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 jetties1, 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.

Modern coastal engineers like to distinguish breakwaters2 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 breakwaters and quay walls were often built on what we would call today ‘very shallow water’3.

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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)
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).
using vertical structures (ashlar⁴) 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.

![Diagram of breakwaters](image)

**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) …

![Chronology of civilizations](image)

**Fig. 2. Chronology of civilizations acc. to Inman⁶**

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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.

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 stones 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. In the Gulf, Mesopotamians were sailing to the Indus valley and to East Africa via Dilmun (Bahrein) and Magan (Oman).

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 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.

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), Marriner (2017), Morhange (2016) and Oleson (2015). For a complete overview on ancient seafaring, see Danny Lee Davis (2009).

The oldest known seaport structure (in 2018) is the wadi el-Jarf breakwater in the Gulf of Suez (ca. 2570 BC, Khufu-Cheops). This structure is ca. 325 m long and ca. 6 m wide. The port of Byblos (Lebanon) is from the same period, but it is located inside a natural cove with no known port structures. 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.

Anchorages more or less sheltered by offshore ridges were used on the Levantine coast in the 2nd millennium BC: Arwad (Syria), Beirut, Sidon, Sarepta, Tyre (Lebanon). In Yavne-Yam (Israel) submerged boulders may have been used to improve the shelter.

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

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.

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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 TALLET, P. and MAROUARD, G., 2016: Khufu-Cheops is therefore a precursor, not only for his Great Pyramid, but also for his maritime works.
15 JONDET, G., 1916; Leopold SAVILE, 1940; Raymond WEILL, 1916.
The next oldest port structure is the Sidon north breakwater (ca. 1700-1500 BC), which is 230 m long with large headers up to 5 m long.

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). A possible Minoan twin-slipway with 2 galleries of 5-5.50 x 35-40 m is located at Nirou Khani (Crete). Mycenaean ports on the Peloponnesus also date from this period: Epidauros, Egina, Asini, Tyrins, Gytheion, Pylos.

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

- Dor (Israel, ca. 1200 BC) with a shallow water quay, 35 m long made of large ca. 1 x 1 x 3 m ashlar headers facing the sea,
- Tabbat el-Hammam breakwater (Syria, ca. 900 BC, 160 x 8 m),
- Tyre (Lebanon, ca. 800 BC, 70 x 12 m),
- Athlit breakwater (Israel, ca. 700 BC, 130 x 10 m).

The three latter breakwaters are made of ashlar headers ca. 0.5-0.7 x 0.5-0.7 x 1-2 m. These early breakwaters consist of two ashlar vertical walls with interspace filled with rubble. However, this type of structure was still built much later in the 3rd c. BC (Amathous in Cyprus, 380 m with 3 m headers) and in the 2nd c. AD (Leptiminus in Tunisia, 370 m with 1 m headers). They even re-emerged in the 18th c. when international sea-borne trade asked for them again.

The Samos breakwater (ca. 530 BC) described by Herodotos (Hist, 3, 44-60) is 480 m long, consisting of a rubble mound. 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, more than 3200 m for both breakwaters). 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 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 22 and 10 BC. Also this construction method is still used by modern engineers.

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.

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\(^31\). A similar but smaller structure was found at **Athlit**. Ashlar headers of 0.7 x 0.7 x 3 m were found in **Amathous** (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)](image1)

![Fig. 4. Roman quay wall at Marseille, built with ashlar stretchers (Inrap, 2006)](image2)

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\(^32\) (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).

![Fig. 5. Timber caisson acc. to Brandon (2014)](image3)

![Fig. 6. Portus' north breakwater showing imprints of transverse caisson beams (de Graauw, 2011)](image4)

This type of structure was used also as a massive concrete jetty at **Cosa** inside the harbour basin protected by a rubble mound breakwater\(^33\).

\(^{31}\) **NOUREDDINE, I., 2010.**

\(^{32}\) **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).**

\(^{33}\) **McCANN, A-M., et al., 1987.**
Timber caissons could also be prefabricated elsewhere and floated to the final location where they would be filled with marine concrete (Fig. 7). This construction method was used in 20 to 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 archaeology34.

