HISTORY OF COASTAL ENGINEERING IN ITALY

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ABSTRACT: The paper first describes the main relevant geographical, morphological and meteoceanographic characteristics of the Italian seas and coasts. A broad overview is then given of the long historical evolution of coastal and harbour engineering in Italy, with emphasis on the ancient developments and particularly on the advanced technological achievements of the Romans. The historical perspective includes the "architectonical" approaches of the Renaissance age, the fascinating hydraulic developments of Leonardo da Vinci and the valuable experience of the Venetian and Genoese engineers. The more recent and innovative technical and scientific contributions are also highlighted, with special reference to the typical tradition of composite caisson breakwaters. In the end the present status and prospects of both research and practical applications of coastal engineering in Italy are summarized and referenced.

INTRODUCTION

The Italian peninsula is like a giant *pier* jutting out in the middle of the Mediterranean Sea, the world closest large continental sea. Due to this unique strategic geographical location at the convergence of three continents, with a total coastline extension of 7500 km and over 3000-year long history of human civilization (with difficult inland communications, for both geographical and political divisions), it is easy to understand that Coastal Engineering has played here a relevant role since the ancient times.

Coastal Engineering is a newly defined specialist branch of Civil Engineering which developed in the last decades with the growing human pressure in the coastal zones and the increasing beach erosion problems. As young modern scientific discipline it generally deals with the hydrodynamics of the nearshore zone and with its interactions with sediments and structures, mainly related to harbour and shore protection problems. As old technical field of practical engineering it includes the design and

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construction of any work at sea (traditionally related to maritime navigation) and it may be considered as a complex "art", strongly based upon experience. Today Coastal Engineering can broadly encompass many other aspects, such as environmental control, survey and planning, water pollution, economics and management.

Up to 170 ports are now classified in Italy (77 of national interest) which need upgrading and maintenance, and new activities are related to offshore platforms and marina developments. However a greater attention is paid to the protection of the coastal areas and to the understanding of the complex nearshore processes. The present importance attached to these problems in Italy is also demonstrated by its high population density (some 56 million people mostly concentrated along the coastal zone, due to the largely mountainous interior land) and by the tourist summer pressure upon its beaches: over 100 million people are coming just to the northern Adriatic shores from all over Europe. It is claimed that the present capital value of a square meter of beach, as derived from all revenues from tourist-related activities, can reach US $ 3,500 ! (Brambati 1993).

Given the special long-term Italian heritage and the fundamental contributions in practical construction at sea, this historical review is mostly addressed to the development of harbour technology and hydraulic design since antiquity. In fact it can be noted that only Italy and a few neighbouring Mediterranean countries retain the unique valuable heritage of ancient harbour engineering. Since no other country from the south-east Mediterranean region is represented in this volume, the detailed review of the ancient heritage has been given a wider Mediterranean scale, thus covering somewhat the global history of early harbour engineering.

Emphasis is then on the remote history, since the related bibliography is of more difficult access for coastal engineers, being mostly produced by archaeologists, historians and geographers. A humanistic and historical background is believed useful to modern coastal engineers, who can always learn from others'experience, also because the present abundance of computational approaches may overshade the fundamental importance of the old natural observation of the physical processes.

On the other end, the review of the "contemporary age" is rather short, in relation to the present much larger amount of available information, since it is also too close to allow a proper historical perspective. However a final quick overview of the present state-of-the-art of both research and applications is included to complete the overall picture and provide useful references to projects and organizations of international interest. Preference is given to review papers and to publications in English.

In fact the aim of this review is to document the Italian coastal setting, facts, circumstances, locations and personalities that have contributed to the progress of Coastal Engineering and indirectly to the national economic development. It may be observed that most advancements are due to individuals, rather than to institutions, as typical of the character of the Italians. It is quite difficult to summarize in a relatively short paper the enormous amount of information. Attention is therefore focussed on the main original and innovative *Italian* achievements. One typical example is the old and new tradition of monolithic breakwaters, which has been favoured by the necessity to build deep sea defence structures along open coasts in nearly tideless conditions.

It can be noted that our rich history of water and coastal sciences has hitherto been largely neglected, being documented to a very small extent if compared to other scientific and technological disciplines (eg.architecture, medicine). In fact no previous historical review of the scattered information on maritime engineering could be found to help the preparation of this paper. This is actually a concise compact report of a long exciting "adventure" in the "ocean" of precious old manuscripts and books (often in Latin or arcaic Italian) which are preserved in many not easily accessible libraries. Due to page and time limitations, this history cannot be fully complete. The content reflects the personal interests and experience of the author, who apologizes for any overlooked fact, personality or reference publication that could have been unwillingly omitted.

Before the historical review, a paragraph is introduced, which gives a brief synoptic description of the Italian coastal environment, with general figures of the relevant geographical, morphological and meteoceanographical characteristics of the Italian coasts and seas. It is reasonable to believe that these conditions have not changed since the ancient times, although there is some evidence that the sea-level has risen by over 1.5 m in the last 2500 years. Most old survived coastal structures are infact underwater, but coastal tectonics and erosion/deposition effects have locally altered the coastline position, so that ancient port sites may be found totally landlocked (Ostia) or deeply submerged (Mysenum).

ITALIAN COASTAL ENVIRONMENT

Geographic, Geomorphological and Administrative Conditions

Italy is located in southern Europe in the middle of the Mediterranean Sea, approximately within latitude 36-46 N and longitude 8-18 E. The country total surface is just above 300,000 Km^2 and the coastline extension, including the islands, is about 7,500 km (40 km^2/km or 0.025 km/km^2). Therefore its "insularity index" (defined as the ratio of shoreline length to the circumference of the circle of equivalent continental area) is pretty high, since it nearly reaches the value of 4. The maximum land distance from the sea is only about 200 km. Maps are shown in figs.1,2,3.

Coastal Geomorphology. The coasts are for some 55% of the high rocky type, while 45% are beaches, mostly shallow sandy beaches, particularly along the northern Adriatic Sea. Steep gravel beaches are common in the regions of Liguria, Calabria, Sicily and Sardinia, where small "pocket-beaches" are often found between rocky headlands. The 32% of Italian beaches is suffering erosion problems, only 5% is accreting and 63% is stable (Caputo et al.1991), also with the help of protection works, which globally defend some 700 km or 20% of beaches. An overall "radiography" of the morphological asset and evolutive trends of some 2000 km of

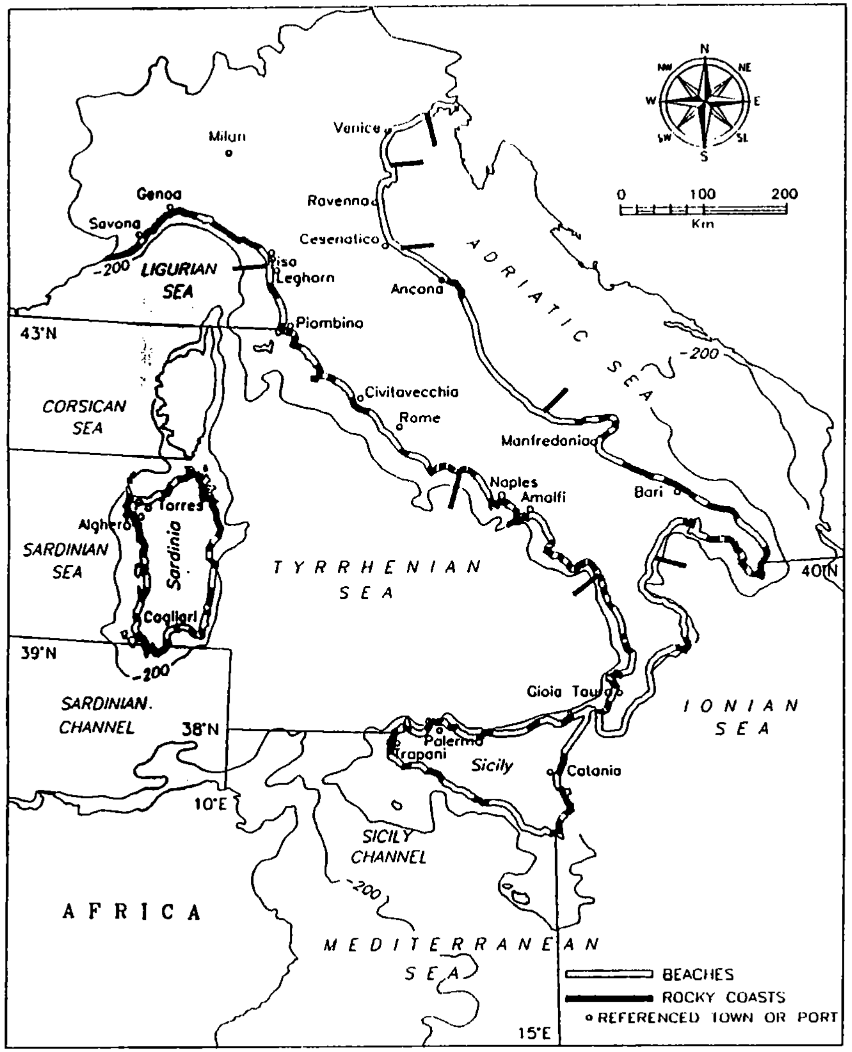


Fig. 1. Geographical subdivision of Italian seas and coasts

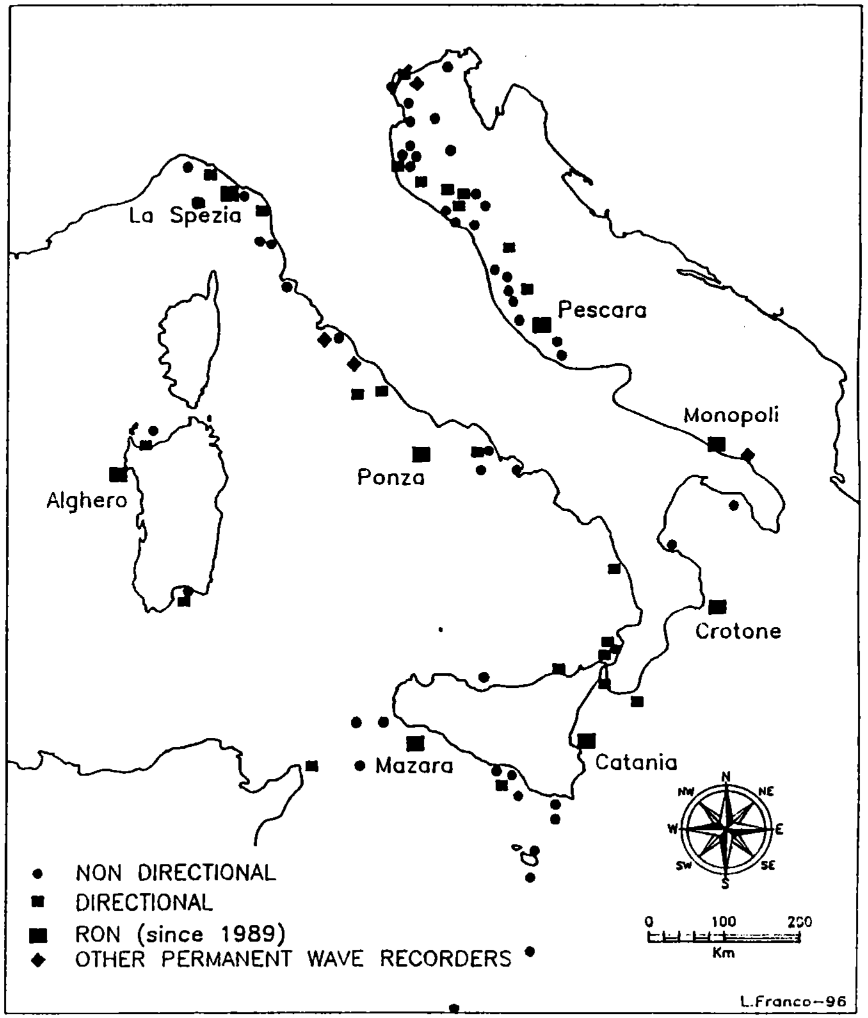


Fig. 2. Distribution of wave recording stations off the Italian coasts

littorals is given in the 60 maps at 1:100,000 scale of CNR's Atlas of Italian Beaches (1984). Reference is also made to Zunica 1976, 1985 and to the vast CNR's bibliography.

Italy is a "geologically young" region, but the variety and ancient age of rock formations indicate a very complex geological history. Volcanic and tectonic activities are still present. The articulated Italian orography has kept rising and, despite the small catchment basins of the fragmented hydrographic network, the numerous streams and rivers have been feeding the beaches with sediments eroded from the steep slopes. This material built up wide coastal plains which have stopped marine ingression: morphological deposition forms can be observed, such as deltas, lagoons and "*tombolos*" (a widely used Italian word, because typically formed by wave diffraction behind nearshore islands in almost tideless seas). The coasts have been modelled by the sea level variations induced by the glaciations (with final rise of 120 m between 15000 and 5000 years ago) and "fossil" beaches can be found either on the mountains of Calabria or in the sea floor of the south-central Tyrrhenian Sea and northern Adriatic (the latter is now quarried for beach nourishment of Venice lidos).

Quaternary deposits are made with marine and continental rocks of various kinds. Sediments are predominantly quartz but a variety of mineralogic types (siliceous, volcanic) can be found, with the exception of the carbonate sands from marine biota.
Italian beaches have been accreting until the end of last century, but they are now generally eroding, especially after the reduction of river sediment supply (mainly due to human activities such as damming and aggregate excavation).

Sea Level Rise. Measurements in the Tyrrhenian sea have been carried out since 1884 in Genoa. The computed rate was 1.2 mm/year for the period 1897-1942 and 1.54 mm/year in 1931-1971, while the present mean rate of sea level rise is 1.6 mm/year (Mosetti,1989). However this worldwide issue has not been so far a problem on fashion for Italian scientists and coastal engineers, with few exceptions such as the recent studies related to the design of the Venice flood barriers (CVN) and an application of a new Bruun-type model to predict shoreline retreat along the Tuscany coast (Pranzini et al.1995). However high rise eustathic scenarios would have dramatic consequences, especially for the shallow Adriatic beaches. Here, also coastal subsidence (due to the compaction of sediment deposits favoured by groundwater abstraction) has played a negative role with a land settlement of some 0.15 m in the first half of this century until recent deceleration after proper countermeasures.

Administrative Regulations. It can shortly be said that all Italian coasts belong to the State, although the jurisdiction for coastal protection works is now shared with the Regions (numbering 15 with sea shores out of the total 20) and new laws are now just being enforced which define coast classifications according to the importance of the river catchment basin. The technical authority for design and supervision of coastal works is the *Genio Civile Opere Marittime* of the Ministry of Public Works, subdivided in 11 geographical compartments as shown in fig.1.

Meteoceanographical Conditions

Seas and shelf. The very special shape of the 1200 km long Italian peninsula and the near large islands of Sardinia, Sicily and Corsica defines a number of "narrow" seas or basins (named in fig.1) with somewhat different meteoceanographical features. The largest depth of the Mediterranean occurs in the Ionian Sea with more than 5000 m, while the deepest point of the Tyrrhenian Sea is at -3700 m. The continental shelf is quite small (typically 10 to 40 km wide) all along the western and southern coastline, which is often bordered by nearshore deep waters. Only the narrow Adriatic basin has a relatively shallow seabed with the shelf extending for over 500 km from the northern shores to the area off the big Gargano promontory to the southeast.

Tides and Surges. This long shelf, together with the special semi-closed geometry of the Adriatic basin is responsible for the well known storm surges in Venice and neighbouring coastal areas, due to the setup of southeasterly winds and 22-hours seiching. The north Adriatic is also the only sea area in Italy where the astronomical tidal range can reach 1 m at springs. In most other Mediterranean coastal seas the semidiurnal micro-tides have an amplitude of just 0.4 m at springs and 0.2 m at neaps. In fact chart elevations are often simply referred to the Mean Sea Level Datum.

This peculiar feature has obvious important consequences in the design of harbours and shore protection works: port developments could not generally take advantage of sheltered estuaries as in oceanic locations and thus often needed costly breakwaters in deep wave-exposed waters; with regards to coastal defence works, the modesty of tides promoted the diffusion of detached breakwaters with tombolo formation and now the boom of submerged structures, which are more "environmentally friendly".

Currents Either density, tidal and wind-driven currents are generally weak (less than 1m/s), with the exceptions of the Messina Straits (up to 3 m/s due to tidal phase shift between the Ionian and Tyrrhenian Sea) and the Bonifacio's (between Corsica and Sardinia) and a few tidal inlets, such as those of Venice lagoon. A permanent weak density current runs in the anticlockwise direction all along the coastal water surface. The full water exchange of the Med Sea takes about 100 years, thus producing little autodepuration capacity and consequent ecological fragility, also due to the increasing human pressure along the shores and to pollution. Average seawater salinity is 3.8%.

Wind. Wind conditions are generally moderate: average speeds range between 5 to 7 m/s onshore at ground level, with strongest and more persistent winds occurring in northern Sardinia under prevailing north-westerly directions (Troen et al. 1989). Peak velocities associated with the fall/winter low pressure systems tracking across the Med Sea from west to east may reach 30 m/s. Useful overwater wind data have been recorded at some 60 stations located near the shore and on small islands by the Hydrographic Naval Institute of Genoa from 1927 to 1960 (IIMM 1984) and by the Air Force Meteorological Institute (AM) since 1951. Statistics from the latter data had been produced together with ENEL, National Electricity Board (AM-ENEL 1980).

Global wind forecasts are issued by AM, based on the advanced model results from the European Centre for Medium-range Weather Forecast located in Reading (UK).

Waves. Wind waves are the main hydraulic parameter affecting the response of Italian beaches and coastal structures. Storm waves are mostly generated in geographically limited fetches, thus producing short steep 3-D seas and modest swell activity. Directional and extreme wave statistics were typically gained from offshore shipboard observations and with simple hindcasting methods, but more accurate and reliable data are now obtained from advanced 3rd generation wave models and from systematic instrumental measurements. An updated inventory (Franco 1993) showed nearly 100 wave recording stations installed since 1974 along the Italian coasts (fig.2) by some twenty different institutions (including ENEL, oil companies, universities), after the pioneering observations off Genoa breakwater in the early 30's (described later).

A remarkable achievement is represented by the integrated permanent National Wave Measurement Network (RON), operational since 1989 with an average data acquisition rate above 90%. It is managed by the Italian Hydrographic and Tidal Service and includes 8 directional Wavec buoys moored in 100 m depths (remote-controlled by the Argos satellite) and the corresponding onshore receiving stations for real-time data transmission (De Boni et al.1992). New deepwater wave statistics from these 6-year directional records can be found in Archetti et al.1995.

The wave climates are more consistent, unidirectional (westerly) and energetic along the western shores, while reduced and more variable wave activity affects the Adriatic and Ionian coasts (with prevailing northerlies). In these eastern basins the average specific gross wave power is smallest (3-4 kW/m), while it is largest at the Sardinian Sea coasts (16 kW/m), but yet not enough for a convenient production of wave energy with the present technology.

Typical storm durations are 2-4 days, with spectral peak periods in the range of 5-13 s and 1-year return significant wave heights of 3-4 m and 50-year return H_s of 7-8 m. Wave energy spectra at storm peaks are typically well fitted by the unimodal JONSWAP shape, though the mean value of the peak enhancement factor γ is found to be 1.9 (instead of 3.3 as for the North Sea). The directional energy spread is well described by the cosine-power function with an exponent between 2 and 4.

The most severe sea states occur off the western coasts of Sardinia and Sicily, under mistral wind storms (from WNW): the highest sea state was instrumentally recorded by the RON buoy off Alghero on 1.1.1994 with H_s=9.2 m, T_p=12.5 s and H_{dmax}=15.0 m. However, severe damages to various port and coastal structures along the eastern Tyrrhenian shores were caused by another exceptional storm reaching H_s=11 m off west Sicily on 11 January 1987, as hindcasted with a refined wave spectral model covering the whole Mediterranean Sea. In fact either 2nd and 3rd generation wave forecasting models are being used with good results. The advanced WAM model is now operational for the Med Sea upon a computational grid of just 25 km mesh size (Cavaleri et al.1991).

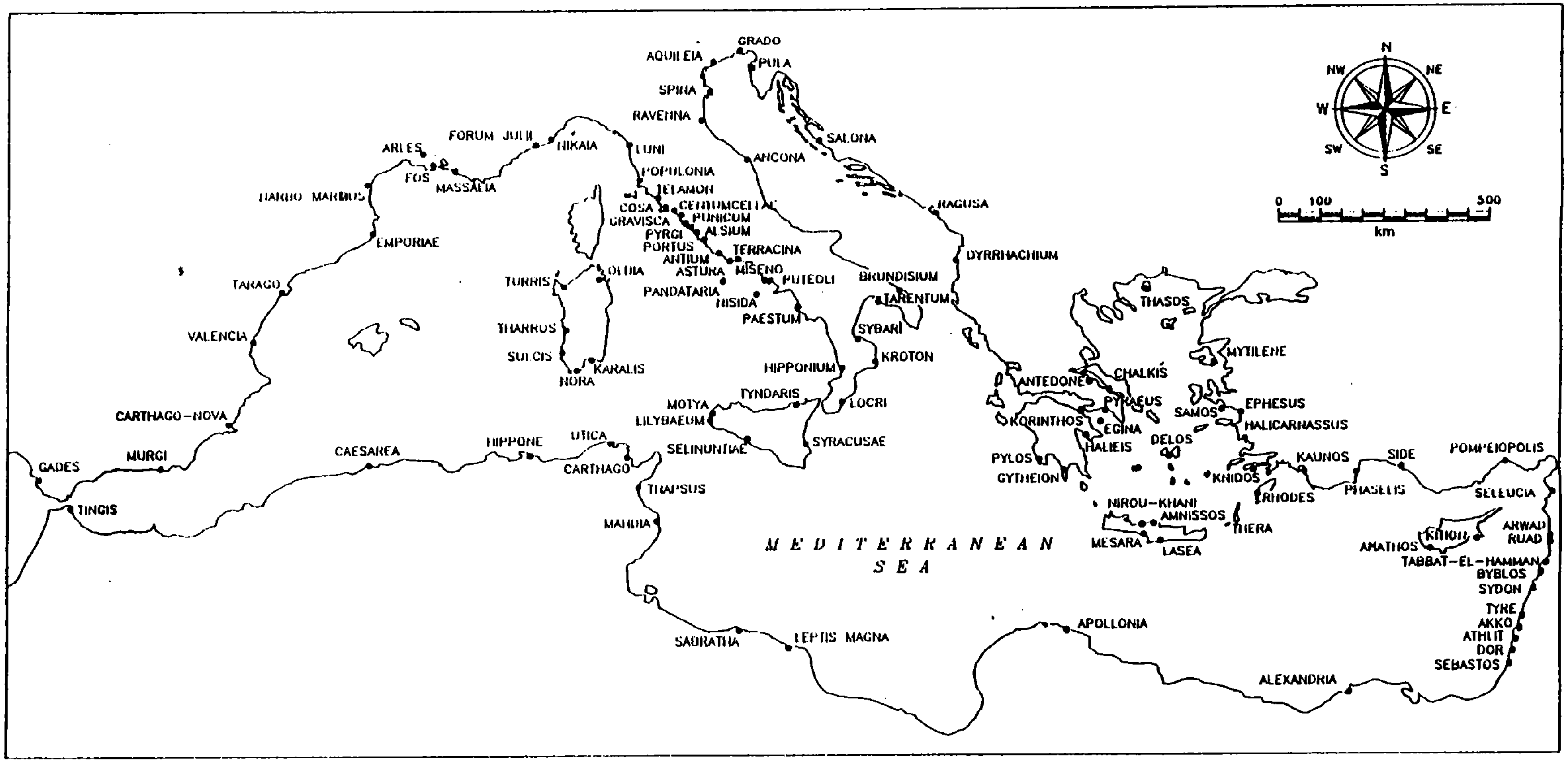


Fig.3. Location map of main ancient Mediterranean harbours, generally called with their original names (mostly with visible remains)

HISTORICAL DEVELOPMENTS

Coastal Engineering developed very early in the history of human civilization, particularly in the Mediterranean basin, together with the origin of maritime traffic, which has always been a key factor in the economic and political growth of nations. In fact past efforts were mostly devoted to port structures, with the exception of a few places where life has been dependent on the coastline protection. One such case is Venice and its lagoon, where sea defences (hydraulic and military) were vital for the survival of the thin coastal strips: the old impressive shore protection works built by the Venetians are still admired today.

The developments in the ancient classic times were related to the different dominations and cultures which followed especially in the eastern and central Mediterranean basin: Egyptians, Minoans, Phoenicians, Carthaginians, Greeks, Etruscans and Romans. After the Roman age nearly no technical evolution took place until Napoleon times! Therefore it is believed worthwhile to give a broader review of this unique valuable antique heritage, which is still visible in many surprisingly advanced and intact coastal structures. The study of these "monuments" can give to present coastal engineers and managers a useful humanistic background and even some good ideas for new designs, especially in view of the *gentle* environmental harmony of the early natural harbours. Moreover the conservation, restoration and valorization of these remains in suitable "archaeological coastal parks", or even re-use for modern marinas, could enhance the touristic-cultural offer of many Mediterranean countries (Franco, 1996).

In a simple historical classification coastal/harbour engineering might be subdivided in a "naturalistic" *antique age* (2000 BC - 500 AD), a "technological" *modern age* (500-1950 AD) and a "scientific" *contemporary age* (after the first ICCE in 1950). However these chronological boundaries, as usual in the history of sciences, are inevitably conventional and somewhat artificial: they are not be considered as a rigid frame, but as a simple marking criterion for the organization of this paper.

Antique Age

For a general review of ancient harbour archaeology reference is made to Shaw (1974) and Blackman (1982) with an extensive bibliography. Two monographical books on ancient Italian harbours were also edited by the Navy (Marina Militare 1905). A more technical overview has been recently given by De la Pena et al.1994. A reference map of the main ancient harbour sites in the Mediterranean Sea is proposed in fig.3.

It is expected that more information on the outstanding achievements of ancient coastal engineers is still to be gained after future discoveries from modern underwater archaeology and more sophisticated survey techniques. In fact very few written reports on the ancient methods for design and construction of coastal structures are available. The only technical handbook is the one of Vitruvius (27 BC) mainly related to the Roman engineering experience. Further useful descriptions are given in the classic Greek and Latin literature by Herodotus, Josephus, Suetonius, Pliny, Appian, Polibius, Strabo and others. They also show the ancients' capability to understand and handle various complex physical phenomena without supporting data or computational tools, such as the tidal phenomenon, the Mediterranean currents and wind patterns and the wind-wave cause-effect link. The Romans first introduced the wind roses too.

