A History of Quay Walls

Techniques, types, costs and future

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Proefschrift

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Samenvatting

Kademuren zijn een middel om betrouwbaar en snel goederen over te slaan. Zonder handel over water zouden deze constructies niet zijn ontstaan.

Voor havenbedrijven zijn kademuren belangrijke infrastructurele objecten die ook een flink kapitaal vertegenwoordigen.

Dit betekent, dat er in toenemende mate niet alleen naar technische maar ook naar de financiële aspecten van dergelijk constructies wordt gekeken.

In 2003 en 2005 zijn respectievelijk het Handboek kademuren en het Handbook Quay Walls verschenen. In deze boeken staan verschillende ontwerp- en uitvoeringszaken uitvoerig beschreven. Tijdens het schrijven van deze boekwerken is regelmatig de vraag gesteld: waarom bouwen we nu kademuren zoals we ze bouwen?

Deze vraag en de beperking van de kennis verzameld in de boekwerken zijn de aanleiding geweest om dit promotie onderzoek te starten.

De wetenschappelijke interesse hiervan is:

- Het bestuderen van het verleden geeft inzicht hoe mensen verschillende constructies ontwierpen en bouwden en hoe zij omgingen met fysieke condities en omstandigheden, de beschikbare ontwerpmethoden en de beschikbare constructie technieken.
- De invloed van verschillende constructie materialen op het ontwerp van de constructie. Beschouwing van het ontwikkelen en doorgeven van kennis over de eeuwen. Het laatste blijkt geen continu maar een onregelmatig proces te zijn.
- Kosten van kadeconstructies in verleden en heden.

Met betrekking tot de sociale aspecten zullen de volgende onderwerpen worden besproken:

- De arbeidsomstandigheden, die nu meer eisen aan veiligheid stellen dan in het verleden.
- Milieu- en omgevingsaspecten zoals duurzaamheid, die pas relatief heel kort belangrijk zijn.

De geschiedenis leert dat er al vanaf 6000 BC, transport over water bestaat. Dit transport over water ontstond op rivieren en in delta gebieden zoals die van de Nijl, Tigris en Eufraat, de Indus en de Gele rivier. In de Middellandse zee dreven de Phoeniciers en later de Romeinen intensief handel. De Phoeniciers voeren al naar Engeland om daar tin te halen.

De Arabieren, Indiërs en Chinezen hebben al sinds1000 AD, zowel over land als over zee handelsrelaties met elkaar.

Cheng Ho, de Chinese zeevaarder, bereikte Afrika al circa 100 jaar eerder dan de Portugezen, Spanjaarden en Nederlanders, dus rond1433. De Arabieren hadden het monopolie op de handel van producten van Azië naar Europa lang voor 1500, de periode van de westerse ontdekkingsreizen. In 1296 is dit Arabische monopolie doorbroken door de reis over land van Marco Polo naar China.

De Portugese ontdekkingsreizen vanaf 1490 werden ingegeven door het feit dat in 1300 Venetië een monopolie had verkregen omdat het over land dezelfde goederen kon aanvoeren en verkopen zoals daarvoor de Arabieren eeuwen hadden gedaan.
In Noord Europa had de Hanze gedurende 5 eeuwen, 900-1400, een monopolie op de handel van West-Europa naar het Oostzee gebied. In die tijd voeren de Nederlanders ook naar Zuid Europa om daar handel te drijven. Grote havensteden waren in die tijd o.a. Brugge, Antwerpen en later Amsterdam. Vanuit Amsterdam is de Verenigde Oost-Indische Compagnie (VOC) gecoördineerd vanaf 1602 tot 1800. De VOC was in bepaald opzicht de eerste multinational. De VOC heeft een lange tijd het monopolie op de handel in Aziatische goederen gehad maar verloor dat aan Engeland. Deze handel is daarna voor een deel overgenomen door de Engelsen. Vanaf het ontstaan van de industriële revolutie,1750, is de wereld in snel tempo veranderd en zijn de landen in de wereld veel afhankelijker van elkaar geworden.

De schepen zijn in de periode vanaf 6000 BC tot heden geëvolueerd van een simpele uitgeholde boomstam tot de grote erts- en containerschepen. De gemiddelde vaarsnelheden zijn toegenomen van 3 tot 50 km per uur.
De eerste kademuren in zijn gebouwd in Lothal India in 2400 BC . De Romeinen bouwden ook kademuren meestal in combinatie met een havendam om bescherming te bieden. De kerende hoogte bedroeg ongeveer 3 à 4 meter. Deze bestonden voornamelijk uit houten damwandconstructies - en gewichtsconstructies zoals caissons. Bij de bouw van caissons werd door de Romeinen gebruik gemaakt van puzzolanic cement. Na het einde van de Romeinse tijd in 400 is de techniek en wetenschap pas weer tot ontwikkeling gekomen in 1500 - 1700. Het ontwerp van kademuren is pas echt begonnen in 1500 - 1600. De principes van de mechanica en grondmechanica zijn toen beschreven en er is aandacht besteed aan het ontwerpen van keerwanden. De ontwikkeling van kennis heeft als resultaat gehad dat het beton, gewapend beton en de ontwikkeling van staal heeft kunnen plaatsvinden. Dit heeft voor het ontwerpen en bouwen van kademuren het gevolg gehad dat vanaf 1900 alle constructiematerialen gebruikt worden om kademuren te bouwen.
De kademuur constructies kunnen worden onderscheiden in kerende constructies, eigen gewicht constructies en combinaties van deze twee ontwerpen. De snelheid van bouwen van kademuren is in de periode van1850 tot 2008 met een factor 40 à 60 toegenomen. Het materiaalgebruik is gereduceerd met 20 - 40% en de kerende hoogte is toegenomen van 5 naar ruim 30 meter. De constructietechnieken met name het heien, de verwerking van beton en de logistiek van het bouwproces zijn verregaand verbeterd. Om de kosten van kademuren in heden en het verleden met elkaar te kunnen vergelijken zijn twee methoden ontwikkeld. De eerst methode, Methode van Individueel Indexen (MII), gebruikt indexen voor alle componenten waaruit de kade is opgebouwd. De andere methode, Methode van Totaal Indexen (MTI), gebruikt een overall index. In dit geval is dat de Consumenten Prijs Index, CPI, omdat daarvan sinds 1450 gegevens beschikbaar zijn.
Beide methoden zijn vergeleken en daaruit bleek een verschil van gemiddeld 4%. Vervolgens zijn alle beschikbare bouwkosten volgens de MTI methode bewerkt en uitgedrukt in de prijzen van 2008.
Op basis van deze studie is gebleken dat de bouwkosten van kademuren gerelateerd aan de kerende hoogte nagenoeg gelijk zijn gebleven als voor inflatie wordt gecorrigeerd en uitgedrukt in de prijzen van 2008.
De kosten van een strekkende meter kademuur variëren tussen € 10,000,- en € 40.000,- voor respectievelijk 10 meter en 30 meter kerende hoogte.
Tevens is in deze studie aangetoond dat de kosten van kademuren gebouwd over de hele wereld slechts een variatie vertonen van plus en min 20%.

Het bouwen van kademuren is geen massaproductie zoals bijvoorbeeld de productie van consumenten producten. Dit betekent dat er slechts beperkte schaalvoordelen zijn te bereiken.
Voor geringe kerende hoogten 5 à 10 meter zijn er nauwelijks schaal- en dus kostenvoordelen te bereiken. Bij kerende hoogten van meer dan 20 meter en kadelengten van meer dan 1000 meter zijn kostenvoordelen te bereiken van 20 à 30% door optimalisatie van de logistiek van het bouwproces.

Flexibele kadeconstructies zoals verplaatsbaar of aanpasbaar lijken op basis van kosten overwegingen in onze omgeving niet aantrekkelijk.
De bouw van kademuren is in die zin niet uniek omdat de technieken min of meer gelijk zijn aan die bij andere civieltechnische constructies zoals sluizen en tunnels.
Voor de toekomst worden geen grote veranderingen voorzien dan mogelijk alleen de toepassing van andere constructiematerialen.
De kosten van kademuren zijn niet van doorslaggevend belang voor de keuze van een bedrijf om voor een bepaalde haven te kiezen. Daarbij wegen andere factoren zoals de aanwezigheid van financiële instellingen, goede woningen en scholingsaanbod en het aanwezig zijn van goede verbindingen en culturele faciliteiten zwaarder.

SUMMARY

Quay walls provide a means for the reliable and rapid transshipment of goods. They would not exist if trading over water had not developed. For port authorities quay walls are important infrastructure objects. This means that to an increasing extent not only the technical aspects of such structures should be considered, but also the financial aspects.

In 2003, the Dutch, and in 2005 subsequently English editions, of the Quay Wall Handbook were published. These books describe various design and construction techniques. While they were being written a question that frequently arose was: Why are quay walls constructed in such a variety of ways? This question and the restrictions of formation collected during the compilation of the books provided the motivation for me to embark on this PhD thesis.

The scientific content includes:
- A study of the past which provides insight into how the various structures are designed and constructed and also how they relate to the physical conditions and circumstances, the available design methods and construction techniques.
- The importance of the various construction materials to the design of the structure.
- Consideration of the development of knowledge and how this has been passed on to others over the ages. These are irregular rather than continuous processes.
- Past and present day costs of quay construction.

In relation to the social aspects the following subjects are discussed:
- Past and present working conditions in relation to safety to which, in comparison with the past, much stricter conditions now apply.
- Environmental aspects, like sustainability, which in the past were much less important than they at present.

History teaches us that transport over water has been taking place for a very long time, certainly since 6000 BC. This practice started in delta areas such as those of the Nile, Tigris, Euphrates, Indus and Yellow River. In the Mediterranean Sea the Phoenicians and the later the Romans established an intensive trading network. The Phoenicians also extended their activities to England in order to obtain tin. Following this there was a long period of trading carried out by the Arabs, Indians and Chinese.

Before the Western voyages of discovery, the Arab traders had the monopoly in transporting the products of Asia to Europe. The Chinese navigator, Cheng Ho had already reached Africa ca 100 years, around 1433 years, earlier than the Portuguese, Spanish and Dutch. This monopoly was broken after the overland journey of Marco Polo to China in 1296.

The European voyages of explorations were prompted by the fact that Venice enjoyed a monopoly because it could import and sell the same goods as the Arabs had been doing over the centuries. The same situation also arose later in northern Europe, where for 500 years (900-1400), the Hanseatic ports maintained a monopoly over trade between Western Europe and the Baltic area.
At that time the Dutch were also trading with southern Europe. Bruges, Antwerp and Amsterdam were the large ports of that time.
Between 1602 and 1800 the The Verenigde Oostindische Compagnie (VOC) was coordinated from Amsterdam. VOC was considered to be the first multinational and for long time had a monopoly on trade in goods from Asia, but in the end that too was broken, being partially taken over by the English.
From the start of the industrial revolution, 1750, there was a rapid rate of change throughout the world and the countries become much more closely dependent on each other.

In the period between 6000 BC and the present, ships evolved from a simple hollowed out tree trunk to the great ore and container carrying vessels of today. The average sailing speeds increased from 3 tot 50 km per hour. In Lothal, India quay walls were constructed from bricks in 2400 BC. During the Roman period, the quay walls were usually constructed in combination with a harbour mole to provide protection. The retaining height was 3 to 4 metres. These quays mainly consisted of wooden piled structures and caissons. Puzzolanic earth was used in the fabrication of the caissons.

After the end of the Roman period, around 400, technique and science only came into their own again between 1600 and 1700. However, the design of quay walls really started in the period 1500-1600. The principles of mechanics and soil mechanics were described and attention was paid to the design of the quay walls. The result of the advances in knowledge was that the use of concrete, reinforced concrete, and steel could also take place. From 1900 onwards this resulted in the use of all types of construction material for the building of quay walls.

For the construction of quay walls a distinction can be made between retaining structures, gravity walls and combinations of these designs.