In the 6th c. AD, Procopius’ description of the Byzantine Hieron35 breakwaters (Bosphorus) 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 conditions36 (Fig. 8).

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).

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34 OLESON, J., et al., 2014.
35 PROCOPIUS, 6th c. AD, Buildings, 1, 11, speaking about Justinian’s works in the 6th c.: “He prepared great numbers of what are called "chesets" 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 cribs 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.
36 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.
The **Wadi el-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.

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\(^{37}\).

Nearly vertical blockwork walls with rubble infill placed on an underwater rubble mound were built in tidal areas in the 19\(^{th}\) c. (e.g. Alderney, one of the Anglo-Norman Islands, Fig. 11)\(^{38}\).

However, most modern vertical breakwaters on deeper water (say 15 to 50 m) are built by means of monolithic reinforced concrete\(^{39}\) 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 foundation layer\(^{40}\). 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

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\(^{37}\) [https://www.youtube.com/watch?v=lnYIGAnx1mY](https://www.youtube.com/watch?v=lnYIGAnx1mY)

\(^{38}\) ALLSOP, W., et al., 2017.

\(^{39}\) Marine concrete was rediscovered by John Smeaton (1756) and was followed by the invention of reinforced concrete by Joseph Monier (1867).


\(^{40}\) [https://www.youtube.com/watch?v=iKeGKYBOK50](https://www.youtube.com/watch?v=iKeGKYBOK50)
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\textsuperscript{41}.

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\textsuperscript{43}.

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 18 wave-absorbing 27 m high caissons.

\textsuperscript{41} TAKAHASHI, S, 2002.
\textsuperscript{42} US ARMY CORPS of ENGINEERS, 2012.
\textsuperscript{43} EUROTOP, 2016.
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\(^{44}\) (Fig. 16).

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

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\(^{45}\) (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.

![Fig. 17. Brandon’s interpretation of Vitruvius’ method (Oleson, 2014)](image)

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

\(^{44}\) DE GRAAUW, A., 2000.

\(^{45}\) 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.
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)](image)

The arches are supported by massive piers, which are made of stone or concrete. According to Oleson 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". An arched structure was called *opus pilarum*.

The ratio of pier width over opening between adjacent piers 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 Oleson et al. (2014) in Brindisi.

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)](image)

The following conclusions can be drawn:
Most sites with pilae are located in Italy (32 out of 45), especially around Naples (25 sites from Caieta to Sapri), which is no wonder as the pozzolana required for underwater pila construction originated from this area.

The average dimensions of the measured pilae are 9.3 m x 7.3 m: nearly square. The average horizontal surface is 41 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.

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 (Lucrino): opening = 0.7 pila width
- Misenum: opening = 1 to 1.5 pila widths

This ratio 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 the arches were probably still in place in the 17th 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). 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.

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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The following hypothetical mole structure has therefore been proposed by the author47 (Fig. 22):

![Hypothetical longitudinal section of Portus’ north breakwater](image)

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

The eastern 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 …

**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 timber piled 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 dock48 and in Bordeaux49.

![Yenikapi excavations](image)

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.

49 GERBER, F., 2005.
In tidal areas, some fishing boats need to dock at any time of the tide and large vertical movement is anticipated by using simple timber piled 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).

**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)\(^{50}\) (Fig. 27).

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\(^{51}\).

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\(^{50}\) DE GRAAUW, A., 2000.

\(^{51}\) GERBER, F., 2005.
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).

The front side, below the capping beam ("A" on the picture above), 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).

**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).\(^{52}\)

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\(^{52}\) [https://www.youtube.com/watch?v=0rl1DNduT2w](https://www.youtube.com/watch?v=0rl1DNduT2w)
Once the concrete has hardened, excavation on the sea side of the quay wall can proceed.

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.

**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. This construction method was interpreted by Dubois (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.

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.

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53 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.

