth. Future offshore wind farms will probably use a similar technology.

Large concrete blocks

In places where pozzolana was not available, concrete blocks could be built on shore and floated in caissons used both for prefabricating and for transporting each block[51] (Fig. 16).

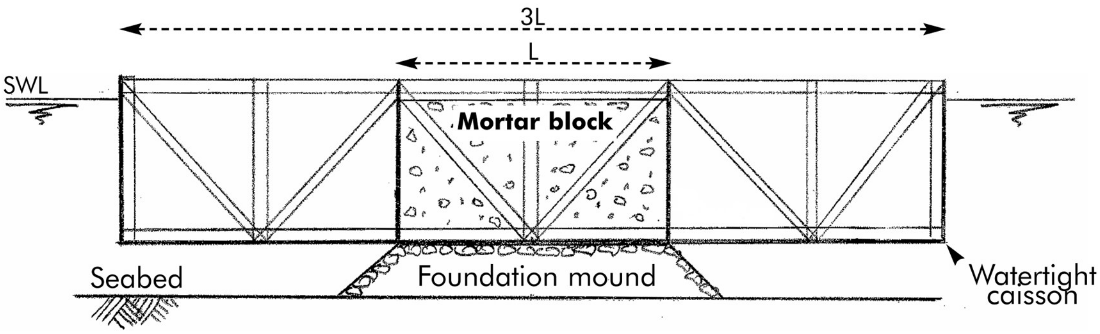

Fig. 16. Hypothetical floating caisson used for prefabricating and transporting a mortar block (de Graauw, 2000)

Vitruvius described a method using large concrete masses that are supposed to be cast on the beach and to slide into the sea after some undermining occurred[52] (Fig. 17). However, much debate has taken place on the interpretation of this text and no remains corresponding to this construction method are known.

The WWII bunkers at Cap Breton (France) were initially located on the dune that recessed several hundreds of meters during the past 75 years (Fig. 18). This shows that large concrete blocks placed on a beach or on a dune do not provide any coastal protection on an eroding beach as they are undermined by wave action and tilted in an unpredictable way.

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[51] DE GRAAUW, A., 2000.

[52] VITRUVIUS, ca. 20 BC, "de Architectura", 5, 12, provides a description of this construction method using large concrete blocks: “If, however, from the violence of the waves and open sea, the dams cannot be kept together, then on the edge of the main land, a foundation for a wall is constructed of the greatest possible strength; this foundation is laid horizontally, throughout rather less than half its length; the remainder, which is towards the shore, is made to overhang. Then, on the side towards the water, and on the flanks round the foundation, margins, projecting a foot and a half, are brought up to the level already mentioned. The overhanging part is filled up underneath with sand, brought up level with the foundation. On the level bed thus prepared, as large a pier as possible is built, which must remain for at least two months to set. The margin which encloses the sand is then removed, and the sand being washed away by the action of the waves causes the fall of the mass into the sea, and by a repetition of this expedient the work may be carried forward into the sea”, transl. Lacus Curtius.

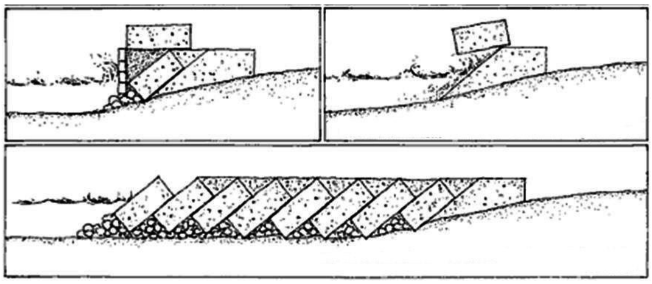

Fig. 17. Brandon's interpretation of Vitruvius' method (Brandon, 2014)

Fig. 18. WWII bunkers on the beach of Cap Breton (France) (Clopeau, 2011)

Pilae and arched breakwaters

Arched breakwaters are not used anymore today as they are not efficient to stop wave penetration and sedimentation inside a harbour basin. An arched breakwater looks like an aqueduct with a single tier (Fig. 19).

Fig. 19. Pont du Gard aqueduct (France)
an arched breakwater might look like the upper level.

The arches are supported by massive piers (*opus pilarum*), which are made of stone or concrete (*opus caementicium*). According to Brandon et al. (2014), the Latin word *pila* designates a "large mass of concrete, generally square in plan, and often a cube or upright rectangular prism in shape".

The ratio of opening between adjacent piers over pier width is as follows on the Pont du Gard aqueduct:

- Upper level: opening = 1.4 pier widths
- Lower levels: opening = 4.1 pier widths

"Maritime pilae" seem to be more "closed" than aqueducts. This might be explained by their completely different aim which is not to support some kind of road or canal, but to stop wave penetration into the port while providing limited opening for water circulation inside the port, also supposed to reduce sedimentation in the port.

The method of construction of pilae with marine concrete was described by Vitruvius and tested by Brandon et al. (2014) in Brindisi.

Except in Civitavecchia, no ancient arched breakwater can be seen today, but remains of concrete pilae have been found in many places (Fig. 20). A list is presented in Appendix 1, along with pictures of those that can be seen under water on Google Earth, and some of them may be remains of arched breakwaters.

Fig. 20. Pilae at Portus Iulius (Italy) (Google Earth 2007)

The following conclusions can be drawn:

- Most sites with pilae are located in Italy (35 out of 50), especially around Naples (25 sites from Caieta to Sapri), which is no wonder as the pozzolana required for under water pila-construction originated from this area.
- The average dimensions of the measured pilae are 9.3 m x 7.2 m: nearly square. The average horizontal surface is 68 m^2. The height cannot be determined on Google Earth.
- The largest pila was found at Nesis (Nisida): 14.5 x 14.5 x 8 m[53].

Various types of alignments can be distinguished from the pictures in Appendix 1:

- single isolated structures (e.g., Punta Fuenti, Fréjus, Caesarea Maritima, Alexandria-Antirhodos), possibly a foundation for some heavy structure such as a tower or lighthouse,
- rather continuous structures in the open sea, probably part of a vertical breakwater (e.g., Castellabate, Scidrus, Gnathia, Side, Psamathos).
- rather continuous structures in a sheltered area, perhaps forming a massive jetty or quay platform inside a harbour basin protected by a breakwater (e.g., Cosa, Horrea Caelia),
- pilae spaced with regular intervals (say 0.5 to 1.0 pila-width), perhaps the base of arched breakwaters or timber decks, or intervals meant to be filled with rubble dumped into timber formworks placed between the pilae (e.g., Caieta, Misenum, Baia, Portus Iulius, Nesis, Pausylipon, Alexandria-Qait Bey). The pictures show that the distance between adjacent pilae is usually less than their width:
    - Caieta: opening = 0.3 to 0.4 pila width
    - Portus Iulius: opening = 0.7 pila width
    - Misenum: opening = 1 to 1.5 pila widths

  Several alignments of pilae have been claimed to be remains of arched breakwaters, including the Roman breakwaters at Tarragona[54] and Izmit[55] but little evidence was provided, except for Pozzuoli where many pictures are available and Nisida with a picture from 1635, and Civitavecchia, which is still visible.

The ratio of opening between adjacent piers over pier width may depend on the wave incidence: the more perpendicular to the pilae alignment, the smaller the opening between pilae must be to provide protection against wave penetration.
This leads us to have a closer look at the most famous ancient arched breakwater which is located at **Puteoli** (Pozzuoli). The pictures of Appendix 2 show that some arches were still in place in the early 19th c., but that the structure was gradually destroyed after that.
Paolo Antonio PAOLI produced a detailed drawing in 1768 showing 15 pilae (including 2 supposed pilae, but the inscription CIL X.1641 dated 139 AD, mentions 20 pilae). The largest pilae of ca. 15 x 15 m are at the offshore end of the structure. The nearshore pila is somewhat smaller: ca. 8 x 12 m. The opening ratio between adjacent pilae varies from 0.7 to 1.0, which is close to the values found for Portus Iulius and Misenum.
At **Centumcellae** (Civitavecchia) the arches are still visible on the Molo del Lazzaretto where the opening ratio is ca. 0.7. The arches seem to have been placed on top of a rocky shoal[56].
And how about **Portus Claudius**' north mole?! Nero's coin might point towards an arched breakwater as the water flow between piers is clearly indicated on the right side of the coin. This flow is very similar to the bow wave of a ship (Fig. 21):

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[53] MATTEI, G., 2018

[54] TERRADO, P., 2019, citing (p 178) Sanahuja (1859) telling about masses of marine concrete and citing Echanove about arches. This ancient Roman breakwater was removed in 1843.

[55] TEXIER, C., 1839, "Description de l'Asie Mineure", Nicomédie, (p 17-28), ed. Firmin Didot, Paris.