Pre-Roman harbours. The so-called *proto*-harbours were mainly used for refuge, unloading of goods and freshwater supply for the shallow-draught wooden vessels cruising along the "inside routes" of the Mediterranean Sea (only during the good season). These early harbours were "natural", typically located in favourable geographical conditions, such as sheltered bays near capes or peninsulas, behind coastal islands, at river mouths, inside lagoons or deep coves, where short breakwaters were often sufficient to supplement the natural protection. Harbours were generally close to high coastal mountains easily visible from the sea in the distance and they were possibly spaced at 40-50 km intervals to allow safe day by day tranfer to the vessels sailing coastwise at a speed of 3-5 knots. Ports were necessarily built on the numerous islands and along the mainland coasts to serve a large hinterland and they were often closely linked with city sites. In fact the harbour basin was often enclosed with fortifications, even closable from the sea, and separated from the city for reasons of security (military harbours) or control of goods and passengers.

Probably the oldest man-made seaport was the first harbour of Alexandria (Egypt), built by the **Minoans** to the west of Pharos island around 1800 BC. The main basin was 2340 m long, 300 m wide and 6-10 m deep to accomodate 400 ships of 35 m length; the numerous breakwaters and docks (14 m wide) were made with rock blocks (5 m long). Remains of early Minoan coastal structures are also visible at the harbour of Nirou Khani, Crete (1500 BC), which still shows two rectangular slips (43 x 6 m) cut into the dune rock and divided by a 0.8 m wide masonry rock wall (Inman 1974). The earliest harbour works on the Italian coasts were probably made later by the expert **Phoenicians** who set up the maritime trade with various southern coastal towns since the 7th century BC. However the best known Phoenician harbour structures are found on the eastern Mediterranean shores of today's Lebanon and Israel (e.g. Arwad, Byblos, Tyr, Sidon, Dor, Akko, Athlit) (fig.4).

The design of these early harbours was mainly dictated by nautical and military constraints, such as providing safe access even in hard weather through usually narrow entrances, which could be easily controlled and even closed with chains. Two or more entrances were sometimes provided, either to ease navigation under variable winds, and to separate different port routes and traffic (commercial, military and fishery) and to favour water flow in the relatively tideless basins; in order to keep silt in suspension and avoid harbour siltation. Prevention of siltation was infact a fundamental issue, since mechanical dredging was not feasible. Not only multiple port entrances were provided, but also underwater channels and tunnels through the moles (eg. Syracuse). River flow, sometimes diverted in settling-tanks, was also used to prevent siltation. The flushing channels, often controlled by sluice gates, would be open to the sea above MSL at the side where the seabed was rocky and shallow enough for the waves to break and release most suspended sediment before reaching the breakwater. Even ramps were constructed to allow the wave crests to sweep over the breakwater and collect sand-free water in a tank at an higher elevation for periodical release into the harbour.. This "wave pump" system is now proposed for flushing Mediterranean marinas with the novel scope to improve the quality of polluted water and openings through the breakwaters (also with the help of pumps) are again being created for the same reason.

The natural de-silting concept was still in use in the imperial Roman harbour of Caesarea Maritima. The recent discovery of a dump off the entrance seems also to show that the outflowing current not only prevented the sand from entering the port, but even kept the floor of the closed basin free of jettisoned garbage. Moreover the funnel-like topography of the entrance would channel the outgoing current through the whole opening. (Raban 1988).

In order to reduce large wave overtopping at the vertical rocky cliffs and breakwaters the Phoenicians excavated hollows and trenches in the rock. These "wave catchers" would channel and drain the water off back to the sea and were also used as an immediate source of building stone. This concept was also later applied by the Romans at the harbour of Pandataria island (now Ventotene) (fig.5) and a modern artificial version of this crownwall modification was recently patented by Sogreah under the name of "Overspill Basin" breakwater and it was used at Fontvieille, Monaco (on top of precast cellular caissons towed from Genoa in 1968) (Borzani 1973).

Another typical characteristic of the earliest harbour works cut out of rock reefs or islands was that the rock mass was flattened on its sheltered landward side to make a quay, leaving a protective rock wave-wall on the sea side (Frost 1972). A wonderful example of the natural “carved breakwater” is again represented by the imperial Roman harbour of Pandataria (fig.5). This remarkable “coastal structure” is cut from the bed-rock by creating a suitable wave-absorbing seaward profile, with a deep parabolic shape and a mild grooved absorbing slope near the waterline.

A high level of technology for submarine construction was already achieved, as shown by the regular placement of small stones to build smooth walls which are still in place. An innovative technical feature was the use of ashlar header quaywalls: the slim blocks were laid in tight courses with their long joints in a very close fit to give maximum drag and thus solving the problem of the vacuum effect of the retreating water from the vertical wall (Raban 1988). The Phoenician engineers were also able to prevent the undertrenching of walls laid on sand by paving it with a layer of large pebbles. External breakwater slopes were mostly armoured with randomly placed rock.

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

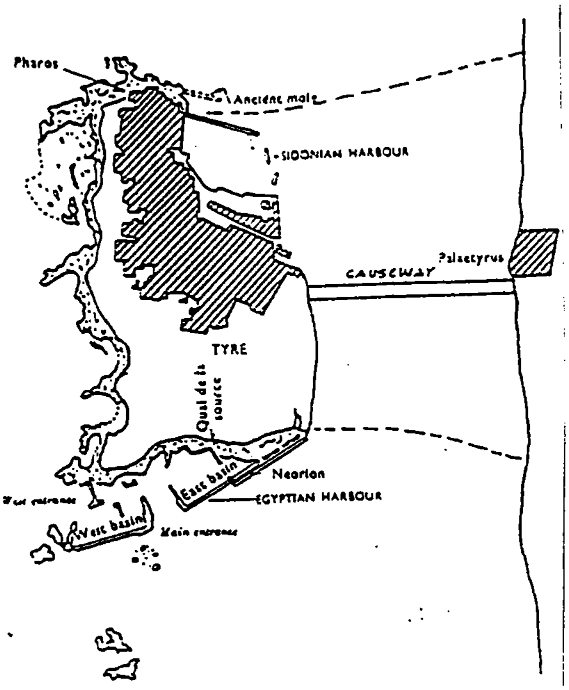


Fig.4. The multiple harbours of Tyr

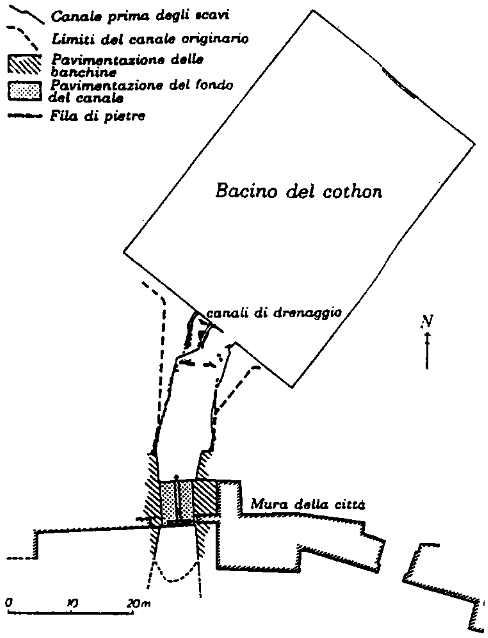


Fig. 6 Plan of the Phoenician harbour of Motya (Shaw)

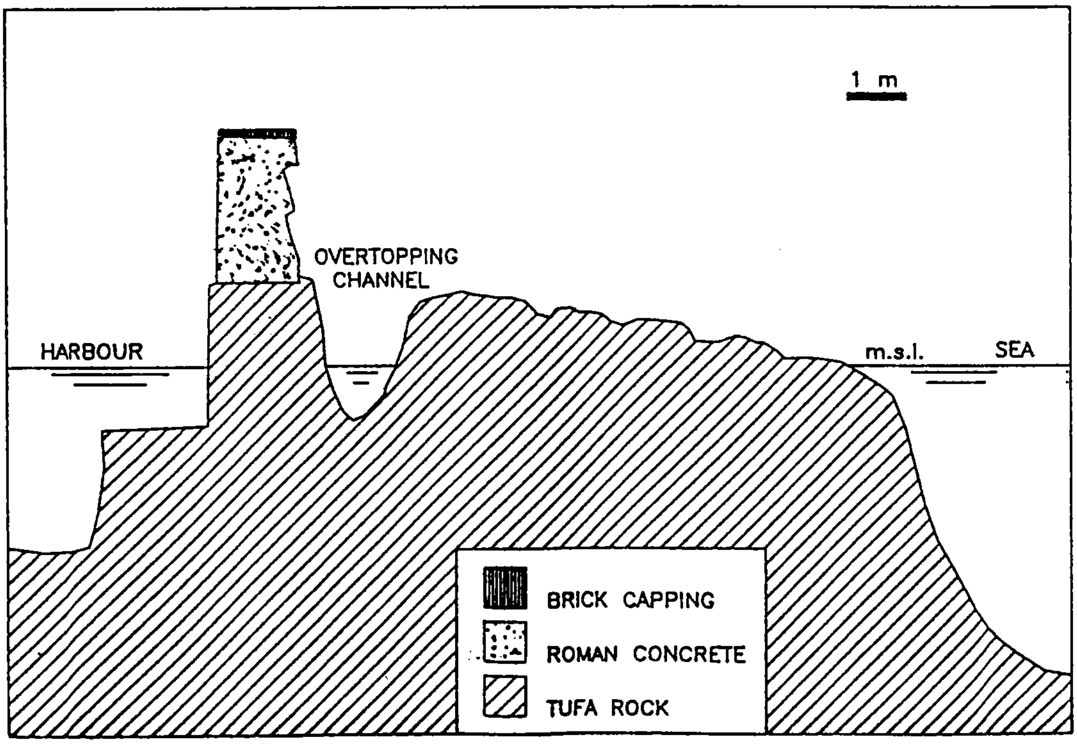


Fig.5. Cross-section of the Roman "carved rock breakwater" with overspill stilling channel at Ventotene

visible at Motya (Sicily) and Carthage (Tunisia). At Motya the cothon might have been closable and drainable to be a dry-dock (fig.6).

The famous harbour of Carthage, recently studied under a UNESCO safeguard program, shows two large basins excavated inland, a rectangular one probably devoted to commercial traffic and the inner ring-shaped refuge basin for the navy, invisible behind a long high wall. Right in the centre of the inner basin the 125 m wide circular Admiralty island was used as a shipyard for up to 200 war-ships and dominated by a control tower. It seems that radial wooden finger piers were also provided along the circular perimeter for an easier sideways berthing, like in modern marinas. Columns were also used as bollards instead of mooring rings and covered berths were arranged within monumental arcades. Other Punic harbour ruins are visible in Sardinia (Nora, Tharros) and in Sicily (Lylibeum), besides the north-african coast.

The **Greeks** (VI-III c. BC) also took advantage of narrow peninsulae for building safe "multiple harbours" (Cnidos had four). The breakwaters were mostly built with cut rocks regularly placed without mortar on rubble mounds. Herodotus reports of a breakwater at Samos built on 530 BC in water depths up to 35 m ! The large Athenian triple harbour of Piraeus is famous for his 372 covered slipways ("shipsheds" 37 m long and 6 m wide with a slope of 1:10). Alexandria was also a well known monumental Greek export port, actually built by Alexander the Great in later Ellenistic times (III-I c. BC) behind the coastal island of Pharos. A 1.5 km long breakwater, with two openings, joined the island to the mainland dividing two basins with an area of 368 hectars and 15 km of quay front . The port also became famous for its impressive 130 m high lighthouse tower, to guide ships from a distance of about 50 km towards the port in a sea without landmarks. The multi-storey building, one of the Wonders of the Ancient World, eventually collapsed due to earthquakes in the middle ages, though it was made with solid blocks cemented with melted lead and lined with white stones, which are just recently being finally recovered underwater by archaeologists.

Another peculiar feature of the Graeco/Ellenistic harbours was the use of colossal statues to mark the entrance. The most famous application reported by historians was the 30 m high Colossus of Rhodes, standing on top of the breakwater heads (but not yet discovered). It is interesting to observe that three ancient windmill towers are still surviving upon Rhodes breakwater, impressive precursors of today's wind turbines for energy production. Greek ports in Italy were created in the southern regions (*Magna Grecia*). Typically they are still part of the town (even closed within the walls like Delos), whereas in the Roman Empire they will become an independent infrastructure, with own buildings and goods storage deposits (*horrea*).

In the same times the western central part of the Italian peninsula was ruled by the **Etruscans,** who also constructed new harbours (often in coastal lagoons), later used and upgraded by the Romans. Several marks still exist along the Tyrrhenian coast north of Rome. An interesting example is the *colonia maritima* of Pyrgi (now S.Severa), where an inland basin with quaywalls is connected to the sea where submerged offshore rubble breakwaters still exist (Protani et al.1989). Shore protection works have recently been built here also to defend a superimposed nice medieval castle, deteriorated by the wave activity focused on the shallow promontory.

The Etruscans were also expert in controlling water circulation against siltation by linking the lagoon to the sea with one or more canals, as still visible at Ansedonia. Here the excavations of the ancient harbour of Cosa (further developed by the **Romans** in the II century BC) were carried out by the American Academy in Rome since 1948 (Lewis 1973, Brown 1980). The harbour represents a transition between the natural anchorages of the early Etruscans and the elaborate artificial harbours of the later Romans (fig. 7). It was composed by a lagoon and an outer basin sheltered by the limestone promontory and by breakwaters (now submerged) made with 2 t rock blocks directly quarried from the adjacent cliff, piled on the seabed and later cemented with natural sand concretion, hydraulic cement and addition of broken pottery to increase the bond. The rocks are now worn to an oval shape and reduced in size due to sand abrasion and animal borings over 2000 years. A few tufa-and-mortar eroded piers (docks?) are still standing out of the water and some detached breakwater extensions are visible underwater near the 50 m wide entrance: their staggered arrangement was probably intended to provide the usual scouring de-silting currents. Existing spectacular features are the gigantic natural sluiceways formed by two nearly parallel cuttings along the adjacent rocky cliff, the natural crevasse Spacco della Regina (260 m long, 30 m deep and 1 to 6 m wide, after suitable wall scarping and bed clearing) and the artificial Tagliata (70 m long and 4 to 5 m wide, partly tunneled), which link the deep sea with the inner harbour and lagoon (fig. 8). Vertical rockcut slots are clearly visible on opposite sides of the channel which were surely used for sliding boards as sluice-gates to control the water flow (probably also the fish flow to and from the lagoon) according to wind conditions and tidal cycle.

Roman harbours. The first harbours of the golden imperial times (since I century BC) are Forum Julii (Frejus), Mysenum (Miseno) and Puteoli (Pozzuoli). Other marks of well known Roman harbours on the Italian shores are still visible at Nisida, Terracina, Antium (Anzio), Portus (Ostia-Roma), Ancona, Centumcellae (Civitavecchia), Astura, typically protected by monolithic concrete breakwaters.

The revolutionary innovation in harbour engineering was infact introduced by the Romans, who learned to build walls underwater and therefore managed to construct solid breakwaters to protect fully "external" harbours with free planshape, even curvilinear (to enhance de-silting currents) along a coastline without many natural protection. They learned the use of metal joints and clamps to fasten neighboring blocks and discovered the hydraulic cement made with pozzolanic ash (from the volcanic region around Naples), which hardens underwater. Therefore the Romans replaced the traditional Greek rubble mound breakwaters with vertical and composite concrete walls (*opus pilarum*), even for the rehabilitation of the old Greek harbours. In fact on deep seabeds they also used to lay a rock foundation up to -6 or -7 m MSL and then construct the vertical wall. Monolithic coastal structures could be built rapidly and needed little maintenance: in fact many works have survived to sea attacks for over 2000 years. Another possible reason for the Roman preference for vertical

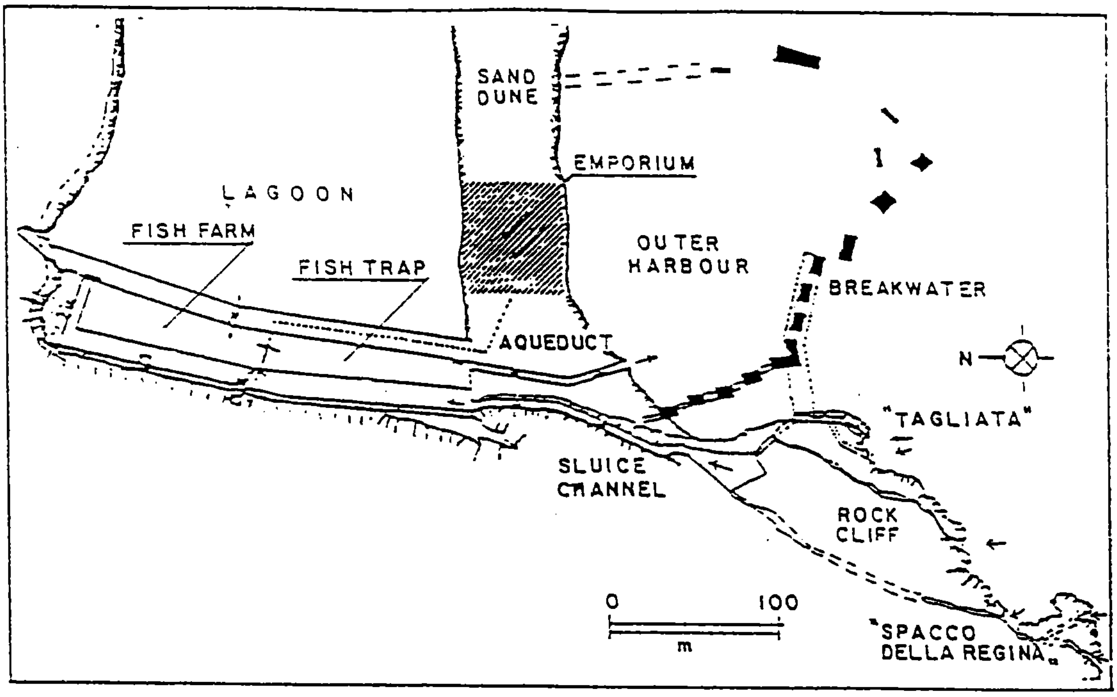


Fig.7. Reconstruction of the Etruscan and Roman harbor layout at Cosa (Brown)

Fig.8. View of the ruins of Cosa harbour from an ultralight plane, also showing the Etruscan artificial rock-cut channel named *Tagliata* (photo by Franco 1991)

coastal structures was the potential of wave reflection for desilting. Anyway either rubble or bronze slabs were placed by the Romans in front of the vertical walls to protect the seabed from toe scour (Oleson 1988).

However the Romans did not just follow a single codified tradition, but properly used a variety of design concepts and construction techniques at different coastal sites to suit the local hydraulic and geomorphological conditions, and availability of materials. Geotechnical conditions were analysed in order to choose a suitable foundation method. In hard bottom soils only a superficial layer was dredged to be replaced by a smooth rock bedding layer. If the bottom was sand a trench wider than the wall was excavated (typically in the dry, as shown in fig. 9) and then filled. In case of high layers of mud, according to Vitruvius, the Romans used to drive numerous short piles, (with 0.45 m square section) made of wood from olive tree, black poplar or holm-oak with scorched tip, and put coal rock between the pile heads. Infact the Romans developed the mechanical technology of cranes and pile drivers (Julius Caesar 55 BC). For pile driving in water the crane was placed on a raft or barge, and guides, hoist and pile-hammer were used. The iron pile caps were covered with lead against corrosion. The fig.8 also shows the method for building a rock-block vertical structure after pumping out water and leveling the seabed within two 1.5 m wide cofferdams made with sheetpiles (wooden posts set closely together) filled up with clay bags (Prada et al. 1995), probably strengthened by cross tie-rods (ropes).

Instead, the typical breakwater construction technique in sheltered sites consisted in pouring a mix of cement, pozzolan and brick pieces (impermeable mass concrete) within immersed wooden forms (*arcae*) supported by driven piles and tie-rods (*catenae*) and later casting a concrete emerged superstructure, about 6 m wide, covered by bricks or joined squared rock slabs (fig.10) (Clementi 1981). Figure 10 also shows the characteristic block with a hole (*dactylium*) used for ship mooring on the rear side: the hole axis could be either horizontal for mooring lines or vertical for tie piles, as still visible at the river port quaywall of Aquileia (fig.11).

Several prints (and even some remains) of a more complex reinforcing “skeleton” of oak pillars and cross-bars can be observed in the moles of the Neronian port of Antium. The pillars inside the formwork (*destinae*) could have worked as anchors, while the horizontal cross-bars (at +1 m MSL) could have also usefully supported a working floor. The modular frames are repeated with 2.5 m spacings. The joints show that half mole width (6 m) was probably cast against the quickly hardened solid wall edge of the other half. The “staggered”construction sequence thus allowed saving the forms for the adjoining portions. The perimetral wooden forms could also be “sunk” in a first fresh cast of mortar to increase the frame stability (Felici 1993).

Sometimes, instead of the forms, old ship hulls were sunk and filled with concrete, saving time and material. A well known example is the main west breakwater of Portus (Rome) built under Claudius (around 50 AD) partly by sinking the 7400 t DWT, 104 m long Caligula's ship (probably the largest wooden hull ever), which had transported the Vatican obelisk from Egypt, in order to create a solid foundation for the big

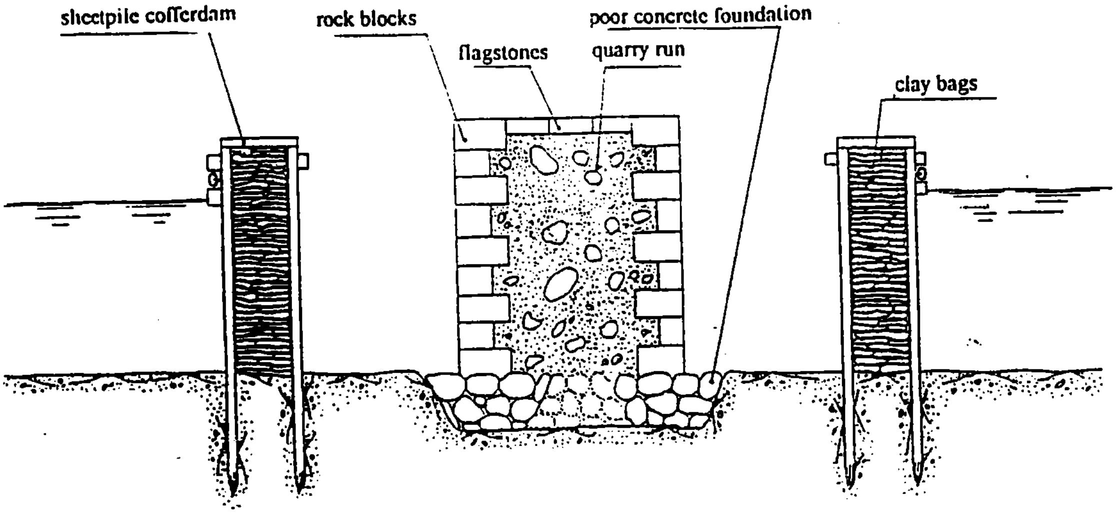


Fig.9. Roman method of construction of a rock block vertical breakwater in good seabed conditions at exposed sites according to Vitruvius (Prada et al.1995)

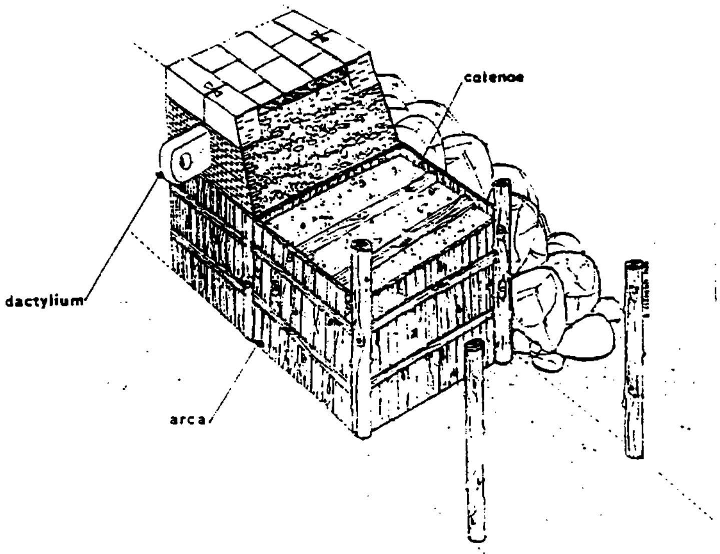


Fig.10. Reconstruction of the Roman construction system of a vertical breakwater with cast-in-situ concrete within wooden forms and tie-rods (Clementi)

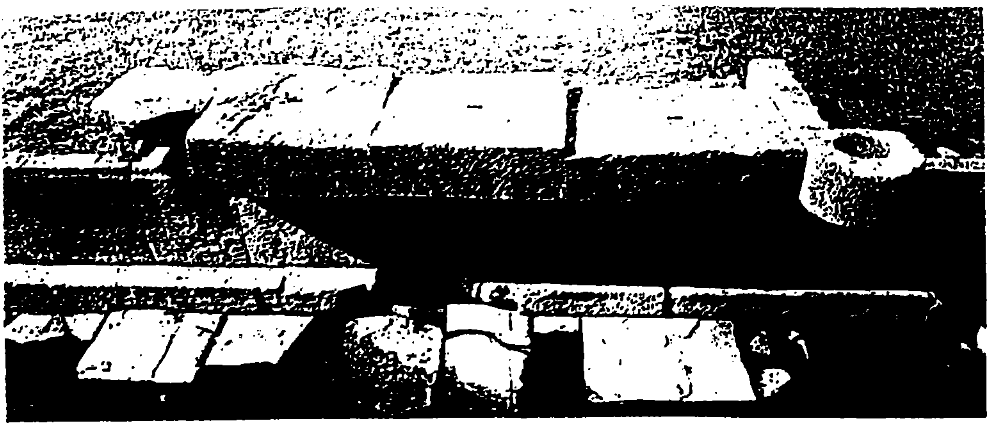


Fig.11. Double level quaywall with tie-pile mooring block at Aquileia river harbor

lighthouse (fig.12) (Testaguzza 1970). The great breakwater is still partly visible, abandoned within the grass grounds of Fiumicino airport.

In wave-exposed locations a different construction method could be used according to Vitruvius. Work progressed from the shore by dumping a submerged rubble mound. A perimetral sheet-piling was then filled with sand and topped with concrete. After the opening of little doors in the cofferdam the natural removal of sand allowed the concrete block settlement (Prada et al.1995).