Over the period from 1850 to 2008 the construction rate of quay walls increased by a factor of 40 to 60. At the same time the quantity of material used has been reduced by 20 - 40% and the retaining height has increased from 5 metres to over 30 metres. The construction techniques, especially those used for pile driving, and the use of formwork advanced considerably as well as the logistics of the construction process improved.

Two methods which can be used to compare present day costs with those of the past have been developed. The first of these, the Method of Individual Indexing (MII method), uses indexes for all the components of a quay. The second, the Method of Total Indexing (MTI method), uses an overall index. In that case the Consumer Price Index , CPI, is used because data extending back to the year 1450 can be obtained.
These methods are also compared and from this comparison it emerges that the average difference between them is 4%. All available figures for construction costs were processed according to the MTI method in order to determine the costs for the base year 2008.

Based on this study it appears that provided that they are corrected for inflation and expressed in the costs for 2008, in relation to the height of retaining walls the construction costs of quay walls have remained constant. The cost per running metre of quay wall varies between 10 000 and
40 000 Euros for retaining heights of 10 and 30 metres respectively. This study also shows that the cost of the quay walls constructed throughout the entire world shows a variation of only 20% either way.

The principles of mass production, such as are used in the manufacture of consumer goods, can not be applied to the construction of quay walls. This implies that only limited advantages can be obtained in relation to scale. For very low retaining heights of 5 to 10 metres, scarcely any advantages of scale can be gained and thus little reduction in costs. For retaining heights greater than 20 metres and quay wall lengths greater than 1000 metres, savings in costs of 20% to 30% can be achieved by optimalisation of the building logistics.
In Dutch circumstance the use of flexible quay wall structures, like adaptable or replaceable components does not seem to be a viable option if costs are taken into consideration.
In this sense the construction of quay walls is not unique, because the techniques used are more or less similar. The environmental conditions may be different, but this results only in the design being adapted at more or less the same cost.
The costs of quay walls are not a significant consideration for a company when selecting the location for a port. For this other factors such as the presence of financial institutions, good housing and schools and good transport links and cultural facilities are more important.

Contents

1 Introduction

1.1 Why this study?

In 2003, in collaboration with the Port of Rotterdam and the Publics Works Department of Rotterdam, CUR Building & Infrastructure, a network and meeting place for public and private organisations, which focusses upon innovation in civil engineering (the field of attention being civil engineering, infrastructure, building techniques and geotechnics), took the initiative to publish the “Handboek Kademuren”. An updated version in English, “Handbook Quay Walls”, was published in 2005. While these books were being written a question that frequently arose was: Why do we build quay walls in the way that we build them today? This thesis is the result of an attempt to answer that question. It is not purely technical but also traces the historical background to which the present situation owes so much.

1.2 Background

Even in prehistoric times mankind had a longing to travel and explore the environment, initially in search of food and later driven by various motivations such as the search for raw materials, goods, trade, the desire to explore the unknown or to conquer.

From the simple fishing boats made from hollowed out tree trunks, which even today are still used in some remote areas, ships progressed to serve a variety of functions in the various marine environments encountered throughout the world. The result is that from sheltered natural harbours in which boats were drawn up onto the beach we have seen the development of the enormous ‘mainports’ of today, such as Shanghai, Kobe, Pusan, Antwerp, Hamburg and Rotterdam.

If there is no sea trade then ports and quay walls are not required. Present-day large ports are immense nautical- and industrial complexes, which by their nature are interesting locations. The construction and operation of such huge complexes involves many disciplines from soil mechanics, civil and mechanical engineering and chemistry, to economics, logistics, marketing and sociology.
Within the industry there have always been discussions about the cost of quay walls. It is generally thought that there is a considerable difference between the costs that can be related to the construction types and materials used.
However the problem of the variation in costs may be exaggerated: the differences maybe relatively minor if one bears in mind that construction companies have to make a profit at all locations where they work. Although the structures of the costs may be very different, the total costs may not greatly differ. Thus this aspect will also be addressed.

1.3 Research objectives

The scientific interest of this study can be categorized as follows:

Studies of the past show:

1. How people constructed various types of quay wall structures and how they coped with the physical conditions, in the light of the available design theories, construction materials and techniques.
2. The influence of different construction materials on the design of these structures.
3. The development and transfer, dissimination of knowledge, which is a continuous but nevertheless very irregular process.

4. Construction costs of historic quay wall structures compared with the cost of modern quay walls.

In relation to the social aspects the following are considered:
- In today's working conditions safety aspects are significantly different from those in earlier times.
- In earlier times the environmental aspects that became so important today were taken into consideration less.

1.4 Structure of the thesis

This study describes the development of world trade (Chapter 2) and the development of shipping (Chapter 3) and cargo handling at different locations around the world (Chapter 4).

Various materials are used in the construction of quay walls so Chapter 5 highlights the availability of construction materials throughout history. Although some materials have been used for a very long time, it is only relatively recently that we have become able to measure the physical properties of these materials in detail and to increase our understanding of the physical- and chemical processes to which they are subjected in the marine environment. Chapter 6 highlights typical examples of quay walls throughout history, indicating the differences between the structures and construction methods.

This consideration leads to the development of the construction techniques and design tools that are considered in Chapters 7 and 8, while Chapter 9 discusses the factors that determine the selection of a particular type of quay wall in specific cases. This includes a review of the boundary conditions that govern the selection of a type of quay wall in relation to the project requirements. Chapter 10 presents a classification of types of quay walls.

The costs of quay walls around the world are compared in Chapter 11, taking into account the influence of local conditions. However these costs are largely based on net market prices and this is illustrated in a discussion of the net market prices for a variety of ports in 2008.

Some considerations relating to possible future developments in quay wall design are highlighted in Chapter 12, while Chapter 13 presents the conclusions and recommendations.

2. Development of Sea trade and Ports

2.1 Introduction

Compared with other means of transport such as road, rail and air, transporting goods over water is by far the easiest method with regard to carrying capacity and energy used. Therefore it is not really surprising that the first waterborne trade developed in the great river-based civilizations like those of the Nile, the Indus, the Tigris and Euphrates and the Yellow River.

This chapter illustrates the development of sea trade in different regions of the world over time. However some reference will be made to overland trade since sometimes these various types of trade have considerably influenced each other. The development of trade usually started with overland journeys of discovery such as those of Alexander the Great and Marco Polo and it must be realised that trade across water was initially only relatively local, developing largely from local fishing activities. Many of the great harbours in the world were originally fishing ports.

The following sections describe the development of sea trade from around 6000 BC up to the present.

2.2 Sea trade around the Mediterranean and Africa

The oldest maritime nations whose records are preserved are Egypt, Crete and later Phoenicia [Kirkpatrick, 1926, Savile1940]. There is evidence of interaction between Egypt and Crete in the pre-dynastic period of Egypt, around some 6,000 years ago. Already at that time special ships had been designed to transport cargoes like cattle, and grain. Other commodities, including tin, were shipped from Britain and Spain. About 600 BC the Egyptians sailed in the western direction round Africa, an epic voyage that lasted three years.

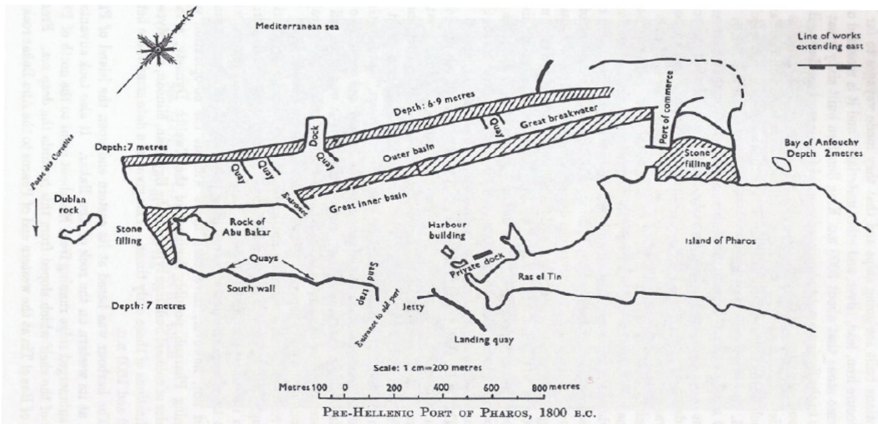


Figure 2.1: The harbour of Alexandria in 1800 BC [Savile 1940]

In Egypt te early harbours were located at the mouth of the Nile. Crete however, had to make its harbours on the open sea coast as it is almost without rivers. There are some remains of very ancient harbour works in Crete, but as a result of tectonic movements most of these ruins are now under water and some have been covered by later works. In Alexandria the most complete record of an ancient harbour built in the Cretan manner is found. The original work is estimated to date from around 1800 BC, which is 1700 years earlier than Alexander the Great's harbour.

Alexander de Great's port is in Egypt and the work is massive in character as is typical of Egyptian works. The construction methods used and the placing of the harbour on the open sea follows the Minoan tradition of Crete. As Cretan workmen were commonly employed on engineering and architectural work in Egypt it is probable [Savile1940] that the work was done by Cretan engineers and artisans in cooperation with the Egyptian Government. The port built by Alexander was situated between the island of Pharos and the mainland; the older harbour was on the seaward side of the island. The Great Basin, which had an area of 60 hectares, made use of a natural depression in the seabed and had its entrance through a deep natural channel on the south side. To the east of the entrance was a 15 metres wide landing-quay constructed from rough-hewn blocks up to 5 metres long. The 760 metres long south wall of the harbour featured an angular salient that was typical of a Cretan structure. The great breakwater on the north side was 2145 metres long The western section, with two walls 8 to 13 metres wide at the top and with rubble filling the space between them, formed a breakwater about 70 metres wide. Seaward of the great breakwater was another breakwater that enclosed a basin half as large as the great basin. The construction material was limestone that was quarried on the mainland at Mex.

Investigations [Duplat Taylor 1949] show that there was trade between Crete and Britain in the Early Bronze Age (1600 - 1200 BC), several centuries before the Phoenicians came to Spain and England. The main evidence for this is the discovery of Cretan or Egyptian beads in the Bronze Age mines of the south of England, as well as in Spain, Sicily and other places. The highly developed ancient civilization of the Minoan Cretans depended on the insular position of their country, which for 1000 years kept them out of the wars. The Minoans were able to develop their arts, industries, and commerce in times of peace, but over the course of time other nations of the Eastern Mediterranean developed their sea power and put an end to the supremacy of Crete. As the Cretan civilization decayed many of the inhabitants spread out to different locations on the coasts of Asia Minor, the present Turkey and the east coasts of the Mediterranean Sea.

A later centre of maritime commerce was Phoenicia, on the coast of what is now Syria. Sidon was the first port of Phoenicia. After the capture of that city by the Philistines in 1245 BC, some fugitives founded Tyre. This, the first city on the Phoenician mainland with a harbour and fortifications, was destroyed by Nebuchadnezzar after a siege that lasted 13 years. The new city of Tyre was built by the inhabitants who withdrew to a small rocky island off the coast. It surpassed the old city in both wealth and importance. Trading expeditions were sent out, including some to Britain, and several colonies were founded, like Utica, Carthage and Cadiz. In 332 BC Alexander the Great succeeded in destroying the city during a siege of seven months. Later he built a causeway connecting the island to the mainland. The remains of his causeway are now covered by the tarmac of a modern road.

