Portus Claudius' Breakwaters

A few words on coastal morphodynamics

Coastal engineers are supposed to predict the impact of new coastal structures (i.e. ports, seawalls, manmade beaches, etc.) on the adjacent coastal morphology. Their methodology is usually as follows:

1. Understand coastal processes at hand (waves, tides, morphodynamics);
2. Build numerical models of these processes (physical scale models are used also) and calibrate them on the past decade(s) if enough data is available;
3. Use these models to predict trends over future decade(s).

The following (very) short summary can be deduced from coastal engineering textbooks (e.g. Komar, 1998[1]).

As ports and harbours are supposed to be "low energy" areas (with reduced waves and currents in order to provide sheltering for ships) they are subject to sedimentation.

Sediment (sand and silt) moves in the coastal zone both along (longshore littoral drift) and across (cross-shore sediment movement) the coastal zone which runs from the dune to a certain water depth (frequently in the order of 10 m). The energy required for sediment motion is mainly provided by wave action (and wind and tidal currents, if any).

- The source of sediment for littoral drift can be fluvial sediment load from river outlets, or erosion of another stretch of the coast. Waves push sediment in front of them when they break on the coastline with an oblique angle. Hence, depending on the wave direction, the rate, and even the direction, of littoral drift can vary in time.
- Cross-shore sediment movement occurs mainly during storms when sediment is taken away from the top of the beach or dune down to deeper water. Reconstruction occurs in milder weather and wind will take fine sediment back to the top of the dune, especially in a tidal area.

[1] KOMAR, P., (1998), « Beach processes and sedimentation », 2nd ed., Prentice Hall.

Let's have a look at a typical river outlet with Piero Bellotti[2].

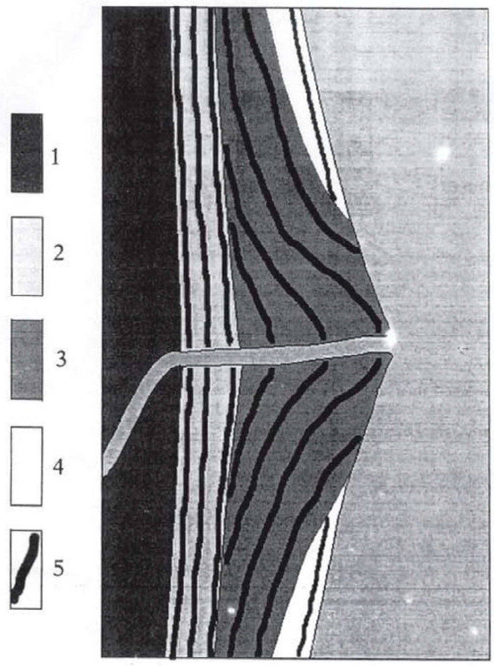


Fig. 9 - Meccanismi di progradazione riconosciuti nei delta tirrenici. Nel primo tipo il depocentro delle sabbie è disposto lungo la battigia, nel secondo tipo è ubicato nell'area di foce, nell'ultimo è spostato lungo le ali. 1) piana deltizia interna, 2) progradazione di primo tipo, 3) progradazione di secondo tipo, 4) progradazione di terzo tipo, 5) cordoni litorali.
– *Progradation mechanisms in tyrrhenian deltas. In the first type sand depocenter is located long the shoreline, in the second one sand depocenter is close by river mouth, in the last type sand depocenter is located long delta wings. 1) Inner delta plain, 2) first type progradation, 3) second type progradation, 4) third type progradation, 5) beach ridges.*

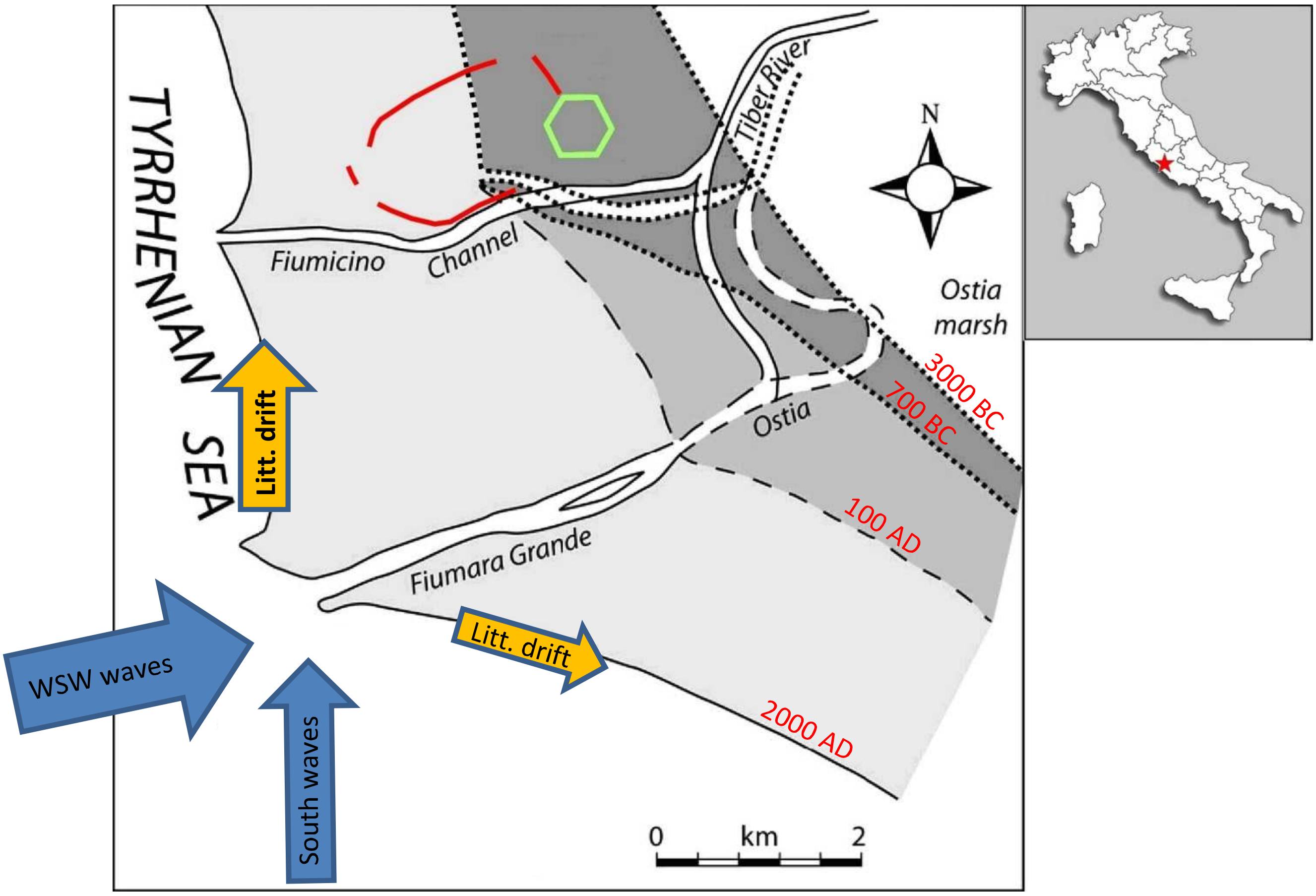
Beach ridges (5) show the progradation of the shoreline due to sediment supply from the river. In this case, wave propagation is perpendicular to the initial shore line (from right to left on this picture). Waves spread the sediment on both sides of the outlet leading to a shape that will remind the Fujiyama (3).
It can be seen also that the total volume of sediment between two equidistant ridges increases in time because the lateral extent is increasing. Hence, the speed of progradation of the outlet cone reduces in time (if the fluvial sediment load is constant).
Obviously, the ratio *fluvial sediment load / wave power* is a dominant parameter here: more wave action and/or less sediment input lead to a flatter cone, and reverse.
If, for some reason, this ratio is reduced (e.g. reduced fluvial sediment load due to reduced fluvial water discharge, due to a drought), the cone will be flattened out and sediment will drift laterally on both sides (4).