Another advanced technique was invented by the Romans for deep water applications: the watertight floating cellular caissons, precursors of the modern widespread technology of monolithic breakwaters. Double-walled wood forms constructed nearshore were towed into position over a foundation of boulders on sandy bottoms and waterproof mortar packed between the double walls to sink the form. Concrete was then poured into the water-filled frames by lowering baskets. This system was used by Herod the Great's engineers in 18 BC to build the 60 m wide breakwaters of Sebastos (Caesarea) harbour (Hohfelder 1987).

The recent large excavation project at Caesarea (CAHEP) also revealed a subsidiary parallel breakwater to reduce wave impacts onto the main walls (fig.13). The crest of this small "tandem" rubble barrier was probably at the sea level, some 15-30 m seaward of the main breakwater. It was interrupted with gaps to provide an exit for rip currents and prevent the wave setup piling up in the "stilling basin"(Raban 1988). Another unique feature of the main breakwater at Caesarea is the "natural" construction technique used for building up the very wide core: the block walls or caissons on the rubble foundation were framing hollow "trap"compartments which would be filled by the wave-carried sand within 2-3 years and then paved and built-on above water level (fig.14). The large width of the imperial port breakwaters allowed the innovative location of various installations (eg.warehouses) upon the crown.

An original vertical wall breakwater was built at Thapsus (today Rass Dimas, Tunisia), whose 259 m long and 12 m wide impressive remains were still surviving in 1869. The peculiar feature of this monolithic mole was the presence of vents through the wall to reduce wave impact forces (fig.15) (Tasco et al. 1965). This idea was resumed some 30 years ago by Jarlan to provide absorbing chambers in perforated caisson breakwaters and has numerous modern applications in Italy (as described later).

Another particular version of the Roman vertical-type breakwaters was the system of detached piers joined by arches. Remains of "arched moles" have been found in Nisida, Mysenum and Puteoli (all in Naples Gulf). As depicted in a famous fresco of Stabiae (fig.16c), the ancient monumental superstructure of Pozzuoli's mole was adorned with arches and columns to be an important social walkway. It was 372 m long and rested on 15 piers each 16 m square (now incorporated in the modern breakwater) as shown in the surveys of De Fazio in 1814 (fig.16 a, b). The large water depth at the last pier (-16 m) can be surprising due to the shallow draught of the ships at that time: it demonstrates that not only nautical but also hydrographic reasons (wave disturbance,

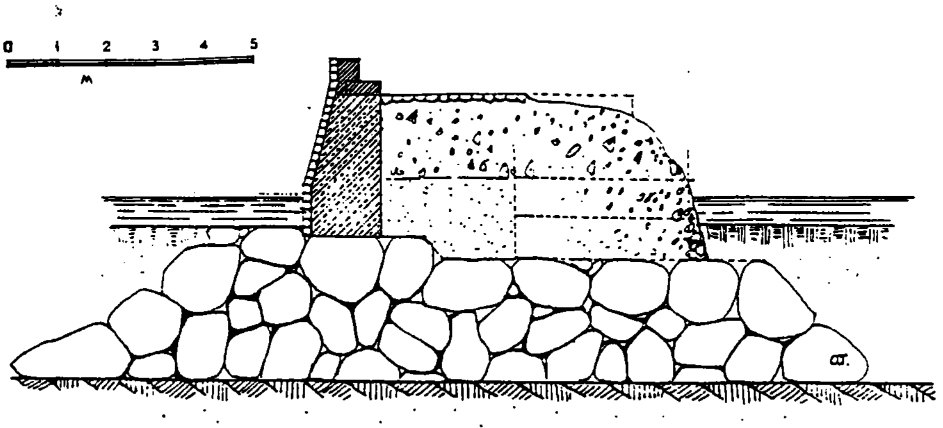


Fig. 12. Cross-section of the main breakwater of Claudius Port (Rome): the concrete superstructure was cast after sinking ship hulls as lost forms (Testaguzza 1970)

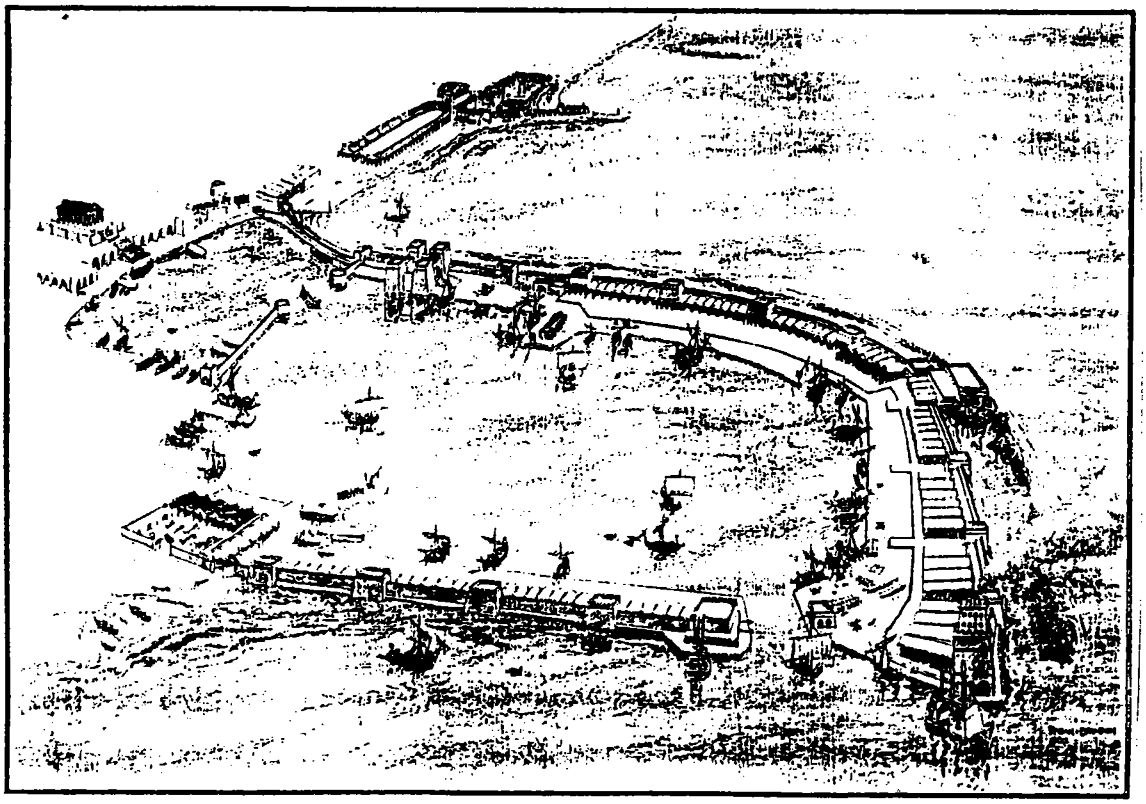


Fig. 13. Conceptual depiction of the ancient harbour of Sebastos based on recent archaeological data (Center for Maritime Studies, University of Haifa, Israel)

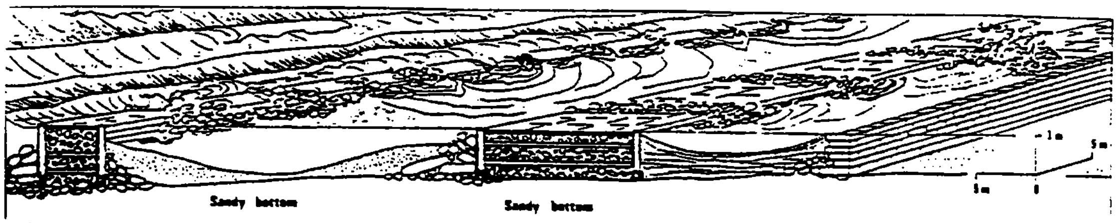


Fig. 14. Schematic block diagram across Sebastos main breakwater during the initial phases of construction (C..M.S.- University of Haifa, Raban 1988)

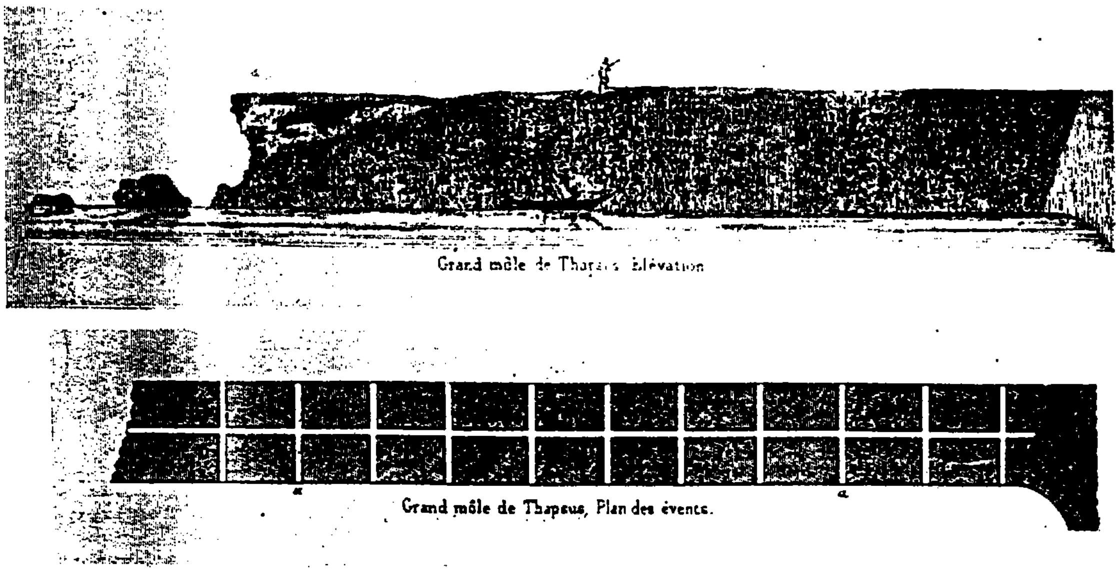


Fig. 15. The perforated vertical breakwater at Tapsus in a drawing of the XIX century

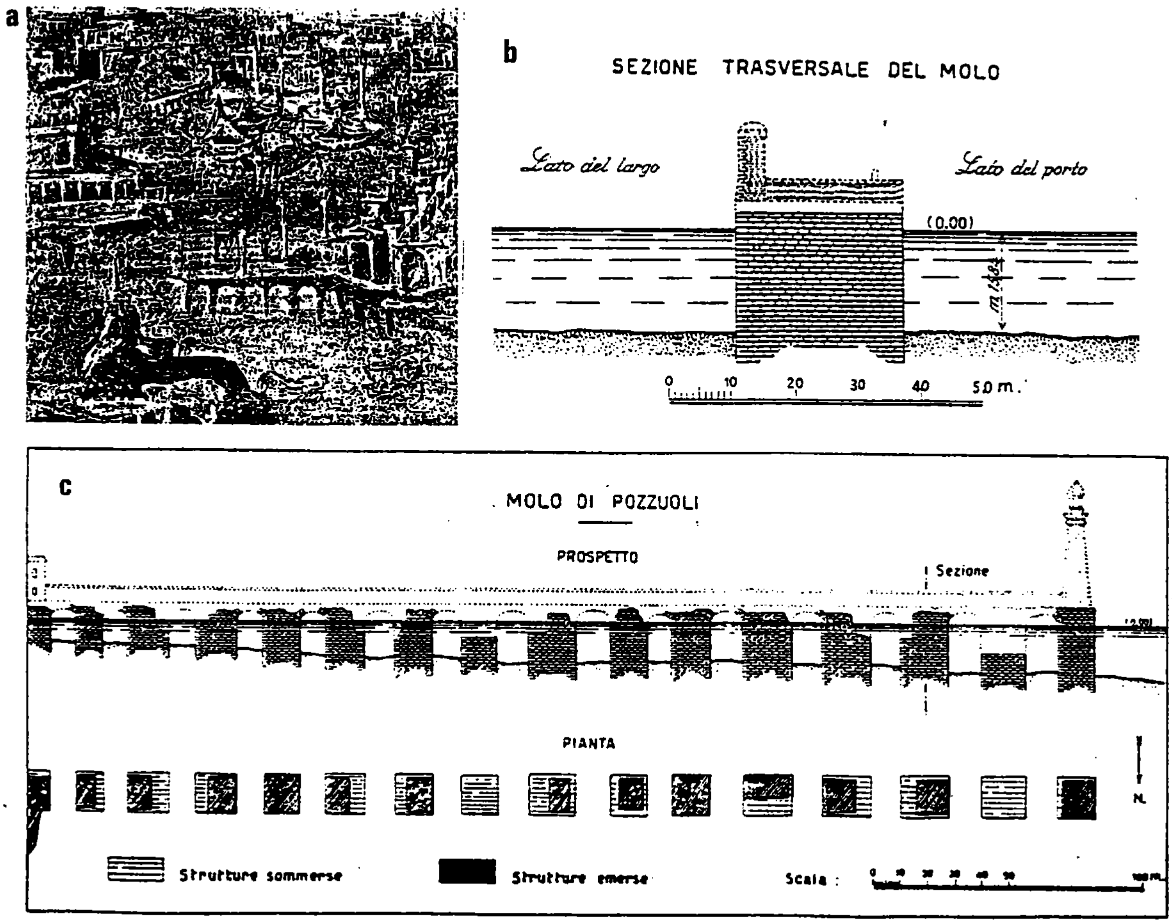


Fig. 16. The arched mole of Puteoli as depicted in the fresco of Stabiae (a) and as surveyed by De Fazio in 1814: b) typical pier section; c) view and plan

port siltation) were taken into account in the design of harbour protection structures. At Mysenum the breakwater was even made with a double row of arches in an off-set position to reduce wave penetration. The technical reasons for these unconventional arched breakwaters may be: control water circulation against siltation; reduce wave reflection which affects coastal navigation; save material in deep water; borrow the successful construction techniques and aesthetical views of the famous Roman aqueducts and bridges. This kind of "open" breakwater was still favoured by harbour engineers of the XIX century (De Fazio, 1814), despite its obvious uneffectiveness due to the actual sedimentation and unacceptable wave disturbance in the sheltered basin (at Astura they appear partially closed at a later stage). However, they were probably only used in sheltered locations as outer port protection, and the arcades could have been equipped with sliding gates for temporary closure during storms.

In antiquity the largest artificial harbour complex (1.3Mm^2) was the imperial port of Rome: the maritime town at the Tiber mouth was infact named Portus (=*The* Port) (Lugli et al.1935, Testaguzza 1970). It is now some 4 km from the sea, partly buried under Rome-Fiumicino airport (the outer port of Claudius) and partly within a private estate (the inner hexagonal basin later built by Trajan with sides of 360 m and a depth of 5 m) (fig.17). Despite its importance for the supply to the empire capital (over 300,000 t/year of wheat from Egypt and France), the port always suffered from river siltation, but this is also the reason for its conservation in modern times, though not yet fully accessible to the public. Numbered columns have been found, set back from the edge, on the quays of Trajan harbour, which meant to identify each berth.

Trajan (around 100 AD) also built the ports of Terracina and Centumcellae (Civitavecchia). The former one was excavated at a river mouth and the mooring quays and columns are well visible along the nice circular perimeter (Schmiedt 1975). The harbour of Centumcellae was built just to serve his villa in a site chosen on purpose for the favourable rocky morphology, but after the decline of Portus it became (and still is today) the port of Rome and remained unchanged for over 1000 years. The inner Roman Basin, presently still in use, was dredged in the rock (200,000 m^3), which was reused for the construction of the composite type breakwaters. The main structure has been reshaped over the centuries to reach an efficient mild-sloping profile (1:10 down to -2 m, 1:8 until -7.5 m, and 1:2 down to the bottom around -15 m MSL), which is considered a reference for modern rubble mound breakwater design (fig.18).

The harbour layout shows a characteristic Roman scheme with an island breakwater which supplemented the two main converging arms in order to reduce wave penetration through the gap, thus providing a double entrance for manouvrable vessels and possibly avoiding siltation at the entrance. The offshore breakwater generally supported a large fire-lighthouse (fig.17a). A similar planshape is observed in the small well preserved port at Astura point near Antium, again serving a seaside villa (where Cicero had stayed) and fishing ponds (Clementi 1981).

However, the most modern and efficient harbour planshape can be observed in the beautiful intact Roman harbour built under Augustus in the exposed small prison

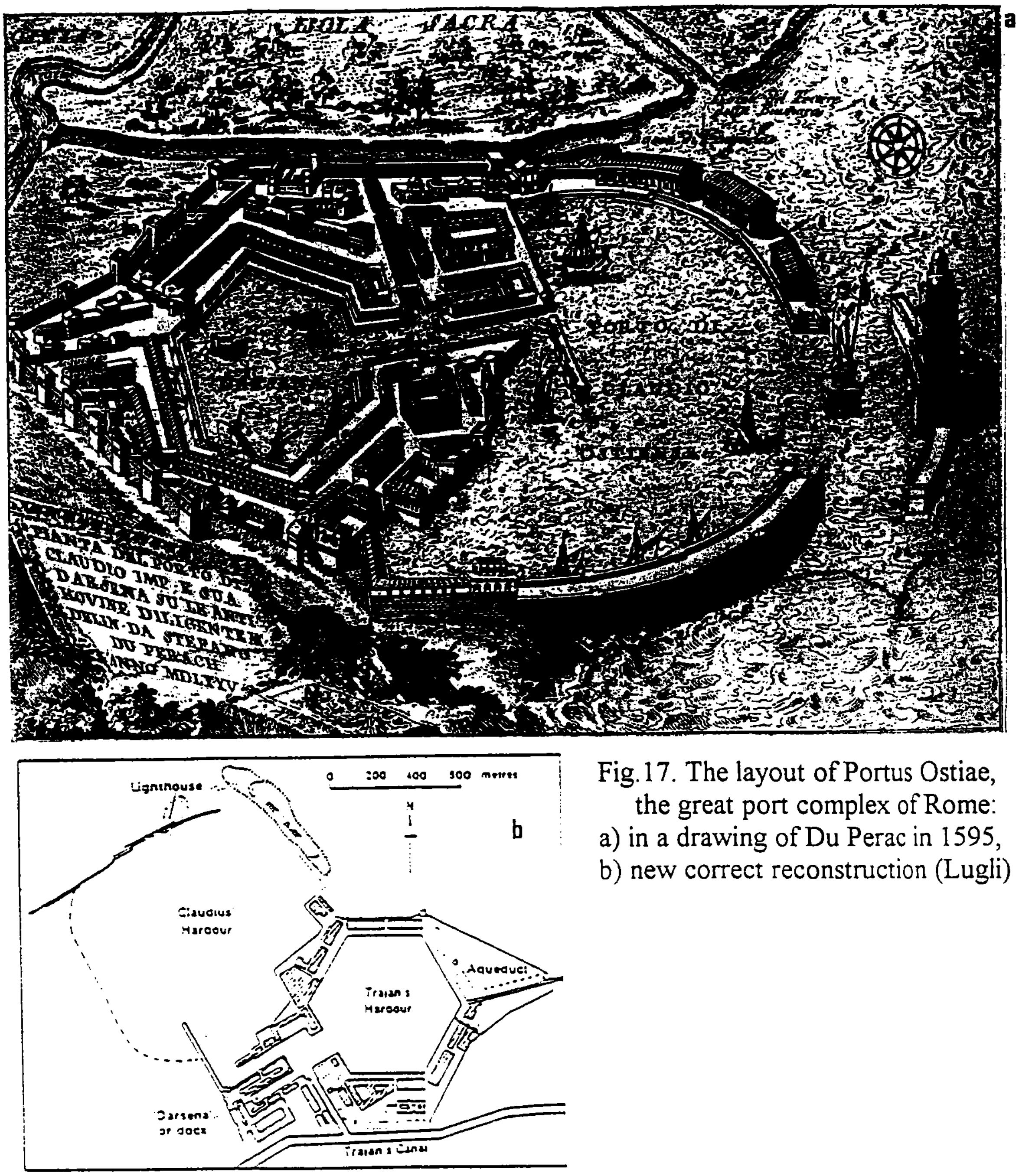


Fig. 17. The layout of Portus Ostiae, the great port complex of Rome:
a) in a drawing of Du Perac in 1595,
b) new correct reconstruction (Lugli)

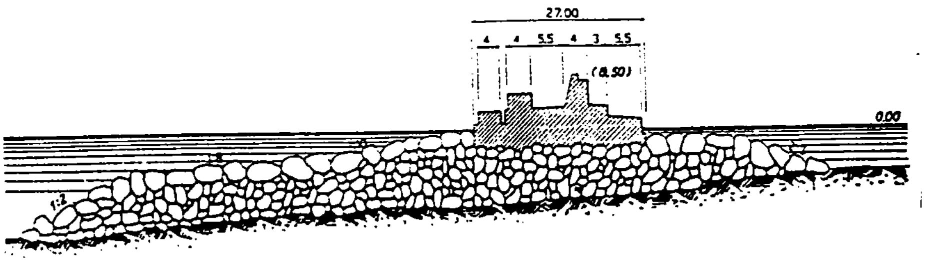


Fig. 18. Modern section of the Trajan island breakwater of Civitavecchia harbour

-island of Pandataria (now Ventotene): a bay with spending beach (used as slipway) is located straight after the entrance and a lateral mooring basin is still preferred for its tranquillity to the modern port by the fishing and tourist fleet (fig.19). This layout is very similar to the most modern industrial harbour of Gioia Tauro (fig.20). Ventotene harbour is actually a colossal sculpture, fully excavated into the dark tufa-rock (60,000 m^3 with an average cut depth of 9 m) to create artificially a "natural" basin of 7,000 m^2 with 3 m depth, a "carved breakwater" (see fig.5), quays and grotto-storerooms, carved within deteriorated arcades resembling petrified elephants. Other apparent ancient port facilities are two aqueduct outlets, a number of large rock-cut bollards and a cave at the roundhead to contain the chain for closing the entrance. Again a small secondary opening was still documented by drawings of the 18th century, but is now obstructed despite the need of harbour flushing (De Rossi 1993).

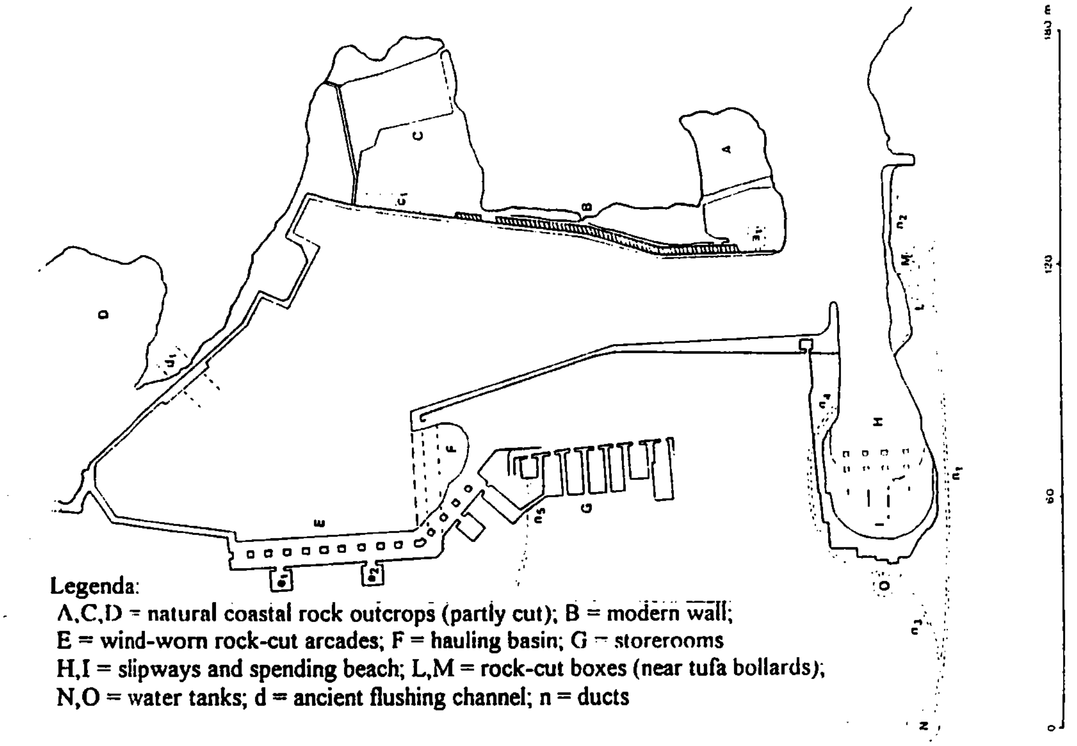
Well preserved monumental structures are also existing at Leptis Magna (Libya), partly covered by red quick-sands. Here early Punicum and Neronian harbours created at the mouth of a wadi had rapidly silted up. A new basin of 400 m diameter was later excavated in the dry behind breakwaters under the emperor S.Severo (210-216 AD) and the river was diverted upstream with a dam to avoid siltation, which occurred anyway due to the littoral drift.

The Roman engineers also made elaborate harbour works in northern Europe, often near river mouths and along the main waterways of the Rhine and Danube, or even in lakes (Geneva). Recent archaeological discoveries have revealed that they were the first dredgers in the Netherlands in order to maintain the use of a river harbour at Velsen on 15-30 AD (van Rijn 1995). Siltation problems at Velsen were finally solved by building new "open" piled jetties to replace the solid piers which had previously been made by filling the drained space between sheet-piles with locally available material, such as wicker work and clay in reed mats. Another nice example of inland river port is the early harbour of Aquileia built at various stages since the 2nd century BC. The well preserved landlocked remnants of the Istrian stone quaywalls show two loading levels to cope with high and low water levels. Also visible at some 35 m spacing are the mooring blocks made with three cut stones morticed together to form a vertical round hole of 43 cm diameter along the upper crown, and horizontal 35 cm mooring rings in indented blocks of the lower step (fig.11).

Moreover it seems that the Roman officer T.Abudio Vero (19 AD) first built a detached breakwater just for the sea defence of the town of Parenzo (D'Arrigo, 1940).