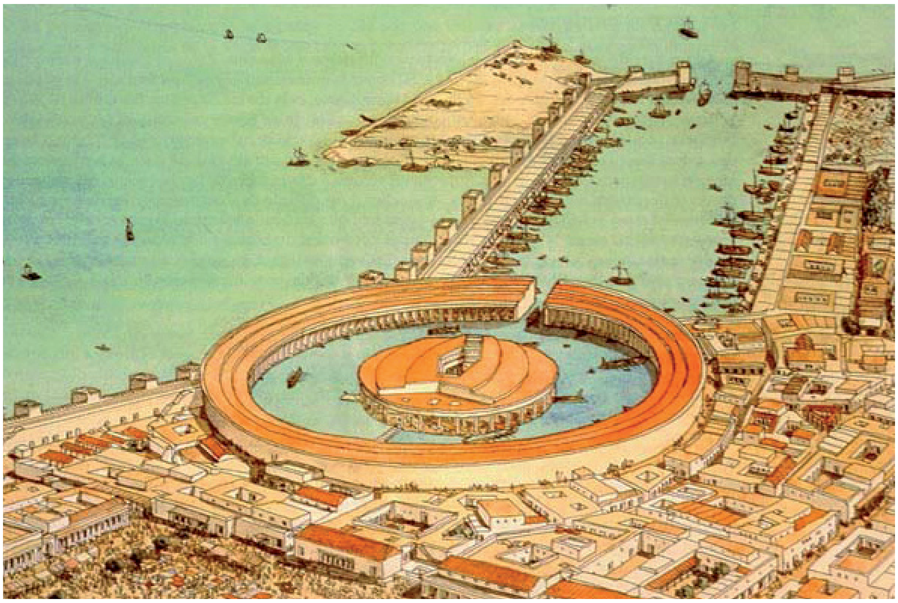


Figure 2.2: The harbour of Carthage 200 BC [Navis]

The harbour of Carthage consisted of a circular inner harbour basin and a rectangular outer basin. The inner harbour basin was used as naval base. In this base the ships were hauled out of the water and put into a shed to dry. In this way their speed and manoeuvrability was improved. The outer basin was a commercial harbour.
Timber for shipbuilding was obtained from the forests of Lebanon.

Figure 2.3: The harbour of Caesarea 20 BC [Navis]

Another important Phoenician harbour was Cadiz. There were also two harbours in Cadiz, a naval one in the north and a commercial one in the south, both protected by moles terminating in lighthouses. The moles were probably constructed on dumped stone foundations with masonry superstructures, the ends being in 8 to 10 metres of water. On the shores were places for building and careening ships, as well as store houses and other necessary buildings.

The port of Caesarea was founded by the Phoenicians in 400 BC and further developed by the Romans after 20 BC.
The port of Caesarea, located in present day Israel, was surrounded by moles to protect the harbour basin. The inner parts of the moles were also used as quay walls. In this sense we already have multi-functional use of one structure.

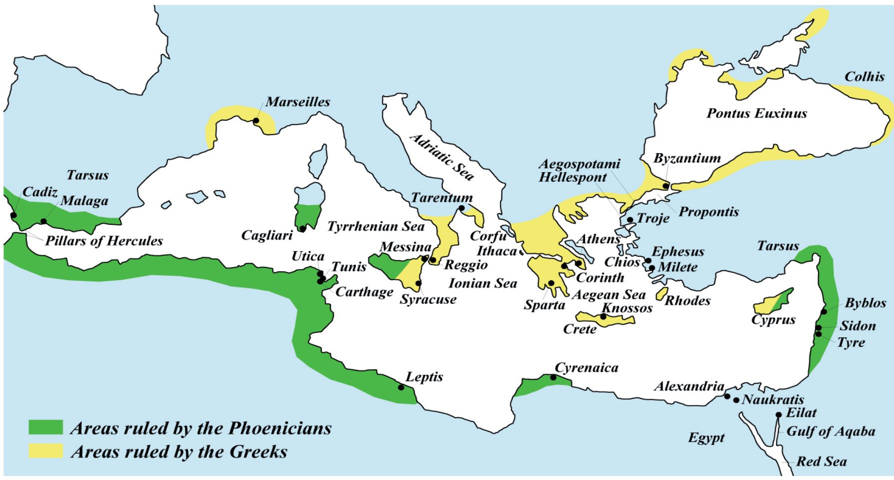


Figure 2.4: Map of the areas ruled by the Phoenicians and Greeks around 500 BC [De Gijt et al 2003]

After the destruction of Tyre in 332 BC, Alexander the Great founded Alexandria. It is not known whether there were any remains of the older Cretan harbour at that time, or whether these works had already been submerged by a land subsidence that had taken place in this region. The construction work was entrusted to Dinocrates, who placed the town on the narrow strip of land between Lake Mariut and the sea. A causeway, called the Heptastadion, was built between the Island of Pharos and the mainland, forming two harbours connected by two bridged channels. Later Sostrates built the 150 metre high great lighthouse of Pharos on a rock to the east of the island. A causeway connected the rock and the island.

Alexandria also had access to the Nile and, via a canal from the Nile to the Red Sea, to the interior of Africa and the Orient. The causeway between the mainland and the island has grown by accumulation to an 800 metres wide isthmus. Currently the main harbour is the western one, a reversal of the old order, and it is now enclosed by a long breakwater. Channels have been dredged through the offshore shoals and recently many improvements have been made, while further development is envisaged.

In 26 BC the Romans annexed Egypt to their Empire, partly destroyed Alexandria and also created a new city. The city of Rome was the capital of the immense Roman Empire and all the power to rule the Empire was centralized in Rome.
Rome was connected to the port of Ostia on the Tiber. The river harbour of Ostia had several limitations. Large ships could not enter it, because there was a sand bar in front of the mouth. Therefore goods that arrived in large ships had to be transferred at sea to smaller ships that could enter the port. Shallow-draught vessels could moor at the Tiber quays, but capacity was very limited in relation with Rome's growing needs.

In about 100 BC Trajan added an artificial octagonal basin of 32 hectares to the port, using parts of the two canals as entrances and filling up the remaining canals. A new canal, connecting the harbour, the Tiber, and the sea was made further inland. The trouble of silting eventually re-asserted itself, and the harbour became inaccessible and had to be abandoned. A new harbour for Rome was established at Civita Vecchia, 45 kilometres farther north, and this still remained the port of Rome during the reign of Trajan. The harbour of Ostia is situated now 2.5 kilometres from the sea.

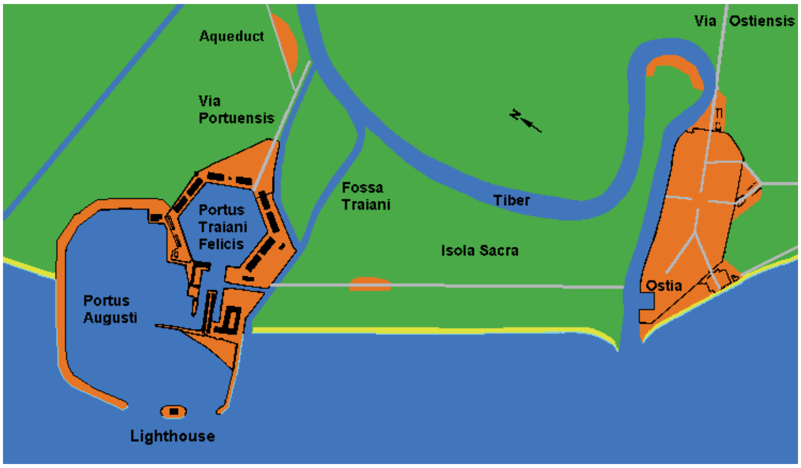


Figure 2.5: Port of Ostia around 100 BC [Felici 1993]

In 42 Claudius started the construction of an artificial harbour a few kilometres to the north of Ostia. There may have been a small, natural bay here. A huge basin was created, this being partly dug out, protected by two curved moles, and with a lighthouse. Recent research [Felici 1993, 1998] indicates that there was a long continuous northern mole. The southern mole was considerably shorter. Ships filled with concrete were used as the foundation. The width of the basin was 800 metres, the length several kilometres and the depth seven metres. The amount of soil that had to be removed was tremendous. It has been calculated that for a period of 20 years 30000 people and 1000 oxen must have been active during the construction period.

It must be borne in mind that although they were handicapped by having none of our modern construction equipment and no mechanical power, these ancient empires had regular supplies of slave labour [Florman 1987]. The lack of any means of maintenance dredging was also a great handicap, as we see so clearly in the case of the forced abandonment of Ostia. Due to the lack of this dredging equipment the siltation of the port of Ostia could not be prevented.

There is evidence [Norman1978] that during their occupation the Romans constructed quay walls in various countries including Britain (fig. 2.6), Germany and Holland.

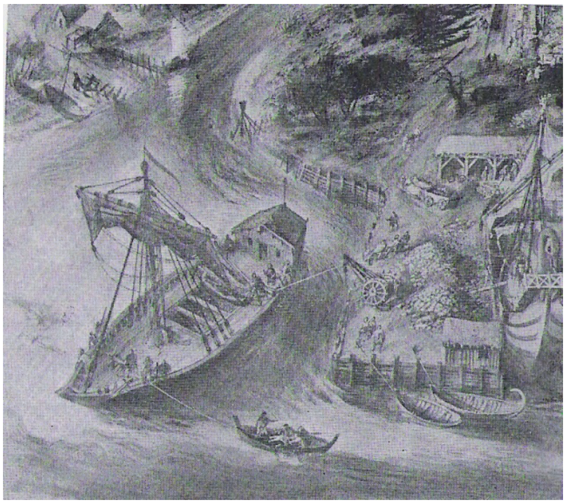


Figure 2.6: Roman quay, London 200 [Norman 1978]

In London ships would unload in the Fleet River and the Walbrook, now both covered over. Others would moor in the river Thames and use small boats to unload or load.

2.3 Sea trade Northern Europe from 500 to 1000

Northern Europe has more natural harbours than the Mediterranean. There are many fjords on some of the western coasts. The greater tidal ranges along most of the other coasts created large estuaries which made it possible to establish fishing harbours in relatively sheltered areas. For many centuries these natural facilities sufficed for the shipping of the time with a few of the simplest improvements.

At the end of the Roman occupation in 407 an established overseas trade had developed in Northern Europe, exporting corn and raw materials and importing manufactured goods. Sea-going ships were small enough to reach as far inland as Oxford, Cambridge, Lincoln, York, Dorestad and Cologne.

After the fall of the Roman Empire the centre of maritime activity moved out of the Mediterranean into Northern Europe. Here shipbuilding and harbour construction reacted to the different geographical and climatic conditions.

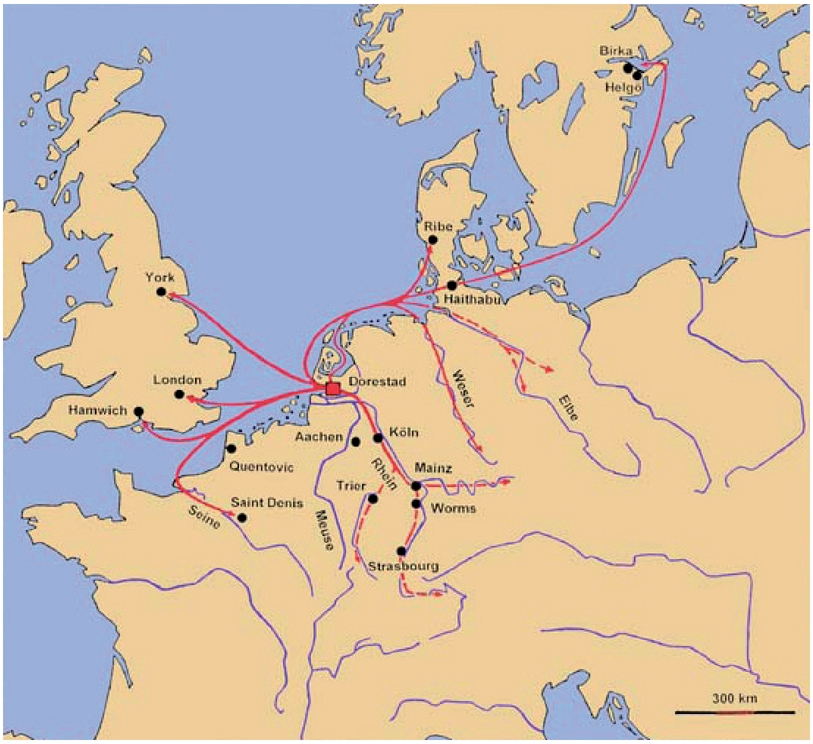


Figure 2.7: Sea trade Northern Europe around 800 [van Es 1994]

In the Netherlands Dorestad [van Es1994] played an important role owing to its situation. This settlement was included in the network of Northwest-European shipping routes: the Lower Rhine formed a direct link with the German Rhine area and the Kromme Rijn a link with sea routes to England, the North of France, the northern Netherlands, north Germany and Scandinavia. The Lek possibly gave access to the lower reaches of the Meuse and the Scheldt.