What happens if men interact with Nature? e.g. building some obstacle in an area with littoral drift.

This picture shows the initial shoreline near Cotonou (Benin) (straight yellow line). This was the shoreline before any human construction (a port) was built in the sixties. This coast is known for its littoral drift of around one million cubic meters per year from West to East (left to right on the picture).
Fifty years later, the western shoreline progressed more than 1 km in the offshore direction to the South (i.e. around 20 m/year!). The same volume of sediment was taken away by wave action on the eastern side, inducing erosion over many kilometres … What Nature gives with one hand, she takes back with the other hand.

[2] BELLOTTI, P., (2000), « Il modello morfo-sedimentario dei maggiori delta tirrenici italiani » Boll. Soc. Geol. It., 119 (2000), p 777-792.

Coastal morphodynamics near Portus



Southern breakwater

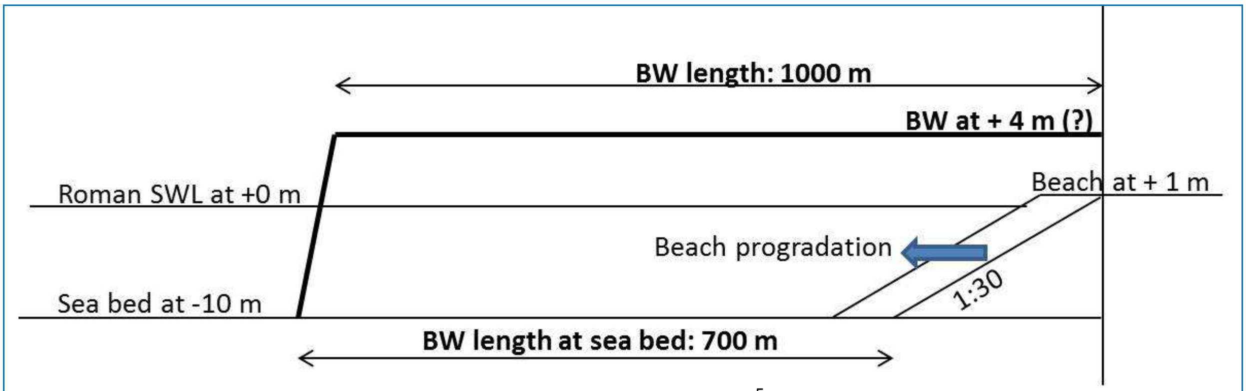
The picture above (based on P. Bellotti's, 2011 study[3]) shows that the Tiber outlet moved from the North (into the future Roman ports) to the South (close to future Ostia), probably around the 7-8th century BC, before Ostia developed in the 5th century BC. It also shows that the shoreline between the present Fiumicino Canale and Fiumara Grande progressed 3.5 to 4 km between 100 AD and 2000 AD. That is an average close to 2 m/year. A more detailed analysis shows that this value might vary locally and reach 5 to 10 m/year near both outlets (Bellotti, 2011).

Waves are dominant from West-South-West, but some secondary waves also approach from South.

Considering the local coastal morphology, the fluvial sediment load from the Tiber is supposed to flow as a littoral drift on both sides of the outlet, and offshore. The present total sediment load is 0.3 million ton/year (Milliman, 2014[4]) (that is around 150 000 cubic meter/year). It must be noted here that this fluvial sediment load was drastically reduced by a factor thirty (30!) during the 20th century due to upstream dam building. Anyway, the finer fraction (silt) flows offshore and only the coarse fraction (sand) remains in the coastal area (estimation of 50 000 to 100 000 cubic meter/year over the past centuries). The South breakwater of Portus Claudius obviously was a large obstacle to sediment movement towards North and sedimentation took place on the South side of the South breakwater.

[3] BELLOTTI, P., (2011), « The Tiber river delta plain (central Italy): Coastal evolution and implications for the ancient Ostia Roman settlement » The Holocene, 21(7) p 1105-1116, Sage Publications Ltd.
[4] MILLIMAN, J., (2011), « River Discharge to the Coastal Ocean: A Global Synthesis », Cambridge University Press, UK (384 pp).

Let's see this in a simplified vertical cross-section placed just South of the South breakwater, and just after its completion.