Modern age

Early Middle Ages. After the decline of the Roman empire (V century AD) due to the northern barbaric invasions, a long "blackout" occurred to the development of human civilization in the medieval age, till about 1000 AD. In general this historical period is the least studied and very little is reported about civil engineering achievements. The danger of attacks from the sea by the Saracens caused the abandonment of the coastal zones and their ports which rapidly silted up (also due to the continuous



Legenda:
A,C,D = natural coastal rock outcrops (partly cut); B = modern wall;
E = wind-worn rock-cut arcades; F = hauling basin; G = storerooms
H,I = slipways and spending beach; L,M = rock-cut boxes (near tufa bollards);
N,O = water tanks; d = ancient flushing channel; n = ducts

Fig.19. Layout of the Roman imperial port of Pandataria-Ventotene (De Rossi)

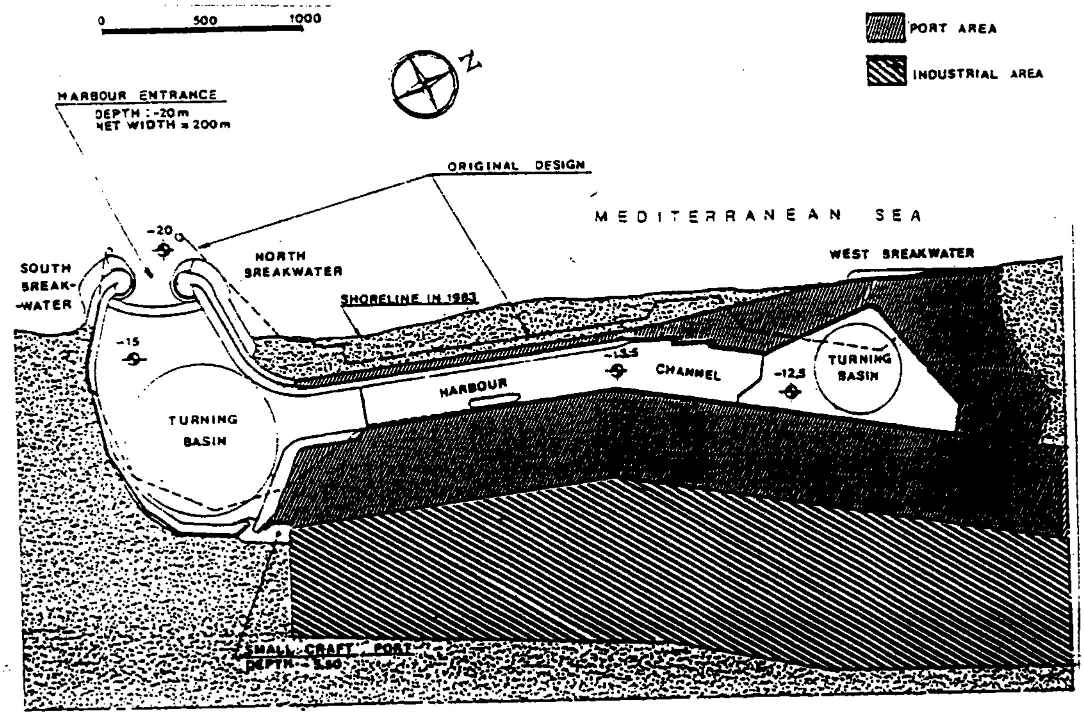


Fig.20. Layout of the modern industrial port of Gioa Tauro (Grimaldi et al.1984)

shoreline advance, like at Portus near Rome) and often became unhealthy swampy places. Other harbours declined for natural reasons, like Puteoli which sank deeply due to a well known local bradeysism.

However many little harbours were surviving along the Italian shores, as described in the famous *Tabula Peutingeriana* and reviewed by Schmiedt (1978), although the only important port was the one of Ravenna, keeping strong commercial links with the East. This harbour was created in a coastal lagoon and the two inlet jetties were made with waterproof caissons filled with concrete according to the Roman tradition. The shoreline here has now advanced by some 7 km into the Adriatic sea.

One of the few inhabited coastal areas was the Venice lagoon, where an autonomous "land-detached" community had settled upon island marshes to defend from barbarians. Written reports of local shore protection works date back as early as 537 AD: wicker faggots were used to hold the earth dikes reinforcing the sandy dunes formed from river supply, wind and wave action. The elastic but fragile willow branches for bank protection were then supplemented by the use of timber piles and stones, often combined in a sort of cribwork. The protection from the sea was so vital for the Venetian lidos since the early times that strict "environmental" regulations had been issued to preserve the littoral defences. Law documents of 1282 to 1339 state the prohibition to cut or burn trees from coastal woods; to pick out mussels from the rock revetments; to make cattle transit upon the dikes; to remove sand or vegetation from the beaches and dunes; to export materials used for shore protection (Grillo 1989).

Late Middle Ages. The Maritime Republics. The dawn of modern times appeared at the end of XIIth century when from the coastal village of Amalfi (near Naples) new sea routes and trades were opened. The new political and economic power was then held in succession by the four "Maritime Republics": Amalfi, Pisa, Genoa and Venice. In particular during the Crusader times the Genoese and Venetians constructed some remarkable ports also in the eastern Mediterranean and a brief resurgence in harbour development took place. A new integration of ports and cities is then observed, also for military defense purposes. Important reference documents of these times (1275) are the Mediterranean Chart (called *Pisana*) and the *Compasso de Navigare*, which describe the status of all coastal harbours, mainly from a nautical point of view.

Amalfi rapidly declined, also due to the disastrous tsunamis of January 1270 and November 1343, which destroyed the harbour structures and a portion of coastline. Many new artificial harbours developed, such as Naples, Leghorn, Palermo, but it may be just worth recalling here the construction of the most important one: Genoa. In its exposed coast the old east breakwater was built with a massive walled superstructure to serve as fortification too. This coastal structure was so important for the city life that in 1245 it was declared "Pious Work" (*Opera Pia*), which means that each citizen had to leave a legacy in his last will to support the breakwater maintenance.

Renaissance Technology. The Renaissance actually took place in the XV-XVIth centuries, when Italy was again playing a leading role in science and technology, including the field of coastal engineering, although the standards for design and construction of works at sea were still those codified by the Romans (eg.for monolithic concrete moles). However a great technological progress was favoured by the development of mechanical equipment, such as for driving piles, dumping blocks and placing forms with pontoons. One of the innovative techniques was the impermeabilization of the forms by means of pitch or with hemp curtains laid over the caisson bottom, typically floated into position (fig.21a) (Di Giorgio Martini 1470).

Even primitive techniques for breathing and working underwater were developed. Moreover the first dredging machines were developed: in 1413 a Genoese inventor was hired in the port of Marseille. In the *Codicetto* by Di Giorgio Martini the first dredger is drawn with two boats holding a wheel equipped with four arms ending with sharp buckets (fig.21b). Advanced dredgers designs were later made by Leonardo and Veranzio 1595 (fig. 21c) and others. However seabed levelling and cleaning was generally carried out by closing and drying out the harbour basin. Siltation was still the greatest problem of harbours. Openings through the moles (generally equipped with mobile gates) were still a favoured solution, but even fixed sheetpiles or mobile barriers made with wooden plates hinged to the seabottom at the harbour entrance were experimented by Tibaldi (a forerunner of the present floodgates for Venice...). These innovative devices were also introduced for military defense purposes (together with other artificial submerged obstacles). Ingenious rhomboidal wooden elements, also in inclined position, were conceived to strengthen current velocity at the entrance.

Renaissance Architectonics. Ideal city planning began in Renaissance Italy during the 15th century by preserving a balance between beauty and usefulness. This humanistic vision of symmetry and proportion is also evident in harbour design. Moreover the Italian engineers introduce a new design procedure, in which several alternatives are studied and the chosen solution is finally visualized by means of small-scale wooden models. The famous architect L.B.Alberti in his global handbook *De re aedificatoria* (1452) follows Vitruvius' technical recommendations with a nature-wise approach, even in the hydraulic design of coastal structures, such as harbour breakwaters and navigational channels. He suggests to have a mild seaward slope for rubble mounds "to allow a smooth run-down to restrain the assault of next waves" and avoid toe scour. A high crownwall is also recommended to provide shelter from wind too. He also deals with siltation and dredging problems and with historical shoreline variations and beach equilibrium profiles.

In his first general description of the artificial harbour layout Alberti, as well as other famous engineers of those times, strongly favours narrow entrances with curvilinear or even circular basin planshapes, to satisfy the ideal aesthetical/phylosophical (as well as the hydraulic/functional/military) standards in the "closed" vision of the fortified city-port (pirates' raids in fact continued until about 1570). It is even a symbolic reference to the elementary spherical shape of water according to Leonardo. The "perfect" monocentral circular shape is also the one which encloses the largest basin area. A semicircular port layout would even resemble to a theatre since it offers an attractive "show" (fictitius ship battles have been actually performed in harbour basins...).

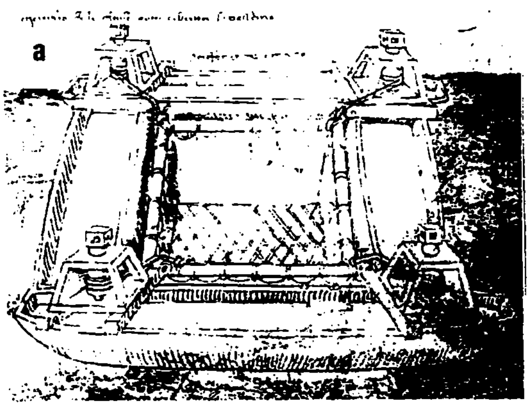
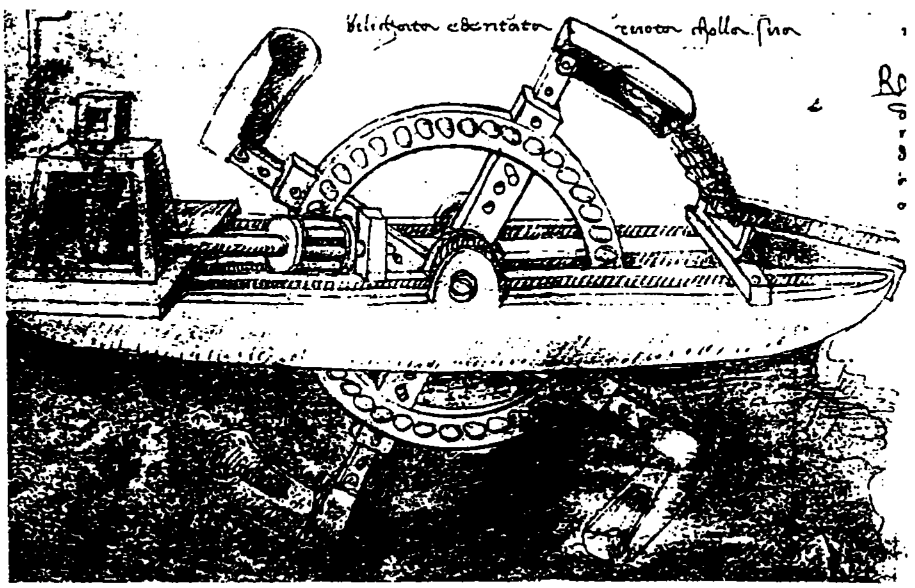
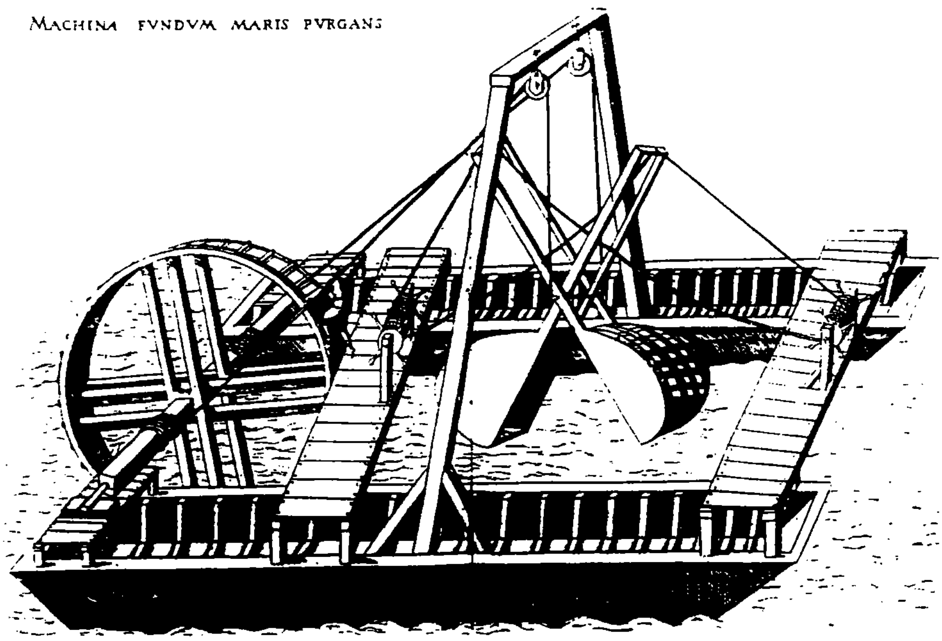


Fig.21. Technological progress
in the Renaissance Age:
a) floating equipment for dumping foundations in shallow water (Di Giorgio Martini 1475)
b) Lagoon bucket dredger (Di Giorgio Martini 1475)
c) A dredger (Veranzio 1595)





Di Giorgio Martini (1480) even fixed the "golden measures" of the ideal harbour layout: a convex-shaped island breakwater, 100 m long, to shelter the 70 m wide central entrance between two moles 70 m behind and a breakwater width of 25 m. However he also proposed a different layout with a long mole parallel to the coast, which would ease the defense of the fortified town, or a double nearshore entrance with a horse-shoe shaped breakwater with closable gaps for water circulation (fig.22).

Therefore the classic Roman layout of Centumcellae harbour was considered in the Renaissance, also by Leonardo (fig.24c) and later by Michelangel, as the model of the "ideal city-port". The oval planshape of its converging arms was even considered as a symbolic reference in the design of the famous columnates of S.Peter's square in Rome: "the Port of Salvation of the Roman Catholicism devoted to the Saint fisherman and true safe pilot". Other famous Italian architects worked in the port of Civitavecchia and its fortifications, such as Sangallo, Bramante, Bernini and Vanvitelli.

However the Renaissance period is marked by the important birth of the hydraulic sciences, including maritime hydraulics. In fact it was noted (Rouse et al, 1957) that "The Italian school of hydraulics was the first to be formed and the only one to exist before the middle of the 17th century".

Leonardo da Vinci. The most important innovations can be attributed to the extraordinary eclectic genius of Leonardo da Vinci (1465-1519). By means of his well known experimental method, based on the systematic observation of natural phenomena supported by an acute intellectual reasoning and a passionate creative intuition, Leonardo was really the precursor of the modern coastal engineering science, often anticipating ideas and solutions by more than three centuries. Unfortunately, such anticipation was to remain unfruitful, because for centuries his results continued to be practically unknown to both the scientific and technical world. His notebooks exhibit some astonishingly accurate descriptions and graphical representations even of complicated flow patterns, also taking advantage of his extraordinary skill in painting. Some descriptions of water movement are essentially qualitative, but often so correct and acute, that some of his drawings could be usefully included in a modern treatise of coastal hydrodynamics. Of course the quantitative interpretation and the mathematical formulation of the results were far beyond the scientific capabilities of those times. The jump from kinematics to dynamics proved impossible for almost two centuries, until some basic steps towards the correct theory of gravitation were taken (Fassò 1987).

The variety of problems of hydrokinematics dealt with in Leonardo's notebooks is so vast that would be hard even to enumerate in this review. Most phenomena related to maritime hydraulics are described in the 36 *folios* (sheets) of the beautiful Codex Leicester (1510) (ex C.Hammer,now renamed by B.Gates), where he even gives a glossary of the main technical definitions (folio 12 *verso*). A full English translation is given by Richter (1970). Leonardo clearly defines the progressive nature of surface waves with transmission of "impetus" and not matter comparing it to the oscillation of wheat in a field under the impulsion of wind (36 *verso*) ("a *tremor* rather than a motion"). In folio 14 *verso* he describes the circular waves produced on the still water surface when one throws a pebble into it and explains that "floating bodies do not change position". The observation of this phenomenon is rather trivial but Leonardo tried to go deeply into the mechanics of waves by studying either the intersections of the families of circular waves produced by the impact of three pebbles at a time and the wave pattern produced by the impact of a triangular and bar-shaped objects (rapidly assuming a circular shape). In the same page he also anticipates the concept of relative wave celerity by writing "An object thrown into flowing water will make an oval undulation, and this will extend little in the direction opposite to the flow and much in the direction following it". Leonardo also describes the nearshore wave shoaling (12 *recto*), wave breaking (4 *verso*), air entrapment (28 *verso*) and wave reflection and impacts at walls (25 *verso*), for which he suggests a concave parabolic profile "to make the wave percussion falling onto itself...". Some nice drawings of sea waves (also breaking at walls) are shown in fig.23.

Leonardo beautifully illustrates the water movement around obstacles (14 *recto*), the techniques for measuring current velocities (13 *verso*) and the mixing of fresh and salt waters (21 *verso*). .Moreover he correctly defines the current circulation pattern in the Mediterranean Sea and explains the astronomical tides, also giving their exact amplitudes at various coastal locations (6 *verso*, 27 *recto*). Furthermore Leonardo studied sediment transport, even using small-scale mobile model tests with sand (15 *recto*), dealing with sand ripples (23 *recto*), bed-load (20 *verso*), cross-shore transport and grain size distribution ("the coastal silt is transported offshore by storm sea waves...", 35 *recto*). He even suggests measures to reduce erosion effects, such as with a counter-jet against the erosive toe current (13 *verso*). Well ahead of times he attributes to the sea waves the prevailing role in the morphological evolution of beaches (2 *verso*, 6 *verso*) and defines the sediment equilibrium line and the seabed depth at which the orbital motion of the waves is still present (9 *verso*), three centuries before the experiments of the Weber brothers.

As far as we know, Leonardo was also the first to describe and probably to test several experimental techniques now employed in all hydraulic laboratories, such as flow visualization by means of both suspended particles and dyes; glass-walled tanks; use of movable bed models, both in water and in air. A synthetic review of such techniques was recently made by Levi 1982, who pointed out in particular that Leonardo was aware of both the limitations and possibilities of the experimental method and noted the scale effects when testing on small models.

Leonardo often used simple suggestive similitudes to clarify complex physical processes in his unitary vision of nature.("pulsating sea motion alike the blood flow in the human body...", 34 *recto*). The blood circulation system analogy is resumed again to describe the tidal flushing of lagoons and "canal-ports". As a matter of fact he also gave a significant contribution to harbour engineering, particularly as related to the so-called "canal-ports" which are typical of the northern Adriatic coast, taking advantage of both river and ebb tidal flows to keep the inlet navigable. In his famous drawing of Cesenatico harbour in 1502 he shows a canal with a wider section at the bend to ease navigation and a narrower section at the mouth to increase flushing current velocities

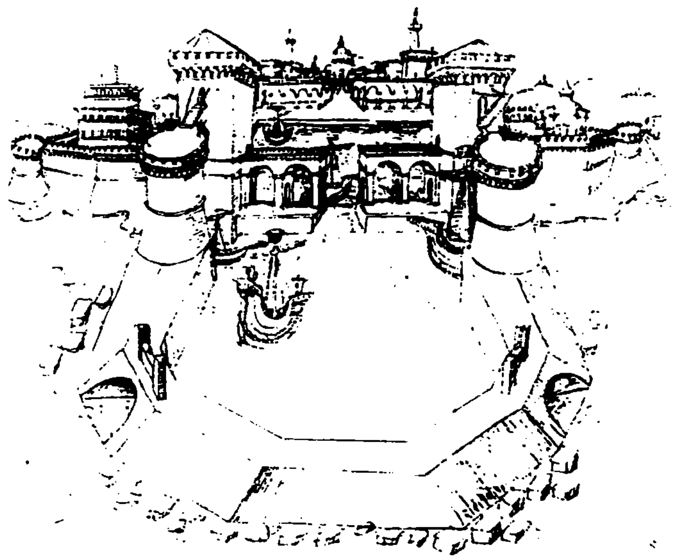


Fig.22. Drawing of an ideal harbour (Di Giorgio Martini 1475)

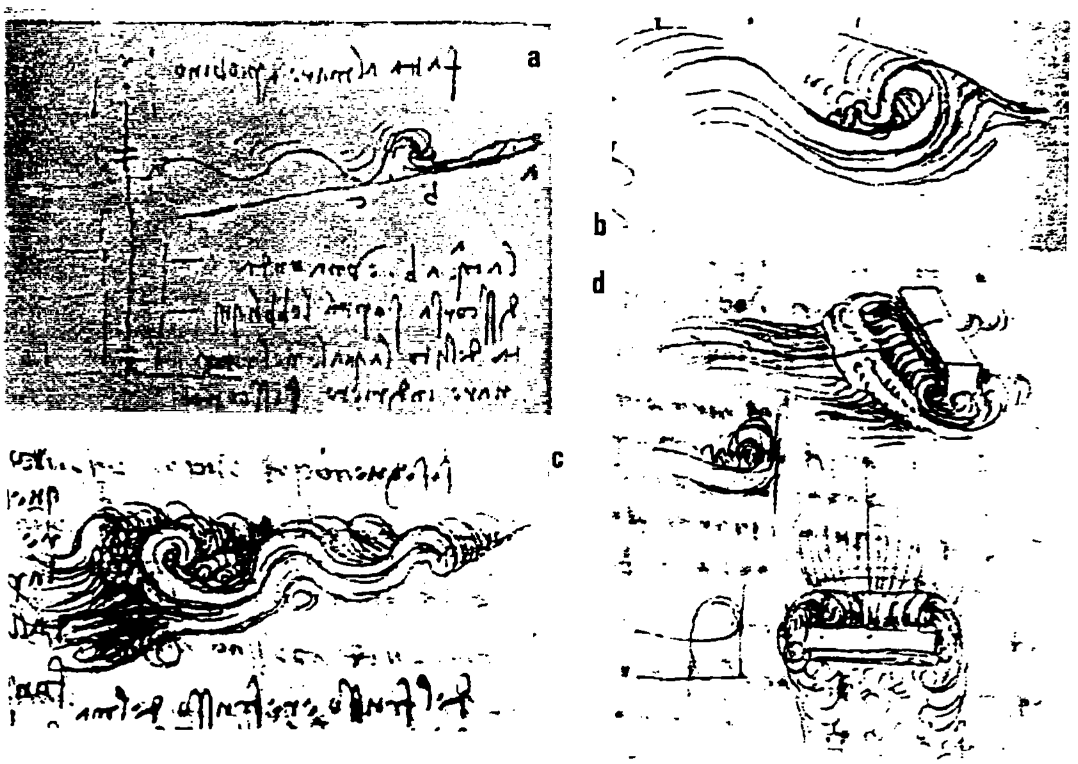


Fig.23. Leonardo's drawings of breaking sea waves (1510): a) Codex L, folio 6r; b) c) d) Codex Leicester, f. 4v, 26v, 25v

(fig.24a) (D'Arrigo 1940). He also introduces the favourable effect of an inland large pond or artificial basin linked with the canal to increase the ebb flow and remove the inlet siltation. The upstream bridge had a wooden mobile gate which could also release water at low tide to clean the entrance. This system was then favoured by the Venetian hydraulic engineers until today (with their motto "a large lagoon makes a good port"), also with the occasional artificial help of sliding gates. In the quoted plan the shoreline position at the updrift side of the inlet jetty is about 100 m from the tip.

The interest of Leonardo in harbour engineering is also reflected in the Codex Madrid, where he represents a design of a harbour at Piombino with a triangular planshaped island breakwater (to reduce wave forces) and two other small port designs (one without the island breakwater) (fig.24b). Leonardo is the first harbour designer to understand that the above breakwater layouts would not only reduce wave penetration but also the siltation at the entrance, which was to be caused by the wave action. His port designs are inspired to the ancient ones but he first performs a detailed survey according to his new scientific approach. In the Codex Atlanticus, Leonardo reports the mentioned detailed survey of the port of Centumcellae (folio 271 *recto*) (fig.24c) and its vertical block east breakwater (63 *verso*). In folio 4 he also examines the damage to the "Old Mole" superstructure of Genoa harbour occurred during a great storm in February 1498. An innovative harbour layout is then presented in folio 285 *recto* (fig.24d): the special spiral shape should provide a good shelter and recalls the wave form itself, as typically depicted by the artist, or the interior curl of a sea shell.

Leonardo da Vinci was also involved in the design and construction of locks and is credited with having introduced the idea of locks in France, where he spent the last years of his life from 1516 to 1519: still in use are the well known *Vincian gates.*

Locks. However the first navigational lock had been already constructed in 1438-39 at Viarenna (Milan) by Fioravante da Bologna and Filippo degli Organi in order to ease the inland waterway traffic and particularly the transport of material for the construction of Milan's Cathedral. Most historians regard the Viarenna lock as the first one in Europe, though it was preceded by the Vreesvijk lock in Holland (1373) (Fassò 1987). But the two engineers were surely unaware of the existence of previous applications and must be credited for the independent invention of this useful device. This simple but revolutionary idea of the short canal between two gates had a tremendous impact on the economic and social progress of entire countries and was later used also for tidal ports. Viarenna lock is 38 m long and 6.2 m wide and could rise boats by about 3 m. It was dried in 1936 after 500 years of regular operation.