The Danes started their attacks on England in 787 and up to 1016, when Canute gained the English throne, there was a succession of naval battles round the south and east coasts. Many times the Danes landed and ransacked inland towns. To defend England the number of English ships was greatly increased. During the peaceful intervals these ships were used for foreign trade that grew in spite of these difficulties.

In the 11th Century King Ethelred made regulations for the collection of tolls at Billingsgate and mention is made of English trade with France, Flanders, and Germany. The main export was wool, but lead, tin, and cattle were also exported. Imports included timber, cloth, wine, and provisions. Wheat and rye were both imported and exported, according to the harvests.

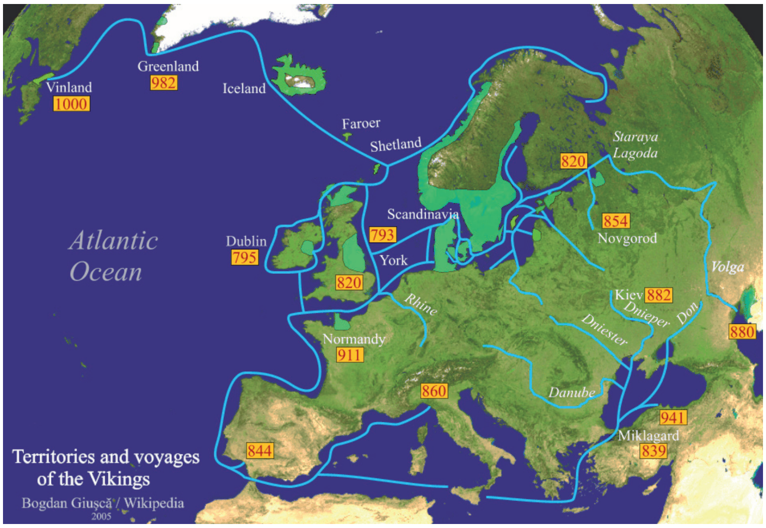


Figure 2.8: Map showing the territories and voyages of the Vikings [Giusca 2005]

2.4 Hanseatic League 1000 - 1500

In the 10th century the German and Dutch merchants who later formed the Hanseatic League first appeared in England. The Hanseatic League was a powerful trading combine with depots in London, Hamburg, Bremen, Lübeck, Bergen, Bruges, Visby, Amsterdam, Novgorod and other centres. It received its charter from Henry III of England in 1260 and almost monopolized the north European trade. In the 16th century the League declined and lost all its privileges.

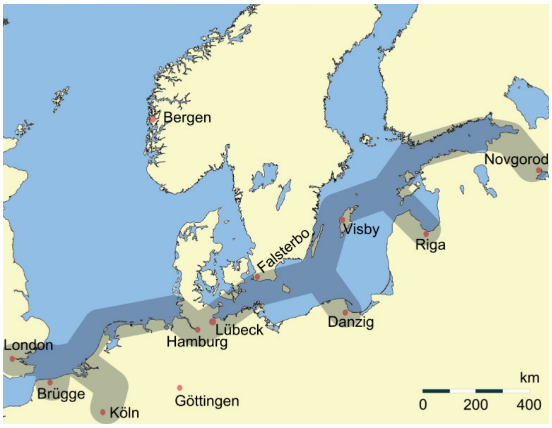


Figure 2.9: Map showing the cities that formed the Hanseatic League [Gee 1929]

After the Norman Conquest in 1066 there was an increase in trade with France which had been impossible during the Norman domination. To safeguard communications across the Channel an attempt to create an organized naval service was made by a charter given to the ‘Cinque Ports’, originally the five ports of Dover, Hastings, Hythe, Romney and Sandwich, to which Rye and Winchelsea were later added. These ports enjoyed certain privileges in return for which they had to provide warships when called upon to do so.

In the 13th century, goods from the Far East came overland to the Baltic and were imported to Europe by the Hanseatic League. The Arab monopoly of the silk trade was ended by the journey of discovery of Marco Polo to China in 1296. Up to that time the Arabs had held a monopoly in transporting goods over the sea from China and other South East Asian countries to Europe. A few voyages were made to Genoa and Venice, which were the chief Mediterranean ports of that time.

On the north coast of the European mainland, in addition to the Hansa ports, ports such as Amsterdam, Dunkirk, Calais and Honfleur developed, shortly afterwards followed by Antwerp and Rotterdam. Between the 13th and 15th centuries trade in the Baltic region was mostly carried out by Dutch merchant ships. During this period the Dutch merchant fleet consisted of 20 000 ships, which at that time was about 50% of the total world merchant fleet [Den Heijer, 2002].The English merchant fleet in that time consist of only 4500 ships. The Dutch transported grain and wood from the Baltic area to western and southern Europe. From southern Europe they carried home wine and salt. During this period the trade of the Dutch merchant fleet with the Baltic region was much more profitable than the East Indian trade.

2.5 West-European voyages of discovery 1400-1800

The end of the 15th century saw the first of the great voyages of discovery by Europeans. Columbus reached America in 1492. In 1497 Cabot sailed from Bristol to Canada, also the starting port for the voyages of Eliot and Thorne to North America. The Portuguese and Spaniards, rivals of the port of Venice which had over 3000 vessels at that time, were looking for other routes to obtain goods from Asia and found the route around Africa.

Their discoveries did not initially lead to great enthusiasm in England and the Netherlands and it was not until around 1600 that England and The Netherlands took a greater part in world exploration.

Early in the 17th century England was occupied by political troubles and civil war. Cromwell tried to revive trade by pursuing a strong naval policy, but the Plague and the Fire of London seriously disorganized business. The Dutch advanced rapidly in both merchant- and naval shipping. Amsterdam could scarcely meet the growth of the trade with the development of the port. During this period Rotterdam started to develop its harbour.

The 16th century was a century of great development in shipping. Figure 2.10 shows some of the first European voyages. Spain and Portugal ruled the Atlantic, keeping the traffic with the Americas to themselves. The Treaty of Tordesillas in 1494 confirmed the decision of the Pope that in order to prevent war and to foster the spread of Catholic belief the ‘New world’ should be divided between Spain (western half) and Portugal (eastern half).

Figure 2.10: Treaty of Torsedillas and early Spanish and Portuguese voyages of discovery [Rodrigue 2004]

The Dutch established the Verenigde Oostindische Compagnie (VOC) in 1602 and retained the monopoly of the trade to Asia for 200 years. This was achieved through competition with the Portuguese and to lesser extent with the Spaniards. The VOC is considered to be the precursor of the present day 'multinationals'. The main commodities that were traded were herbs and spices, cotton, silk, copper, porcelain, coffee and tea. These goods were financed by selling silver and gold that came mainly from South America

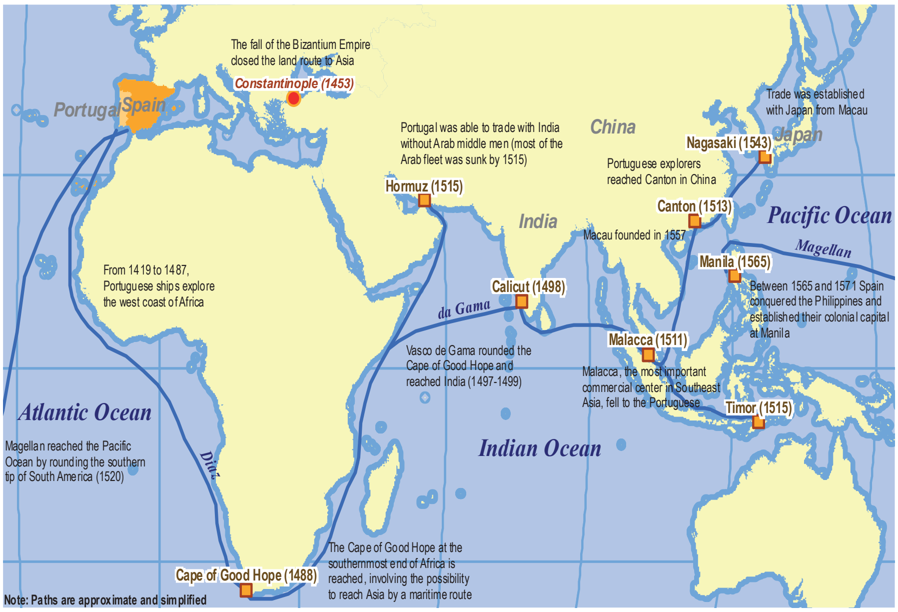


Figure 2.11: Journeys of discovery [Rodrigue 2004]

It took about a hundred more years before sailing voyages reached Japan (Fig. 2.11). The VOC was the first organization that was permitted to trade with Japan via the Island of Decima that was built especially for foreigners.

In England Henry VIII concentrated on the Navy. The Royal Dockyard at Portsmouth was enlarged and new dockyards were established at Woolwich, Deptford, Erith and Chatham. In 1517 John Hopton made a basin with an entrance to the river at Deptford. There are references to the construction of dry docks, but these were usually temporary structures. Docks for civilian use at Ratcliff and Lime house are mentioned [Savile 1940]. The policy of Elizabeth I was to develop trade and make London the commercial centre of Europe. The Royal Navy was kept short of money and was expected to make profits by plundering. In spite of this the Navy grew and by destroying the Armada in1588 ended Spanish domination of the seas. Warships ran up to about 1000 tons and merchantmen to 600 tons. Bounties were paid to private ship owners, so that their ships could be put into royal service when required.

A customs Act was passed in 1558 to ensure the collection of dues. This act ordered that goods should be landed only on certain specified quays in London, Southampton, Bristol, Newcastle and some other ports. In London there were twenty-two such 'Legal Quays', all on the north side of the river.

The owners of the legal quays were oligopolists, and grave scandals resulted, eventually leading to the establishment of 'Sufferance Wharves' and later to the dock system of London.

Long voyages of discovery were made and new trade routes were opened up by Frobisher, Gilbert, Hawkins, Raleigh, Drake and many others. The Dutch, particularly Barendts, van Heemskerck, van Noort en Tasman [Mollema1939], were also active in seeking new sea routes. This period saw the formation of several trading companies, beginning with the Merchant Venturers of Bristol in 1552. These were followed by the Russia Company, the Turkey or Levant Company, the Eastland Company (trading to Scandinavia), the Africa Company, the Virginia Company, and, in 1660, the East India Company. The East India Company broke the Dutch trade monopoly in India and the East Indies and laid the foundations of the British Indian Empire.

2.6 Arab sea trade

The Arab trade with the Far East and India goes back to 300 BC, when there were already contacts with the Chinese. The trade routes followed the coastlines of the Arab countries and the Indian continent. The main commodities that were shipped were silk, beads, herbs and spices.

Although the monopoly of the silk trade of the Arabian seafarers was broken by Marco Polo (Section 2.4) the Arabian seafarers still continued to trade with the peoples along the east of Africa and to India and Asia.

Figure 2.12: The Arab trading routes [Rodrigue 2004]

2.7 Chinese Sea trade

The Chinese maritime trade tradition goes back to 5000 BC. Initially the trade was limited to the inshore and inland waterways. However, since the eastern Zhou (770-256 BC) the Qi kingdom had possessed many ships that sailed the Yellow Sea. During the Han Dynasty (305-BC-23) sea-borne trade became an official state activity. Canton then became a major port from which Chinese vessels regularly sailed to trade with Vietnam, Malaysia, Sumatra, India and the Middle East. Some of these journeys lasted four years or even longer, depending on the weather conditions (Fig. 2.11).