[56] https://www.romanports.org/en/articles/human-interest/137-centumcellae-the-port-of-trajan.html

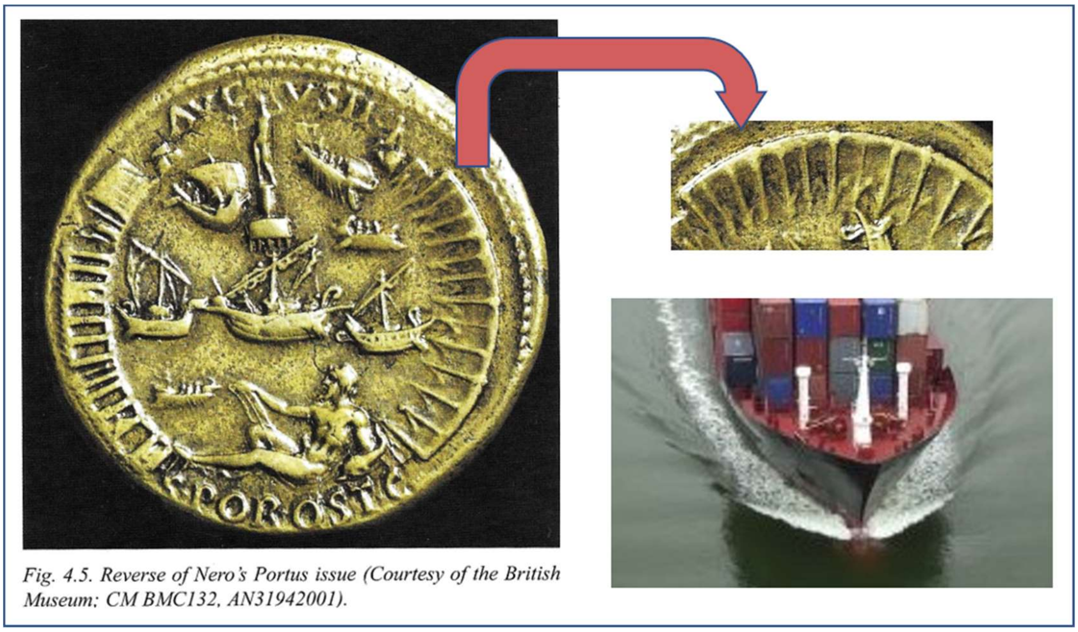

Fig. 21. Nero's coin showing Portus Claudius (64 AD) and the similarity of water flow between pilae with a ship's bow wave.

The following hypothetical mole structure has therefore been proposed by the author[57] (Fig. 22):

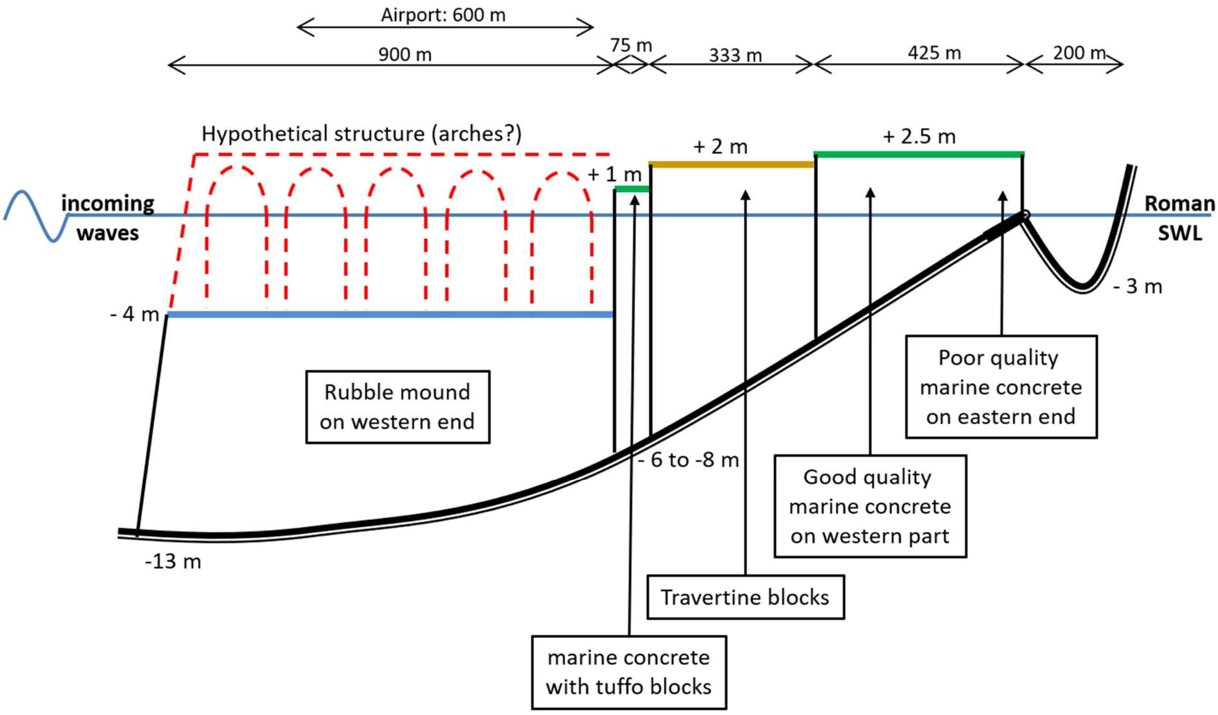

Fig. 22. Hypothetical longitudinal section of Portus' north breakwater (Beware the 1:50 distorted scale!) (de Graauw, 2019)

The landward end is made of marine concrete, a deeper part is made of travertine blocks and a rubble mound was found in the deepest stretch where it is believed an arched breakwater may have existed. However, the arch blocks still have to be found …

[57] http://www.ancientportsantiques.com/a-few-ports/portus/

Piled jetties (wharves)

Ancient timber piled jetties have been built in many places, but few remains have been found. A picture is available on top of the famous villa Stabiae fresco of the port of Puteoli (App. 2).

Recent archaeological excavations at Yenikapi (Istanbul) have uncovered a large piled timber jetty with three rows of piles (Fig. 23).

A similar timber piled jetty with three rows of large piles was also found in Marseille in front of the dolia dock[58] and in Bordeaux[59].

Fig. 23. Yenikapi excavations (Aramco World 2009)

Many modern timber, concrete or steel piled jetties exist all around the world. They are used to reach water deep enough for loading / unloading ships near beaches in tidal areas or shallow areas.

Fig. 24. Small timber jetties at Port du Bec (Goix, France) used by oyster farmers (de Graauw, 2018)

In tidal estuaries, some fishing boats need to dock at any time of the tide and large vertical movement is anticipated by using simple piled timber jetties with high vertical poles for mooring (Fig. 24). Such piled jetties may have been around for several millennia.

Modern piled jetties can be several kilometres long in places with very fine sand where the seabed slope is mild, like in delta areas. Concrete or steel piles are driven into the seabed and a concrete or steel platform with an access deck is built on top (Fig. 25).

Fig. 25. Jetty at Idku (Egypt) for exporting LNG (Archirodon 2005)

Piling walls

Ancient timber quay walls have been used in sheltered areas and on river ports. They are usually built with vertical piles holding horizontal planks (Fig. 26). Similarly, a horizontal timber deck may be resting on piles (Alexandria)[60] (Fig. 27).

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[58] HESNARD, A., 1994.
[59] GERBER, F., 2005.
[60] DE GRAAUW, A., 2000.

Fig. 26. Timber quay wall of place Jules Verne, Marseille (Inrap 1993)

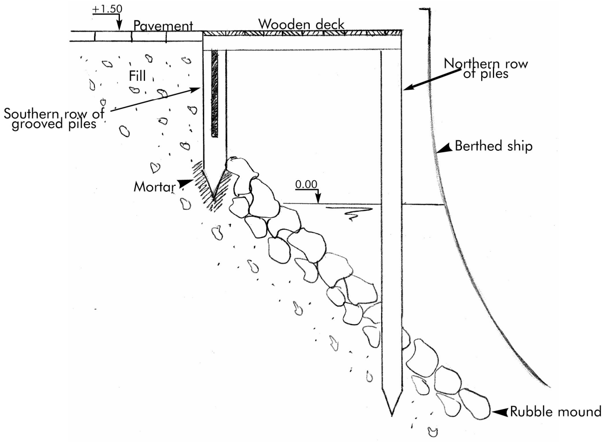

Fig. 27. Timber quay at Magnus Portus in Alexandria (de Graauw 2000)

In **Ratiatum** (Rézé, south of Nantes) the river port had a heavy-duty quay wall with piles attached to a lower beam and with flat stones placed between the piles (Fig. 28-29). Similar but less sophisticated constructions have been found at Bordeaux, Irun and London[61].

Fig. 28. River quay at Ratiatum with lower beam and piles (Mus. Le Chronographe, 2018)

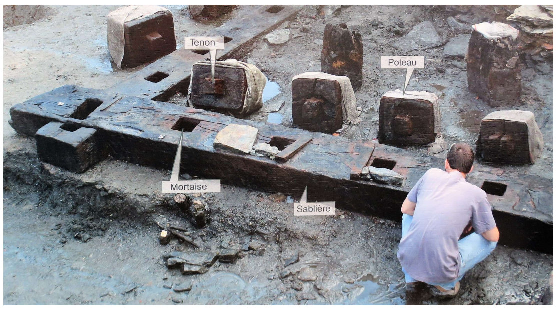

Fig. 29. River quay at Rézé showing connection between lower beam and piles (Mus. Le Chronographe, 2018)

Modern quay walls often consist of a reinforced concrete slab resting on steel or concrete piles. Oblique piles are meant to resist horizontal forces due to ships and due to possible backfilling behind the front wall (Fig. 30).