Port and Breakwater Developments (1600-1850). A general decline of harbour activities occurred in Italy after the development of oceanic navigation at the end of XVIth century . The center of scientific and technological development began to move from Italy to northern Europe. Even harbour design concepts started to change. Since then the technical aspects have been dissociated from the formal architectonic ones and the new professional category of the hydraulic engineers took over this ever more specialized technical field, despite the lack of a sound "harbour theory", losing any

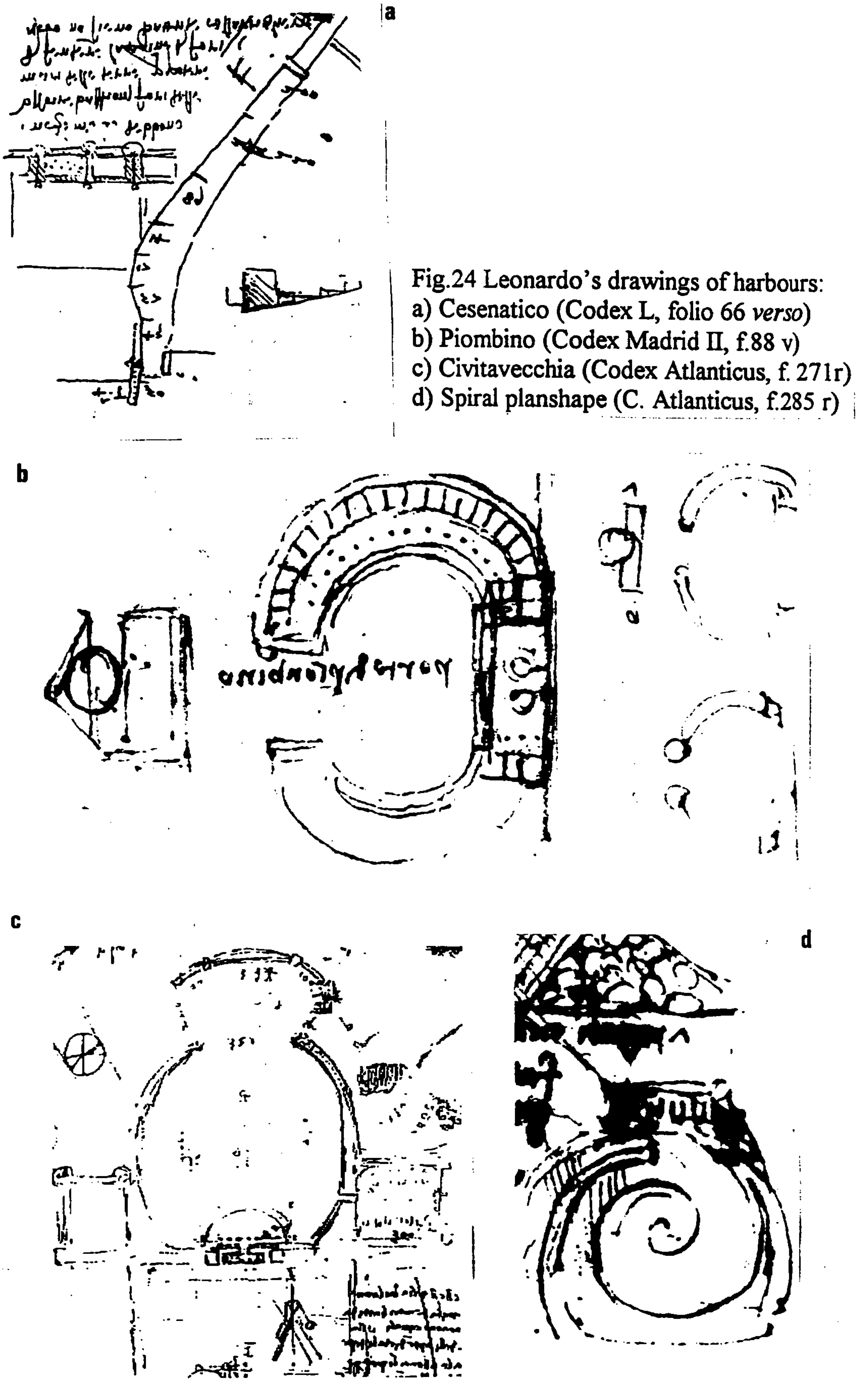


Fig.24 Leonardo's drawings of harbours:
a) Cesenatico (Codex L, folio 66 *verso*)
b) Piombino (Codex Madrid II, f.88 v)
c) Civitavecchia (Codex Atlanticus, f. 271r)
d) Spiral planshape (C. Atlanticus, f.285 r)

interest for the formal and functional aspects of ports. The unitary approach of the Renaissance was replaced by the merely decorative aggregation of building elements in formal figurative baroque stile (Simoncini 1993). The harbour planshape became polycentric: Vasari in 1598 proposed elliptic basin layouts. However circular shapes were still attractive as shown by De Marchi (1545) (fig.25) and Gallaccini (1603), who resumed Leonardo's idea to produce a number of fascinating, though unrealistic, spiral-harbour designs (fig.26a,b). In his beautifully illustrated treatise on sea harbours Gallaccini (1603) also gave a decalogue of prescriptions for a good harbour design and described breakwater construction methods, advanced floating equipment and original mechanical devices to work underwater and even walk overwater ! (fig.27a,b,c).

In fact in the XVIIth century the technology of coastal structures was again receiving attention. The eternal debate about the choice between rubble mound or vertical breakwaters was still active. Based on his experience in the restoration of Civitavecchia harbour, Crescentio (1607) recommended the use of irregular rock mounds (so-called "lost stones" system...) with a pozzolanic concrete crown above sea level. Quite modernly he was suggesting not to use small stones to fill the porosity of the large rock armour and to let the sea waves naturally shape the rubble mound profile. Scamozzi (1615) proposed to use this system only in deep waters and on weak soils, while heavy squared blocks could be regularly placed on hard bottoms. In shallow calm waters the Roman system of cast-in-situ monolithic walls was preferred. Actually the caisson technique kept being widely used in Italian harbours according to the literature (in Naples on 1302 and 1470, in Palermo on 1575, in Savona on 1626)

Long discussions on this matter also occurred for the necessary protection of Genoa harbour, which was suffering severe damaging storms in 1613, 1630, 1636, also due to high reflections inside the basin. As described by Faina (1969), interesting design solutions for the new breakwater were submitted by L.Bianco (1637), who proposed the use of tronco-pyramidal caissons for a better connection (fig.28a). Finally an innovative composite-type design by De Mari was approved in 1638, which had a larger and lower rubble foundation up to - 4 m MSL and a monolithic superstructure cast-in-situ within caissons or ship hulls to be sunk exactly over the leveled foundation (fig.28b). Another new feature was the use of both small and large stones to obtain a more compact foundation. Important merits of the composite caisson breakwater are the reduced costs and time of construction, which particularly reduce the risk of storm damage during the execution of works. De Mari also stated some general principles (only partly correct), such as: "the wave force strongly reduces with depth and it is almost zero at -5 m MSL in the Mediterranean; in fact 5-10 t rocks are stable at this depth; the optimum rubble mound profile has a 1:2 seaward slope and 1:1 landward".

Despite the scientific limitations the methods of De Mari had a large international resonance, as stated by Clark (1948): "The English were indebted, in the building of the Tangiers Mole,1663-83, *the largest engineering work till then undertaken by their nation*, to the advice of Genoese engineers". He also admitted that "Italy in 1600-1700 was still the most prolific country for technical and scientific developments and its superiority lasted longer than supposed". The success of the composite caisson

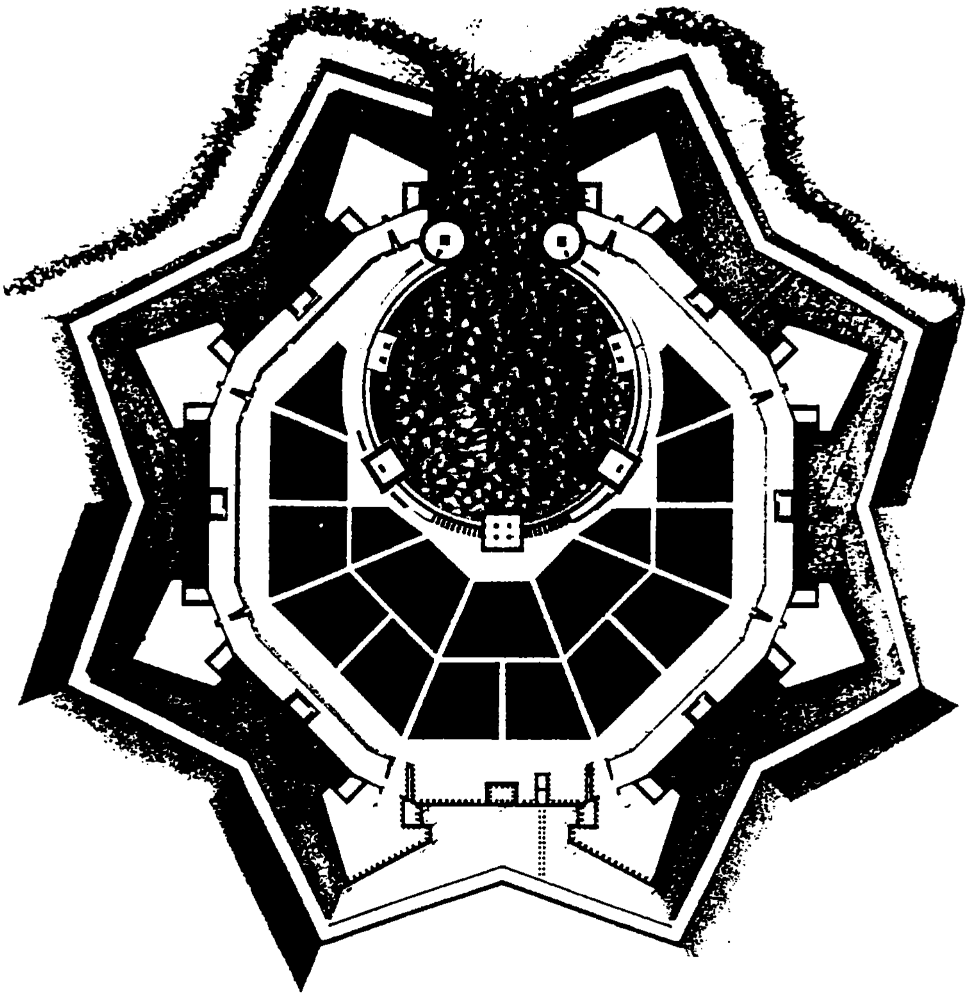


Fig.25. Fortified sea town with circular harbour (De Marchi 1545)

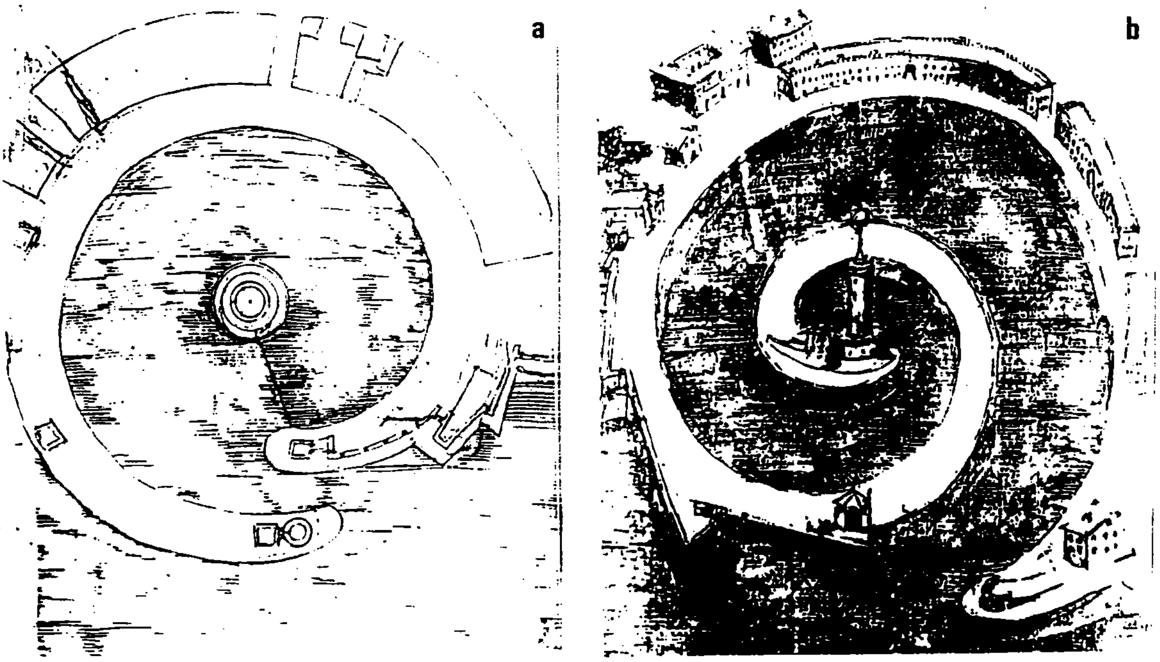


Fig.26. Drawings of circular (a) and spiral (b) harbours by Gallaccini (1603).

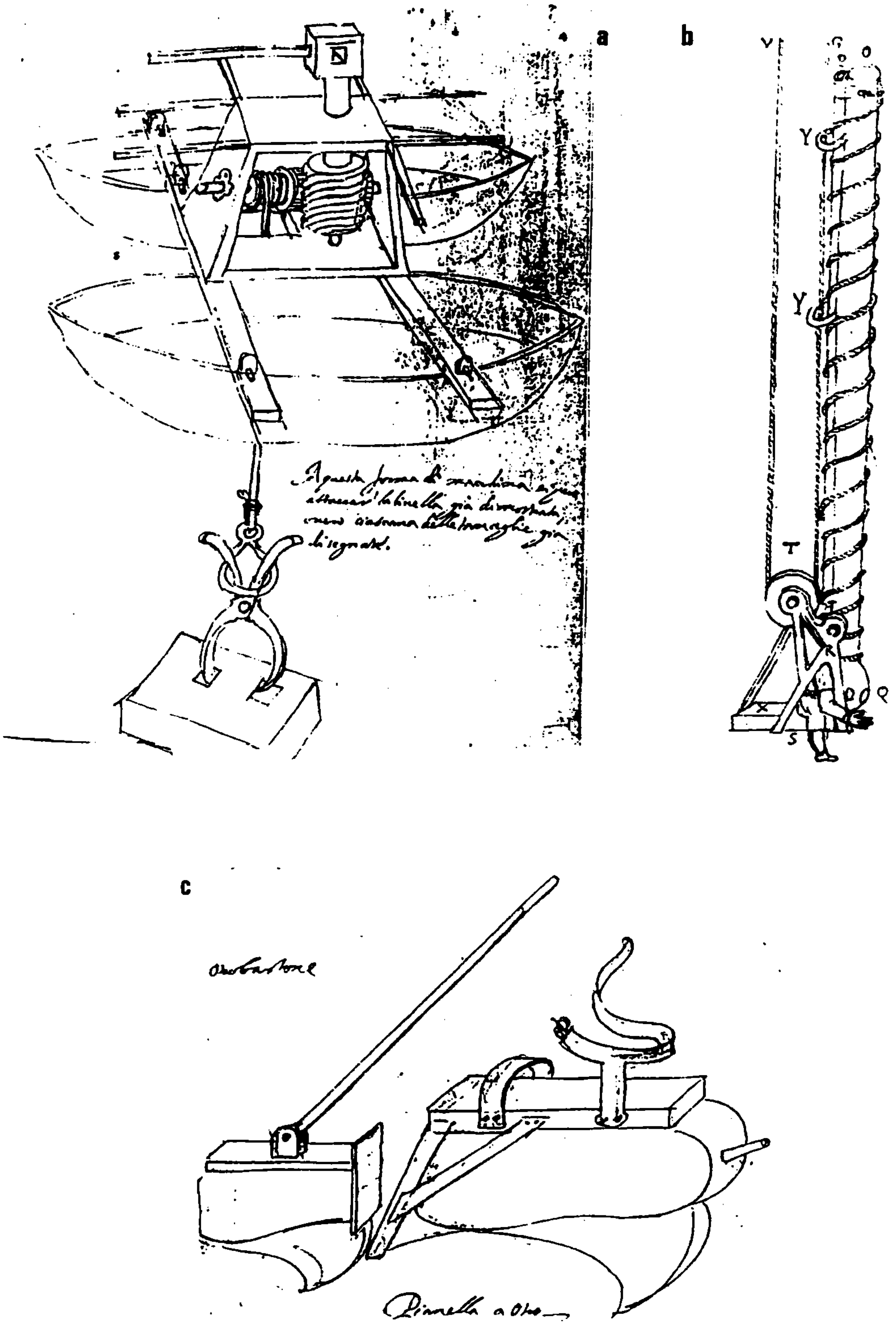


Fig.27 Advanced mechanical devices for maritime works (Gallaccini 1603):
a) placement of a breakwater armour block from a pontoon
b) a new device to allow underwater work
c) a system to walk overwater

breakwater built in Tangiers by Shere then demonstrated a more general applicability of this Italian solution even in high tidal ranges.

Venice - Shore Protection (1500-1800). In the XIV-XVIII centuries it was the independent Venetian Republic to become the main maritime power, the bridge of communication and commerce between the West and the East, and also the leader in the progress of hydraulic and coastal engineering (Adami 1992, Marchi 1992) (fig.29). The importance of the problems related to the preservation of the tidal lagoon, to the protection of the littoral barriers dividing it from the sea and to navigation, required the creation of a special absolute Water Authority ("Magistrato alle Acque") managed since 1501 by elected hydraulic experts. A careful management and severe control of its delicate hydro-morphological system and related engineering works has been carried out ever since in Venice. The works included the river mouths diversion to avoid the lagoon siltation, the construction of inlets jetties to ease navigation and the defence of the thin barrier islands from wave-induced erosion.

The earliest shore protection works before the 18th century were typically revetments and groins made with timber piles in multiple longitudinal rows to contain layered rock slopes (fig.30). The forerunners of modern groins were about 100 m long and their purpose was actually to intercept the littoral drift to avoid both erosion and siltation problems at the navigable tidal inlets. However maintenance costs were very high, due to the limited durability of wood (5 years) and the long travel distance for rock transport. Frequent repair was needed after damaging storms, sometimes afforded by sinking barges filled with silt, reed and stones. Therefore the Authority seeked for innovative designs: various technical solutions were proposed and experimented at the own risk of consultants and contractors (who were paid only after the effectiveness of the work had been proved...), such as: riprap revetments; gabions; smooth marble blocks linked with mortar and steel; flexible steel strips; stepped limestone blocks in regular pattern; various artificial elements to increase the roughness of the revetment slope; and even beach nourishment with sand dredged from offshore ! (Grillo, 1989).

Finally the project of a durable massive seawall presented by a group of experts headed by the State Mathematician (B.Zendrini et al.1743) was approved. The so called "murazzi" are composed by a smooth heavy flagstone revetment supported at toe and crest with massive block walls; the average width is 12 m and crest elevation at +5 m MSL (see original drawing in fig.31a). The innovative technology (actually based upon an earlier idea of Abbot Coronelli in 1706) was represented by the use of pozzolanic cement as effective bond between the rock-cut blocks, instead of the timber pile fencing. This seawall was built in about 40 years for some 20 km along the lidos and has lasted up to the present time, becoming a significant Venetian monument and a historical landmark of coastal engineering. However repairs have been necessary, particularly after the exceptional storms of 1825 and 1966: the reinforcement has been made with a rubble mound at the toe and recently with anchor piles and jet-grouting diaphragms (fig.31b). The main impermeable screen has been constructed along the lagoon side (down to a clay layer at -20 m MSL) to prevent siphoning risk, while the seaward screen was to reduce the uplift pressures enhanced by the main diaphragm.

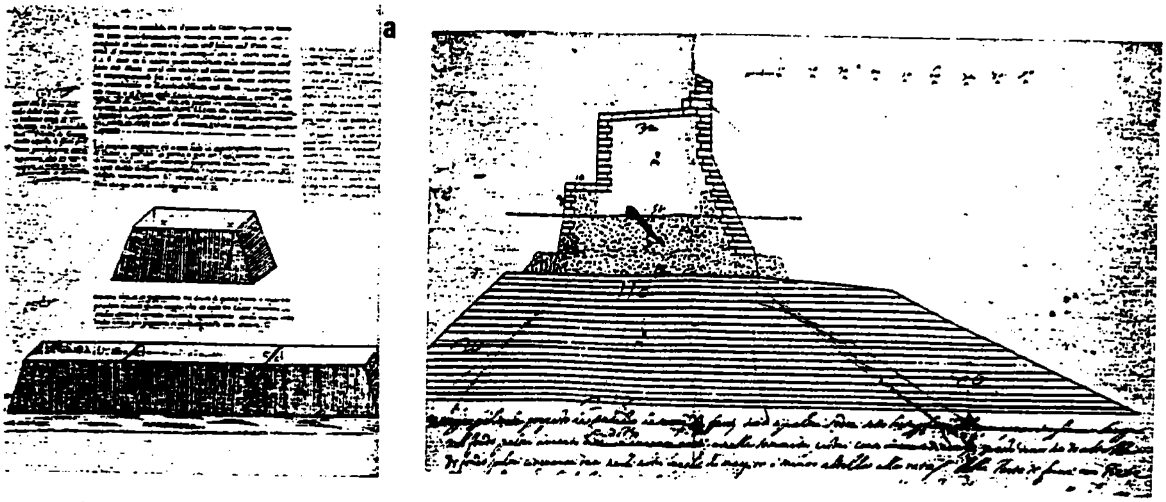


Fig.28 Designs for the new breakwater of Genoa harbour in XVII century:
a) Models of pyramidal caissons by Bianco (1637)
b) The new composite-type design by De Mari (1638)

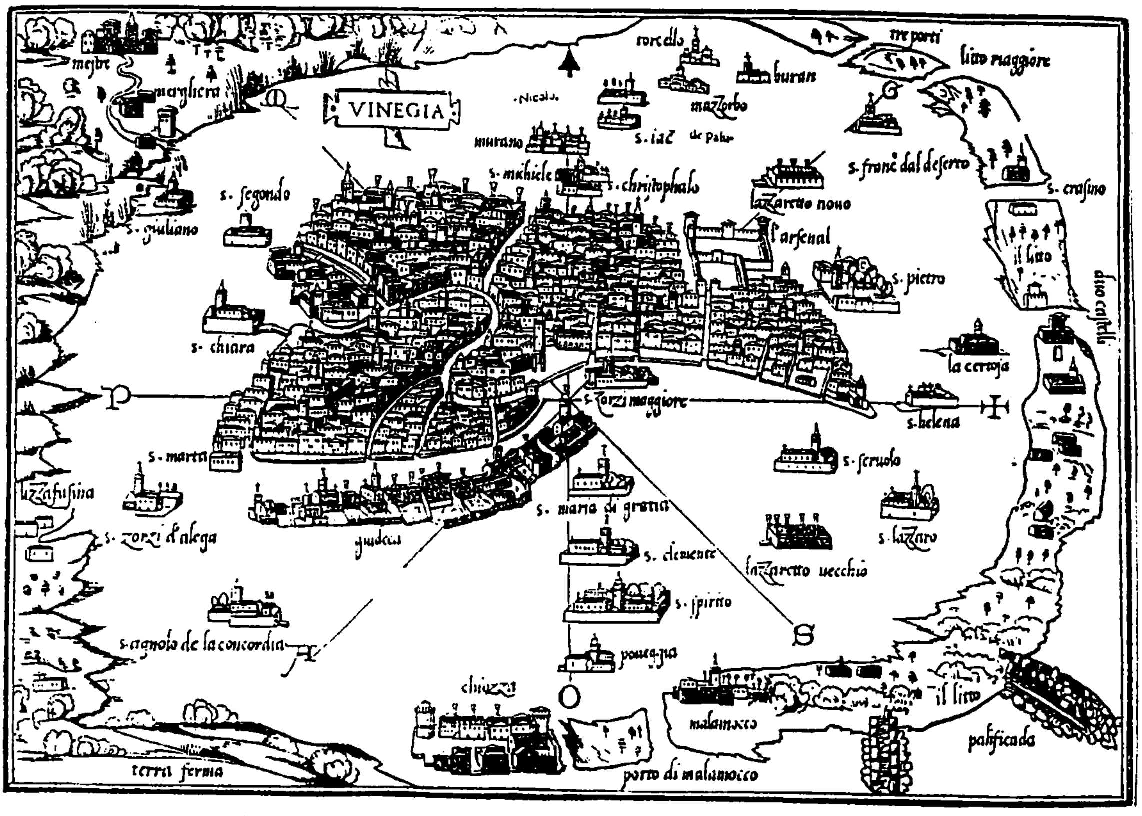


Fig.29. Map of Venice lagoon in 1528 (B.Bordone) with piled groins for littoral defence (CVN 1995)

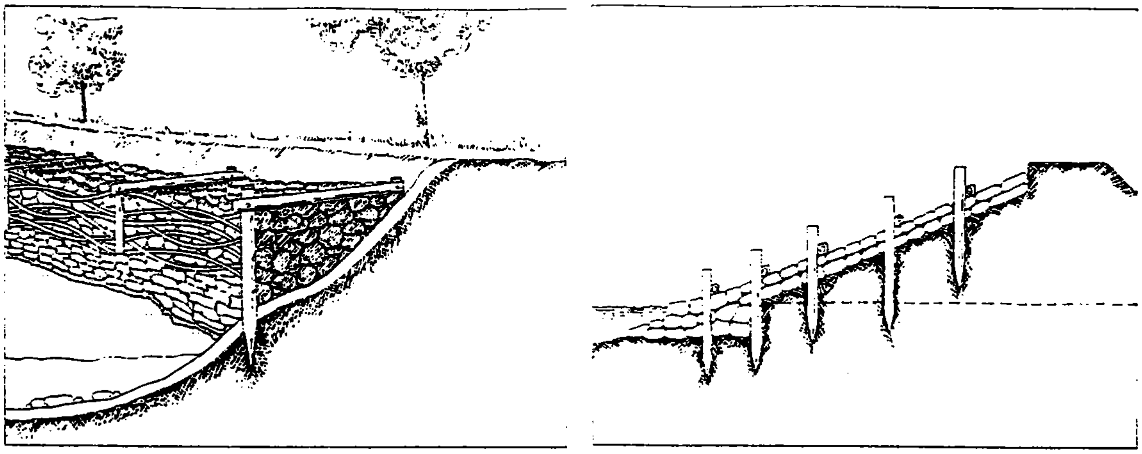


Fig.30: Ancient coastal defences in Venice: rubble revetments within timber piled fences (6 to 17th century)

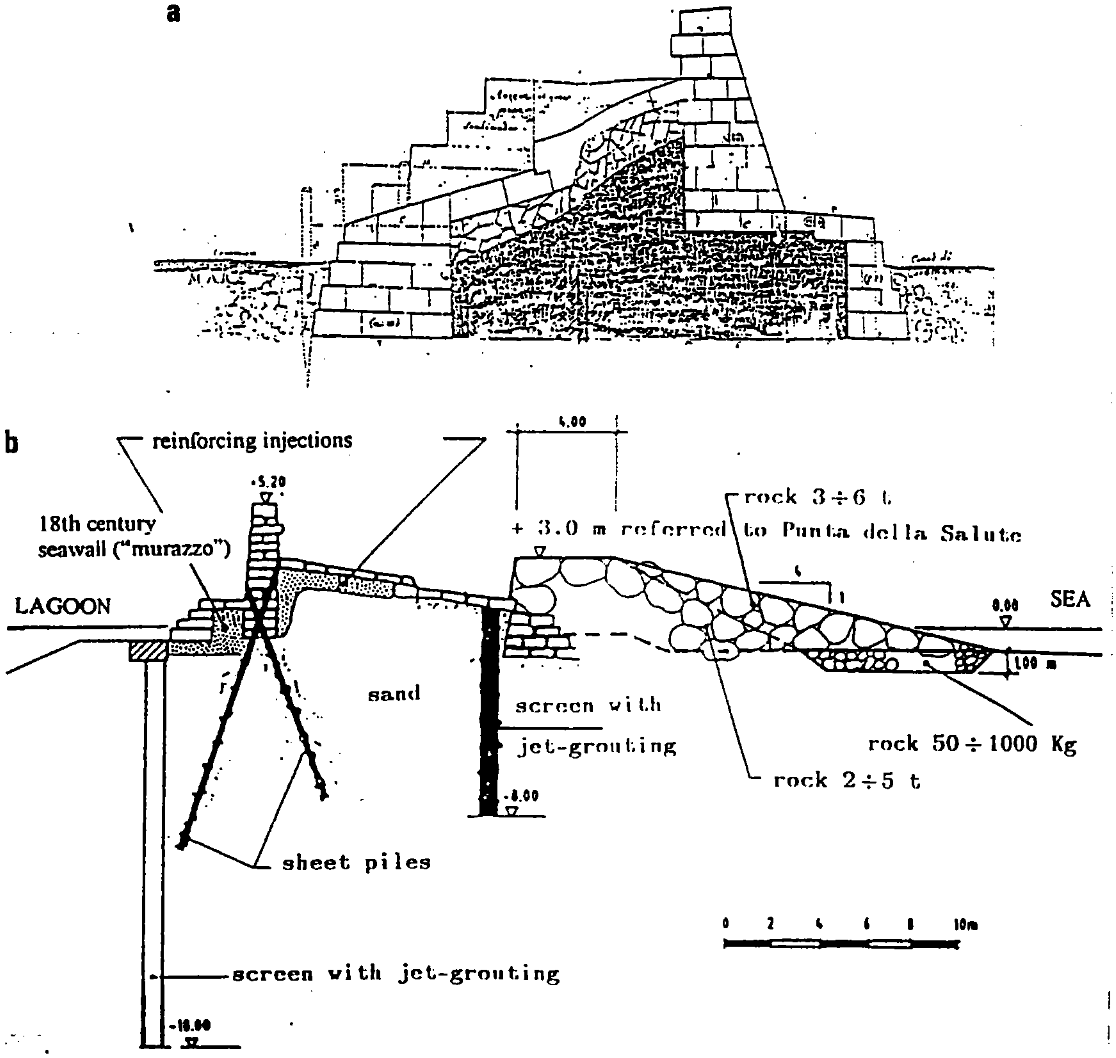


Fig.31: a) Original design of the "murazzi" seawall by Zendrini in 1743
b) Modern reinforcements to the 250-year old *murazzo* at Caroman

Other important Venetian maritime works were related to navigation in and out the lagoon, which was dangerous for the variable shallow waters. In fact a special pilot company had been set up long since, navigational aids were installed and channels dredged. In 1725 a new 4.5 m deep, 18 m wide shipping channel was excavated in order to link Venice to the main (deepest) inlet of Malamocco. However, the old groins could not prevent progressive siltation of the three tidal inlets and the need for longer training jetties was envisaged by the Venetian engineers. The first big project to develop the Port of Venice was commissioned by Napoleon in 1807 to a French group of experts, who followed the proposal of the local naval officer Salvini to build two parallel breakwaters normal to the shore with the longer north jetty overpassing the bank off the Malamocco mouth and deviating the littoral currents. After many interruptions the 2 km north jetty was finally completed in 1845 after the brilliant redesign and supervision of P.Paleocapa (one of the engineers who worked at the Suez Canal project), who avoided any dredging to rely upon the tidal flow for the natural deepening of the access channel (Noli 1990), which in fact rapidly happened (today reaching -15 m MSL). The construction of the south jetty was completed in 1872 and the successful results stimulated similar works at the other two inlets of Lido (1882-1910) and Chioggia (1911-34). The rubble mounds were built with advanced criteria, but they are presently undergoing substantial rehabilitation works. Moreover they have assured safe navigability even to the larger vessels which have been later entering the lagoon to reach the large modern (XX century) industrial port of Marghera. However the jetties have also stopped the littoral sediment transport, thus contributing to the recent erosion problems of the central lidos, which are now been tackled with new protection systems, as described further on.