The Tang Dynasty (618-907) was a time of great prosperity for both maritime trade and shipbuilding. During this period two main sea routes existed. One led eastwards from Dzenghou on the Shandong Peninsula across the Yellow Sea to Korea and from there to Japan, while the other route went westwards from Canton across the South China Sea to the Malay Archipelago and Sumatra, a major point of call for Chinese traders. When continuing their voyages the ships went across the Gulf of Bengal to India and then to the Arabian Gulf to trade with the Arabs. The commodities traded included silk, iron and beads.

Around 1000 the Han Dynasty had trouble with the Mongols and this led to stricter regulations for foreigners trading with China. During this time the foreign sailors were mainly Arabs and Indians. Until then the Arabs and Indians had enjoyed a monopoly of trade with China, which had lasted from the time of the Egyptian monarchy, through to the journey of discovery by Marco Polo in 1296, when he established the silk route over land.

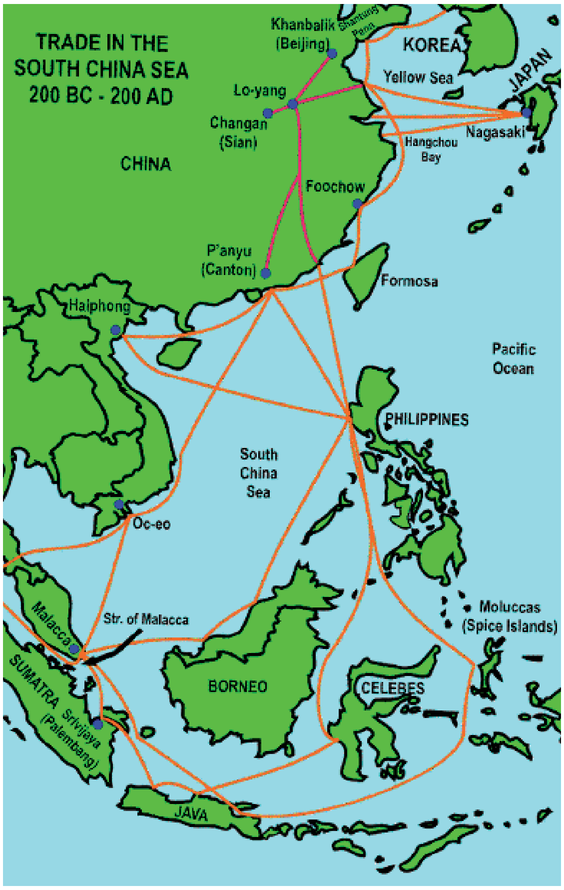


Figure 2.13: Sailing Routes, 200BC-200, in the South China Sea [Nabatheans 2004]

Once the Chinese had sea-going junks they sailed the Indian Ocean and to East Africa to engage in trade. The Chinese reached India during the Roman times, visiting the port of Palk Bay at the northern tip of Sri Lanka place where the Chinese boats would unload their cargoes and buy various goods, including animals, to transport back to China. The Chinese maritime trade reached its ultimate extent in 1433, when during his voyages Cheng Ho reached the east coasts of Africa (Fig. 2.14).

At that time, 1400, the Chinese merchant fleet was the biggest in the world. However, as a result of heavy internal conflicts at the northern border the ruling dynasty closed China to foreigners since they believed that everything in China was better than anything produced elsewhere and thus there was no need for foreign influences. In essence, this situation lasted about 500 years.

Figure 2.14: Map showing Cheng-ho's voyages in Asia, Arabia and Africa [Levathes 1954]

Around 1820 Shanghai was already a big port. However after the Boxer revolution in 1901 China again went into isolation.
This isolation changed in the 1980s when China started to open its borders to foreign manufacturers and investors. In the 21st century China is once again playing an important role in maritime trade.

2.8 Indian sea trade

Indian sea trade goes back as far as 3000 BC. During that time a big dry dock constructed of bricks already existed in Lothal, in the Indian state of Gujarat. In 2400 BC Lothal's dock (the world's earliest), connected the city to an ancient course of the Sabarmati river on the trade route between Harappan cities in Sindh and with the peninsula of Saurashtra. The surrounding Kutch desert of today was then a part of the Arabian Sea. Lothal was a vital and thriving trade centre in ancient times, with its trade in beads, gems and valuable ornaments reaching the far corners of West Asia and Africa.

Figure 2.15: City of Lothal India 2400 BC including the harbour basin [ASI 1960]

Figure 2.15 shows the town of Lothal, including the harbour. The Indians traded with the Arabs, the Chinese and the people of Indonesia, mainly in spices and dyes (Fig. 2.16). Through their trade they also spread Hinduism and Buddhism to Asia.

Figure: 2.16: Sailing routes, 200BC-200, of Indian merchants [Nabatheans 2004]

2.9 American sea trade

Intercontinental sea trade, such as that developed in China, India and Europe, did not occur on that scale in America in ancient times. Most of the native Americans did not engage in sea trade. There are indications that the Mayans carried out some sea trade along the coastal areas of Mexico, although their travelling was rather limited (Fig. 2.17), compared that in other areas of the world. The Mayans sailed along the coast of the Holmes Peninsula, and the Maya Peninsula. They did not cross the Gulf of Mexico. Later, after the discovery of America by Columbus in1492, sea trade developed and was extended by the Spaniards.

Figure 2.17: Mayan sailing routes [Morales 2005]

2.10 Port development from 1800-2008

The increases in the number and size of ships, of cargoes and in trading led to the development of the ancient ports into the modern ports of today. It is interesting to observe the different types of ports in the world and also to consider how these have changed from their original shapes and dimensions to their present configurations.
During the period before 1300 China was richer than the rest of the world and also possessed an enormous merchant fleet prior to 1400 (Chapters 1 and 2). This is reflected in the Gross Domestic Product (GDP) as shown Figure 2.18 [Magnusson 2003].

The later changes and withdrawal from the sea trade were mainly caused by the decision of the Chinese rulers not to expand. During the period before the Second World War communism, capitalism or even slavery dictated world economies.

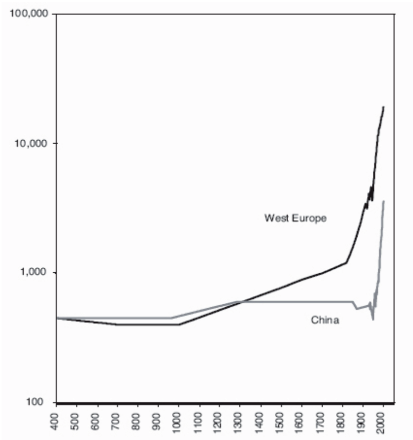


Figure 2.18: Development of GDP (USD) from 400 to 2001 for West Europe and China [Magnusson 2003]

2.11 Stages in port development

In Table 2.1 the stages in the development of ports over time, as compiled by [Rodrigue 2004], is indicated and expanded by the addition of a 5th stage [De Gijt 2010].

Table 2.1 indicates that since the 19th century port development has changed from cargo and storage to overall logistic location. The trend towards specialization and globalisation will continue for many years to come. Today most big ports are complex industrial areas with very important logistic functions.

In the 21st century the reduction of emissions, energy consumption and noise reduction will become important issues that ports have to deal with. Another aspect that will be increasingly important within ports is the specialization in transport and handing of commodities. Ports will cooperate with each other more closely or will take part in activities in other ports. This partnering will increase in the years to come.
The stages in the development of ports clearly show that the industrial revolution (1750-1850) was a very important contributory factor. This revolution greatly increased the potential for advances in shipping, cargo handling and manufacturing, while there was also a change from purely local to global economies, thereby introducing very strong mutual dependence.

Table 2.1: The stages of the development of ports versus time

Role of port authority	Nautical services	Nautical services Land and infrastructure	Nautical services Land and infrastructure Port marketing	Nautical services Land and infrastructure Port marketing Network	Nautical services Land and infrastructure Port marketing Network Partnering
Spatial scale	Port city	Port area	Port region	Port network	Concentration within ports
Dominant cargo	General cargo	Bulk cargo	Containers	Containers and information flows (supply chain)	Containers
Main port function	Cargo handling Storage Trade	Cargo handling Storage Trade Industrial manufacturing	Cargo handling Storage Trade Industrial manufacturing Container Distribution	Cargo handling Storage Trade Industrial manufacturing Container distribution Logistics control	Specialization Cargo handling Storage Trade Industrial manufacturing Container distribution Logistics control
Development rationale	Rise in trade	Industrialization	Globalization	Logistics	Climate awareness Clean port
Period	Up to the mid 19th century	Mid 19th century to mid 20th century	Late 20th century	Late 20th century	21th century
	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**

The managements of port authorities have an increasingly larger scope to attract more clients to their ports than they had in the past. In this respect it is not only the depth of the harbour basins in the ports that is important; even more important are other factors, such as the availability of finance, inter modal traffic capacity, the environment, education and cultural potential.

In the 13th century the leading port in northern Europe was Bruges. In the 14th century Antwerp took over this position, which it held until the Spanish invasion and the closure of the Schelde in 1585 [Alderton, 1999]. After the period of Spanish government, Amsterdam, 16th century, became the biggest port in Europe for approximately a century, which was the Golden Age in Holland.

From about 1840 London claimed to be the biggest port, largely as a result of a change from mercantile capitalism to industrial capitalism. The cargo passing through this port increased from 2 to 25 million tons. London remained the biggest port until 1920, when New York took over the position as leading world port. This it retained until 1963, when Rotterdam took over the first place and held this position until overtaken by Shanghai in 2004. In 2008 Shanghai handled 582 million tons of cargo against Rotterdam's 421.1 million tons.

Table 2.2: Relative share of the top 20 container carriers in 2008 (Containerisation International 2008)

Company	TEU per carrier	% per carrier
Maersk Line	1 746 349	23.1
Mediterranean Shipping Co SA	1 260 098	16.7
CMA CGM SA	721 879	9.6
Evergreen Line	628 110	8.3
Hapag Lloyd AG	503 732	6.7
Cosco Container Lines Ltd	461 573	6.1
APL Ltd	426 937	5.6
China Shipping Container Lines Co Ltd	405 398	5.4
NYK Line	353 318	4.7
Orient Overseas Container Line Ltd	351 429	4.7
Hanjin Shipping Co Ltd	344 755	4.6
Mitsui OSK Lines Ltd	342 429	4.5
Kawasaki Kisen Kaisha Ltd	305 818	4.0
Yang Ming Marine Transport Corp	277 606	3.7
Zim Integrated Shipping Services Ltd	252 267	3.3
Hyundai Merchant Marine Co Ltd	229 729	3.0
Hamburg Sudamerikanische Dampfschiffahrt-Gesellschaft KG	221 263	2.9
Pacific International Lines Pte Ltd	152 057	2.0
Wan Hai Ltd	131 595	1.7
United Arab Shipping Co (SAG)	124 009	1.6

Another reason for the dramatic growth of ports was the introduction of the container in the nineteen fifties. This introduction brought about a change from manual unloading and loading of the ships to completely automated loading and discharging of the cargoes. In Table 2.2 is the TEU capacity for the top 20 container carriers shown.

The container trade is now divided between ship owners and shipping companies from several countries. In 2008 Maersk had a market share of approximately 23.1 % while in the future the Chinese shipping companies like Hanjin and Yang Ming will attain a greater share.

Figure 2.19 shows the main sea routes between the continents that are in current use. These are broadly similar to those used by sailing ships. The map below shows the sailing routes used by Dutch, Spanish and English sailing ships in the 16th century before the opening of the Suez and Panama canals (Fig. 2.19).