54 DUBOIS, C., 1902.
Modern cofferdams are usually made of steel sheet-piling (Fig. 35). The impressive cofferdam shown here requires much attention to avoid collapsing due to water pressure (Fig. 36). 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)

**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 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. Rubble mound breakwater at Kissamos (Crete)**
(H. Hampsa, 2006)

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55 [https://www.youtube.com/watch?v=kfgf5ZmZbGo](https://www.youtube.com/watch?v=kfgf5ZmZbGo)
Some remarkable ancient rubble mound breakwaters can be listed as follows:

- Portus (Fiumicino, Italy): over 3200 m long, now inland;
- Pharos (Alexandria, Egypt): over 2300 m long, submerged in open water;
- Thapsus (Bekalta, Tunisia): about 870 m long, submerged in open 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;
- Sullecthum (Salakta, Tunisia): about 350 m long, submerged in open water;
- Tienon (Filyos, Turkey): over 350 m long, submerged in open water;
- Mytilinii (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 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 as described for nearby Centumcellae (Civitavecchia) by Pliny the Younger.

According to Jondet (1916), the main north breakwater at Pharos with a total length of more than 2300 m consisted of two rubble mounds on a water depth of 4 to 5 m with 40 to 60 m in-between (Fig. 38). The total width of the main north breakwater was therefore 60 to 80 m. Both rubble mounds were made of large rocks (2 to 3 m ‘soft limestone’ from local quarries).

The area between both rubble mounds was filled with sand which was found by Jondet in some places, but in other places, sand has been washed away over time. The crest of the breakwater was covered with 2 to 3 m rock slabs.

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$^3$) 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.

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56 Probably built between 40 and 50 AD. See also: http://www.ancientportsantiques.com/a-few-ports/portus/
57 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”, transl. J.B. Firth (1900).
58 JONDET, G., 1916. See also: http://www.ancientportsantiques.com/a-few-ports/alexandria-pharos-island/
59 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”.
60 YOUNES, A., 1997. See also: http://www.ancientportsantiques.com/a-few-ports/thapsus/
The rubble mound breakwater at Pythagoreion on the isle of Samos has a length of 480 m while Herodotos estimated it at “more than 1200 ft” (370 m) when he saw it\textsuperscript{61}. Its largest water depth is presently ca. 14 m, but some sedimentation is likely to have occurred since Herodotos estimated it at 120 ft (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). 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\textsuperscript{62}.

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\textsuperscript{63}. 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).

\textsuperscript{61} NAVIS II Project (\url{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, and more than twelve hundred feet in length”. Transl. A. D. Godley (1920).

\textsuperscript{62} See also: \url{http://www.ancientportsantiques.com/a-few-ports/leptis-magna/}

\textsuperscript{63} 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 conditions64. 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. 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 Earth65.

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 sediment66. 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.

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 river67. 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.

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64 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’ 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/


66 Many cases of harbour sedimentation are known, but we would like to emphasise Sharm Yanbu (Saudi Arabia) which might be the site described by 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/.

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.

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

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

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 m³/year in the access channels of Rotterdam and Hamburg, but around 15 million 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)](image)

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

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). 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):

\[ Q = K \cdot H^{2.5} \cdot \sin(2\theta) \]

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 \( \theta \) 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, \( \theta = 0° \)), 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).

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 (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)](image)

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

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 because of wave diffraction, like at the peninsulas of Giens (France), and Argentario-Orbetello (Italy), or at a smaller scale at Emporia (Spain, Fig. 50). Ancient places like Tyre, Pharos, Peniscola and Gijon (Spain), and Peniche (Portugal) are also the result of large-scale tombolo development.

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

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.](image)
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.

Our aim is not to summarise here one year of hydraulic courses for coastal engineers within one page, but to stress the importance of wave action and to note that this knowledge is only available since the mid-20th c.