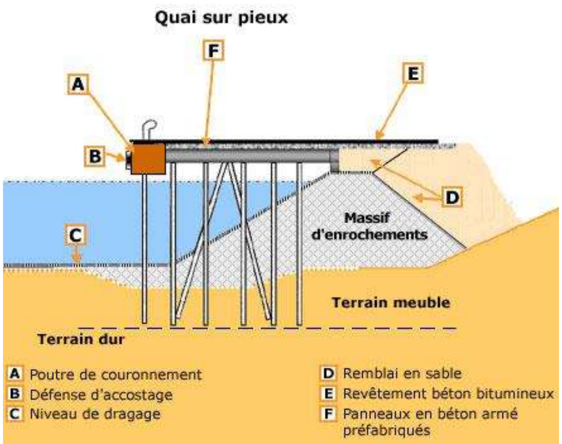

Fig. 30. Quay on piles (www.planet-tp.com)

Fig. 31. Steel sheet-piling with heavy concrete capping beam and anchoring beam (Wikipedia)

The front side, below the capping beam ("A" on Fig. 30), often consists of steel sheet-piling. The back side is then backfilled with sand. An additional anchoring beam is often used to anchor the wall into the backfill (Fig. 31).

[61] GERBER, F., 2005.

Moulded structures

This is a typical modern construction method. A **diaphragm wall** (or slurry wall) is a technique used to build reinforced concrete quays in areas of soft earth close to open water, or with a high groundwater table. No formwork is required: while a trench is excavated with an adapted narrow grab or hydrofraise to create a form for a wall (Fig. 32), it is simultaneously filled with slurry (usually a mixture of bentonite and water). The dense but liquid slurry prevents the trench from collapsing. The trench is at all times kept filled with slurry, but the liquid filling allows the excavation machinery and excavation spoil to be moved without hindrance (Fig. 33). Once a particular length of trench is reached, a reinforcing cage is lowered into the slurry-filled pit and the pit is filled with concrete from the bottom up using tremie pipes. The heavier concrete displaces the bentonite slurry, which is pumped out, filtered, and stored in tanks for use in the next wall segment, or recycled (Wikipedia)[62].

Fig. 32. Slurry-wall grab fitted on a crawler crane (Liebherr, 2018)

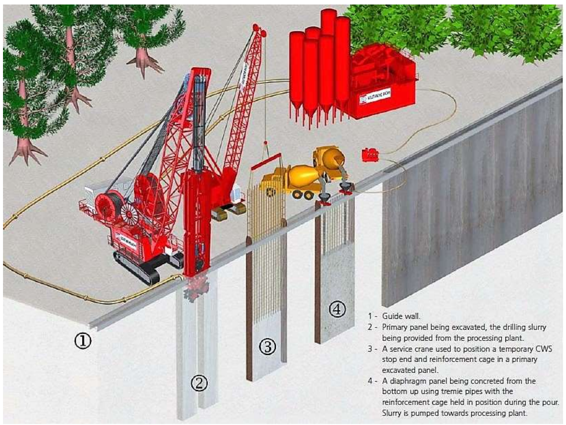

Fig. 33. Construction steps of a slurry wall (Soletanche Bachy, 2018)

Once the concrete has hardened, excavation on the sea side of the quay wall can be carried out.

This method is very cost-effective when a wall can be built on land before dredging away its sea side in order to obtain the desired quay wall and port basin. Very deep trenches up to 50 m can be reached with this method.

Even if the basic concept is different, this modern method reminds us the ancient double walls of the timber caissons filled with a semi-liquid mortar found in Area G at Caesarea Maritima (Fig. 7)[63].

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62 https://www.youtube.com/watch?v=0rl1DNduT2w

63 RABAN, A., 2009:98.

In-the-dry construction

Vitruvius described an “in-the-dry” construction method where marine concrete was not required and regular concrete could be used in case no pozzolana was available[64].
This construction method was interpreted by Dubois[65] (Fig. 34).
The watertight structure (now called a “cofferdam”) allowed water to be pumped out. However, the walls had to resist the pressure of water and shoring may have been required, even if the height of the enclosure did not have to exceed 1.5 to 2 m which was a sufficient water depth for ancient ships.

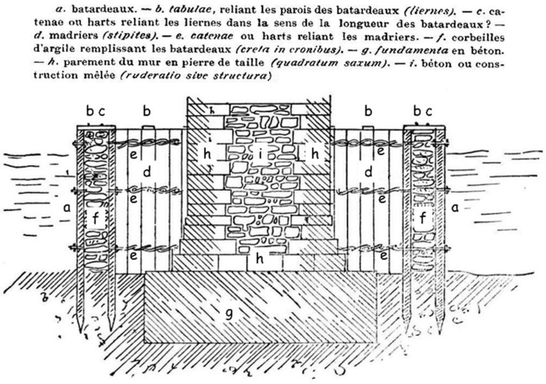

Fig. 34. Vitruvius’ cofferdam construction method (Dubois, 1902)

Moreover, large pumping capacity had to be provided depending on the permeability of the subsoil. It was therefore difficult to use this method on a sandy sea bed as water would seep into the enclosed area through the bottom and Vitruvius rightly recommended digging out the area down to the rocky substratum. He also indicated that the foundation had to be wider than the planned structure. This foundation could be a mound of concrete placed on top of the rocky bottom or on a series of timber stakes if the subsoil was unstable.

This method was mainly used to build some pilae and bridge piers in rivers.

Modern cofferdams are usually made of steel sheet-piling (Fig. 35). The impressive cofferdam shown on Fig. 36 requires much attention to avoid collapsing due to water pressure. The quasi-round shape and the massive peripheral beams provide the required strength. In addition, the deep excavation would induce much seepage from the bottom into the pit if the subsoil was not watertight (clay). Should this not be the case, then a concrete slab would have to be built as a plug on the bottom of the excavation inside the cofferdam.


Fig. 35. Cofferdam for bridge pier in river Isère (France) (Eiffage, 2017)


Fig. 36. Cofferdam on the Godavari river for the Polavaran irrigation project (Hans India 2017)

[64] VITRUVIUS, ca. 20 BC, "de Architectura", 5, 12, provides a description of this construction method using a cofferdam: “Double dams are constructed, well connected with planks and chain pieces, and the cavity between them is filled up with clay and marsh weed well rammed down. When rammed down and squeezed as close as possible, the water is emptied out with screw pumps or water wheels, and the place is emptied and dried, and the foundations excavated”, transl. Lacus Curtius.
[65] DUBOIS, C., 1902.

Rubble mound breakwaters

Rubble-mound breakwaters consist of piles of stones more or less sorted according to their unit weight: smaller stones for the core and larger stones as an armour layer protecting the core from wave attack[66] as shown in Fig. 1 (1-2).

This kind of structure has been around for over 2500 years and modern coastal engineers still build them to create harbours sheltered from wave penetration. It was widely used for breakwaters in water deeper than a few meters where positioning of ashlar headers by divers was difficult. Without going into the details of breakwater design, it can be understood easily that stability of a structure made of stones depends primarily on the stone size in relation to the strength of wave action: breakwaters in open waters exposed to storms acting on a large sea and therefore inducing high waves, must consist of larger stones than breakwaters located in sheltered areas (Fig. 37).

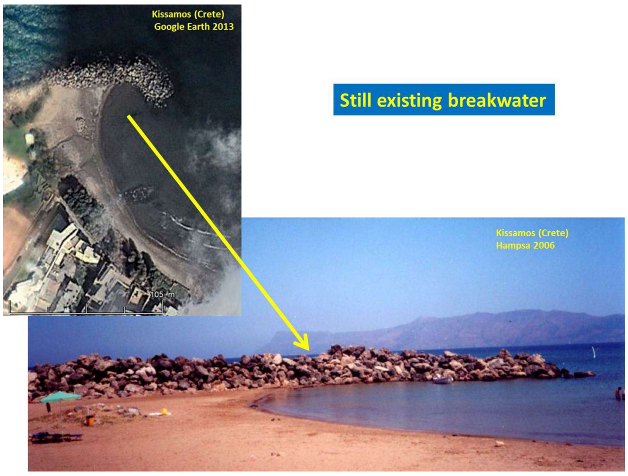

Fig. 37. Ancient rubble mound breakwater at Kissamos (Crete)
(H. Hampsa, 2006)

This is possibly the only large rubble mound breakwater that is above the sea today as it was uplifted by 6 meters during the 365 AD earthquake and therefore protected from further wave attack. It can be seen that the armour layer consists of ca. 1 m rock boulders, or around 1 to 1.5 ton. It would be interesting to check if this structure includes a core with finer material located underneath the armour layer, or if the whole structure was made of the 1 m rock still visible at its surface.