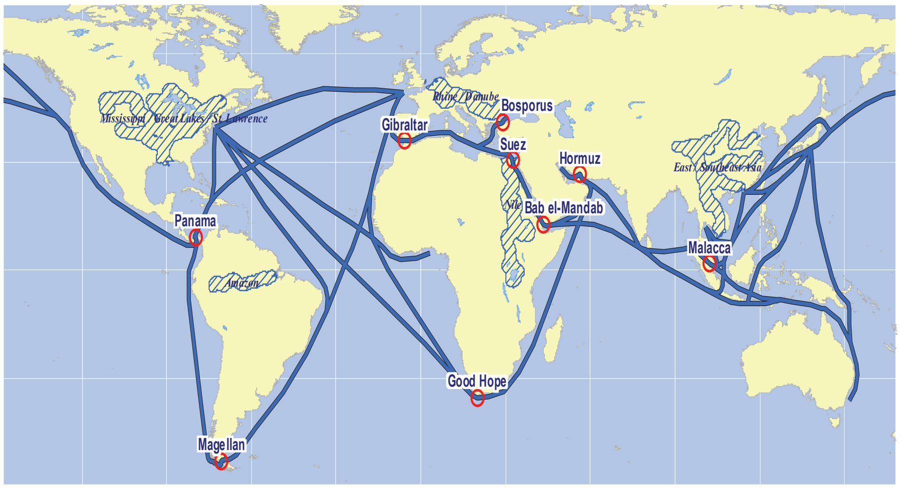


Figure 2.19: The main sea routes between the continents 2004 [Rodrigue 2004]

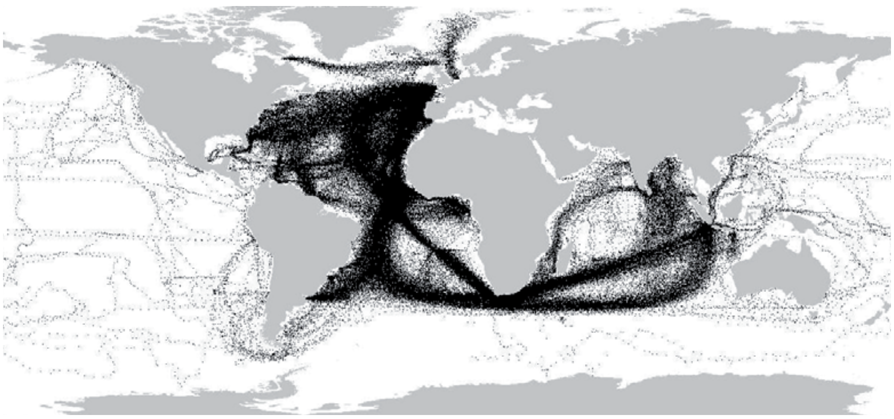


Figure 2.20: The main sea routes used by sailing vessels in the 17th and 18th centuries [CLIWOC 2004]

The dependence on the prevailing winds and currents during the sailing era is clearly shown in Figure 2.20
The most frequently used sea routes of today (Fig. 2.19) can be compared with those of 500-600 years ago (Fig. 2.20). The main traffic flows are comparable.
The great changes in sailing routes used in the past and at present occurred after the construction of the Panama and Suez canals, which shortened sailing times.

The 20 biggest ports in the world in 2008 in relation to volume (metric tons) throughput are listed in Table 2.3.

Table 2.3: The world's 20 major ports in 2008

Ports	Gross weight (million metric tons)
Shanghai[1]	582.0
Ningbo	520.1
Singapore	515.3
Rotterdam	421.1
Tianjin	355.9
Gunzhaou	344.3
Quindao	300.3
HongKong[1]	259.4
Qinhuangdao	252.2
Busan	241.7
South Louisiana	233.7
Houston	227.0
Nagoya	218.1
Shenzhen	211.2
Gwangyang	200.0
Antwerp	189.5
Dalian	185.2
Los Angeles	170.1
Chiba	170.0
Rizhao	151.0

[1] Including river trade
[2] Freight tons
Validity of comparisons is limited due to difference in definitions
Source: Port Authorities

The introduction of the container in the nineteen fifties brought about a big change in cargo handling. Today's modern ports handle large volumes of containerised goods. Table 2.3 gives an indication of the container handling in the 20 biggest ports in the world.

Table 2.4: The world's 20 major container ports 2008

Ports	1000 TEU's
Singapore	29,918
Shanghai	28,010
Hong Kong	24,494
Shenzhen	21,420
Busan	13,425
Dubai ports	11,827
Guangzhou	11,200
Zhoushan/Ningbo	10,920
Rotterdam	10,784
Qingdao	10,020
Hamburg	9,737
Kaoshiung	9,677
Antwerp	8,663
Tianjin	8,500
Los Angeles	8,081
Port Klang	7,970
Long Beach	6,488
Tanjung Pelepas	5,600
Bremen	5,529
New York/New Jersey	5,236

TEU's (Twenty Feet Equivalent Units)
1Including river trade
Source: Port Authorities

2.12 Port design in general

Ports have been built at many locations around the world which have completely different geographical- and physical conditions. Depending on its location a port has to be designed in such a way that the transhipment of goods can be safely and quickly performed.
This means that measures have to be taken to attain the goals of safe and quick cargo handling and to create an excellent business climate for people to live and to work in.

The main physical threats to ports are siltation, excessive currents, waves, tides, bad weather conditions and pollution (dust and noise).
The types of harbour in current use indicate that the following distinctions have been used: coastal natural ports, coastal breakwater ports, river basin ports, river tidal gate ports, coastal tidal gate ports, natural river ports, open roadstead ports.
Figure 2.21 indicates the location of the major ports of the world and also shows the different types of port.

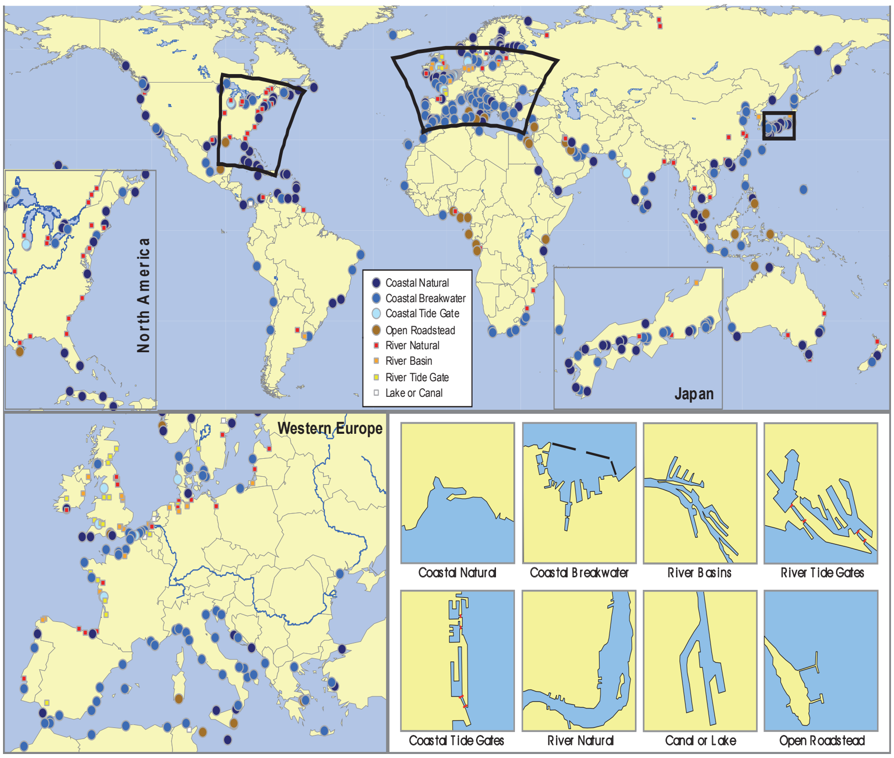


Figure 2.21: Major ports of the world sorted by type of port [Rodrigue 2004]

Each of these types of port requires some method of maintenance and/or structures to reduce the natural threats mentioned above. Deltaic areas are very sensitive to siltation. Examples of older ports that were abandoned are Lothal, Ostia and Bruges. Also longshore sediment drift tended to be disastrous for ports, as was in case of the Cinque Ports in England.
To remedy the effects of siltation, breakwaters were built and use was made of the tidal

difference to scour the harbour clear of silt and to create enough depth, as was done in the port of Dunkirk [Belidor 1753].
In 1872, on the initiative of Caland, Rotterdam had improved its entrance by dredging the Nieuwe Waterweg. This passage considerably reduced the travel time.
Today, with the aid of modern equipment, the ports such as Rotterdam are kept open by maintenance dredging.

If, however, the tidal range is too great it is necessary to build docks, as was done e.g. in Lothal India in 2400 BC, Dunkirk in 1686, Liverpool 1710 and London 1696 to improve the cargo handling. In Antwerp the docks are also still in use.
Most ports in the Mediterranean are physically protected by the construction of moles to safeguard the operations. The port of Marseille, originally founded by the Romans, is a good example.
To maintain ports in their optimum functional condition it is necessary to ensure that the port authorities must maintain constant awareness of possible threats. This is certainly the case today where alertness is required to safely handle the commodities transported as well as their storage. Furthermore, attention must be paid to the prevention of accidents in the port, while today there is also the threat of attack by terrorists.
In addition more attention must be paid to the prevention of noise and dust in order to improve the residential environment in and around the port area.
Some ports have already taken the initiative by providing electric power for the mooring of vessels to reduce both emissions and noise.
Since it is recognized that climate change might influence the operation of ports studies are being carried out to investigate the possible effects of climate change on port operations. Options that are being considered include increasing the height of the present quay walls or the construction of sluices.

2.13 Summary

This section has provided a general description of the development of sea trade and ports. This development was initiated by the search for goods or by increasing populations.
Literature studies show that in the past impressive ports had already been built in various parts of the world to accommodate the ships. However up to 1600 Asia and Europe were the areas where the sea trade had made the greatest progress.
Only after 1700 did America take more part in the sea trade which had been initiated by the Arabs, Spanish, the Portuguese, Dutch and English seafarers and explorers.
Of course this sea trade would not have been possible without the technological developments in ship design, crane design and quay wall construction techniques which are discussed in the following chapters.

3. Development of ships

3.1 Introduction

As it is necessary to know the dimensions of the ships that will be using the port facilities before quay walls can be designed, it is also necessary to consider the historical evolution of ship design.
A historical review provides some insight into the ways ships are built for various purposes. An indication of when important new concepts were introduced, with the consequences for the design of quay walls is also of interest. Therefore here an overview of ship development in several locations in the world is presented. By considering the development of ship building in Europe, Arabia, and Asia we can begin to grasp the effectiveness of the merchant fleet of the Arabs as well as the tremendous distances they travelled in order to obtain their goods.

3.2 Egyptian Ships

In Egypt the principal means of transport was navigation on the Nile. The Egyptians had developed a range of boats that were well adapted to the different uses as well as to the geography and climate of Egypt.

One of the earliest known representations of Egyptian sea-going vessels is on a bas-relief of 2500 BC in a pyramid tomb near Cairo. These vessels had masts and used paddles for propulsion and steering. An interesting feature is the ‘hogging truss’ , a cable stretched from bow to stern and kept in tension to prevent the ship from drooping at the ends.

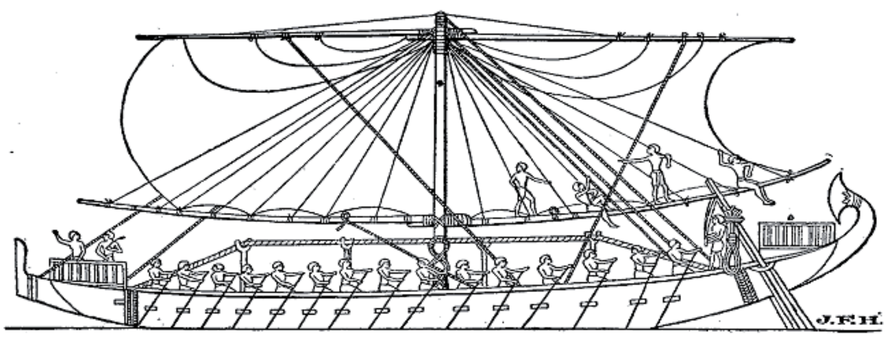


Figure 3.1: Egyptian ship showing the use of the ‘hogging truss [Torr 1964]

This principle is still employed in shallow-draught vessels of the present day. There are also other records of ships almost as ancient, some being merely descriptions, while others are depicted on sculptures, seals and hieroglyphics [Casson 1971].