NB: Roman Sea Water Level is around 1 m below present SWL[5] (sketch distorted and not to scale)

Sediment from the prograding beach will start to get around the toe of the breakwater (BW) after a distance of 700 m. Sedimentation will start inside Portus Claudius at this moment. In the simplified scheme shown above (1:30 slope on a 10 m water depth, note that Morelli found 15 m[6]) and considering the 5 to 10 m/year progradation, the *beginning* of harbour sedimentation would be expected after 70 to 140 years, say one century, and that is well after Trajan decided to build his Portus Trajanus. This leaves many more years for the harbour to be still (partly) operational, as long as the water depth is at least 4 to 5 m inside the harbour. This seems to have been the case until the 10-12th century AD (Giraudi[7]). We would consider nowadays that this is fairly overdesigned …

It would however not be surprising that Claudius' engineers anticipated this, at least in a qualitative way, and this would then explain why they built such an expensive, long and deep, South BW, as they did not need a 10 m water depth for contemporary ancient ships, but *they had to create a large sedimentation sink outside the harbour*.

Hypothetical Sequence of construction

If Claudius' engineers realised that sediment coming from the Tiber was flowing North along the coastline as littoral drift, they must have thought that they had to build the South BW *first* in order to stop this material from settling inside the future harbour area against the Northern BW, if that one was built first. They may not have realised that if sedimentation was to occur on the South side of the South BW, then erosion was to occur on its North side, i.e. inside the future harbour … That was quite a nice opportunity to let Nature do the work of cleaning up the area that would have to be dredged anyway … After some time, they would decide to start building the North BW and the coastline would readjust with some erosion near the northern side of the South BW combined with some sedimentation near the southern side of the North BW. The coastline between both breakwaters would then be stabilised and ready for further dredging up to its eastern end at Monte Giulio[8] (where 'Molo Destro' would be built later on). No problem so far.

[5] GOIRAN J.-P., et al, (2009), « Découverte d'un niveau marin biologique sur les quais de Portus: le port antique de Rome », Méditerranée, 112, pp 59-67.
[6] MORELLI, C., (2011), « Porto di Claudio: Nuove scoperte », in "Portus and its hinterland: Recent archaeological Research", ed. Simon Keay & Lidia Paroli, The Britisch School at Rome, p 47-65.
[7] GIRAUDI, C., (2009), « Late Holocene Evolution of Tiber River Delta and Geoarchaeology of Claudius and Trajan Harbor, Rome », Geoarchaeology, Vol 24, N° 3.
[8] ARNOLDUS-HUYZENDVELD, A., et al, (2015), « Il paleoambiente di Monte Giulio e della parte nord-orientale del bacino portuale di Claudio », The Journal of Fasti Online, Associazione Internationale di Archeologia Classica (www.fastionline.org/docs/FOLDER-it-2015-324.pdf)

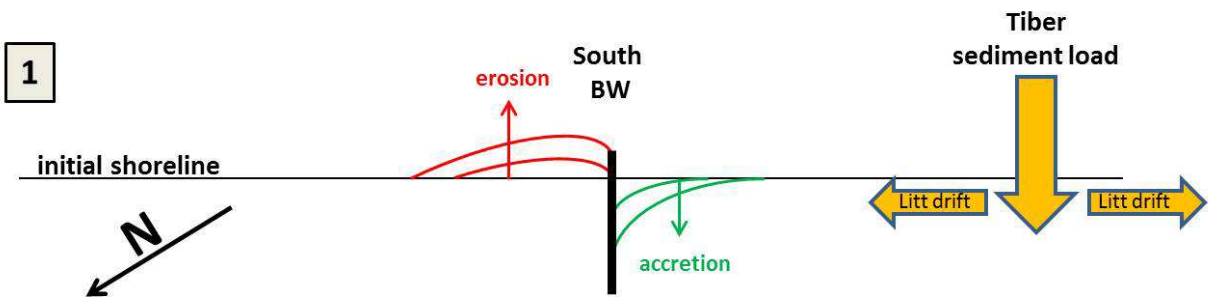
However, as sedimentation on the southern side of the South BW continued, erosion had now to occur on the northern side of the North BW and this would soon start to undermine the landward end of the brand new North BW.

This picture shows the erosion area East of Cotonou where diffracted waves turn around the breakwater head, then follow the curved breakwater and take sand away at the landward end of it.
Portus' configuration is reversed: waves follow the breakwater on the North side and "try to enter" the port from North to South by getting around the landward end of it, while sand is taken away further North.

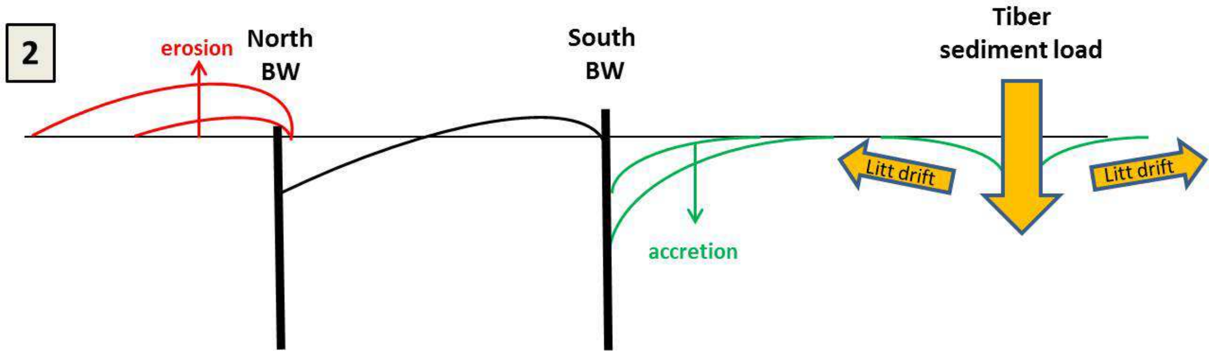
This may be an explanation for the somewhat hectic layout of the North BW near Monte Arena[9], where several designs are used, *possibly showing repair actions*. A northern access channel for ships[10] may not have been anticipated from the onset by Claudius' engineers, but the opportunity provided by this local erosion may have been taken to use it, and even to enhance it artificially, for river transit from Portus Claudius through the Northern Canal leading to the Tiber.