Some remarkable ancient rubble mound breakwaters can be listed as follows:

- Portus (Fiumicino, Italy): deepest section of the 3200 m long breakwaters, now inland;
- Pharos (Alexandria, Egypt): over 2300 m long, submerged in open water;
- Thapsus (Bekalta, Tunisia): about 1100 m long, submerged in open water;
- Eretria (Eretria, Evia, Greece): at least 600 m long, submerged in sheltered water;
- Paphos (Kato Paphos, Cyprus): about 600 m long, with a parallel one 200 m long, submerged in open water;
- Leptis Minor (Lamta, Tunisia): about 560 m long pier, submerged in open water;
- Leukas/Ligia (Lefkada island, Greece): about 540 m long, submerged in sheltered water;
- Pythagoreion (Samos island, Greece): about 480 m long, submerged in open water;
- Acholla (Ras Boutria, Tunisia): about 460 m long pier, submerged in open water;
- Chersonesos (Cape Agami, Egypt): about 400 m long, submerged in open water;
- Eleusis (Vlychada, Santorini): about 360 m long, submerged in open water;
- Sullecthum (Salakta, Tunisia): about 350 m long, submerged in open water;
- Tieion (Filyos, Turkey): over 350 m long, submerged in open water;
- Mytlilini (Lesbos island, Greece): about 350 m long, submerged in sheltered water;
- Sabratha (Libya): about 320 m long, submerged in open water;
- Leptis Magna (Lebda, Libya): about 300 m long, berm breakwater in open water.

The north breakwater of **Portus**[67] consists of several sections as shown above. The deepest section consists of a rubble mound which was identified by modern archaeology between 13 m and 3 m below Roman Sea Water Level (0.80 m below present Sea Water Level).
This submerged rubble mound might consist of roughly one million cubic meters of stone dumped into the sea and topped by a concrete crest-structure (pilae), as described for nearby

[66] https://www.youtube.com/watch?v=kfgf5ZmZbGo

[67] Probably built between 40 and 50 AD. See also: http://www.ancientportsantiques.com/a-few-ports/portus/

Centumcellae (Civitavecchia) by Pliny the Younger[68]. A rather sophisticated crest structure was probably found at **Alexandria Troas** (Dalyan, Turkey)[69].

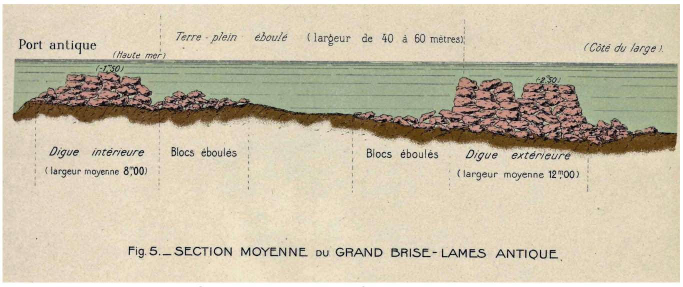

Fig. 38. Cross-section of Pharos' breakwater (Jondet, 1916)

According to Belova (2019) and Jondet (1916)[70], the main north breakwater at **Pharos**[71] with a total length of more than 2300 m consisted of two mounds on a water depth down to 10 m with 40 to 60 m in-between (Fig. 38). The crest is at 1 to 1.5 m below present sea level. The total width of the main north breakwater was therefore 60 to 80 m. Both mounds were made of large quarried blocks (2 x 2 x 1 m 'soft limestone' from local quarries).
The area between both mounds was filled with rubble which was found in some places, but in other places, it was washed away over time.
The dating of this structure is a matter of debate, but it can probably be dated between 2000 and 1000 BC, which makes it the second oldest and second largest known to date. A large modern land reclamation project covering the ancient port area is ongoing since 2016.

The main port of **Thapsus** is sheltered by the third longest known ancient breakwater. The general feeling is that this breakwater is made of Roman concrete, but much natural rock is also scattered around the site. The volume of the breakwater remains (ca. 130 000 m^3)[72] could be from a vertical breakwater made of layers of Roman concrete as well as from a rubble mound breakwater, or some kind of combination (Fig. 1, 6).

The rubble mound breakwater at Pythagoreion on the isle of **Samos** has a length of 480 m while Herodotos estimated it at "more than two stadia" (370 m) when he saw it[73]. Its largest water depth is presently ca. 14 m, but some sedimentation is likely to have occurred since Herodotos estimated it at "twenty fathoms" (37 m).

Leptis Magna's north coast is protected by what would be called today a "berm breakwater" consisting of rock that is intentionally unstable under wave action (Fig. 1, 3).

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[68] PLINY the YOUNGER, Letters, 6, 31, to Cornelianus: "a broad barge brings up a number of immense stones, which are thrown into the water, one on top of the other, and these are kept in position by their own weight, and gradually become built up into a sort of breakwater. […] Subsequently, concrete (pilae) will be added to the stones", transl. J.B. Firth (1900).

[69] FEUSER, S., 2011.

[70] JONDET, G., 1916. See also: http://www.ancientportsantiques.com/a-few-ports/alexandria-pharos-island/

[71] The island and its port are mentioned by HOMER, Odyssey, 4, 353: "Now there is an island in the surging sea in front of Egypt, and men call it Pharos, distant as far as a hollow ship runs in a whole day when the shrill wind blows fair behind her. Therein is a harbor with good anchorage, whence men launch the shapely ships into the sea, when they have drawn supplies of black water".

[72] YOUNES, A., 1997. See also: http://www.ancientportsantiques.com/a-few-ports/thapsus/

[73] NAVIS II Project (https://www2.rgzm.de/Navis2/Home/FramesE.cfm), and
HERODOTOS, Hist., 3, 60: "a breakwater in the sea enclosing the harbor, sunk one hundred and twenty feet [twenty fathoms, orgye], and more than twelve hundred feet [two stadia] in length". Transl. A. D. Godley (1920). This breakwater was probably built by Polycrates around 530 BC.

Rubble is dumped on the beach and in the sea down to a depth of around 5 m located at around 50 m of the shore (Fig. 39). Rubble is rounded on the beach and angular on the upper beach and under water. Quarry blocks smaller than 500 kg (decommissioned building blocks?) seem to have been used as a coastal protection. Their weight is not sufficient and they have been rolling in the wave breaking area during storms, which may explain their rounded shape due to abrasion[74].


Fig. 39. Berm breakwater on the north coast of Leptis Magna (de Graauw, 2000)

Modern rubble mound breakwaters usually include several layers with finer material in the core and larger rock or concrete blocks as an armour layer on the sea side for protection against wave action (Fig. 1, 1).
A concrete crest-structure, or crown wall, is often added on top of the rubble mound in order to provide access (Fig. 1, 2).
Large artificial blocks of concrete are used instead of rock on most modern rubble mound breakwaters because they generate some interlocking and are therefore more stable than rock. In addition, they are much larger and heavier (up to 50 tons, and even more for cubes, while rock does usually not exceed 10 tons) (Fig. 40).

In order to keep finer materials underneath, some filter rules must be considered[75]. This leads to several layers of rubble with decreasing size down to the core of the structure which is made of cheaper quarry run. Similarly, the whole mound is built on a geotextile in order to avoid the underlying sand to be sucked out by wave action.
The toe of the armour layer is required to stop the armour layer from sliding downwards under repeated wave action.
The crest of the breakwater is usually a large concrete structure with an “L” shape. It provides a vertical wall reducing wave overtopping, and a horizontal slab giving access for vehicles.
The lee side of rubble mound breakwaters with a crest structure are sometimes fitted with a piled jetty enabling ships to berth (e.g., oil tankers, Fig. 41).


Fig. 40. Fujairah breakwater under construction (UAE) (CLI, 2002)


Fig. 41. Oil terminal on main breakwater at Sines (Portugal) (www.landseaairmagazine.com, 2014)

[74] See also: http://www.ancientportsantiques.com/a-few-ports/leptis-magna/
[75] DE GRAAUW, A., 1984.

The modern design of a rubble mound breakwater is always tested with help of small-scale models in order to take into account the many hydraulic and structural parameters.
Design of coastal structures is based on the principle of “accepting a certain level of damage to the structure, for a certain probability of occurrence of the waves”. One could indeed accept a lot of damage for a very rare event, or very little damage for a more frequent event. For modern coastal structures, it is usually accepted to have very little damage for a one in hundred years storm event. Hence, coastal engineers will speak about the “1 in 100 years significant wave height” to define the design wave conditions[76].
A few ancient rubble mound breakwaters are still in good shape today but most are now submerged as a consequence of 2000 years of storms[77]. If a rubble mound is undersized, sooner or later a storm will occur that is able to move the armour layer. Blocks will then be moved downwards on the sea side and pushed over the crest into the lee side. After a few centuries, the rubble mound breakwater is reduced to an underwater submerged breakwater (Fig. 1, 4). Many of them are still visible on Google Earth[78].

Training walls

The ancients often looked for estuaries to shelter from the sea and to find fresh water. In this way, they solved the problem of exposure to waves but fell into another problem: the silting-up of harbours by fluvial sediment. This induced shifting of port structures from upstream to downstream, the construction of an access canal, like in Ephesus, or diversion of the river by means of a dam like in Leptis Magna. However, 75% of silted ancient harbours were abandoned, like Sharm Yanbu (Saudi Arabia) which might be the ancient Charmotas[79].