The ships built by the Egyptians varied enormously in size, some of which were very large. The Greek historian Diodorus mentioned a ship built of cedar, which measured about 150 metres in length. Another boat, a naval vessel, built on the orders of Ptolemy Philopater, was of the same length, 22 metres wide and 30 metres high. According to Diodorus this ship could carry four hundred sailors, four thousand oarsmen and three thousand soldiers. This certainly seems a heavy load and poses social problems.

Some very large freighters were also employed by the Egyptians. These freighters were used to transport grain, stone, bricks, and obelisks that were hewn out of a single block in the quarries of Aswan and then carried on the river to the temple site. A single statue weighing a thousand tons was quarried in Aswan. This was transported several kilometres from the quarry to the river and lifted onto the boat. After sailing for about two thousand kilometres the boat was unloaded and the stone was again transported several kilometres to the site of the temple, where it was finally erected.

Since the 12th Dynasty, about two thousand years BC, trade on and around the shores of the Mediterranean and Red Sea was protected by the formidably strong Egyptian navy. Herodotus and Diodorus both mentioned the ships of war, which were fitted out on the Red Sea. All together there were four hundred 100 metre long King Ship's, most of which operated on the Nile and along the Mediterranean coast. These commercial and naval ships were served by several ports, guiding landmarks, water markers, and loading- and unloading facilities. Several roads and supply stations were provided between the seaports and the populated centres along the Nile.

The Arabs challenged and eventually defeated these 'King's Ships' so that they could monopolize the sea-going trade on the Red Sea and beyond that to Asia.As indicated by historians, the Egyptian and Roman navies sailed only in the Red Sea and not beyond.

3.3 Asian Sailing Ships

Water transport played an important role in Asia and especially China with its vast land areas and very poor road communication systems. The Chinese boats, called junks, were excellent for sea travel as well as for beaching in shallow water and were first built in around 6000 BC. The Chinese joined the planking, forming a square punt, or raft. Next, the side, the bow, and the stern were built up with planking to form a large, flat-bottomed wooden box. The bow was sharpened by making a wedge-shaped addition below the waterline. Chinese shipbuilders contrived a watertight box extending through the deck and bottom that allowed the steering oar or rudder to be placed on the centre line. The stern was built to a high, small platform at the stern deck so that waves from the rear could not spray into the ship.

The principal advantage was the junk's great structural rigidity. To support the side and the bow planking, the Chinese used solid planked walls. These bulkheads , ran both longitudinally and transversely, thus dividing the ship into several compartments. This provided strength and also protection against damage. The Chinese junk had a fine rigging system, the sails consisting of narrow panels, each tied to a sheet (line) at each end so that it could be reefed by many lines rather than on the mast alone. It could also be hauled about to permit the ship to sail on a different course.

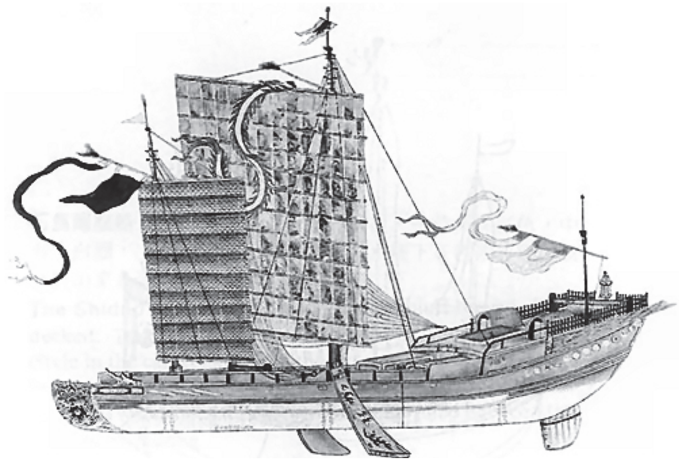


Figure 3.2: Chinese Junk 1300 [Wikipedia]

Figure 3.3: Photo of a Korean junk 1871 [Wikipedia]

3.4 The South Arabian merchant ships

The Sabaeans [Nabatheans 2004] of southern Arabia (Yemen) used rafts and leather boats to transport goods from Ethiopia to Arabia. The Minoans, Gerrheans, and others would unload their cargo at an island off the coast, probably Tiran, so that Nabataean boats could collect it. The Sabaeans themselves confined their maritime activities to crossing the Red Sea. By the second century BC the Nabataeans in the north had already taken part in maritime transport over the Indian Ocean. The Nabataeans transferred the goods from the Sabaean rafts and leather boats to their own wooden Dhows.
A very early type of boat was the coracle, a small almost round boat consisting of a wooden framework, often of split and interwoven willow rods, tied with bark and covered by animal skins. Such boats are still in use today in some parts of the world, including India and Wales.

Figure 3.4: Coracle [Wikipedia]

Figure 3.5: Classic Dhow [Wikipedia]

Figure 3.6: Modern Dhow [Wikipedia]

The Arabs were already masters of sailing long before the Europeans switched from rowing galleys to using sails of the lateen type. Within their grasp they had, knowledge of astronomy and the equinoxes. They were familiar with the fixed rudder, compasses and the use of triangular sails that permitted them to tack with the wind. Their smaller ships were far more agile and much faster than the Roman or Egyptian rowing galleys. As long as the wind blew, they were masters of the sea. However when the wind fell away, the rowing galleys could easily catch them and ram them. Diodorus tells us that Egyptian or Greek quadriremes were responsible for sinking several Nabataen pirate ships on the Red Sea.

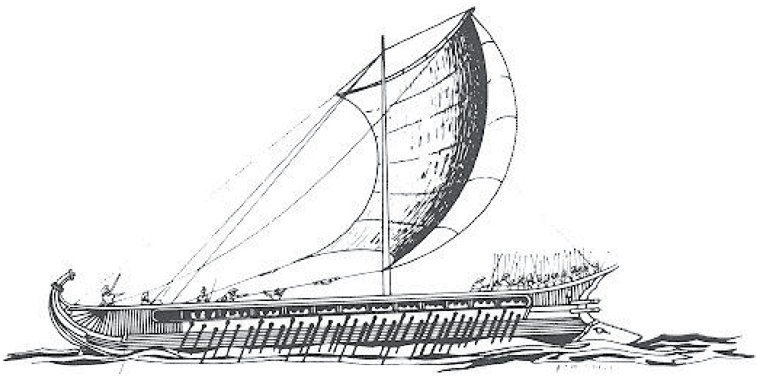


Figure 3.7: Greek quadriremes [Wikipedia]

On the Mediterranean Sea the Greek traditional form of sea-going vessel involved the combination of a square sail and rowing from Egyptian times throughout the Roman Empire and on to the time of the Viking long boats, the square sail was used with slight modification. The Romans took immediate notice when the Arabs appeared on the Mediterranean Sea with their dhows. Arab pirate boats sailing out of Gaza could make better use of the wind and the slower Roman boats were often out-sailed. This triangular sail was most probably developed on the Red Sea where strong head winds often blew from the northern direction. The traditional square sail of Rome and India was severely hampered in these conditions, and it seems that on the Red Sea the triangular sail quickly replaced it. Soon the Romans adopted the use of the Arab sail pattern, and eventually the Vikings in the north of Europe called the triangular Arab sail the 'lateen' or Latin form of sail. The lateen sail was fixed to a crossbar, mounted at its middle to the top of the mast and angled to extend aft far above the mast and forward down nearly to the deck. The sail, with its free corner secured near the stern, was capable of taking the wind on both sides. The lateen sail immensely increased the potential of the sailing ship by allowing the ship to sail close to the wind. In 1000 BC the shipbuilders in China introduced the sternpost rudder. This invention was rapidly adopted by Arab shipbuilders for their dhows, allowing the dhows to take full advantage of the improved sail power when tacking into a head wind and greatly increasing their manoeuvrability.
This improvement was followed by the introduction to the Arab world of the magnetic compass that was originally invented in China around 200 - 300 BC. With the compass it became possible to check the direction at sea independently of the weather. The Arabs developed their sailing technology to include the use of the compass, the lateen sail, the sternpost rudder and navigation by the stars, and with these four advantages they could dominate the seaways for five hundred years.

When the Arab empire waned the Arabs of South Yemen and Oman took their place as maritime traders between Asia and Europe.

Navigation by the stars was an important Arab skill, but it is now accepted that the precession of the equinoxes, discovered by the Greeks, was already known in pre-Dynastic Egyptian times. The most ancient astronomical texts known are dated from the Egyptian Ninth Dynasty, 2150 BC. Using their knowledge of astronomy and the equinoxes, sea-going Arab sailors could navigate their way across the Indian Ocean by the stars, rather than by following the coastline.

3.5 The development of ships in Northern Europe

Towards the end of the Middle Ages the Europeans would incorporate these improvements into their sea going vessels. Then, with better equipment, such as barrels to store water, more reliable ropes, sails, anchors, the availability of navigational charts (first recorded in use on board Dutch ships such as the Kogge ship), and with the astrolabe for measuring the angle of the sun or a star above the horizon, these adventurous European mariners could make voyages of discovery that would mark the end of the Middle Ages and the beginning of the expansion of Europe westward across the Atlantic Ocean.

After the fall of the Roman Empire, the art of engineering, like most branches of knowledge, fell into decay. Not until 1500 was the standard of Roman construction overtaken. The centre of maritime activity moved out of the Mediterranean into Northern Europe. Here the different conditions of geography and the harsher climate had influenced both shipbuilding and harbour construction.

In the Mediterranean the long periods of calm made rowing possible and necessary. The more frequent winds of the northern seas and the rougher waters favoured the use of sails but Viking war vessels still relied on oarsmen for the rapid and accurate manoeuvring necessary in battle. Although they also carried sail.

The warships of the Danes and Saxons, so active on the coasts and rivers of Northern Europe between the 5th and 10th centuries, were probably similar to the Viking ship unearthed at Gokstad, Norway, in 1880. The length of this ship was 24 metres, its beam 5 metres, and draught about 1.2 metres. There were sixteen oar-ports on each side, and the full complement would be about seventy men. The single mast would carry a square sail and a special oar was used for steering. The ship was clinker built of oak and is a better example of shipbuilding than are many later vessels. Merchantmen used sails in preference to oarsmen, thus saving manpower and increasing cargo space.

Up to the 16th century the same ships were used for both trade and war. Fore and aft castles were added temporarily for the use of the fighting men, but these are interesting as the first examples of enclosed cabins comparable to those of the Chinese junk. These ships were much wider in proportion to length than the Viking ships, their length being about three times their beam. They were ‘carvel’ built, that is, the planks butted against each other instead of overlapping and they were caulked. Though oars were probably still carried for emergencies, more use was made of the single square sail. Tonnages for warships ran up to about 1,000 tons and merchantmen often reached 600 tons. Bounties were paid to private shipowners, whose ships could then be put into Royal service when required. This type of piracy was promoted by several countries to safeguard their trading posts and trading routes. At the time of the Spanish Armada the largest English warship was the ‘Triumph’ of about 1000 tons.

Figure 3.8: Viking ship [Wikipedia]

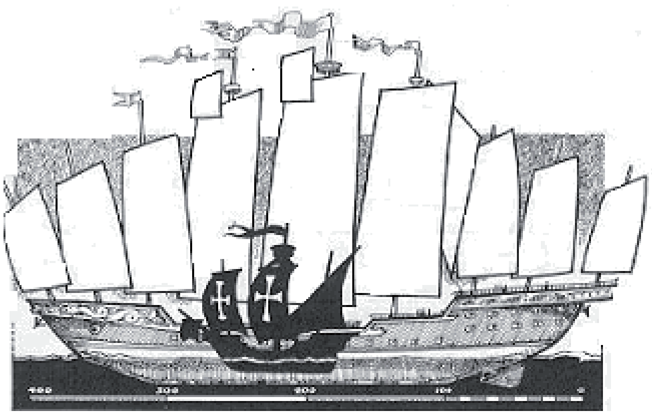


Figure 3.9: Zheng He's (1405) Treasure ship (120 metres) and Columbus (1492) Santa Maria (25 metres.) Illustration by Jan Adkins, 1993.