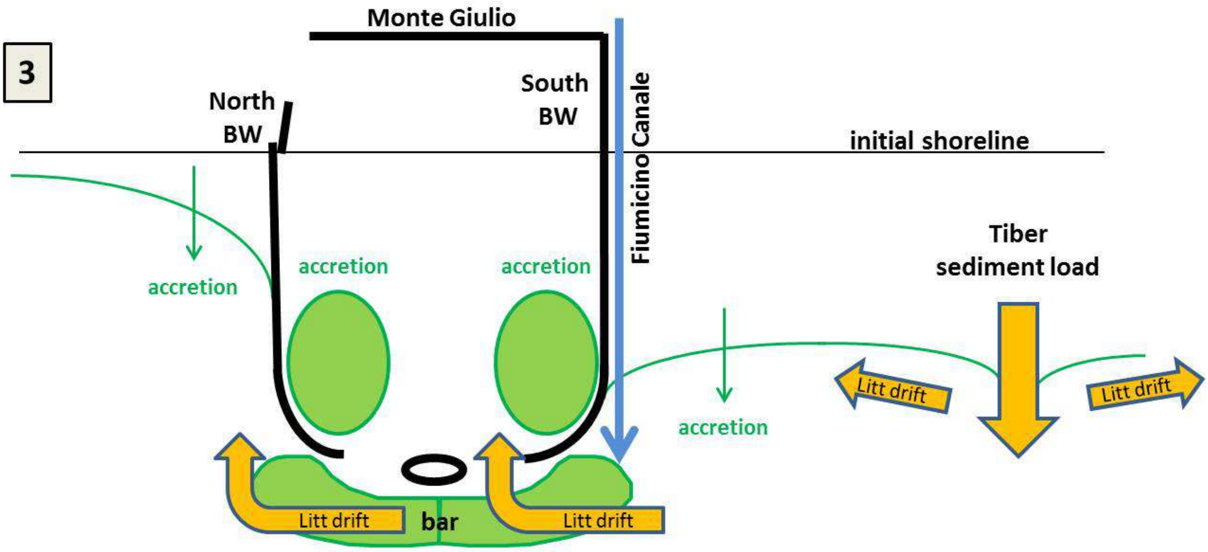
In the meantime, fine marine sediment was driven into the sheltered harbour area not only by residual waves behind the breakwaters, but also by small sea level variations such as those due to barometric variations, tidal effects and wind action. This fine sediment is therefore now found underneath coarser fluvial sediment that entered the harbour much later, coming from Fiumara Grande and drifting north along the coast to the harbour entrance.

These processes are summarised on the following hypothetical geomorphological evolution of the Portus Claudius area:



[9] FELICI, E., (2013), « Il Porto di Claudio e Vitruvio », Atlante tematico di topografia antica: ATTA : rivista di studi di topografia antica, 23(2013), Roma: «L'ERMA» di BRETSCHNEIDER.
[10] GOIRAN J.-P., et al, (2008) « Portus, la question de la localisation des ouvertures du port de Claude : approche géomorphologique », *Mélanges de l'Ecole Française de Rome*, 121, pp 217-228.





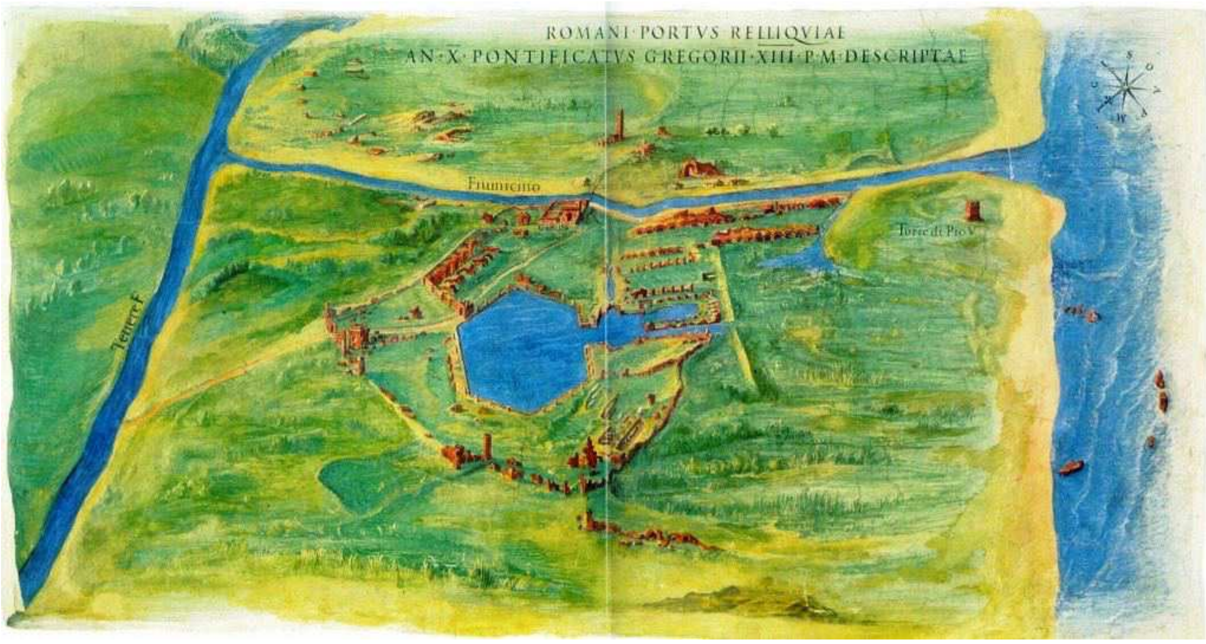
Hypothetical construction sequence of Portus Claudius
1) Construction of first breakwater (South),
2) Construction of second breakwater (North),
3) Coastal progradation and harbour sedimentation.

Fiumicino Canale

But let's get back to the southern side, where it remains to be explained how Fiumicino Canale could survive with such a large volume of sediment drifting to the North from the Fiumara Grande outlet. Many centuries after the Tiber outlet moved from the North to the South, Fiumicino Canale was artificially dug in the 1st century AD and later called Fossa Traiana. It provided a short connexion between the port (via Canale Traverso) and the upstream river portion leading to Rome. Although this canal is the shortest way for the Tiber to sea, it was narrower than the branch flowing to Ostia and therefore did not attract a lot of river discharge water (and sediment). It is said that nowadays, the discharge ratio is 20% via Fiumicino Canale and 80% via Fiumara Grande, but that may have been very different at times (droughts, floods). A small hydraulic power of Fossa Traiana would not enable to keep its outlet open against massive sedimentation coming from the South and it seems likely that the outlet was closed periodically (if not permanently) near the landward end of the South breakwater, downstream of the Portico Claudio.