Advances in Maritime Hydraulics and Coastal Dynamics.(1700-1950). As far as the study of sea and beach dynamics is concerned, valuable contributions in the XVIII-XIX centuries were given by a number of scientists, like Marsili, Montanari, Cialdi, Rovereto, Uzielli, Chelussi, Clerici, Cornaglia, Boscovich and others. L.F.Marsili was a precursor of modern oceanography, since he made in 1715 detailed investigations on submarine sand banks off the Adriatic shores.

A large interesting collection of shipboard observations of storm waves and their effects in deep sea-bottoms was produced by captain Cialdi (1866). He was convinced that wind waves could induce strong water movements down to the seabed ("even at 200 m depth in the ocean"), which he called "current-wave" (*flutto-corrente).* He correctly understood that the wind waves were the main cause of sediment transport along beaches and felt the need for a general theory describing both beach evolution and harbour siltation. His ideas were opposed by other experts of his times, such as Paleocapa, who believed that the main transport agent was the general littoral density current (which was first measured in the Mediterranean Sea by Montanari). Cialdi also produced a treatise on harbour construction and a book on Leonardo's wave theories.

However, the most original theoretical studies are due to P.Cornaglia (1891) who proposed his famous theory of the "bottom wave"(*flutto di fondo*) to explain either coastal sediment.transport and wave forces on breakwaters. He demonstrated that the elliptical orbital motion induced by sinusoidal surface waves degenerates into alternate horizontal particle movements at the sloping seabed and a high momentum is then transmitted near the bed with wave propagation. Cornaglia then defined a *neutral line* on the seabed where the shoreward and seaward components are balanced : the bodies are then pushed onshore within the nearshore zone and are directed offshore if located off the neutral line He also tried to determine the wave pressures on walls from the elevation of water jets at the impact. Cornaglia's theories are partly contradicted by the evidence of real observation (eg. the too high speed of the "wave current" approaching the shore in relatively deep water), but they were among the few theoretical references available to coastal engineers for decades.

Later on an important contribution to the theoretical analysis of wave kinematics was given by the mathematician Levi-Civita (1925) who found the rigorous exact solution of the theory of irrotational oscillatory waves on infinite depth, which had been given with approximate solutions by Stokes and Raileigh.

In the early decades of the XXth century detailed studies were also produced on the Italian shoreline variations (Toniolo 1910, Marinelli, Merciai, Mori) and systematic surveys were promoted already in the 30's by the National Research Council (CNR).

Further Evolution of Breakwaters (1850-1950). Despite the little financial support given by the newly unified kingdom of Italy (1861) to port development in order to keep pace with the rapid evolution of shipping (also due to its historical heritage of fragmented local policies without global planning), the most important developments are again observed in the design and construction technology of harbour breakwaters. The state-of-the-art at the start of the new century was summarized by Luiggi (1907). An updated general overview is given by Borzani (1995) and, with special reference to the typical composite structures, by Franco (1994) and by Lamberti et al. (1994).

With regards to rubble mound breakwaters, which were more popular in the XIX century, the historical experience (e.g. Civitavecchia, fig.18) had shown the effectiveness of a mild slope in the critical zone near the waterline (Lo Gatto 1925). But in deeper more exposed waters the need to save material and to use heavier blocks, favoured by the rapid increase of capacity of the lifting equipment, had led to the modern type section with steep slopes and large *precast* armour blocks (30 t in the first application of Marseille offshore breakwater in 20 to 35 m depth). The first example in Italy was the S.Vincenzo mole in Naples, built in 35 m depth since 1850 and followed by the Duca di Galliera mole in Genoa built in 1877-88 and reaching 29 m depth (Coen-Cagli et al.1905) (fig.32). Both breakwaters suffered soon severe damages and settlements, thus requiring reinforcement, typically achieved with heavier armour blocks, even placed in an original steep stepped profile (called *Parodi* system from the engineer who invented it). This new armour arrangement had many applications until the beginning of the XX century, but proved to be vulnerable to mound settlements with consequent fragile blocks displacements. Another famous storm in 1898 caused serious damages to the Galliera breakwater in Genoa, as described by Bernardini (1901) (fig.33).

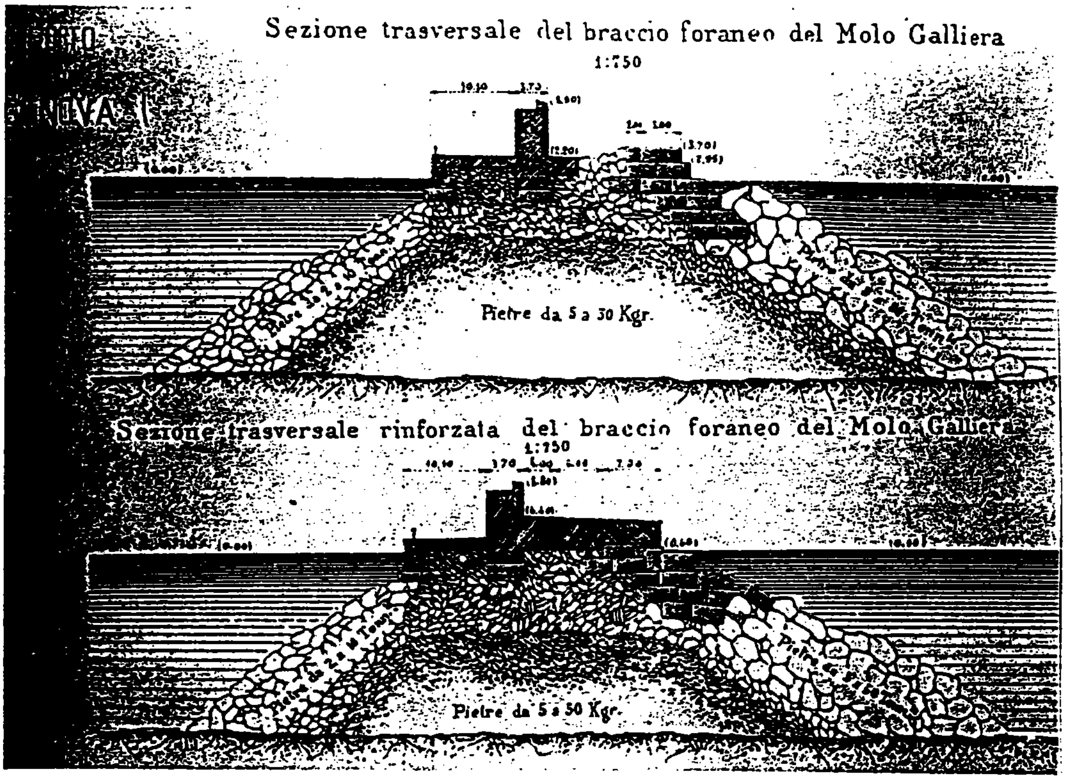


Fig. 32. The Galliera breakwater in Genoa with stepped block armour, before and after reinforcing

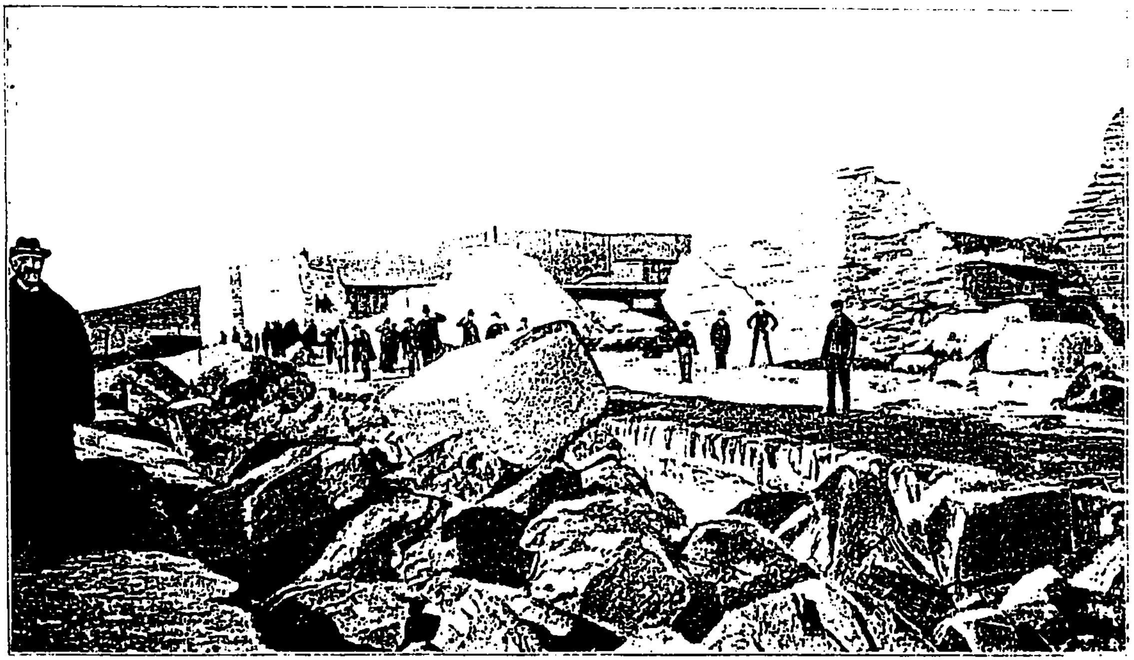


Fig.33. View of Genoa breakwater after Storm of 1898 (Cunningham 1908)

These failures then promoted the revival of the classic vertically composite structure, which was actually reintroduced in Italy by Coen-Cagli after his visit to some English vertical breakwaters. In fact in 1896 he designed the southern extension of the Trajan offshore breakwater in Civitavecchia, which however was soon transformed in a horizontally-composite structure with a block mound protection. The actual first applications of the modern walls, made with 50 t concrete blocks arranged in horizontal layers with staggered joints upon a rubble foundation ("masonry blockwork"), took place in Trapani harbour in 1896 (Colombaia mole) and in Naples harbour in 1905 (offshore breakwater Thaon de Revel, fig.34a) (Coen-Cagli 1936, Greco 1953).

Soon after, both the Galliera mole in Genoa and the offshore breakwater in Naples were extended with a slight different solution for the vertical structure (proposed by the engineer Inglese): a single or double column of weakly reinforced 220 t *cellular* blocks was filled in-situ with mass concrete to join the elements in one monolith (fig.34b). However the filling concrete did not bond well with the walls of the precast blocks under the wave dynamic action and repair works were needed.

Therefore in the 20's the bigger pontoon capacity promoted the use of full-width solid *cyclopean* precast blocks (up to 450 t) with vertical pits to allow the in-situ solidarization with concrete and reinforcing rails or bars (fig.34c). The fear about the weakening effect of these hollows then favoured the superposition of plain solid blocks in single columns without vertical connections, as made in the breakwaters of Genoa, Palermo and Catania (1928-31). The latter structure soon became famous, because it failed dramatically during a storm in 1933, shortly followed by the failure of Mustapha jetty in Algiers in 1934. The main failure reasons were the high wave breaking loads due to the shallow toe depth, the lack of wall monolithicy and toe scour.The rehabilitation of Catania breakwater led to a sloping section with a "natural" parabolic profile (fig.34d). These disasters opened new discussions and international guidelines were given at the next PIANC congress in Bruxelles in 1935. The new design criteria were summarized by Coen-Cagli (1936) and Ferro (1936).

Vertical breakwaters became again out of fashion (mainly outside Italy), but a new construction technology allowed to overcome the above drawbacks: the large monolithic cellular r.c.caissons. Constructed in yards the caissons can be floated into position and then sunk with water ballast and filled with mass concrete (as in the earliest applications at Alghero in 1915 and at Civitavecchia in 1931-36) (fig.35) or with incoherent material (as at Genoa airport breakwater in 1938). The construction of these latter caissons was made with a special fixed platform, which was the first industrial prefabrication yard for maritime structures and judged "worth of attention" by Schorn 1959 (fig.36). The caisson technology later evolved with advanced floating plants and deeper-water applications. In the 70's a 42 m high caisson was designed and built by an Italian contractor in Sines, Portugal (CSPP 1976).

The ingenious creativity of the Italian engineers from either contractors and the *Genio Civile* was especially active in finding more efficient and economic solutions for the

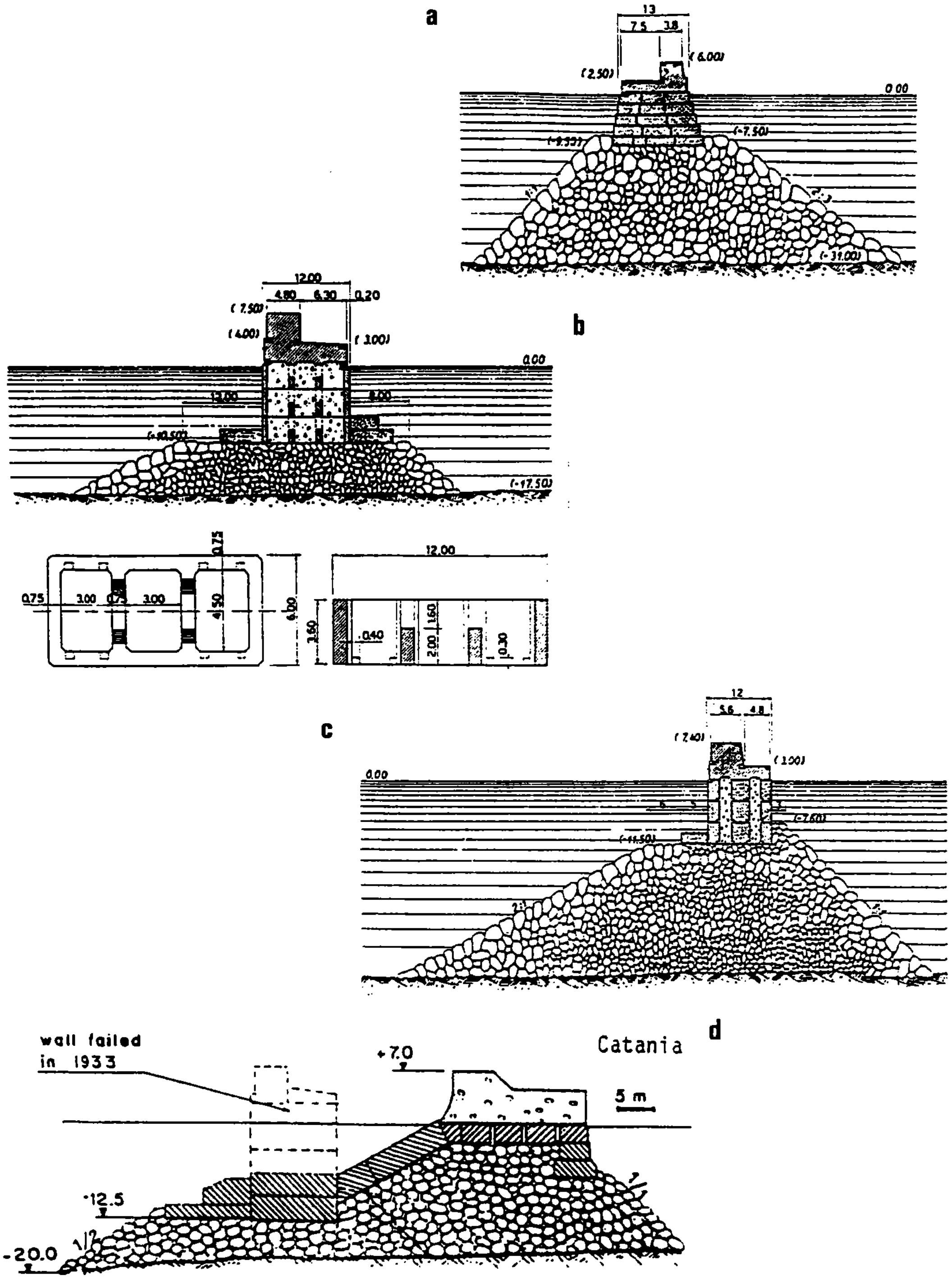


Fig.34. Developments of vertical breakwaters between 1900 and 1940:

a) Early block-type composite breakwater at Naples (1905)

b) Cellular block-type composite breakwater at Genoa (1912)

c) Cyclopean block-type breakwater at Naples "Duca degli Abruzzi" (1929)

d) The failed cyclopean block breakwater at Catania harbour, repaired with a sloping profile construction of coastal structures, although without giving much publicity of their experience (nor patents). New ideas for artificial armour units were applied, such as the cubes with cut-off corners to improve the work compactness (Mariani,1935).

Early advanced approaches were also used for breakwater geotechnical designs on soft seabeds, such as the sand foundation fill on the silty seabed of La Spezia harbour to support the rubble mound offshore breakwater. Geotechnical problems also conditioned the design of the horizontally composite breakwaters which were later built at Ravenna and Sibari harbours (Matteotti 1993).

Early Prototype Measurements. The interest raised by the mentioned breakwater failures also promoted the modern scientific approach in coastal engineering, by means of advanced theoretical and experimental studies and even prototype measurements. One of the first ever used full-scale monitoring system of waves and wall pressures was infact installed on a section of the Genoa offshore breakwater extension in water 15 m deep (Albertazzi 1932, Levi 1933). The wave elevation at the wall (with crest at +7.5 m MSL) was measured by a series of 19 electric contact terminals spaced at 0.5 m intervals between -2 and +7 m. Wave heights on 20 m depth were measured by a 2.5 m spherical buoy bearing a vertical cardanic suspended spar collimated from the shore. Wave length and direction was obtained by observation of some smaller buoys, placed 1 km offshore up to 30 m depth, outside the range of reflected waves, at fixed distances along two orthogonal lines. Two sets of 7 pressure cells were mounted in the wall to measure wave-induced forces. The results of these early prototype experiments showed a good agreement with the Sainflou pressure distribution of standing waves: the pressure at -15 m was found to be half the maximum value at the waterline.

Another monitoring system was installed before the last war in the Duca degli Abruzzi mole in Naples, where a stereophotogrammetric technique was used to measure incident and offshore waves. Unfortunately the transducers did not give reliable results. The station was damaged during the war and later rehabilitated (Greco 1955).

Progress in Coastal Protection (1900-1950). Attention to coast defense engineering started to receive more attention since the beginning of the XXth century, even outside Venice. The urbanization of the coastal areas and the construction of littoral roads and railways grew along the Italian peninsula (due to the mountaneous hinterland) and sea protection works were required on exposed shores. A new legislation was issued in 1907 (only now being updated!) to regulate the intervention of the State, which is the actual "owner" of the coastal strip (normally 75% of the budget is financed by the state and 25% by local Authorities), but only for the defence of endangered infrastructures, typically with "hard passive" works, such as seawalls and revetments. As far as technical innovations are concerned, an original solution was produced by the engineer G.Lenzi: he was probably the first advocate of the detached parallel breakwater system, which he successfully designed for the defense of the endangered marine promenade of Salerno in 1905. However, yet in the 1930 edition of the largest Italian encyclopaedia "Treccani", the term Coastal Defence was still only referred to its military meaning !

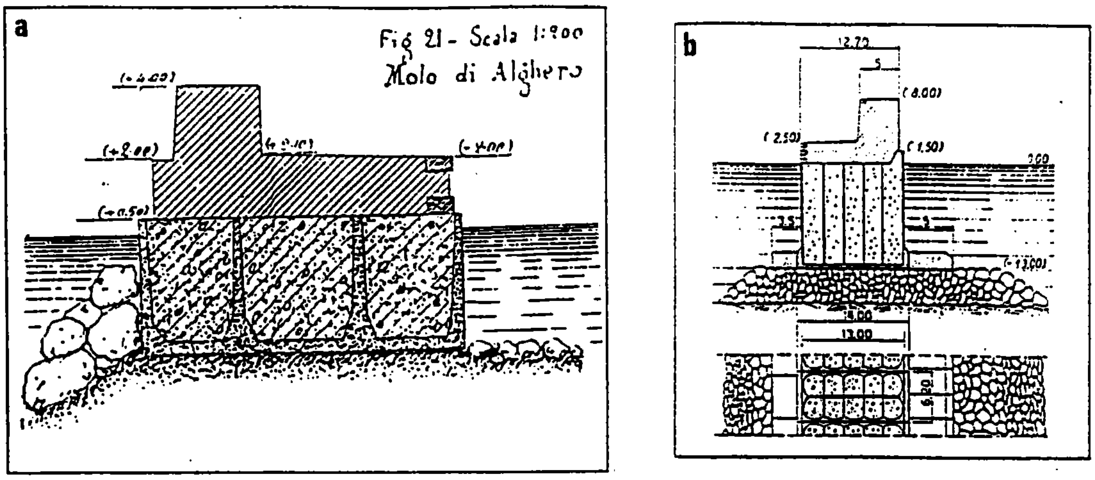


Fig.35. Earliest applications of the floating caisson technology at Alghero in 1915 (a) and Civitavecchia harbour extension in 1935 (b)

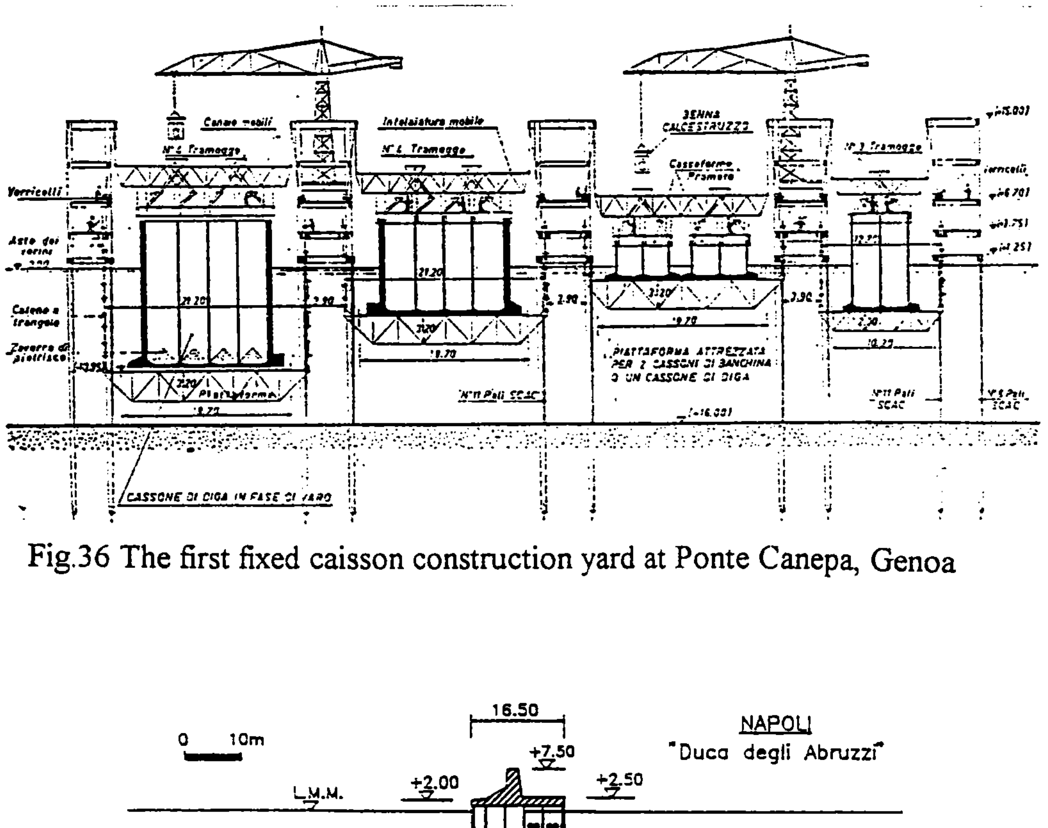


Fig.36 The first fixed caisson construction yard at Ponte Canepa, Genoa

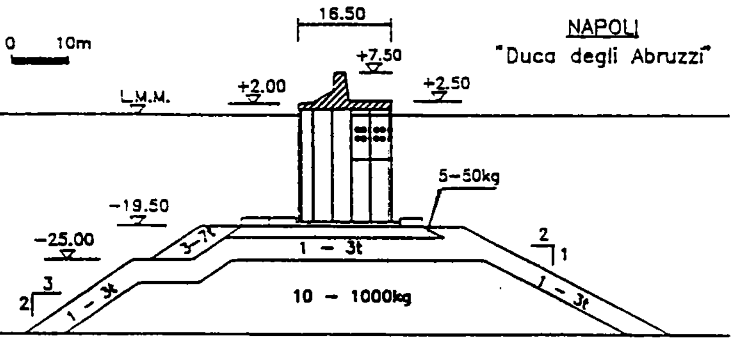


Fig.37. Section of a modern caisson breakwater at Naples

Contemporary Age

Harbours Reconstruction. As mentioned before we could conventionally define the start of the contemporary age after WW2 when the first ICCE was held in 1950. Italy was just recovering from the destructive war. At the 18th PIANC Congress in Rome an interesting illustrated book prepared by the Italian Ministry of Public Works (1953) was handed to participants. It contains a detailed survey of all port structures and facilities before and after the war. Out of the 91 km of harbour breakwaters overall existing in 1939, 20 km had been destroyed and 10 km damaged, while of the 140 km quaywalls (33 km deeper than 9 m) some 51 had been destroyed and 43 damaged. However with a great effort the reconstruction work of the National Ports was fully accomplished in a few years with modern criteria.