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68 See also: [http://www.ancientportsantiques.com/a-few-ports/marius-canal-fossae-marianae/](http://www.ancientportsantiques.com/a-few-ports/marius-canal-fossae-marianae/)
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, but some major ports have been built in places without any natural shelter, for strategic or economic reasons (Portus Claudius, Caesarea Maritima) and this is a 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!\(^70\)

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 1\(^{st}\) 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 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. 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 18\(^{th}\) 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 …

\(^{70}\) See also: [http://www.ancientportsantiques.com/a-few-ports/potential-ancient-harbours/](http://www.ancientportsantiques.com/a-few-ports/potential-ancient-harbours/)
Acknowledgements

I am deeply grateful to Pascal Arnaud for having challenged me on this subject and for providing me with support. I am also much indebted to Leopoldo Franco and William Allsop for their comments and suggestions. I also wish to thank the Wikipedia community and the Google Earth team for providing so much useful information and pictures, hoping this will stay free of charge in the future.

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 nearly 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 Oleson 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 prismatic (e.g. Portus breakwaters) are not listed here.

<table>
<thead>
<tr>
<th>No.</th>
<th>Ancient name</th>
<th>Modern name</th>
<th>Country</th>
<th>Length (m)</th>
<th>Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>666</td>
<td>Massalia Graecorum, Lacydon</td>
<td>Marseille, Vieux Port, place Jules Verne and place Villeneuve-Bargemon (see also nearby Musee des docks: Dolia warehouse)</td>
<td>France South</td>
<td></td>
<td></td>
</tr>
<tr>
<td>881</td>
<td>Domitiana positio, Portus Domitianus</td>
<td>Roman villa at Santa Liberata, on the peninsula of Argentario</td>
<td>Italy West</td>
<td>9-10</td>
<td>8</td>
</tr>
<tr>
<td>890</td>
<td>Cosa, Cossae, Portus Herculis Cosanus, Etruscan Cusi, Cuthi</td>
<td>Ansedonia</td>
<td>Italy West</td>
<td>6.5</td>
<td>6</td>
</tr>
<tr>
<td>900</td>
<td>Centumcellae</td>
<td>Civitavecchia, Molo del Lazzaretto</td>
<td>Italy West</td>
<td></td>
<td></td>
</tr>
<tr>
<td>953</td>
<td>Port of Circei, Circe</td>
<td>inside Lago di Paola, with access via canal and breakwaters</td>
<td>Italy West</td>
<td>6.5</td>
<td>6</td>
</tr>
<tr>
<td>962</td>
<td>Caiete, Caieta, Caetas, Etruscan Caithi</td>
<td>Spiaggia di Fontania, at Gaeta</td>
<td>Italy West</td>
<td>6</td>
<td>5.5</td>
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<tr>
<td>981</td>
<td>Misenos, Misenum, Misene</td>
<td>Punta Terrone, pilae of the southern breakwater</td>
<td>Italy West</td>
<td>8-9</td>
<td>6-7</td>
</tr>
<tr>
<td>982</td>
<td>Misenos, Misenum, Misene</td>
<td>Punta di Pennata, pilae of the northern breakwater</td>
<td>Italy West</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>984</td>
<td>Misenos, Misenum, Misene</td>
<td>Punta di Pennata, pilae within the harbour</td>
<td>Italy West</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oleson</td>
<td>Castello di Baia, is not a port (?)</td>
<td>Italy West</td>
<td>8.5-10.5</td>
<td>7-7.5</td>
<td></td>
</tr>
<tr>
<td>Oleson</td>
<td>Cantieri di Baia, is not a port (?)</td>
<td>Italy West</td>
<td>ca. 8</td>
<td>ca. 7</td>
<td></td>
</tr>
<tr>
<td>986</td>
<td>Baiae, Baies, Portus Baianus, with connection to Lacus Baianus</td>
<td>Baia, two concrete moles over 200 m long</td>
<td>Italy West</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oleson</td>
<td>Villa dei Pisoni, is not a port (?)</td>
<td>Italy West</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oleson</td>
<td>Secca Fumosa is not a port but some kind of platform</td>
<td>Italy West</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>987</td>
<td>Portus Iulius, Julius, port of Julien, with connection to Lacus Lucrinus</td>
<td>Lucrino, two concrete moles over 200 m long</td>
<td>Italy West</td>
<td>8</td>
<td>8</td>
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<tr>
<td>Oleson</td>
<td>Portus Iulius, Julius, port of Julien, with connection to Lacus Lucrinus</td>
<td>East of eastern breakwater</td>
<td>Italy West</td>
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<td>5</td>
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<td>991</td>
<td>Puteoli, Dikaiaarcheia, Dicearche, in the Campi Phlegrei volcano district</td>
<td>Pozzuoli, Pouzzoles, Puteoles, in the Campi Flegrei volcano district, pilae of arched mole are under modern breakwater</td>
<td>Italy West</td>
<td></td>
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<tr>
<td>Oleson</td>
<td>Puteoli, Dikaiaarcheia, Dicearche, in the Campi Phlegrei volcano district</td>
<td>Pozzuoli, Pouzzoles, Puteoles, east of modern breakwater</td>
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<td>10</td>
</tr>
<tr>
<td>993</td>
<td>Nesis</td>
<td>Nisida, very large pila of over 1500 m³</td>