Rutilius' observation[11] shows that such variations could happen, as in his time it was safer to sail out to sea via Fossa Traiana than via Ostia where a dangerous 'bar' had probably formed. He also states that they spent the night inside the port and he does not mention a direct connexion of Fossa Traiana with the sea via a separate outlet. He might therefore have sailed out to sea directly from Portus Claudius.

However, Antonio Danti's famous fresco (Vatican Gallery of Maps) shows an open Fiumicino Canale in 1582! His picture is quite accurate, showing various port remains, including in the sea, and we have no reason to doubt that the Fiumicino Canale was correctly drawn.

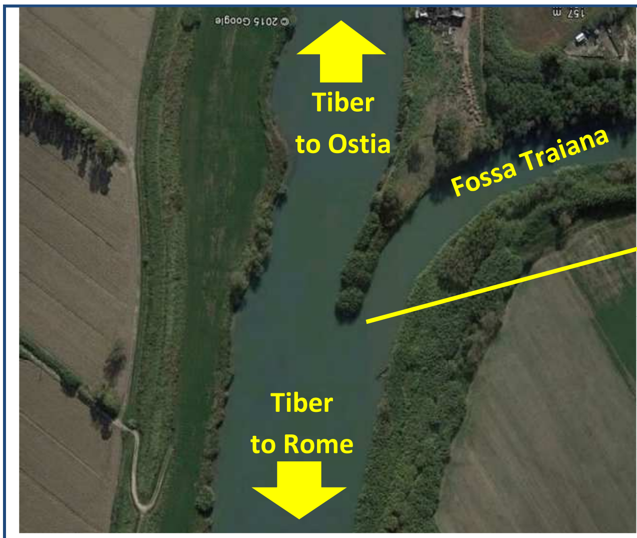


To achieve this, a training wall (e.g. rubble mound running parallel to the South breakwater) would be required to keep the outlet free from sedimentation and such a structure should be found by archaeologists, unless it was destroyed by port development in 1612 inside Fiumicino Canale (Giraudi, 2009[12]) when it was re-opened towards the sea.

On the other hand, the Tiber being known for its strong floods (up to say 2000-3000 m^3/s), it might be accepted that Fossa Traiana was periodically swept by such floods which would clean up the canal and enforce an opening to the sea at least once a year (possibly with a some human assistance). A low sill (e.g. 1 m high) would help to avoid bed load sediment from penetrating into Fossa Triana. The modern day shape of the intake of Fossa Traiana on the Tiber at Capo Due Rami seems to confirm that special care is taken there:

[11] RUTILIUS NAMATIANUS, « De Reditu Suo » Book 1, Verse 179, 5th century AD.

[12] GIRAUDI, C., (2009), « Late Holocene Evolution of Tiber River Delta and Geoarchaeology of Claudius and Trajan Harbor, Rome », Geoarchaeology, Vol 24, N° 3.



The intake structure is obviously calibrated to divert a certain fraction of the flow. It is reinforced in order not to be moved around by erosion.
This arrangement may have been inherited from an ancestral (Roman?) tradition.

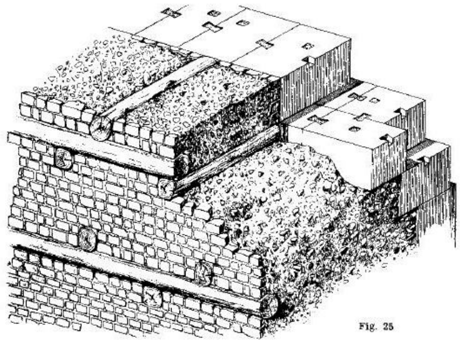
We are thus left with uncertainty as to the opening of the sea outlet of Fiumicino Canale between say 500 and 1500 AD …

Summarizing the morphodynamics in the Portus area: sand brought by the Tiber was spread along the coastlines North and South of its outlet. The South BW of Portus Claudius stopped the littoral drift to the North inducing: a) sedimentation south of the South BW, b) closure of the seaward outlet of Fossa Traiana, and c) erosion north of the northern BW. After around one century sand started to enter Portus Claudius by its main access channel, probably settling near the entrance, while finer materials entered further inside the port. Later on, sand bypassed the port entrance and spread on the coastline north of the port. Even later, the port was filled with sand and the coastline prograded in front of it.

Claudius' breakwater remains

Engineers usually distinguish vertical breakwaters (BW) and rubble mound BWs. The first are built with caissons filled with marine concrete (e.g. Caesarea Maritima, Israel). The latter are built by dumping stones from a lorry, and concrete can possibly be found on top of the rubble mound (above sea level where it is easier to pour); as we still do today (see http://fr.wikipedia.org/wiki/Brise-lames):

This picture (Fujairah) shows a modern BW under construction: large artificial blocks of concrete are used nowadays instead of rock, they are placed on top of, and as an armour layer of, a rubble mound made of quarry rock of several tons, which are themselves placed on a core made of quarry run. The crest structure (under construction) has a kind of "L" shape.



The emerging part of the North BW of Portus Claudius is made of concrete, which was probably cast in the way described by Bartoccini[13].

Morelli's corings[14] show that the crest of the deep section parts of the breakwaters are located at approx. 5 m below present SWL (i.e. 4 m below Roman SWL) with a total remaining structure height of around 10 m reaching approx. 15 m below present SWL. The initial BW may thus have been a 15 to 20 m high structure. We thus have two options: it could have been built higher and been partly destroyed by long term wave action, or have been built as a low crested BW from the onset. The first option is usually built as an emerging BW, built out from land with lorries; however, considerable logistics are involved (lorries meeting each other on top of the BW, etc.). In the second option, building a BW that does not reach the water surface is done with barges from the water surface (like Pliny the Younger described at Centumcellae/Civitavecchia), and consequently the remaining upper level of the BW is built out from land with lorries (or possibly, with marine concrete poured into wooden formworks). In any case, the upper level of the Portus breakwaters would have been lost to sea over the years.