Beside the necessary upgrading of the historical harbours, including deeper breakwater extensions, a few fully new ports have been constructed in the last 50 years. The most modern is probably the industrial harbour of Gioia Tauro, which was designed with advanced criteria (Grimaldi et al.1984). Its plan layout with long internally excavated basin and normally oriented outer harbour is very similar to the ancient Roman port of Ventotene (fig.20). The two deepwater breakwaters have been armoured with 30 t reinforced dolosse.

New developments in port design have been recently observed in the modern sector of pleasure harbours and marinas, especially related to their environmental implications. An overview of the new criteria for design and construction is given by Franco et al. 1993. An updated state-of-the-art is given in the proceedings of a specialty national conference (PIANC 1995). Reference is also made to the illustrated book given to delegates at the ICCE (1992) in Venice, which generally describes the main new Italian projects of coastal engineering.

Vertical Breakwaters. The technological evolution again progressed, especially in the familiar field of composite breakwaters, with the systematic use of cellular floating caissons, with larger size and more complex geometries (CSPP 1976, Tosi 1980). Caissons with semicylindrical external walls were prefabricated for the first time by an Italian contractor to be towed from Sicily to the west breakwater of Marsa el Brega (Libya) in 1967. An even longer journey (2500 km from the yard in Genoa) was undertaken in 1975 by the 5000 t traditional square caissons used for the east mole.

A modern (1988) application of the semicircular planshaped front is observed in the new extension of the Duca degli Abruzzi breakwater in Naples, whose cells on the harbour side are partially absorbing to reduce internal wave disturbance (fig.37). Other new caisson designs include seaward perforated walls and absorbing chambers (to reduce wave reflection, toe scour, as well as forces and overtopping) and sloping curved and set-back parapet walls (mainly to reduce wave forces), sometimes combined with the perforations. Original applications of these designs can be found in the new breakwaters at Civitavecchia, Sorrento, Bagnara and Porto Torres (Noli et al.1995).

A unique example of "pure vertical" breakwater is represented by the steel-piled structure with concrete screen (fig.38), built in the early 70's to shelter an island-harbour at Manfredonia in 11 m of water on a shallow sloping beach. This unusual solution was chosen due to the soft clayey silt foundation soil (Benassai et al.1974).

Better designs have then been favoured by the revolutionary progress in the knowledge of random wave statistics and development of laboratory facilities, which occurred after WW2. Further lessons have been learned from analysis of new failures occurred to old vertical block walls, such as the famous one of Genoa breakwater in 1955 (Grimaldi 1955) and even an old caisson case in Naples slid in 1987 (Franco et al.1992). Again prototype measurements of wave pressures on vertical walls have been carried out on Genoa new offshore breakwater (Scarsi et al.1974, Marchi 1977, Boccotti 1984), which also demonstrated the possibility of a nearly rectangular distribution of uplift pressures on the caisson base. More recently a double measurement station operated on both plain and perforated neighboring caissons of Porto Torres industrial harbour breakwater (De Girolamo et al.1995) (fig.39).

Rubble mound breakwaters. It should be remembered that the long valuable experience of the Italian contractors in the field of maritime engineering has been revealed also abroad. In particular in the last 20 years they have built important rubble mound harbour breakwaters, sometimes in very deep and exposed waters and often with innovative technical solutions, in Sines (Portugal), Bandar Abbas (Iran), Mohammedia (Morocco), Homs (Libya), Djen-Djen (Algeria), Bosaso (Somalia), Ras Laffan (Qatar) (Noli 1993, Burcharth et al.1991, Franco et al 1995).

Beach Dynamics and Coastal Protection. Substantial progresses are observed in the new expanding sector of beach morphodynamics and shoreline defense, due to the dramatic increase of erosion processes in the last 40 years (mainly related to human activities, such as river damming and quarrying, coastal urbanisation, sporadic maritime works, subsidence etc.). The growing socio-economic importance of beaches for recreation and the new environmental concerns called for new territorial policies with more systematic strategies. The earliest Regional and Interregional Plans for coastal defence started at the end of the seventies in the north-central Adriatic areas (Moretti et al.1984).

Research in the field of coastal geomorphology and dynamics had a remarkable boost in the 70's thanks to the "Special Programme for Soil Conservation" promoted by the C.N.R.. A series of interdisciplinary research projects were carried out by sedimentologists, mineralists, geologists, geographers and hydraulic engineers, who produced a large scientific production, listed and summarized by A.V.1985. These projects also led to the edition of the mentioned "Atlas of Italian Beaches" and to a reference technical manual for shore protection works (Cortemiglia et al.1981).

An overview of the present state-of-the-art can be found in the proceedings of a national specialty conference, where engineers and geologists managed to bring together once again to report on the main Italian case studies (Aminti et al.1993).

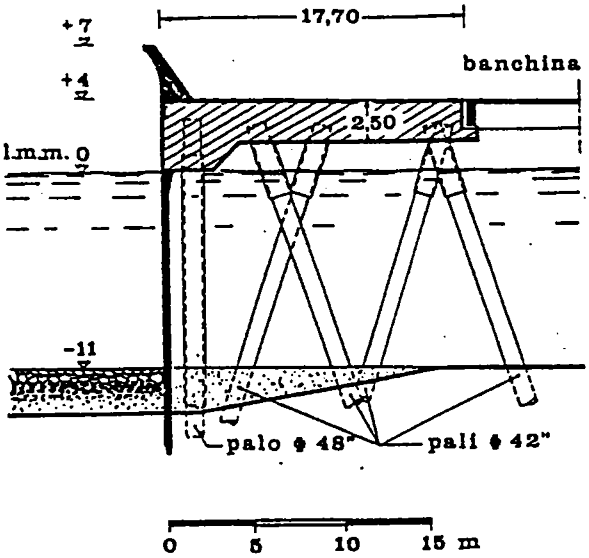


Fig.38. The piled breakwater with vertical screen of Manfredonia island-port

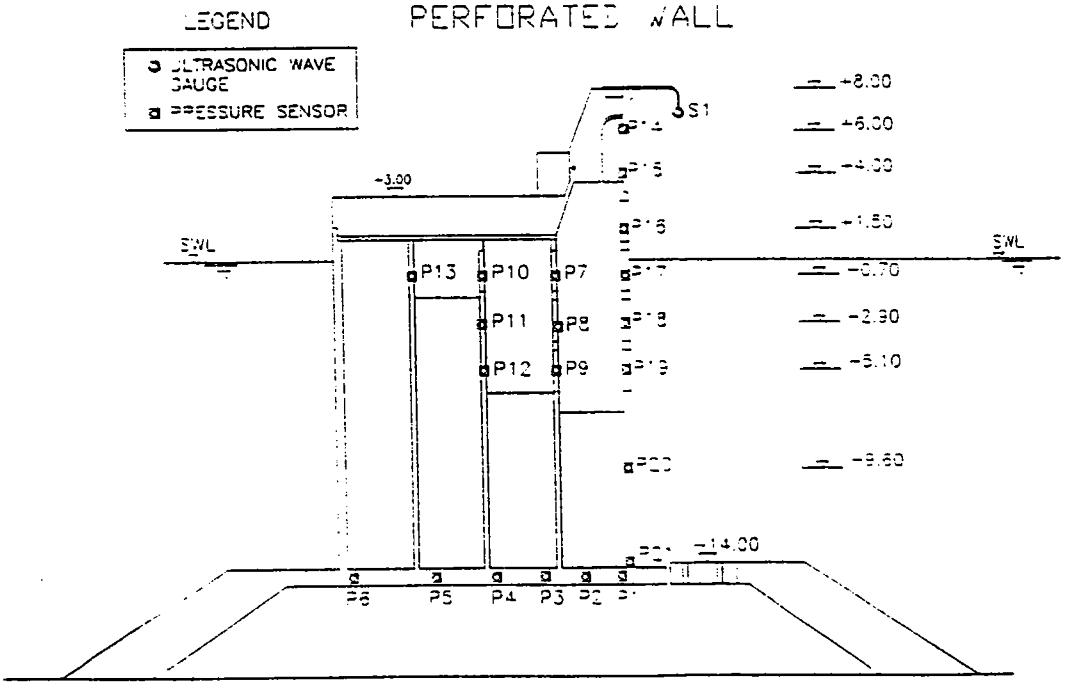


Fig.39. The new instrumented perforated caisson breakwater at Porto Torres

Further references are found in the proceedings of the first edition of the new biennial "Italian Days of Coastal Engineering" promoted by the Italian PIANC section in 1993. Moreover a general inventory of 113 studies related to coastal protection (including bathymetric, sedimentologic, meteoceanographical surveys and modelling), which were carried out in Italy in the last 15 years, has been published by ESTRAMED 1995.

Again a vast empirical knowledge has been gained after many practical field applications, mostly with partially successful "hard" protection structures such as seawalls, groins and the typical rock detached breakwaters : more than 500 barriers of the latter type have been inventoried along 300 km of central Adriatic shoreline. Further information on Italian detached barriers is given by Liberatore (1992).

Sometimes original designs of shore protection structures or systems have been applied. A new original Italian structure is represented by the permeable piled barriers named *Ferran* (fig.40a), which have been used off two sandy beaches near Ancona in 1981-85 with a partial success (Vitale et al.1985). The star-shaped r.c.piles can promote beach accretion and allow water circulation, but they have problems of stability, durability, aesthetics and recreational safety. Other patented concrete elements (perforated or articulated blocks) are used within submerged modular structures also to enhance fish survival (e.g.*Nettuno* fig.40b, *Monobar*).

In fact the traditional emerged discontinuous detached breakwater systems are now being replaced by longitudinal even continuous submerged barriers for their favourable aesthetical and hygienic effects. However the present trend for shore protection works in Italy (as in most countries) is toward natural sand nourishment, although typically combined with retaining structures to reduce sediment losses and maintenance work. The scarcity of offshore sources of suitable borrow material generally forces to use more costly land quarries. Actually early "soft" solutions had been already used in the 50's, when one of the first fixed *bypassing* plants was installed at Viareggio harbour (fig.41). The bypass system was later modified and it is still operational with more flexible floating equipment (Fiorentino et al.1985).

An original perched beach scheme has been applied in 1990 along 3 km of shoreline at Ostia Lido near Rome (Ferrante et al.1992), featuring a sand fill with an underlayer of coarser poorly sorted material and a longitudinal rock sill with crest now at about -2 m MSL (fig.42). The present monitoring shows a predicted beachline rotation due to the longshore sediment transport gradient and to the lack of groins, and the accumulation of gravel near the waterline. Another "protected nourishment" scheme has been used to defend the coastal railway along the exposed steep western Calabrian shores: it combines a gravel beach nourishment with large T-shaped groins (Guiducci et al.1993) (fig.43).

Various shore protection projects made in the last decade along the northern Adriatic beaches are often characterized by sand containment within cells made with groins (only partly emerged) and a submerged longitudinal barrier, sometimes made with sand bags (Preti 1993) (fig.44). A similar system is now also being constructed for the new

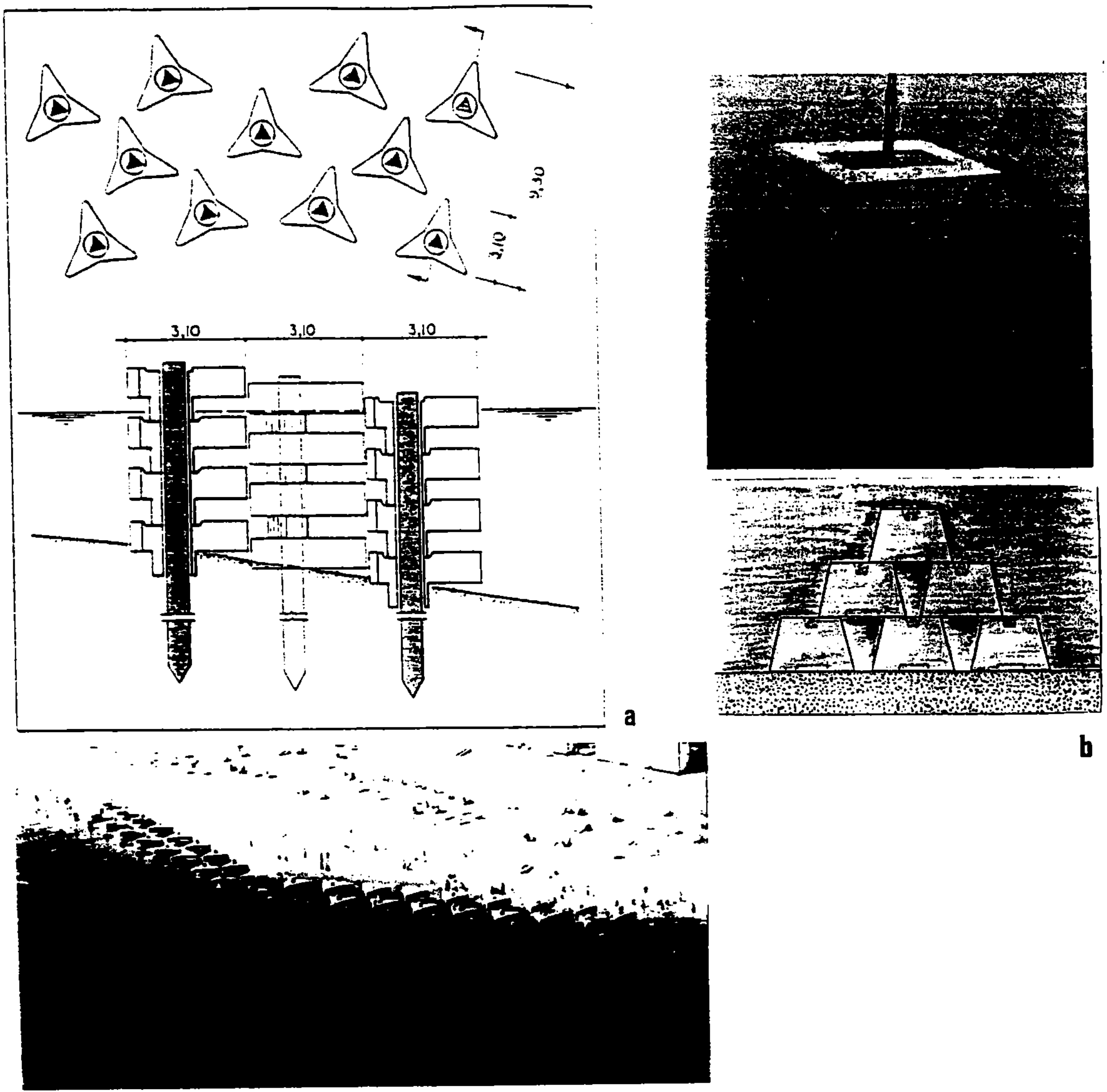


Fig.40. Unconventional examples of modern shore protection works in Italy:

a) *Ferran* piled barriers near Ancona

b) Perforated concrete blocks *Nettuno* for submerged barriers and to enhance fish habitat

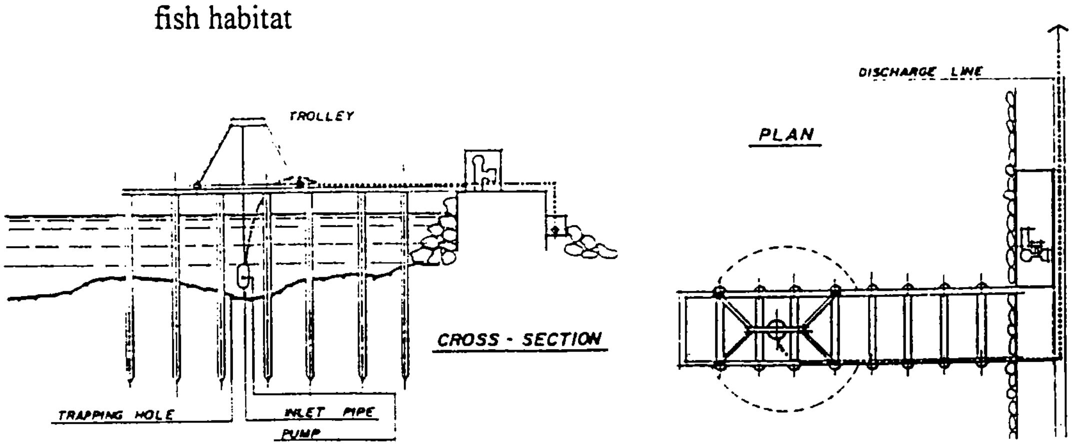


Fig.41. First fixed bypassing plant at Viareggio (1956)

protection of the Venetian littoral of Pellestrina, where, for the first time in Italy, the borrow fill is dredged from 20 m deep offshore "fossil beaches". The same material is used to nourish the near beach of Cavallino, where new groins are only built after the uneffectiveness of the shore-parallel barrier has been proved with advanced integrated modelling techniques (Noli et al.1993, CVN 1995). This shore protection works are the modern development of the historical seawalls previously described and they are part of the integrated Venice Safeguard Project. This project also includes the storm surge mobile barriers at the three lagoon inlets (now designed as shown in fig.45 and undergoing the E.I.A.) and represents today the largest ongoing project of coastal engineering in Italy (Marchi 1992).

Offshore. Significant Italian developments in the last half century may also be mentioned in the new "neighbouring" field of offshore engineering. Actually the first offshore oil well in Europe was drilled in the Sicily Channel in 1959 (by AGIP) and the first European discovery of offshore gas was made in 1960 near the Italian coasts of the North Adriatic Sea. Since then over 100 piled jackets have been installed, mainly in these two areas, together with important submarine pipelines (eg. for gas transport across the 600 m deep Sicily Channel from North-Africa). Offshore related engineering and research activities have then been in the forefront: innovative designs of steel gravity platforms (by Tecnomare)and technology for lying deep sealines (by Saipem) have had important applications even in the North Sea.
As elsewhere the fast progress in the offshore hydrodynamics and practical applications has produced benifits also to the *coastal* community. The engineers of the main oil companies have even joined the researchers and contractors in the traditional civil-hydraulic fields of coasts and harbours to form an Association of Offshore and Marine Engineering (AIOM), which since 1985 is organizing national congresses, meetings, courses and other activities.

Status of Scientific Research. In Italy the research activity in the field of coastal hydraulics and engineering has been quite scattered and isolated in the last century as for other similar scientific disciplines. This is due to various reasons such as: the late diffusion among Italian scholars of the English language (which has replaced Latin and French as official scientific language) and especially the fact that hydraulic research in Italy is run by Governmental Agencies (for 90% State Universities, which are not commercially oriented) with the inherent deficiencies of such institutions. In particular coastal engineering research is mainly carried out by many small separated academic institutes and laboratories within Hydraulic and Civil Engineering departments (over 20 distributed all across the country), which had somewhat neglected it in favour of fluvial and damming problems. Only after 1985 3-year PhD courses are offered each year by Italian Universities: a thesis on coastal engineering subjects can be carried out within three consortiums with administrative seats at the Hydraulics Institutes of the Universities of Padua, Naples and Milan Polytechnic. Admission is open to home and foreign students under public competition.

Another drawback is represented by the absence of a large national hydraulic laboratory for coastal scale models. Advanced experimental facilities are available

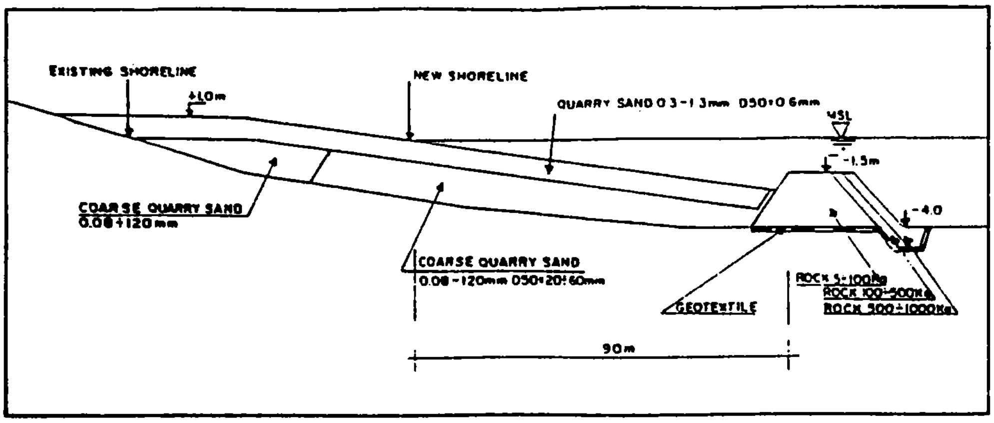


Fig.42. Design cross section of the new perched beach at Ostia Lido (Ferrante 1992)

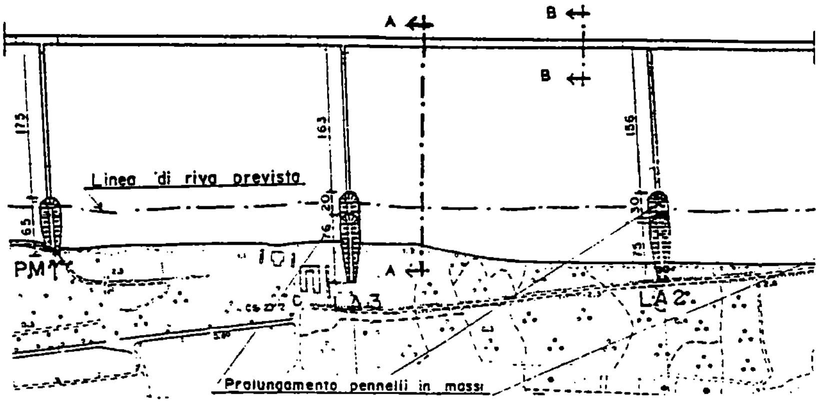


Fig.44 Example of new protected nourishment scheme along the north Adriatic coast

Fig.43. Photo of the beach nourishment within T-shaped barriers to protect the littoral railway at Paola-S.Lucido in Calabria (Guiducci et al.1993)

today at ENEL-CRIS in Milan and at the Center of Voltabarozzo, Padua, which belongs to the *Magistrato alle Acque* (mainly devoted to the problems of Venice), and a new lab is under construction in Bari.

However, despite the traditional lack of coordinated organization and of financial support, either theoretical, experimental and field research work in coastal engineering have produced valuable contributions, especially in the last years. This is partly due to the diffusion of mathematical modelling with inexpensive computational facilities and also by taking advantage of new European programs, such as the various MAST (Marine Science and Technology) projects carried out since 1989 on Coastal Morphodynamics and on Coastal Structures with the participation of some Italian Universities (Rome, Milan, Naples, Bologna, Genoa, Florence) and private companies (Snamprogetti, Tecnomare, ENEL). For the complete list of related subjects and publications the reader is referred to the Commission of the European Community 1995. Another EU-funded program which is worth mentioning is the Large Installation Plan (LIP): it allows young researchers from any European country to carry out selected experimental projects by using the advanced expensive facilities of a few specialized hydraulic laboratories (e.g. DH, HR, DHI). An example of Italian participation is given by a novel 3-D physical model study on the hydraulic performance (wave forces and overtopping) of caisson breakwaters under multidirectional seas (Franco C.et al.1996). Research projects of each university also receive limited annual funds at the national level by the Ministry of University and Scientific Technological Research (MURST).

Most publications of Italian authors on maritime hydraulics and coastal engineering can be found within the national congresses of Hydraulics and the AIOM's ones, and more and more frequently in the international proceedings of the ICCE, IAHR, PIANC and ICE Breakwater conferences, besides various specialized journals. The present production of papers is of the order of hundreds per year and it is obviously impossible to give a full account of them here. However, though uncomplete, a short list of the main research topics is provided in order to outline the global picture and give some useful references of international interest.

The first and only ICCE held in Italy (Venice, 1992) has witnessed - together with a properly organized high surge (...!) - the presentation of twenty papers by Italian authors (out of 263). Nine of these papers were devoted to hydraulic and coastal engineering problems related to Venice. The others dealt with wave forecasting models (Cavaleri et al.), wave transformation over submerged bars (Liberatore et al., Petti et al.), mechanics of wave groups (Boccotti et al.), sand ripple formation (Foti et al), shallow water wave theories (Brocchini et al., Mattioli), sediment suspension (Longo), breakwater monitoring (Muraca et al.), beach profile evolution (Chiaia et al.) and case histories of new shore protection projects. At the next most recent ICCE's in Kobe (1994) and Orlando (1996) the number of papers by Italian authors and co-authors is still around ten, generally dealing with the same above subjects, and also covering 2-D and 3-D model tests of wave overtopping and loads on breakwaters, the stability of berm breakwaters and the behaviour of submerged barriers.