The ancient river Atax (today's river Aude) followed today's canal de la Robine leading into the Etang de Bages south of **Narbo** (Narbonne). Remains of Narbo's port were found recently near Le Castelou-Mandirac in the ancient alluvial plain of the river[80]. The port structures consist mainly of two 2 km-long parallel dikes which concentrate the river flow (they are now called training walls) to avoid unpredictable meandering near the river outlet (Fig. 42-43). River Atax/Aude had a large sediment load that settled down as soon as the flow velocity reduced at the outlet of the river. This induced a sand bar which was feared by seafarers as ships could easily be grounded there. One way to solve this problem was to keep a high flow velocity by means of training walls inducing a kind of jet effect flushing the outlet. Sediment would obviously settle down a bit further downstream and the training walls would have to be lengthened periodically, leading to a kind of canal harbour like the one found at Le Castelou-Mandirac.

[76] Wave generation and propagation are complex processes and statistics play an important role in the description of the wave climate in a given coastal location. A simple way to define a sea state is to mention its ‘significant wave height Hs’ which is defined as the average of the one third highest waves of that sea state. This Hs is considered to be close to the visual estimate which would be given by an experienced observer of the sea.
See also : http://www.ancientportsantiques.com/ancient-port-structures/design-waves/
[77] Tsunamis also destroy breakwaters: see http://www.ancientportsantiques.com/ancient-climate/tsunamis/
[78] See: http://www.ancientportsantiques.com/ancient-port-structures/remains-of-ancient-breakwaters/
[79] According to the description of Agatharchides of Cnidus, in “On the Erythrean Sea” (text lost, around 140 BC), recalled by Diodorus of Sicily (Hist, 3, 21, around 40 BC). See: http://www.ancientportsantiques.com/a-few-ports/sharm-yanbu/ .
[80] SANCHEZ, C., 2014.

Fig. 42. Layout of Narbo's canal dikes
(Cervellin, in Sanchez, 2014)

Fig. 43. Left bank of the canal in 2013
(Durand, in Sanchez, 2014)

Today's busiest European ports are **Rotterdam** on the Rhine estuary, **Antwerp** on the Scheldt and **Hamburg** on the Elbe. Rotterdam is close to the sea but Antwerp and Hamburg are around 100 km away from the sea. All three can host today's largest container ships with draughts of 15 m and lengths of 400 m. As these ports are located in tidal areas, they receive sediment both from the river and from the sea, and maintenance dredging must be carried out continuously in their harbour basins and in their access channel: 3 to 5 million m^3/year in the access channels of Rotterdam and Hamburg, but around 15 million m^3/year in Antwerp. The volume of maintenance dredging obviously depends on the over-depth required in the access channel compared to the natural river depth. The more over-depth, the more maintenance dredging.

It can be advantageous in the long term to build some structures (called training walls) that concentrate currents in order to obtain some natural flushing of the river bed. This was done on the Seine river where the port of **Rouen**, located 120 km from the sea, conducts around 5 million cubic meters per year maintenance dredging. In the second half of the 20th c. submersible training walls were built on both sides of the navigation channel (Fig. 44-45). They were made "submersible" in order to preserve tidal wetlands behind them, but they were high enough to concentrate the main river flow between them and hence minimize dredging works.

Fig. 44. River Seine estuary with north and south submersible training walls
(Google Earth, 2018)

Fig. 45. Typical tidal wetland behind a submersible training wall
(GIP Seine-Aval, 2009)

At a much smaller scale, “gabions” are used in sheltered waters e.g., for river bank protection. Today's gabions are often made of steel wire and filled with small rock (Fig. 46). This may seem a cheap way to create large units, but when the wires corrode and break, the structure disappears.

Fig. 46. River bank protection with gabions made of steel wire and filled with small rock (https://www.lacompagniedesforestiers.com)

Coastal harbours on straight coastlines

Sediment brought by rivers is usually transported by waves along the coastline on both sides of the estuary (this is called littoral drift or longshore sand transport). The direction and volume of this littoral drift is determined by the angle of incidence of waves arriving on the coastline.
This problem of littoral drift is still encountered by modern coastal engineers on almost every coastal project because the purpose of a breakwater is exactly to protect the port from wave action, hence, sand will settle down. Let’s see this in more detail.
Littoral drift is quantified by several more or less complex formulae. We mention here the most popular and simple one, as proposed by CERC in 1984 (US Army Coastal Engineering Research Center):

$$\mathbf{Q = K \,.\, H^{2.5} \,.\, \sin (2\theta)}$$

where Q is the littoral drift (in m^3/year), K is a coefficient (depending on parameters like wave steepness, sand grain-sizes, etc.), H is the wave height at breaking (in m) and θ is the angle of incidence of waves on the coastline at the breaker line (in degrees). This formula shows the importance of the wave height, as anyone would suspect. It also shows the importance of wave incidence: littoral drift is nil with frontal waves (when wave crests are parallel to the coastline, θ = 0°), it increases with wave incidence up to 45° and reduces beyond that. The average wave direction thus determines the volume of sediment transported along the coastline and a sound knowledge of the wave climate and of wave propagation to the coast is required.

The main difficulty of computation of the coastline evolution is that waves reshape the sandy sea bed. This leads to an “iterative” computation of wave refraction and diffraction: the larger the wave incidence, the larger the littoral drift and the more the sea bed is reshaped, which in turn changes the wave propagation pattern and requires a new computation, etc.

Without going into further details, it can be understood that river sediment supply will settle in front of the outlet, forming a sand bar that is feared by seafarers. It is then distributed on both sides of the river outlet, generating two curved coastlines that reduce the wave incidence with increasing distance from the estuary. The most famous example is Portus near the Tiber estuary which moved more than 4 km in offshore direction in 2000 years (Fig. 47).

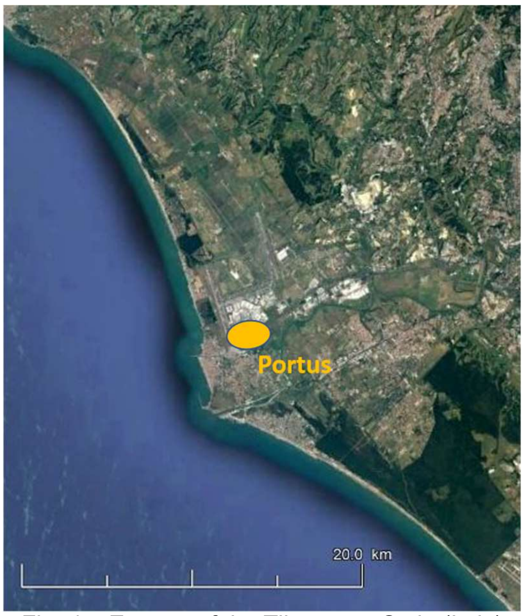

Fig. 47. Estuary of the Tiber near Ostia (Italy)

If a port is built in an area with a resulting oblique wave direction, sedimentation must be expected on one side of the port with erosion of an equal volume on the other side (Portus Claudius, Caesarea Maritima).

A partial opening of the breakwater (e.g., arched breakwater at Puteoli, Centumcellae (Italy)) does not change much to the problem of silting-up as the activator of littoral drift is wave action. However, a canal through the breakwater at the average wave-breaking line where a current is generated by wave set-up may help to flush the port basin and the port entrance channel (e.g., Aptoucha (El-Hanieh), Libya, Fig. 48-49), Caesarea Maritima (Israel), Sidon (Lebanon)).

Fig. 48. El-Hanieh (Libya) western promontory with two flushing channels (Google Earth 18/3/2009)


Fig. 49. El-Hanieh (Libya) northern flushing channel (Misson, 5/10/2010)

It can also be understood that oblique waves generate an oblique coastline that tends to be oriented parallel to the wave crests, e.g., a tombolo is created behind an obstacle when it is reached by a sand spit, like at the peninsulas of Giens (France), and Argentario-Orbetello (Italy). Ancient places like Tyre, Pharos, Peniscola, Gijon (Spain) and Peniche (Portugal) are also the result of large-scale tombolo development. Many examples exist at a smaller scale like at Emporia (Spain, Fig. 50)


Fig. 50. Emporia’s tombolo generated by Las Muscleres Grosses islets (Spain)

Similarly, for a bay between two rocky promontories: the shape of the bay will be curved corresponding to wave spreading due to refraction on the sea bed and to diffraction around the promontories (e.g., bays of Cavalaire, Fig. 51, Alexandria’s Magnus Portus and so many others). It is usually recommended to keep such a beach free of any hard structures and to build ports on the promontories instead.

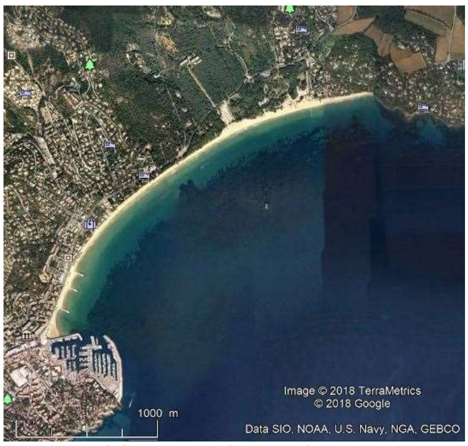

Fig. 51. Bay of Cavalaire (France) with curved beach between promontories.