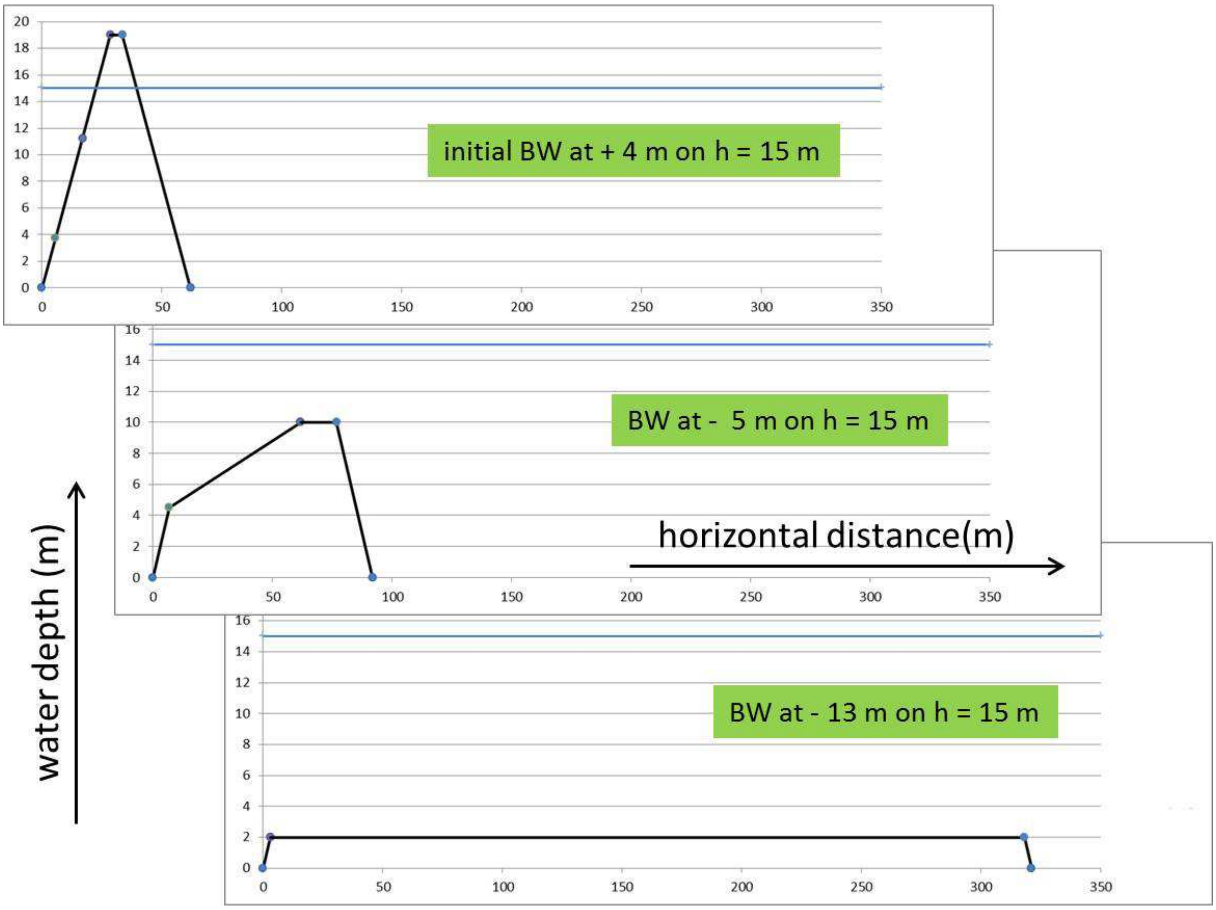
Let's assume (until further data is made available) that the deep section of the breakwaters consists of a rubble mound with an average stone diameter of 0.50 m.

We know from coastal engineers that because of wave breaking, waves cannot be larger than around 0.6 times the local water depth; hence in shallower water, waves are smaller and the required rock size for a stable BW is smaller too; conversely, a BW must thus have an increasing rock size when building out to sea on increasing depth. When we move into even deeper water, say over 10-15 m, breaking waves (of over 6-9 m) will not occur often, but just during storms; however we may consider that any big storm will have occurred during the past 2000 years: so, if the water depth allows big waves to exist, they *will occur* in the long term and destroy the BW accordingly.
Clearly, 0.50 m rock (typically a 2 to 500 kg class of rock) is not stable with waves larger than only 1 m, which occur many times a year.
This is valid for frontal wave attack (wave crests parallel to the axis of the BW). Most of Portus' BWs are not subject to frontal wave attack, but to (very) oblique wave attack, which is far less destructive.

[13] BARTOCCINI, R. (1958), « Il Porto Romano di Leptis Magna », Boll. Centro Studi per la Storia dell'Architettura, N°13.
[14] MORELLI, C., (2011), « Porto di Claudio: Nuove scoperte », in "Portus and its hinterland: Recent archaeological Research", ed. Simon Keay & Lidia Paroli, The Britisch School at Rome, p 47-65.

It is nevertheless expected that this 0.50 m rock placed on a water depth of 10 to 15 m should suffer frequent damage during storms, especially at the roundheads and at the lighthouse island which are both subjected to frontal wave attack.

This is perhaps a first start for explaining why the crest of the deep sections of the breakwaters are located at approx. 5 m below present SWL. Coastal engineers tell us that a rubble mound will be lowered by repeated wave attack until it is no more than a submerged breakwater. Its elevation above the sea bed depends on the size of rock (see: http://www.ancientportsantiques.com/summary-ancient-port-structures/failure-of-rubble-mound-breakwaters-in-the-long-term/). In the case of Portus, with a water depth of 15 m and a rock size of 0.50 m diameter, the crest of the submerged BW would be lowered to 13 m below the water surface , i.e. 2 m above the sea bed.
In addition, the total volume of rock cannot change. Hence, if a BW is flattened out by wave action, rocks must be spread over the sea bed in the following way (with Roman water levels):



This is however not (yet?!) confirmed by archaeology …

Berthing capacity of Portus Trajanus

Like today: *Bread and games to ensure social peace …*
(« Panem et circenses » Juvenal, *Satires*, 10.81)

Concerning the games, we have the Colosseum (built between 72 and 80 AD) and concerning bread, we need a harbour basin enabling us to ensure Rome's supply of grain. We already have Portus Claudius (around 200 ha, built between 40 and 50 AD, acc. to Oleson, 2014) but 200 ships were sunk in this port during a storm in 62 AD. Indeed, when observing the areas sheltered from waves in L. Franco's computations[15] a sheltered area of around 20 ha is found close the South breakwater for SW waves, and around 40 ha is found close the North breakwater for Western waves (NB: dominant waves are from SW to W). As around 10 ships of 25 x 7 m can anchor on one hectare of water area, it can be seen that around 300 ships could be anchored in Portus Claudius. That is quite a lot of ships and a disaster like the one in 62 AD could occur if the wind would suddenly change direction.
We therefore need to add a new basin with better protection from storms: the construction of Portus Trajanus (33 ha) will be undertaken from 106 to 113 AD (acc. to Oleson, 2014).