<td>Italy West</td>
<td>14.5</td>
<td>14.5</td>
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<td>994</td>
<td>Imperial Villa of Pausilypon</td>
<td>Roman villa at Poseilippo</td>
<td>Italy West</td>
<td>10</td>
<td>7</td>
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<tr>
<td>994.1</td>
<td>Imperial Villa of Pausilypon</td>
<td>Palazzo degli Spiriti</td>
<td>Italy West</td>
<td>7.5</td>
<td>6</td>
</tr>
<tr>
<td>995</td>
<td>Imperial Villa of Pausilypon</td>
<td>Pollion’s villa at Porto Marechiaro</td>
<td>Italy West</td>
<td>14</td>
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<tr>
<td>997</td>
<td>Neapolis</td>
<td>Naples, Piazza Municipio, offshore Roman quay made with timber caissons</td>
<td>Italy West</td>
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<td>1009</td>
<td>Capraria, Capreae insula</td>
<td>Bagni di Tiberio, near Marina Grande on the isle of Capri, with lighthouse at Villa Jovis</td>
<td>Italy West 7 4</td>
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<tr>
<td>1010</td>
<td>Capraria, Capreae insula</td>
<td>Palazzo a Mare, near Marina Grande on the isle of Capri</td>
<td>Italy West 11 8</td>
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<td>1011</td>
<td>Capraria, Capreae insula</td>
<td>Scoglio del Monacone, near the isle of Capri</td>
<td>Italy West</td>
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<td>1013</td>
<td>Seirenoussai nesoi, Anthemoessa insulae, Anthemuse, possible Siren islands, no stopover for Odysseus</td>
<td>Isola di Gallo Lungo</td>
<td>Italy West</td>
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<td>1023</td>
<td>San Marco di Castellabate</td>
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<td>Italy West ? 4.5</td>
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<td>1017</td>
<td>Punta Fuente</td>
<td></td>
<td>Italy West 12 10</td>
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<td>1028</td>
<td>Scidrus</td>
<td>Roman villa at Cammerelle, near Sapri</td>
<td>Italy West 8 5.5</td>
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<td>1246</td>
<td>Hadrianou Hormos, port of Lupiae, Milтопiae?</td>
<td>Porto Adriano, at San Cataldo near Lecce; concrete poured into ashlar cells</td>
<td>Italy Adriatic ? 12</td>
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<td>1252</td>
<td>Gnathia</td>
<td>Egnazia, with several pilae</td>
<td>Italy Adriatic 5 3.5</td>
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<tr>
<td>1295</td>
<td>port of Hatria, Adria</td>
<td>Torre del Cerrano, with several pilae</td>
<td>Italy Adriatic</td>
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<tr>
<td>3328</td>
<td>Side, Sida</td>
<td>Selimiye, with possible ancient lighthouse</td>
<td>TR: South ? 7.5</td>
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<tr>
<td>3377</td>
<td>Soles, Soli, Soloi, Pompeipolpis</td>
<td>Mezitli, West of Mersin; concrete poured into ashlar cells</td>
<td>TR: South ? 15</td>
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<td>3492</td>
<td>Caesarea Palaestinae, Cesaree, Ace, Sebastos</td>
<td>Qesaria, Caesarea Maritima, Roman port of Herod, built from 22 to 10 BC, with Drusion lighthouse; concrete poured into timber caissons</td>
<td>Israel</td>
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<td>3498</td>
<td>Apollonia, Sozousa</td>
<td>Arsuf</td>
<td>Israel</td>
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<tr>
<td>3934</td>
<td>Alexandria, Magnus Portus and its Pharos, home port of Classis Alexandrina fleet</td>
<td>Alexandria, also called « Le Phare », The Pharos; concrete poured into timber caissons</td>
<td>Egypt: Med Sea 15 8</td>
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<td>Oleson</td>
<td>Alexandria</td>
<td>Alexandria, SE of Fort Qait Bey</td>
<td>Egypt: Med Sea</td>
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<tr>
<td>4076</td>
<td>Leptis Magna, Lepcis Magna, Lepcitan Septimiani</td>
<td>Leptis Magna, Lepcis Magna, with ancient lighthouse, on R Lebda</td>
<td>Libya</td>
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<tr>
<td>4137</td>
<td>Thapsus</td>
<td>Ras Dimass, near Bekalta South of Monastir, large breakwater of the South port, with concrete poured into timber caissons and possible lighthouse</td>
<td>Tunisia</td>
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<td>4146</td>
<td>Horrea Caelia, Heraklea</td>
<td>Hergla</td>
<td>Tunisia 3 3</td>
<td></td>
<td></td>
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<tr>
<td>Oleson</td>
<td>Carthago, Carthagine, Punic Qart Hadasaht, Knyn, port of Salammbo</td>
<td>Carthago, commercial port, see also so-called “Neptune block” on the coast North of the ports</td>
<td>Tunisia 18 9</td>
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<tr>
<td>4237</td>
<td>Thapsa, Tipasa</td>
<td>Tipaza, sheltered by two islets</td>
<td>Algeria 10 3</td>
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<td></td>
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<tr>
<td>4243</td>
<td>Caesarea Mauretaniae, Cesaree de Mauretanie, Io!</td>
<td>Cherchel, western basin, Roman naval base</td>
<td>Algeria 8 6</td>
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</tr>
</tbody>
</table>