For a wave incidence larger than 45° with respect to the coastline, a sand spit develops, e.g., Flèche de La Gracieuse near Fos where the modern port of Marseille has located its largest container and oil terminals (Fig. 52). The sand spit usually ends with a hook due to wave diffraction. Sometimes successive hooks can be seen as a result of long-term evolution. A sand spit is often very narrow (say 20-50 m) and much effort is devoted to avoid its break-through during storms if it protects major infrastructures like at Fos. This author suggests a similar sand spit may have protected the entrance of Marius' canal[81].

Fig. 52. Flèche de La Gracieuse sand spit near Fos (France)

Our aim is not to summarise here one year of hydraulic courses for coastal engineers within one page[82], but

to stress the importance of wave action,
and to note that this knowledge is only available since the mid-20th c.

[81] See also: http://www.ancientportsantiques.com/a-few-ports/marius-canal-fossae-marianae/
[82] KOMAR, P., 1998. See also: Prof Leo van Rijn's https://www.leovanrijn-sediment.com/index.html

Conclusions

This paper aims to compare ancient and modern port structures hoping that the modern can help us in a better understanding of the ancient.

We may consider that most natural shelters were used in Roman times and around 50% of ancient ports persist today within 1500 m of their ancient location. Some major ancient ports have been built in places without any natural shelter, for strategic or economic reasons (Portus Claudius, Caesarea Maritima) and this is common rule for new modern ports. It might even be said that any excellent natural shelter that is not yet identified as an ancient port should be searched![83].

Sloping rubble mound breakwaters have been around for 2500 years and most of them are now submerged because of wave action and sea water level rise. Modern rubble mound breakwaters are protected by an armour layer consisting of large concrete blocks placed on top of filter layers that keep underlying fine material in place. They are designed to resist a one-hundred-year storm and it is therefore not expected that they will survive more than a few centuries.

Vertical structures are the oldest maritime structures. They were made of ashlar headers and/or stretchers in water depths of a few meters that were easily reachable by divers (Levantine coast). Inside harbours and on rivers, vertical quay walls were made of timber (Marseille, Bordeaux, Rézé). Piled jetties were also made of timber (Marseille, Istanbul). Similar modern structures are made of steel and/or reinforced concrete and can therefore be higher and deeper.

The spreading of the concept of marine concrete (hydraulic lime concrete) using pozzolana by the Romans in the 1st c. BC, is a major step forward in marine works as it allowed concrete to set under water. It became possible to pour marine concrete into formworks such as in-situ-made and floating prefabricated timber caissons. Today's floating caissons are made of reinforced concrete and filled with loose rubble or sand; they are used to build vertical breakwaters and some large quay walls. Even larger floating structures are built for the offshore industry (oil & gas and wind farms) thanks to the prestressed-concrete technology.

Pilae are among the vertical structures that could be erected with marine concrete poured into a formwork. Remains have been found in southern Italy showing a dotted line of defence against wave action, possibly arched breakwaters. This type of breakwater is not used anymore, but it may have been introduced by the Romans to provide limited shelter against waves while keeping openings for water flows flushing the port and its entrance channel from fine sediment. However, a single canal through a massive breakwater seems to have been more efficient for this purpose.

Harbours show a general trend to silting-up because they provide shelter not only for ships but also for sediment. Ports built on sandy coasts receive sand from the littoral drift activated by oblique incoming waves. Ports in estuaries receive sediment from the river. Oceanic tides and even small Mediterranean water level fluctuations due to wind friction on the water surface inducing its tilting with displacement of considerable volumes of water, provide fine marine sediment to harbour basins. Around 15% of the ancient Mediterranean harbours are now silted-up and around 75% of them are not used anymore today.
Fortunately, this silting-up contains essential information for today's geo-archaeologists.

Most of today's concepts for maritime structures were already existing in Roman times and it seems that little progress was made until the 18th c. when large maritime structures started to be built again.
The combination of concrete and steel enables modern engineers to build higher, deeper and larger than Roman engineers could dream of, but some modern structures may not last as long as some Roman structures, especially in salt water …

[83] See also: http://www.ancientportsantiques.com/a-few-ports/potential-ancient-harbours/

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Bios

Arthur de Graauw is a French/Dutch coastal engineer employed by a French Consulting firm, SOGREAH (now ARTELIA) until the end of 2015.
He graduated from Delft University of Technology in 1976 in civil engineering of coastal structures and areas. He used many hydraulic scale models and mathematical models in his work. He worked on numerous projects related to coastal erosion, industrial ports and marinas in the Mediterranean area including Lebanon, Gaza, Egypt, Libya, Tunisia and France.
From 2002 to 2015 he managed the Port Revel ship handling training centre using manned models where maritime pilots from all over the world come for training. This led him to work with the Panama Canal extension.
He has been active in ancient ports since 1998 and created a new catalogue of ancient ports encompassing over 5000 places. He is the webmaster of www.AncientPortsAntiques.com focusing on many technical aspects of ancient ports.

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APPENDIX 1: List of known pilae

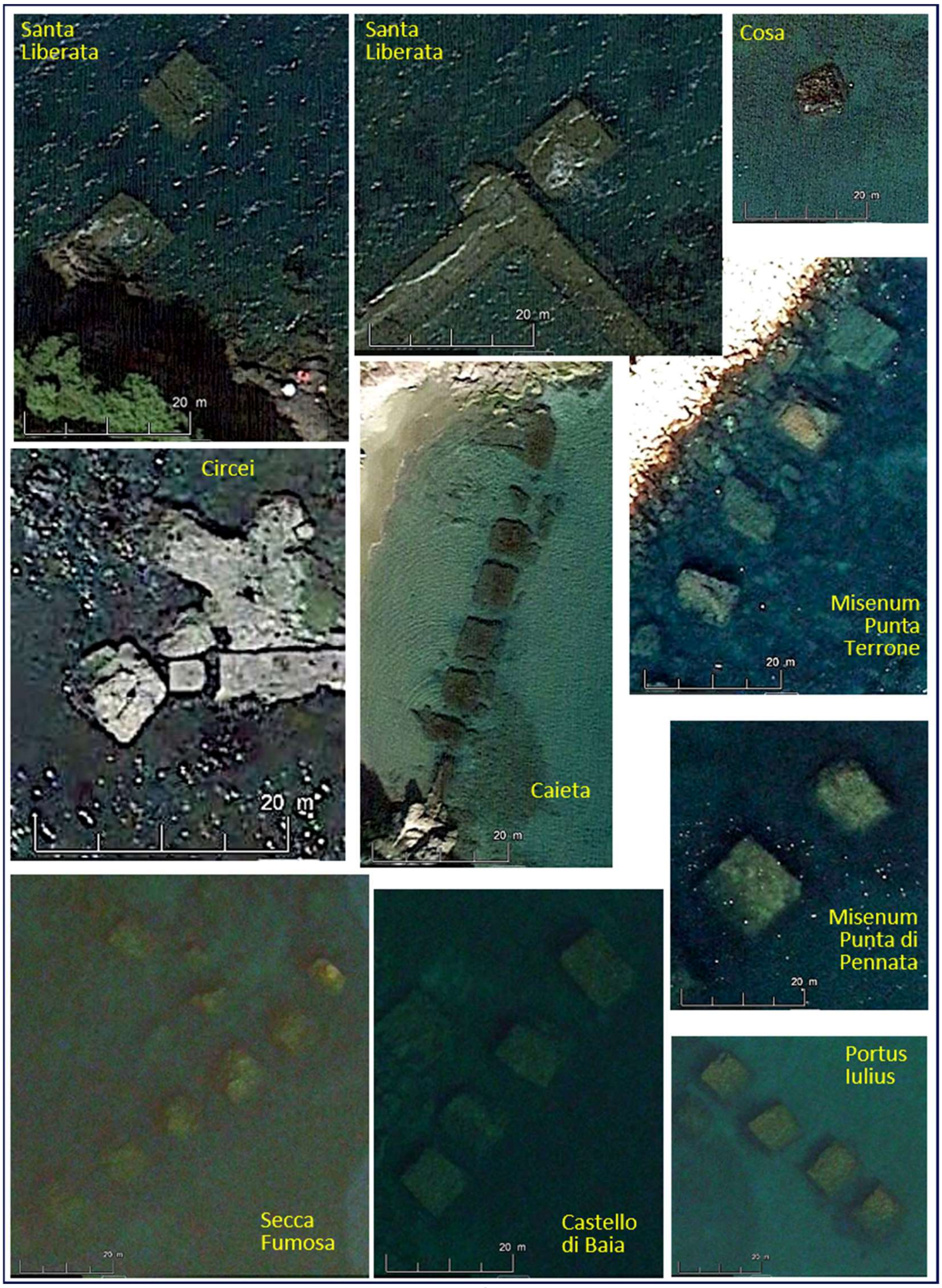
According to Brandon et al. (2014), the Latin word *pila* designates a “large mass of concrete, generally square in plan, and often a cube or upright rectangular prism in shape”. Hence, piles made of ashlar (e.g. Fossae Marianae piles) and masses of marine concrete that are not nearly-cubic (e.g. breakwaters of Portus, Antium & Terracina, the quay of Les Laurons and numerous fishponds-*piscinae*) are not listed hereunder.