This new basin will combine very well with the existing Portus Claudius which has a large basin that can be used as an outer harbour allowing sailing in under full sail and furling sails in a sheltered area. This new basin offers a shelter for around 300 ships at anchor while waiting for unloading in the new basin. This new basin will not only offer better shelter against storms, but also have many warehouses and a new canal to the Tiber from where goods will be moved faster upstream over around 30 km to Rome on hauled barges. Traffic will be separated: deep sea ships on one side of the new basin and river barges on the other side near the new canal, with warehouses in between. This separation is still in use in some ports nowadays (e.g. Rotterdam) as it separates the marine world from the river world (seafarers and customs officers will understand what I mean …).

The logistic chain is thus completely redesigned.

Around 200 000 to 400 000 tons/year of grain[16] coming from North Africa (Egypt, Tunisia) must be provided to feed the one million people of the city. Other goods must be added to this (olive oil, wine, garun, etc.). The total traffic can be estimated at 500 000 tons/year.

With 200 to 500 ton ships making two trips a year, 1000 ships are required. This is probably a minimum.

These ships sail mainly during the good season (early April to the end of October) using the "summer winds" from NW that blow on the Eastern Mediterranean in July-August and allowing a fast trip from Rome to Alexandria (still a few weeks). A concentration of ships arriving at Portus may thus be expected before and after July-August, e.g. in June and in October.

As each ship carries between 4000 and 10 000 bags of grain of 50 kg each and if unloading was organised as a continuous human chain, it might be possible to unload a ship within one or two days, but it is more realistic to expect several days for unloading. If we suppose each ship stays 10 days to unload, take in provisions and settle formalities, and if we wish to host 1000 ships in June (first trip) and 1000 ships in October (second trip), then *we need a basin with quays for around 330 ships.*

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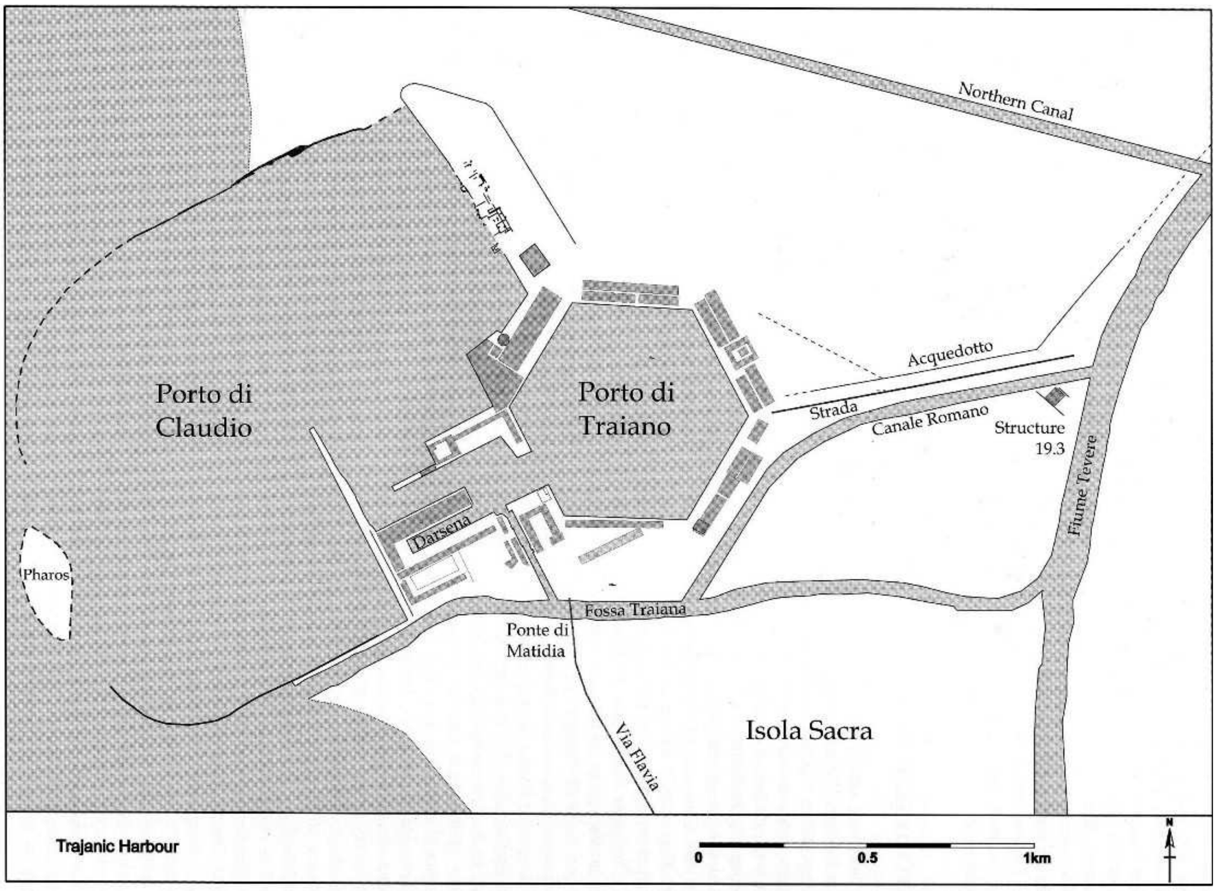
[15] NOLI, A., & FRANCO, L., (2009), « The ancient ports of Rome: new insights from engineers », Archaeologia Maritima Mediterranea, 6, 2009.
[16] REDDE, M., (2005), « Voyages sur la Méditerranée romaine », Actes Sud.