Most of them were listed and studied by Oleson et al. (2014).
Pilae seen on Google Earth

Santa Liberata

Circei

Misenum, Punta Terrone

Misenum, Punta di Pennata

Secca Fumosa

Castello di Baia
Various types of alignments can be distinguished from the pictures above:

- single isolated structures (e.g. Punta Fuenti),
- 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 (e.g. Caieta, Misenum, Baia, Portus Iulius, Nesis, Pausylipon),
- rather continuous structures in the open sea, probably part of a vertical breakwater (e.g. Castellabate, Scidrus, Gnathia, Side, Psamathos).
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:

- Puteoli breakwater fresco at Villa Stabiae, Pompei (1st c.)
  (source: http://www.marine-antique.net/Port-de-la-maison-de-Stabie-Pompei)

- "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".

- Puteoli breakwater on a souvenir glass bottle known as Fiascetta di Populonia showing the pilae (4th c.)
  (source: http://www.archeoflegrei.it/i-souvenir-di-puteoli/)

- Puteoli breakwater on a souvenir glass flask kept at the National Museum of Prague and showing the pilae (4th c.)
  (source: https://web.uvic.ca)

It can be seen from the dates of these pictures that the arches were probably still in place in the 17th century, but that the structure was gradually destroyed after that.
Paolo Antonio PAOLI, provided the dimensions of the ancient arched structure in his “Antichita di Pozzuoli” in 1768 (with some later editions).
(source: http://www.archeoflegrei.it/portodiputeoli/):

The drawing shows 15 pilae (including 2 supposed 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 between adjacent pilae varies from 0.7 to 1.0 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.