N°	Ancient name	Modern name	Country	Length (m)	Width (m)
428.1	Tarraco, Tarrakon	Tarragona, Roman breakwater demolished in 1843	Spain		
666	Massalia Graecorum, Lacydon	Marseille, Vieux Port, place Jules Verne	France South		
704	Forum Julii, Forum Julium	Roman naval base at Frejus, with a pila near the Lanterne d'Auguste	France South	6.75	6.2
881	Domitiana positio, Portus Domitianus	Roman villa at Santa Liberata, on the peninsula of Argentario	Italy West	9-10	8
891	Cosa, Cossae, Portus Herculis Cosanus, Etruscan Cusi, Cuthi	Ansedonia	Italy West	6.5	6
900	Centumcellae	Civitavecchia, Molo del Lazzaretto	Italy West		
949	Astura, Storas	Torre Astura	Italy West		
953	Port of Circei, Circe	inside Lago di Paola, with access via canal and breakwaters	Italy West	6.5	6
962	Caiete, Caieta, Caeatas, Etruscan Caithi	Spiaggia di Fontania, at Gaeta	Italy West	6	5.5
981	Misenos, Misenum, Misene	Punta Terrone, pilae of the southern breakwater	Italy West	8-9	6-7
982	Misenos, Misenum, Misene	Punta di Pennata, pilae of the northern breakwater	Italy West	12	10
984	Misenos, Misenum, Misene	Punta di Pennata, pilae within the harbour	Italy West		
Brandon		Castello Aragonese di Baia	Italy West	8.5-10.5	7-7.5
Brandon		Cantieri di Baia	Italy West	ca. 8	ca. 7
986	Baiae, Baïes, Portus Baianus, with connection to Lacus Baianus	Baia, two concrete moles over 200 m long	Italy West		
Brandon		Villa dei Pisoni	Italy West		
Brandon		Secca Fumosa is not a port but some kind of platform, with opus reticulatum facing	Italy West	8	8
987	Portus Iulius, Julius, port of Julien, with connection to Lacus Lucrinus	Lucrino, two concrete moles over 200 m long	Italy West	8	8
Brandon	Portus Iulius, Julius, port of Julien, with connection to Lacus Lucrinus	East of eastern breakwater	Italy West	5.5	5
991	Puteoli, Dikaiarcheia, Dicearque, in the Campi Phlegraei volcano district	Pozzuoli, Pouzzoles, Puteoles, in the Campi Flegrei volcano district, pilae of arched mole are under modern breakwater	Italy West	12-15	8-15
Brandon	Puteoli, Dikaiarcheia, Dicearque, in the Campi Phlegraei volcano district	Pozzuoli, Pouzzoles, Puteoles, east of modern breakwater; possibly, the largest known concentration of pilae	Italy West	10	10
993	Nesis	Nisida, very large pila of over 1500 m^3, with opus reticulatum facing	Italy West	14.5	14.5
Brandon	Imperial Villa of Pausilypon	Gaiola	Italy West		
994	Imperial Villa of Pausilypon	Imperial villa at Posillipo	Italy West	10	7

994.1	Imperial Villa of Pausilypon	Palazzo degli Spiriti	Italy West	7.5	6
995	Imperial Villa of Pausilypon	Pollion's villa at Porto Marechiaro	Italy West	14	5
Brandon	Imperial Villa of Pausilypon	Villa Rosebery	Italy West		
997	Neapolis	Naples, Piazza Municipio, offshore Roman quay made with timber caissons	Italy West		
1009	Capraria, Capreae insula	Bagni di Tiberio, near Marina Grande on the isle of Capri	Italy West	7	4
1010	Capraria, Capreae insula	Palazzo a Mare, near Marina Grande on the isle of Capri	Italy West	11	8
1011	Capraria, Capreae insula	Scoglio del Monacone, near the isle of Capri	Italy West		
1013.1	Seirenoussai nesoi, Anthemoessa insulae, Anthemuse, possible Siren islands, no stopover for Odysseus	Isola di Gallo Lungo	Italy West		
1017	Vietri	Punta Fuenti, near Vietri sul Mare	Italy West	12	10
1023		San Marco di Castellabate	Italy West	?	4.5
1028	Scidrus	Roman villa at Cammerelle, near Sapri	Italy West	8	5.5
1246	Hadrianou Hormos, port of Lupiae, Miltopiae?	Porto Adriano, at San Cataldo near Lecce; concrete poured into ashlar cells	Italy Adriatic	?	12
1252	Gnathia	Egnazia, with several pilae, one with opus reticulatum facing	Italy Adriatic	5	3.5
1295	port of Hatria, Adria	Torre del Cerrano, with several pilae	Italy Adriatic		
3328	Side, Sida	Selimiye, with possible ancient lighthouse	TR: South	?	7.5
3377	Soles, Soli, Soloi, Pompeiopolis	Mezitli, West of Mersin; concrete poured into ashlar cells	TR: South	?	15
3492	Caesarea Palaestinae, Cesaree, Ace, Sebastos	Qesaria, Caesarea Maritima, Roman port of Herod, built from 21 to 10 BC, with Drusion lighthouse; concrete poured into timber caissons	Israel	14	7
3498	Apollonia, Sozousa	Arsuf, crusader castle	Israel		
3934	Alexandria, Magnus Portus and its Pharos	Alexandria, Antirhodos: concrete poured into timber caissons	Egypt: Med Sea	15	8
Brandon	Alexandria	Alexandria, SE of Fort Qait Bey, dock Ball Trap	Egypt: Med Sea		
4076	Leptis Magna, Lepcis Magna, Lepcitani Septimiani	Leptis Magna, Lepcis Magna, eastern outer breakwater	Libya		
4137	Thapsus	Ras Dimass, near Bekalta South of Monastir, large breakwater of the South port, with concrete poured into timber caissons and possible lighthouse	Tunisia		
4146	Horrea Caelia, Heraklea	Hergla	Tunisia	3	3
Brandon	Carthago, Carthagine, Punic Qart Hadasht, Knyn, port of Salammbo	Carthago, commercial port, Neptune block	Tunisia	18	9
4237	Thapsa, Tipasa	Tipaza, sheltered by two islets	Algeria	10	3
4243	Caesarea Mauretaniae, Cesaree de Mauretanie, Iol	Cherchel, western basin, Roman naval base	Algeria	8	6

Most of them were listed and studied by Brandon et al. (2014).

Pilae seen on Google Earth

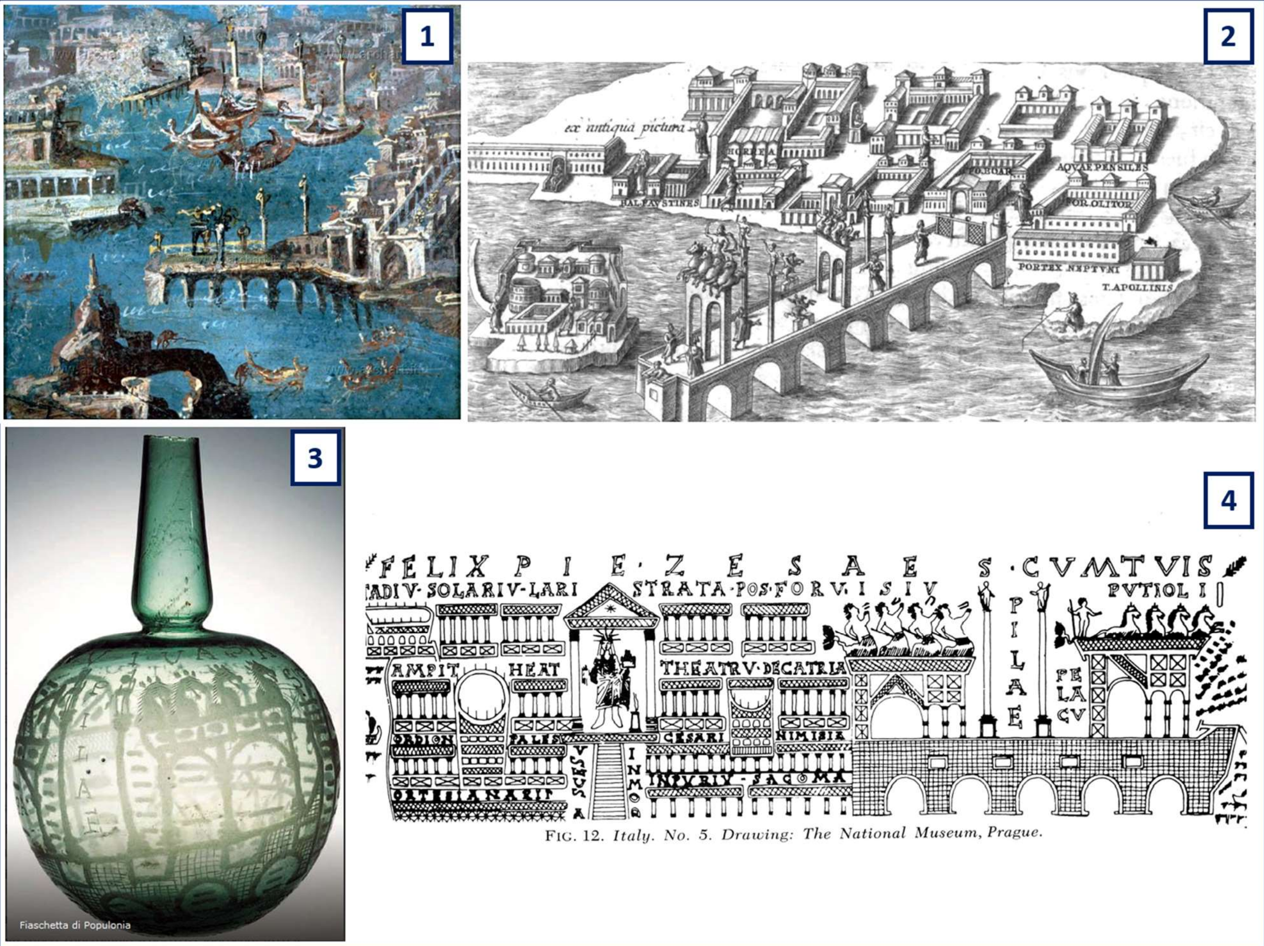


Pilae seen on Google Earth

Pilae seen on Google Earth

APPENDIX 2: An arched mole at Puteoli: jetty or breakwater?