Layout of Portus Claudius and Portus Trajanus (Simon Keay et al, 2005)

On the layout of Portus Claudius[17], 1000 to 2000 m of quay walls are found between the "Darsena" and "Structure 8.15" (including 440 m for the Darsena alone). Not all ships could dock stern first and some ships had to dock alongside the quays although this takes more quay length: e.g. the Darsena is only 45 m wide and this does not allow ships to dock stern first without hindering other ships. *The total number of ships docked in Portus Claudius was thus limited to a maximum of 100-150 ships* and enlarging the port was a necessity.

Harbour Basin Shapes

Let's suppose we get a phone call from the emperor ordering the digging of a new harbour basin for 300 ships of 25 x 7 m … We would first need to provide a quay length of 300 x 7 m = 2100 m (all ships being docked stern first, like modern yachts). Any basin shape might be accepted, from a straight line of 2100 m to a circle with 668 m diameter, including a triangle, a rectangle, a hexagon, etc.

For all angular shapes, some length is lost in the angles if ships are not to hinder each other.

The circular shape would be tempting to reduce the volume of excavation, but the circular shape does not provide linear quays that are preferred for port operations.

Angular shapes have better perimeter/surface ratios. Let's start with an isosceles triangle which offers 30% more perimeter for the same surface as a circle, but quite some length is lost in its sharp angles. Then come the square, the rectangle and multi-faced shapes like pentagon, hexagon, etc. and finally, the circle. The total length lost in the angles obviously increases with the number of angles,

[17] KEAY, S., & MILLETT, M., (2005), « Portus in Context », Portus, an archaeological survey of the port of imperial Rome, The British School at Rome.

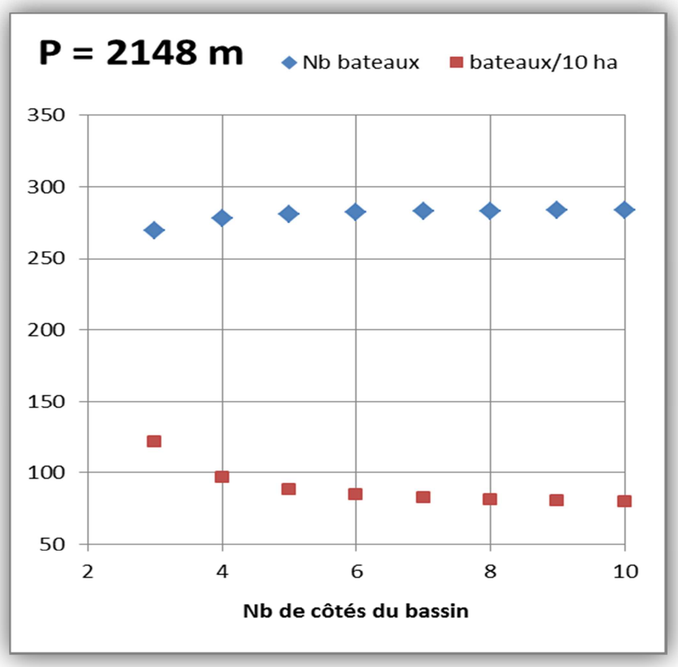
but at the same time the length lost at each angle reduces, and it is seen on parameter C below that both effects more or less compensate each other.

Let's have a closer look at Portus Trajanus. It consists of a hexagon with six 358 m sides which is thus inscribed in a circle with a 716 m diameter. This hexagon has a perimeter of 2148 m and an area of 33.3 hectares. This seems quite close to what we need to host 300 ships with a length of 25 m and a width of 7 m as it has a little more than the 2100 m of quay length we are looking for.

Let's now go back to polygons with a 2148 m perimeter. We computed the number of ships that might be aligned stern first side by side in polygonal basins with an increasing number of sides. We also computed the basin area and the number of ships per unit of area to be excavated.

N = total number of ships in the basinn = number of sides of the basin
a = length of each side of the polygon
L = length of ships (25 m)
b = width of ships (7 m)
D = diameter of the circle in which the polygon is inscribed
C = total quay length lost in the angles
P = perimeter of the polygon = quay length to be built
S = surface of the polygon = surface of the basin to be excavated
N/10 S = number of ships per 10 hectares

n	>> a (m)	>> D (m)	>> S (ha)	>> C (m)	>> P-C (m)	>> N	>> N/10 S
3	716	827	22.2	259.8	1888	270	122
4	537	759	28.8	200.0	1948	278	97
5	430	731	31.8	181.6	1966	281	88
6	358	716	33.3	173.2	1975	282	85
7	307	707	34.2	168.6	1979	283	83
8	269	702	34.8	165.7	1982	283	81
9	239	698	35.2	163.8	1984	283	80
10	215	695	35.5	162.5	1986	284	80
20	107	687	36.4	158.4	1990	284	78
50	43	684	36.7	157.3	1991	284	78
100	21	684	36.7	157.1	1991	284	77



Computation of the number of ships in a polygonal basin with n sides

The number of sides of the polygon is set out horizontally and the number of ships in the basin is set out vertically. It can be seen that the number of ships does not vary much (around 280) with the number of sides. The triangle provides a little less quay length than the other shapes.

It can be seen also that between 8 and 10 ships per hectare can be hosted (except for the triangle which can host over 12 ships/ha).

It must be noted that a linear basin consisting of only 2 long quays of 1000 m each would also host around 285 ships. The surface would be only around 10 hectares (assuming a basin width of 4 ship lengths), leading to 28 ships/ha.

As a conclusion, it can be said that for 2148 m of quays to be built (including a little less than 2000 m really available for docking), 270 ships can be hosted in a triangular basin, and around 280 ships in the other shapes. However, this limited increase of the number of ships requires around 50% more excavation. The linear shape would induce even less excavation as the ships could be hosted on an even smaller surface.

A linear or a triangular shape would be optimal if the volume to excavate was to be minimised, but this approach was clearly not chosen. *The volume to excavate was therefore not the main design parameter and it may be accepted that (like today) excavation was relatively cheap compared to the cost of quay wall building.*

The hexagonal shape must therefore have attracted the Roman designers for other reasons:

- integration into existing geography and land use,
- specialisation of each of the six sides on particular goods and warehouse types.