Generally, relevant Italian contributions are given in the definition of the characteristics of deep and shallow water wave spectra and their interaction with coastal structures, based on theoretical approaches, field measurements and on numerical and physical models. Remarkable is the new theory of "quasi determinism of the highest waves" (Boccotti 1988), which predicts the characteristics of the highest wave groups in a sea-state. Advanced theoretical studies on bedload transport and ripples formation are performed by Blondeaux et al.1990. An analytical computation of random wave direction is given by De Girolamo 1995, who also treated harbour resonance problems (1996). The statistical properties of random waves and groups are also investigated with numerical simulations (Rebaudengo Landò et al. 1989). A numerical study has been addressed to the flow interaction with sinusoidal bed dunes (Sammarco et al.1994). New efforts are devoted to wave propagation in shallow waters, including simulation of nonlinear steep waves at vertical walls (Passoni 1995). Hydraulic model studies on coastal structures have been addressed to wave overtopping response (Aminti et al.1988, Franco et al.1994), toe stability and reshaping breakwaters (Lamberti et al.1994). Original small scale experiments on the real seas action against a vertical wall have been performed at Reggio Calabria (Boccotti 1992). New field/lab tests on the structural integrity of prototype armour blocks confirmed the high strength and durability of Italian marine concretes (Franco et al.1995). Among the few studies on beach dynamics, 2-D mobile bed model tests have been conducted at the University of Bari (Chiaia et al.1992) and Naples (Di Natale et al.1992).

National papers in coastal hydraulics are also internationally distributed through the annual issues of the journal EXCERPTA, published by GNI (Gruppo Nazionale Idraulica) which reviews the Italian academic contributions to the whole field of hydraulic engineering.

Finally a new study area is represented by the modelling and monitoring of the natural coastal ecosystems, including the hydrodynamic transport of surface pollutants, beach dune stabilization and the ecological impacts of coastal works. An example reference on the detailed studies of the vegetation of the Venetian sandy littorals is given in CVN 1995. New protection works at Cavallino beach have included transplanting of local *Ammophila*, sheltered by wooden fences, to "armour" the littoral dunes degradated by erosion and high touristic use.

CONCLUSION AND OUTLOOK

This condensed historical review has shown how the ingenious individual contributions of Italian hydraulic engineers, architects, mathematicians, oceanographers, geologists and even naval officers have helped the development of Coastal Engineering in a time span of over 2000 years. It is in fact acknowledged that Italy has been the leader country in the technological progress since the II century BC until the XVIIIth AD.

The scarcity of natural harbours along the Italian tideless coasts has forced the Romans and later the Italians to build exposed deepwater breakwaters (in particular monolithic composite breakwaters) and hydraulically efficient harbour layouts, developing most modern design solutions well ahead of times. Earliest shore protection works were also experimented by the Venetians. This bimillennial field experience can also provide a valuable knowledge of the long-term response of coastal structures and morphology.

Despite the lack of large organized research centers and laboratories, Italian individuals have also contributed to the scientific development of this discipline, since the earliest advanced intuitions of Leonardo da Vinci to the present revival of both theoretical and experimental research. The growing interest in Italy about the fascinating problems of coastal engineering is also revealed by the number of the PIANC memberships (now the Italian delegation is the world largest together with USA's). In the wake of the ICCE'92 in Venice a new series of biennal national congresses, specifically devoted to coastal engineering, are taking place under the auspices of the Italian PIANC delegation.

It is expected that future coastal engineering works will be mainly related to the restoration of sandy beaches and of old harbour structures, possibly converted to different functions, especially for recreational use. New marinas will be built, but with greater environmental concern. Soft shore protection systems will be preferred.

The understanding of the complex nearshore processes and the reliability of coastal structures design and construction are likely to be improved in the near future by the increasing development of the computational models and remote sensing techniques for field monitoring. Modelling the coastal systems will be account for either physical, ecological and socio-economic aspects. The growing pressure on the Mediterranean shores and on the delicate ecosystem of this semiclosed basin will in fact require a more integrated and careful Coastal Management (Vallega 1993). The necessary coordination of various "expertises" could also include underwater archaeologists, in order to enhance the discovery, preservation, revaluation and even musealization of ancient harbour structures, which are still a neglected valuable heritage.

It is clear that the present trends in Coastal Engineering are again strongly addressed towards harmony with the environment. Therefore it is worth remembering Leonardo's statement in Latin *"Ne coneris contra ictum fluctus: fluctus obsequio blandiuntur"*, which means that "Nature should not be faced squarely and opposed, but wisely circumvented".

ACKNOWLEDGEMENTS

The author wishes to thank all the persons who provided useful information and historical references for the preparation of this paper. In particular the cooperation and advice of prof. G.Borzani (University of Genoa), prof. A.Noli and prof. G.B. La Monica (University of Rome), dott.L.Cipriani (University of Florence), ing. M. Gentilomo (Consorzio Venezia Nuova), ing.A.Ferrante (PIANC-Italy), ing. C.Franco, ing. A.Triola and dr G.Passoni (Politecnico di Milano) are gratefully acknowledged.

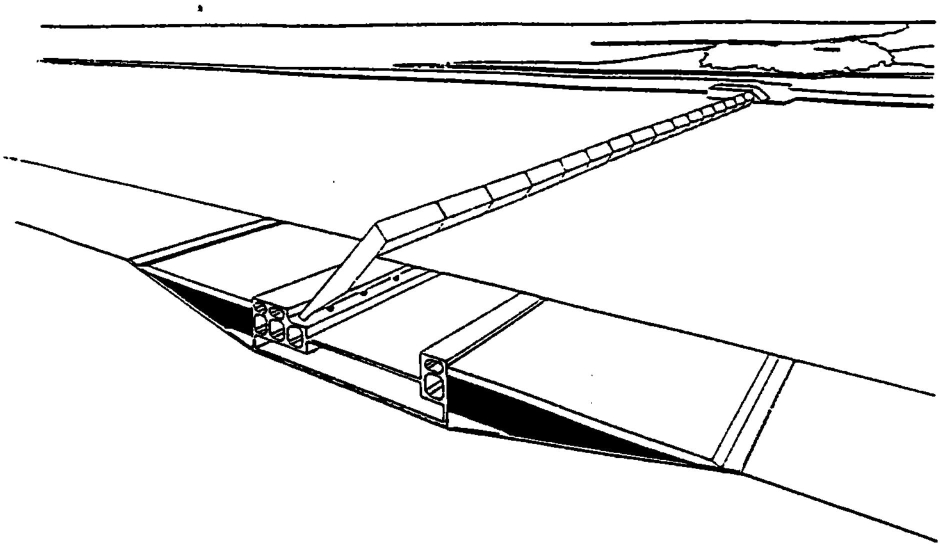


Fig.45 Conceptual drawing of the buoyant flap gates for Venice surge barrier

REFERENCES

Adami A., 1992. "Sea defence works in Venice", *Proc.of ICCE'92 Short Course on Design and Reliability of Coastal Structures,* Venice, pp.397-414

Albertazzi A., 1932. "Recent experiences on dynamic action of waves against breakwaters", Annali Lavori Pubblici, Roma , Feb 1932, p.134 (in Italian)

Alberti L.B., 1465. "De re aedificatoria", G.Simoncini Editor, De Luca , Roma

AM-ENEL, 1980. "Diffusive characteristics of the low layers of the atmosphere" 16 volumes (in Italian)

Aminti P. and Franco L. 1988 "Wave overtopping on rubble mound breakwaters" *Proc. ICCE,* Malaga, ASCE NY, pp.770-781

Aminti P. and Pranzini E. (Editors), 1993. "The littoral defense in Italy" Ed.Autonomie n.34, Roma (in Italian)

Archetti, R., and Franco, L. 1995. "New analysis of wave measurements in the Italian seas", *Proc. AIPCN 2nd Italian Days of Coastal Engineering,* Ravenna (in Italian)

AV1985 "Italian Research on Physical Geography and Geomorphology: an overview", *1st Int. Conf. On Geomorphology,* Manchester, Tecnoprint, Bologna, pp.17-25

Benassai E., Grimaldi F., Scotti A., 1974, "Interaction between waves and the vertical piled breakwater of the new Manfredonia harbour", *Proc. XIV Convegno di Idraulica e Costruzioni Idrauliche,* Napoli (in Italian)

Bernardini O.,1901. "On the damage due to the storm of 27 Nov.1898 and on the repair of Genoa Breakwater" *Giornale del Genio Civile* pp.665-692 (in Italian)

Bianco L., 1637. "On Genoa harbour rehabilitation", ed. FINCOSIT 1955 (in Italian)

Blackman D.J., 1982. "Ancient harbours in the Mediterranean", *Int.Journal of Nautical Archaeology and Underwater Exploration,* part 1 in 11.2 pp.79-104; part 2 in 11.3 pp.185-211

Blondeaux P., Vittori G., 1990. "Sand ripples under sea waves", *J.Fluid Mech.* vol.218, pp.1-39

Boccotti P., 1984. "New wave pressure measurements on the caisson breakwater of Genoa-Cornigliano", *Proc.XIX Congresso di Idraulica e Costruzioni Idrauliche*, Pavia (in Italian)

Boccotti P., 1989. "Quasi-determinism of sea wave groups", *Meccanica* vol.24, n.1

Boccotti P., 1992. "The behaviour of a very light vertical breakwater", *Proc.XXIII Congresso di Idraulica e Costruzioni Idrauliche*, Firenze, (in Italian)

Borzani G., 1973 "On a vertical breakwater for reclamation defence at Fontvieille, Monaco", *L'Industria Italiana del Cemento* n.7-8, pp.481-512 (in Italian)

Borzani G., 1995. "Evolution of design criteria for harbour breakwaters", PIANC Italian Section (in Italian)

Brambati A., 1993. "Preliminary investigations on the physiographic unit", *Proc. ICCE92-PIANC 1st Italian Days of Coastal Engin.*, vol.A, pp.218-237 (in Italian)

Brown F.E., 1980. "Cosa, the making of a Roman town", Michigan University Press

Burcharth H.F., Toschi, P.B., Turrio E., Balestra T., Noli A., Franco L., Betti A., and Mezzedimi S., 1991. "Bosaso harbour, Somalia, a new hot-climate port development", *Proc. 3rd COPEDEC Conference on Coastal Engineering in Developing Countries*, Mombasa, pp. 649-667,

Caesar Julius, 55 BC, "De Bello Gallico" IV,17

Caputo C., D'Alessandro L., La Monica G.B., Landini B., Lupia Palmieri E. , 1991. "Present erosion and dynamics of Italian beaches", *Z.Geomorph.N.F.* Supp.Bd.81, pp.31-39

Cavaleri L., Bertotti L, 1992. "The Mediterranean Sea Wave Forecasting System," *Proceedings 23rd Coastal Engineering Conference*, ASCE, NY, pp.116-128

Chiaia,G.,Damiani,L.,and Petrillo, A. 1992."Evolution of a beach with and without a submerged breakwater:experimental investigation", *Proc.23rd ICCE, Venice, ASCE,NY, pp.1959-1972*

Cialdi A., 1866. "On Sea Waves and currents, especially near the littorals", Roma (in Italian)

Clark 1948. "Science and Social Welfare in the Age of Newton", Oxford

Clementi R.,1981. "The Roman port of Astura". *L'Universo* n.6, I.G.M. (in Italian)

CNR (National Research Council), 1984. "Atlas of the Italian Beaches" SELCA, Florence

Commission of the European Communities,1995. "Marine Sciences and Technologies" *Proc.2nd MAST days and Euromar market, Sorrento*, Project reports, Bruxelles

Coen-Cagli E. and Bernardini O.,1905. "News on Italian maritime ports" Ministry of Public Works, Pirola, Milano (in Italian)

Coen-Cagli E., 1936. "Italian Docks and Harbours" *Journal of the Inst.of Civ.Eng.*, London

CSPP (Centro Studi Problemi Portuali) 1976. "Technological progress and maritime works" *Serie Documenti e Ricerche* n.16-17 (in Italian)

CVN (Consorzio Venezia Nuova) 1995. "QT- Quarterly Notebooks" n.2-3 (in Italian)

Cornaglia P.,1891. "On beach regime and harbour regulation" Stamperia Reale , G.B.Paravia, Torino (in Italian)

Cortemiglia,G.C., Lamberti,A., Liberatore, G.,Lupia Palmieri, E., Stura,S., and Tomasicchio, U.1981. "Technical Recommendations for Coastal Protection" CNR, P.F."Soil Conservation", S:P."Littoral Dynamics" (in Italian)

Crescentio B., 1607. "Nautica Mediterranea", vol.5, Ed.Bonfaldino, Roma (in Italian)

D'Arrigo A., 1940. "Leonardo da Vinci and the regime of Cesenatico beach. Researches on the origins of canal-ports in the Renaissance" Annali Lavori Pubblici n.4, pp.293-325 (in Italian)

De Boni M., Cavaleri L., Rusconi A., 1992. "The Italian waves measurement network", *Proc. 23rd Coastal Engineering Conference*, ASCE, NY, pp.1840-1850

De la Pena J.M., Prada E.J.M., Redondo M.C., 1994. "Mediterranean Ports in Ancient Times". PIANC Bulletin n.83/84, Bruxelles, pp.227-236

De Girolamo P., 1995. "Computation of sea wave direction of propagation of random waves", *Journ.Wat.Port.Coast.Ocean Eng.*, ASCE NY, vol 121 n.4

De Girolamo,P., Noli A.,and Spina D., 1995 "Field measurements of loads acting on smooth and perforated vertical walls" *Proc. ICE Conf.on Breakwaters and Coastal Structures*, T.Telford, London

De Girolamo P. 1996 "An experiment on harbour resonance induced by incident regular and irregular short waves" *Coastal Engineering* (pending publication)

De Fazio G., 1814. "On the best harbour construction method". Napoli (in Italian)

De Marchi F., 1545 "Military Architecture" in Simoncini 1993 (in Italian)

De Rossi G.M., 1993. "Ventotene e Santo Stefano", Rome, (in Italian)

Di Giorgio Martini F., 1475. "Treatise of Architecture, Engineering and Military Art", Ed Il Polifilo, Milano 1967 (in Italian)

Di Natale M., Ragone A., 1992. "Profiles of beach models under regular and irregular wave attack", *EXCERPTA* vol.6, pp.55-96

ESTRAMED (Paolella,G.,Bolatti Guzzo,L.,Corsini,S.,and Schintu C.), 1995. "Survey of the studies performed for shore protection in Italy", Maggioli Editore, 129

Faina G., 1969. "Genoese harbour engineering in 1600" Istituto Italiano per la storia della tecnica, Giunti, Milano (in Italian)

Fassò C.A., 1987. "Birth of hydraulics during the Renaissance period" in "Hydraulics and Hydraulic Research: a Historical Review", *IAHR*, G.Garbrecht Editor, Balkema pp.55-79

Ferro G., 1936. "On wave action on vertical breakwaters", *Annali dei Lavori Pubblici* pp.764-781, 935-946 (in Italian)

Felici E., 1993. "Observations on the Neronian port of Antium and the Roman technology of concrete harbour works", in Archeologia Subacquea, IPZS, Roma (in Italian)

Ferrante A., Franco L. and Boer S., 1992. "Modelling and monitoring of a perched beach at Lido di Ostia", *Proc. 23rd Coastal Eng. Conf.* ASCE, NY, pp.1879-1895

Fiorentino A., Franco L. and Noli A., 1985. "Sand bypassing plant at Viareggio, Italy", *Proc. Australasian Conference on Coastal and Ocean Engineering*, Christchurch (NZ), Vol.1, pp. 441-451

Franco C., Van der Meer J.W. and Franco L., 1996. "Multidirectional wave loads on vertical breakwaters" *Book of Abstracts, ICCE'96*, Orlando, ASCE, NY

Franco L. and Passoni G., 1992 "The failure of the caisson breakwater Duca D'Aosta in Naples harbour during the storm of 11 January 1987", *Proc.2nd MAST G6-S workshop* (also in Bauingenieur 69, 1994, in German)

Franco L., Marconi R., 1993. "Marina design and construction" in Marina Developments. Computational Mechanics Publications, Southampton, pp.143-213

Franco L., 1993. "Wave records in the Italian Seas: results of a new inventory and statistics of extreme storms," *Proc. Italian Days of Coastal Engineering, ICCE'92-AIPCN*, vol.D, Genova, pp.146-181 (in Italian).

Franco L., 1994. "Vertical Breakwaters: the Italian experience", *Coastal Engineering*, 22, pp.31-55

Franco L., De Gerloni M. and Van der Meer J.W., 1994. "Wave overtopping on vertical and composite breakwaters", *Proc.24th ICCE Conference on Coastal Engineering*, Kobe, ASCE, NY, pp.1030-1045

Franco L., Gentilomo M., Noli A. and Passacantando G., 1995. "Constructional aspects of some large rubble mound breakwaters in northern Africa", *Proc.ICE Conf.on Breakwater and Coastal Structures*, London, T.Telford

Franco L., Noli A., De Girolamo P. and Ercolani M., 1995. " Concrete strength and durability of prototype tetrapods and dolosse: results of field and laboratory tests", *Proc. final workshop MAST2-RMBFM project, Sorrento*

Franco L., 1996. "Ancient Mediterranean Harbours: a Heritage to Preserve", *Journal of Ocean and Coastal Management*, Special Issue on the Mediterranean, Elsevier

Frost H., 1972. "Ancient harbours and anchorages in the Eastern Mediterranean". *Proc. UNESCO Congress "Underwater archaeology: a nascent discipline"*, Paris, pp.95-114

Greco L., 1953 "On port technology- Half century of engineering" L'ingegnere n.3, Milano (in Italian)

Greco L., 1955. "On wave theories and necessity of experimental research", *Giornale del Genio Civile*, pp.507-513 (in Italian)

Grillo S.,1989 "Venice Sea Defences" Arsenale Editrice, Venezia (in Italian)

Grimaldi M., 1955. "The disastous cyclone damage at Genoa Breakwater" The Dock and Harbour Authority , vol.36, n.418 pp.117-120

Grimaldi F. and Fontana F., 1984. "Redesign of the main breakwater of Gioia Tauro (Italy)", *Proc.Int.Symp.on Maritime Struct. in the Med Sea*, Athens, pp.2.153-172

Guiducci F., LoPresti F. and Scalzo M.,1993 "Beach nourishment at Paola-S.Lucido", in La difesa dei litorali in Italia, editors P.Aminti and E.Pranzini, pp.195-214

Hohlfelder R.L., 1987. "Caesarea Maritima". *National Geographic*, vol.171, n.2

ICCE, 1992. "Coasts, harbours, lagoons protection works".(under patronage of the Italian Ministry of Public Works, Rome) *23rd Coastal Engineering Conference*, Venice

IIMM (Navy Hydrographic Institute), 1984. "Winds and waves along the Italian coasts" Genova (in Italian)

Inman D., 1974. "Ancient and modern harbours: a repeating phylogeny". *Proc. 15th ICCE*, ASCE NY, pp.2049-2067

Italian Ministry of Public Works, 1953. "The reconstruction of National Maritime Ports" addendum to the *Proc. XVIII PIANC Congress* Rome (in French)

Lamberti A., Franco L., 1994. "Italian experience on upright breakwaters" *Proc. Int. workshop on Wave Barriers in deepwaters*, PHRI Yokosuka, Japan, pp.25-72

Lamberti A., Tomasicchio G.R. and Guiducci F.,1994 "Reshaping breakwaters in deep and shallow water conditions" *Proc. 24th ICCE*, Kobe, ASCE NY

Leonardo da Vinci, edited 1826 "On water motion and measurements", Raccolta d'Autori idraulici italiani, Opuscoli idraulici, Vol.X. Bologna Cardinali e Frulli

Levi S., 1934. “Wave pressures on vertical breakwaters” L’Ingegnere, August issue (in Italian)

Levi E., 1982. “Leonardo precursor of the hydraulic science” in Leonardo e l’età della ragione. Milan: Scientia (399) (in Italian)

Levi-Civita T., 1925. “Rigorous determination of permanent waves of finite amplitude”, Mathematische Annalen, XCIII, pp.264-314 (in French)

Lewis J.D., 1973. “Cosa: an early Roman harbour”. Marine Archaeology, Colston Papers 23, London

Liberatore G., 1992. “Detached breakwater and their use in Italy”, *Proc.of ICCE’92 Short Course on Design and Reliability of Coastal Structures,* Venice, pp.373-395

Lo Gatto D., 1925. “ Treatise on Maritime Works” Anonima Editoriale Romana, Roma (in Italian)

Lugli G. and Filibeck G., 1935. “The port of Imperial Rome”. Roma (in Italian)

Luiggi L., 1907. “Maritime constructions at the beginning of the XXth century” Tip.Genio Civile, Roma

Marchi E., 1992. “Coastal Engineering in Venice”, *Proceedings 23rd Coastal Engineering Conference,* ASCE, NY, pp.4-39

Marchi,E., 1977. ”Problems of vertical wall breakwater design”, *Proc.17th IAHR Congress,* Baden Baden, pp.337-349

Mariani,E., 1935. “A new type of breakwater armour unit” Annali dei Lavori Pubblici, n.4, pp.319-320 (in Italian)

Migliardi Tasco A., D’Arrigo A., 1965. “Italian Report at the XXI PIANC Congress” S.I , II-6 (in Italian)

Marina Militare, 1905. “A historical monograph on ancient Italian harbours”, (in Italian)

Matteotti G., 1993. “Stability of soil-breakwater complex”, *Proc. ICCE92-AIPCN 1st Italian Days of Coastal Engineering,* vol.A, pp. 202-217 (in Italian)

Moretti M., Pedone F., 1984. “Defence plan of the central Adriatic coast, Italy” *Proc.Int.Symp.on Maritime Structures in the Mediterranean Sea, Athens,*pp 4.133

Mosetti F.,1989. “Sea level variations and related hypoteses”, *Boll.Ocean.Teor.Appl.,* vol.VII, n.4, pp.273-284

Noli,A., 1990. “The activity of Paleocapa in maritime engineering and the project of Malamocco inlet”, *Proc. conf. "Ingegneria e politica nell’Italia dell’Ottocento: P. Paleocapa"* Ist.Veneto di Sci.Lett.Arti, Venezia (in Italian)

Noli A., 1993. “Constructional problems”, *Proc. ICCE92-AIPCN 1st Italian Days of Coastal Engineering,* vol.A, pp.218-237 (in Italian)

Noli A., Galante F. and Silva P.,1993 “The Venice littoral nourishment project” *Proc. ICCE92-AIPCN 1st Italian Days of Coastal Eng.,* vol.A, pp.74-89 (in Italian)

Noli A., Franco L., Tomassi S., Verni R. and Mirri F., 1995. “The new breakwater and ore-carrier quay of the industrial harbour of Porto Torres (Italy)”, *Civil Engineering,* London, February issue, vol.108, pp.17-27.

Oleson J.P., 1988. “The technology of Roman Harbours”, IJNA 17.2, pp.147-157

Passoni,G. 1995. “Coupling nonlinear wave models for the simulation of steep waves at vertical walls”, *Proc.Int.Conf.on Finite Elements in Fluids,* Venice

Prada E.J.M., De la Pena J.M., 1995. “Maritime engineering during the Roman Republic and the early empire”, *Proc. Conf. MEDCOAST‘95,*E.Ozhan Ed., pp.305

Pranzini E., Rossi L., 1995. "A new Bruun-Rule based model: an application to the Tuscany coast, Italy", *Proc. MEDCOAST'95 Conf.*, E.Ozhan Editor, Tarragona

Preti M., 1993 "Coastal defence in Emilia Romagna" in La difesa dei litorali in Italia, editors P.Aminti and E.Pranzini, pp.283-296

Raban A., 1988. "Coastal Processes and Ancient Harbour Engineering". Proc. 1st Int. Symp. "Cities on the Sea- Past and Present", BAR Intern.Series 404, pp.185-261.

Rebaudengo Landò L., Scarsi G., Taramasso A.C., 1989. "Random waves in directional seas", *EXCERPTA* vol.4, pp.77-116

Richter, J.P., 1970. "The notebooks of Leonardo da Vinci", Dover Publ., New York

Rouse H. and Ince S. 1963. "History of Hydraulics", Dover N.Y.

Sammarco P., Mei C., Trulsen K., 1994. "Nonlinear resonance of free surface waves in a current over a sinusoidal bottom: a numerical study", *J.Fluid Mech.*, vol.279, pp.377-405

Scamozzi V., 1615. "The idea of universal architecture", Venezia p.333 (in Italian)

Schmiedt G., 1975. "Ancient Italian Ports", L'Universo 45/2,46/2,47/1. I.G.M., Firenze (in Italian)

Schmiedt G., 1978. "Italian ports in the early middle ages", Rome

Schorn E., 1959. "Construction of large r.c.floating bodies". Deutscher Beton Verein E.v., Vortrage auf dem Betontag, Munchen pp.216-252 (in German)

Shaw J., 1974. "Greek and Roman harbour works", from Navi e Civiltà, Milan

Simoncini G., 1993. "On sea ports: The treatise of Teofilo Gallacini and the architectural concept of the harbour since the Renaissance to the Restoration", L.S.Olschki Editor

Testaguzza O., 1970. "Portus". Ed.Julia, Roma (in Italian)

Toniolo A.R., 1910. "On beach variations at Arno's mouth since the end of the 18th century", Pisa, Tipografia Municipale (in Italian)

Tosi R., 1980. "Progress in maritime works" L'Industria Italiana del Cemento n.11, pp.1059-1094 (in Italian)

Troen I. and Petersen E.L., 1989. "European Wind Atlas", ISBN 87-550-1482-8. Riso National Laboratory, Roskilde DK

Vallega, A., 1993. "From the Action Plan to the Mediterranean Agenda 21", *Proc.1st Conf. MEDCOAST'93*, Antalya, E.Ozhan Editor

Van Rijn P., 1995. "The Roman Harbour of Velsen", Terra et Aqua n.61, pp.25-28

Veranzio F.1595."Machinae Novae" (New Machines) Ed.Manunzio,Venezia (in Latin)

Vitale A., Mancinelli A., Cipriani M., 1985. "Structures in prefabricated elements for the defence of beaches: experimental result obtained employing the breakwater in Porto Recanati sandy shore and considerations about the plan of such structures" *Proc. XXVI PIANC Congress*, Bruxelles, pp.85-93

Vitruvius M.L., 27 BC., "De Architectura", vol II -6; vol V-13 (in Latin) (in English in Morgan M.H. 1914, Cambridge or in Loeb Classical Library 1983, London)

Zunica M., 1976. "Coastal changes in Italy during the past century", Italian Contributions to the 23rd Int.Geog.Congr.

Zunica M., 1985. "57.Italy" in *The World's Coastline,* Van Nostrand Reinhold Cmp, New York