Puteoli (now Pozzuoli) was a major Roman port. It was sheltered by the most famous arched mole. This structure was buried under the modern breakwater (!) but it was still visible in the 19th c. and known as “Molo Caligoliano”. It was represented on several supports:



Ancient pictures of the Puteoli arched breakwater:

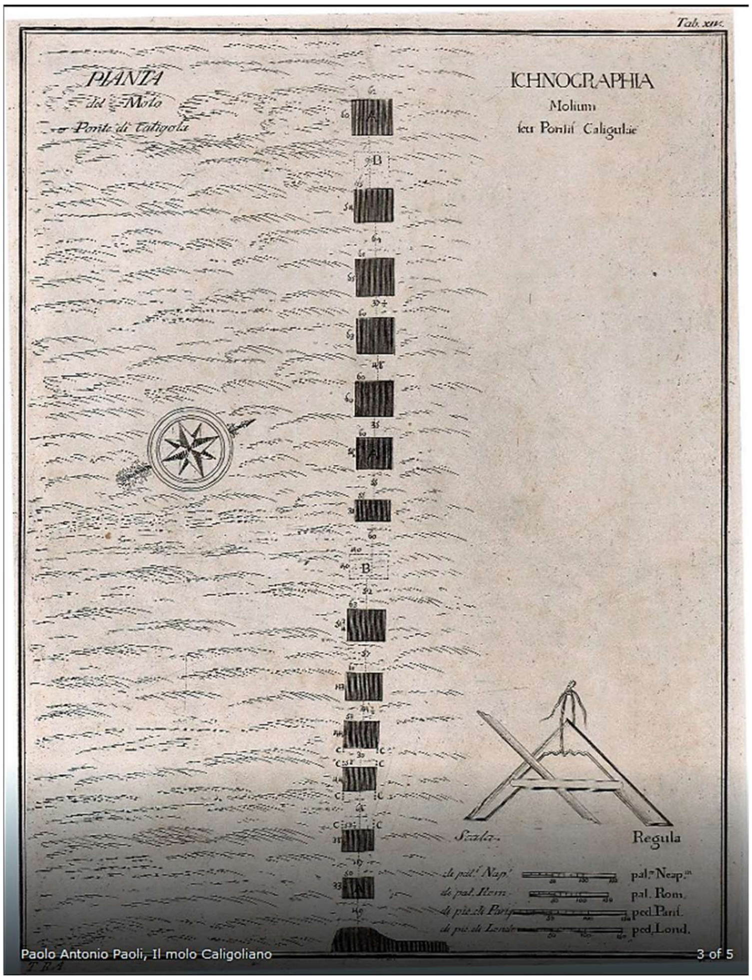
1: Fresco at Villa Stabiae, Pompei (1st c.) (source: http://www.marine-antique.net/Port-de-la-maison-de-Stabie-Pompei).
2: “Il Designo Bellori”, drawing by Pietro Santi Bartoli after a 3rd c. fresco found at Esquilino (Rome) (now vanished) and published by Bellori in 1673 in his "Fragmenta Vestigii Veteris Romae".
3: Souvenir glass bottle known as Fiascetta di Populonia showing the pilae (4th c.) (source: http://www.archeoflegrei.it/i-souvenir-di-puteoli/).
4: Souvenir glass flask kept at the National Museum of Prague and showing the pilae (4th c.) (source: https://web.uvic.ca)
See also: Picard, C. (1959) « Pouzzoles et le paysage portuaire », Latomus, T. 18, Fasc. 1, pp. 23-51.

Modern pictures of the Puteoli arched breakwater:

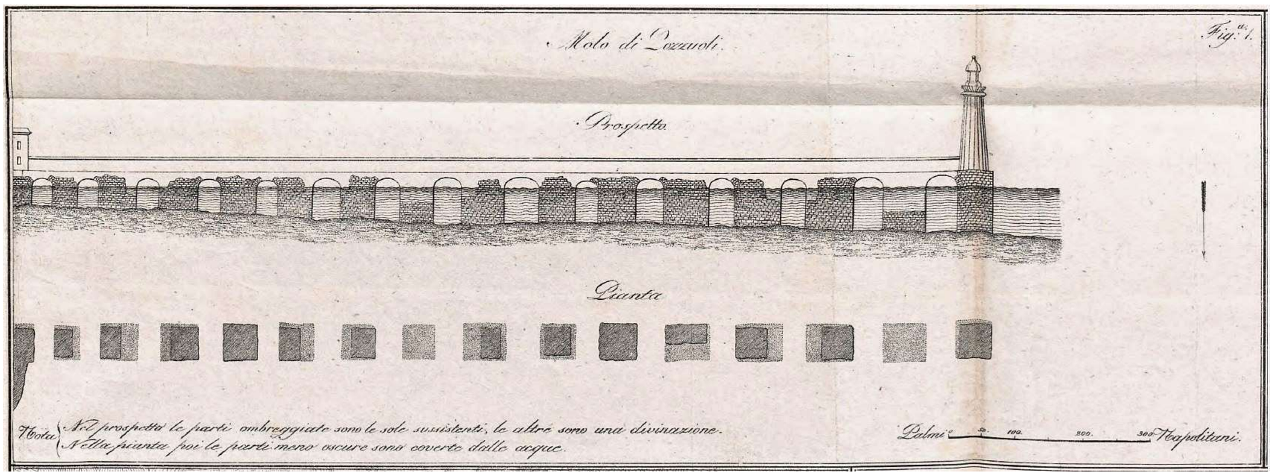
1: Castrum Puteolanum in the 17th c. (?) (detail) (source: http://www.archeoflegrei.it/i-castra-flegrei/)
2: Paoli (1768) (source: http://www.archeoflegrei.it/portodiputeoli/)
3: Morghen (1769) (source: https://www.e-rara.ch/zut/content/pageview/14428247)
4: Hamilton (1776) (source: https://commons.wikimedia.org/wiki/File:William_Hamilton_-_Campi_Phlegraei,_Pozzuoli.jpg)
5: Smargiassi (ca. 1840) (source: http://www.artvalue.com/)
6: Leitch (1840) (source: http://www.antiquemapsandprints.com).

It can be seen from the dates of these pictures that the arches were still in place in the 19th century. They were covered by a modern breakwater in the early 20th century.

Paolo Antonio PAOLI, provided the dimensions of the ancient arched structure in his “Antichita di Pozzuoli” in 1768 (with some later editions, including Giuliano DE FAZIO in 1828).
(source: http://www.archeoflegrei.it/portodiputeoli/):



Pilae at Pozzuoli, after Paoli (1768)



Pilae at Pozzuoli, after De Fazio (1828)

The drawings show 15 pilae (including 2 submerged pilae) over a distance of 372 m (acc. to C. Dubois, 1907[84]). The largest pilae of ca. 15 x 15 m are at the offshore end of the structure. The

[84] DUBOIS, C., 1907, « Pouzzoles Antique (Histoire et Topographie) », Paris. He was one of the last observers of the ancient breakwater as he visited the place during construction of the modern breakwater on top of the ancient one. He estimates that many arches were 10 m wide, and that most pilae were 16 x 16 m. They were made of marine concrete for their underwater part and of dry masonry for their emerged part (that was also underwater when Charles Dubois saw it, because of a ca. 2 m subsidence). He also suggested a double row of pilae in a staggered arrangement, but archaeological evidence is poor.

nearshore pila is somewhat smaller: ca. 8 x 12 m. The opening between adjacent pilae (8 to 11 m) varies from 0.5 to 0.9 pila width, which is close to the values found for Portus Iulius and Misenum.

The area north of the structure had to be protected from waves incoming from south and the arched structure cannot have been very efficient as a breakwater. On the other hand, the massiveness and the height of this structure above the sea water level makes it even less acceptable as a simple jetty for loading/unloading ships, even if some mooring stones have been found.