In the 17th century considerable advances were made in shipbuilding, much credit being due to Peter and Phineas Pett, who broke away from tradition and introduced more scientific methods of design.

Sailing ships continued to be used long after the introduction of steam, and in the 19th century the competition induced great improvements in hull design, rigging and the speed of sailing vessels. In the early part of the century the ships followed the conventional lines with bluff bows and relatively wide beams; then a faster ship, the clipper, was introduced from America and in 1843 the 'Great Britain' was launched at Bristol. This ship was designed by Isambard Kingdom Brunel and was the first iron screw-steamer built for the Atlantic, being at once a great advance in construction and propulsion. The dimensions were: length 100 metres, beam 15 metres, tonnage 3443, equipped with a steam engine of 1000 H P(Horse Power), and at that time this was the largest ship.

Figure 3.10: General cargo schooner [Wikipedia]

Figure 3.11: Clipper ship [Wikipedia]

The clipper ship, developed in America, was originally designed for smuggling and for this type of activity speed is very important. Once the speed was recognized the ships were used for the merchant trade especially to carry tea from Asia and wool from Australia. These clippers could sail at a speed of 30-40 kilometres which is a very high speed compared to modern vessesls (Section 3.6 Figure 3.13).

The main sailing routes of the clipper ships are presented in Figure 3.12.

Figure 3.12: Sailing routes of Clipper ships [Wikipedia]

More than a decade later Brunel's fearlessness as a shipbuilder was again shown by the size of the 'Great Eastern' of 18,915 tons, which was 200 metres long, 26 metres wide, 17.5 metres above the waterline, and with 30 feet draught. She was built on the Thames in 1858 but because the design of this ship was too advanced for that time it became a commercial failure. No attempt was made to copy the dimensions and not until 1902 was her tonnage exceeded. Steel began to replace iron in about 1879, when the 'Buenos Ayrean', the first steel Atlantic ship, was built.
To use paddle wheels efficiently it is necessary that the paddle should be always immersed to about the same depth. As the loaded and light draughts of paddle driven vessels are very different this was a serious disadvantage for cargo-steamers. With the invention of the screw propeller, which is always fully immersed and is less affected by varying draughts, this problem was overcome. The idea of using the screw, which was almost as old as the use of steam, was discovered almost by accident in 1820. However, the screw did not begin to come into general use until about 1850. All the ships built after the 'Great Eastern' are propelled by screws.

The changes from sail to steam and from wood to iron and then steel have necessitated many alterations in the port accommodation and in modern times, from about the year 1890, there has been a further development in the length, width and draught of vessels, which has made it necessary to construct great extensions in all the large ports and harbours around the world.

3.6 Modern ships 1850 to 2009

Cargo ships are categorized by their carrying capacity, their weight, loading methods and their dimensions .Today we distinguish the categories indicated in Table 3.1

Table3.1: Overview showing the characteristics of modern ships

Type	Dead Weight Tonnage (dwt)
Small hand size	Carriers of 20,000-28,000 dwt
Handy size	Carriers of 28,000-40,000 dwt
Handymax	Carriers of 40,00-50,000 dwt
Aframax	Between 75,000-115,000 dwt; (this is the longest size defined by the average freight rate assessment (AFRA) scheme)
Suezmax	The largest size which can pass trough the Suez Canal
Panamax	The largest size that can pass through the Panama Canal; vessels with a beam less than 32.2 metres
Malaccamax	The largest size which can traverse the Straits of Malacca
Cape size	Vessels larger than Panamax and Suezmax, which must round the Cape of Good Hope and Cape Horn in order to travel between oceans;
VLCC (Very Large Crude Carrier)	Supertankers between 150,000 and 320,000 dwt
ULCC (Ultra Large Crude Carrier	Enormous supertankers between 320,000 and 550,000 dwt
LNG tankers	Vessels equipped for the transport of liquid gas

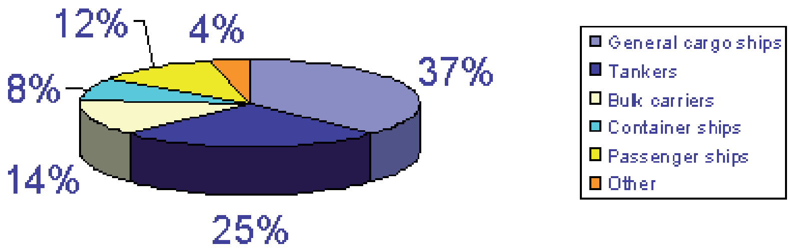


Figure 3.12: Composition world shipping fleet by share of total tonnage [Shipping world trade 2008]

In 2008 the total world shipping fleet consisted of 500,525 ships with a total gross tonnage of 728,225,000 million tonnes.
This total shipping capacity can be subdivided as presented in Table 3.2.

General Cargo ships	18982
Bulk Carriers	6,890
Container ships	4,170
Tankers	12,583
Passenger ships	5,957
Other	1,943

Table 3.2: Composition of type of ship and number in 2008

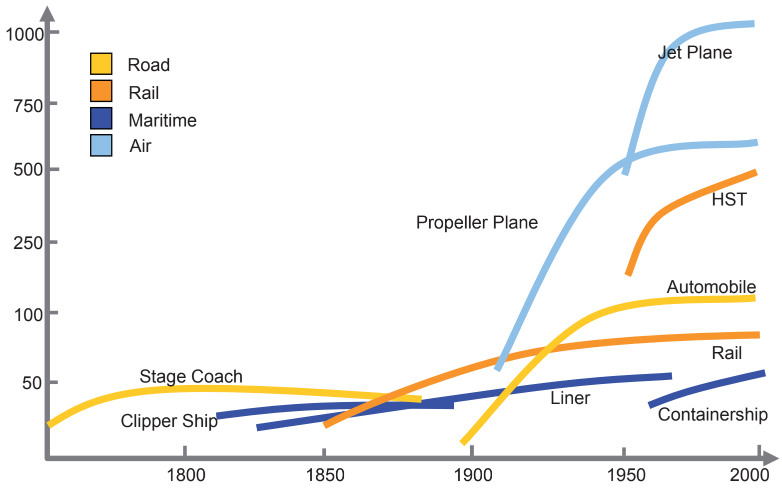


Figure 3.13: Development of average speed for transport Modes (km per hour) versus time [Rodrigue, 2004]

Figure 3.13 indicates the development of speed over time for different transport modes. It is remarkable that the speed of the clipper ships and steam liners of the twentieth century more or less equals that of the container ships of today. If we estimate a speed of 3 to 7 km per hour during the Roman times, over 2000 years the increase in speed is a factor of 10.

Figure 3.14 shows the most recent container carrier the Emma Maersk, 14500 TEU, while Figure 3.15 shows the Berge Stahl, the biggest ore carrier moored in the port of Rotterdam.

Figure 3.14: Container ship Emma Maersk (DWT 215000)

In Table 3.4 the total number of container ships for the top 20 container carriers in 2008 is presented.

Company	Number of ships per company	Average TEU capacity per ship
Maersk Line	457	3821
Mediterranean Shipping Co SA	382	3298
CMA CGM SA	242	2983
Evergreen Line	180	3489
Hapag Lloyd AG	138	3345
Cosco Container Lines Ltd	149	2721
APL Ltd	125	4315
China Shipping Container Lines Co Ltd	119	3406
NYK Line	89	3970
Orient Overseas Container Line Ltd	86	4086
Hanjin Shipping Co Ltd	79	4363
Mitsui OSK Lines Ltd	106	3231
Kawasaki Kisen Kaisha Ltd	98	3121
Yang Ming Marine Transport Corp	84	3305
Zim Integrated Shipping Services Ltd	89	2835
Hyundai Merchant Marine Co Ltd	50	4595
Hamburg Sudamerikanische Dampfschiffahrt-Gesellschaft KG	83	2666
Pacific International Lines Pte Ltd	78	1950
Wan Hai Ltd	75	1755
United Arab Shipping Co (SAG)	43	2884

Table 3.4: Number of ships and average TEU capacity per ship for the top 20 container carriers in 2008 [Containerisation International 2008]

Figure 3.15: Ore carrier Berge Stahl [De Gijt ea 2003]

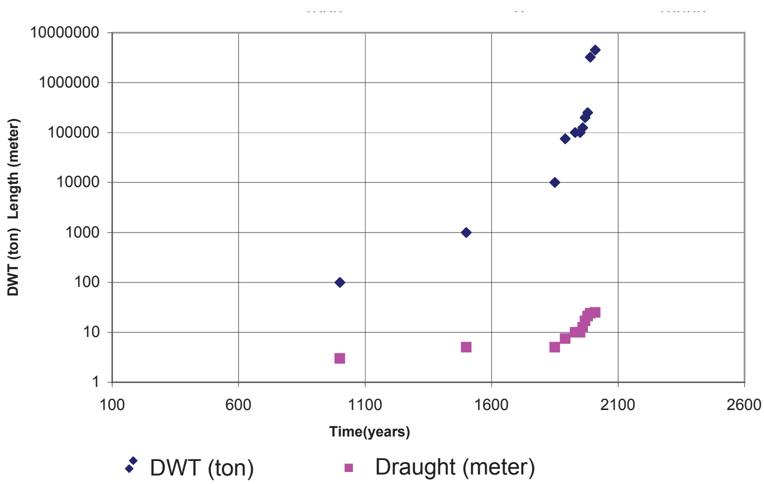


Figure 3.16: Development of shipping.

Over a long period the dimensions of ships changed very little. The big changes occurred with the introduction of steel as construction material and the use of steam power during the industrial revolution. Later changes resulted from the oil crises 1970 and more recently the specialisation in ships like the container vessels and LNG tankers which has occurred since 1950.
The draught of the ships has increased by a factor 2.5 in 500 years time while the dwt has increased by a factor 45 in the same period. This has been made possible by the improvements in the shipbuilding industry and knowledge of the materials used.

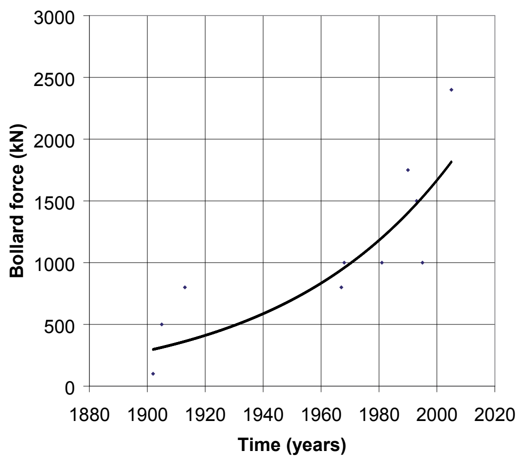


Figure 3.17: Development of bollard force versus time

As the size of ships has increased so have the bollard forces. Today the bollard forces are 3000 kN, as opposed to 50 kN fifty years ago.
This increase is explained by the enormous increase in ship dimensions which has also led to the increase in their wind catching area.

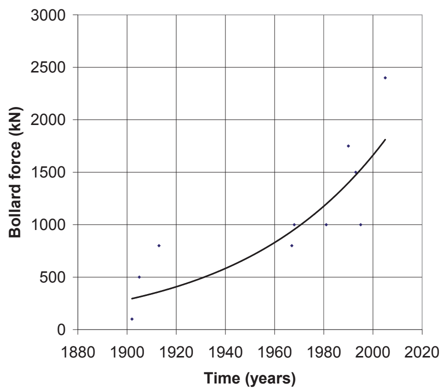


Figure 3.18: The development of berth length

The berth length has increased by a factor 5 since 1900. First in the 1970s the oil tankers considerably increased in length, while since 1990 container vessels have also done so.

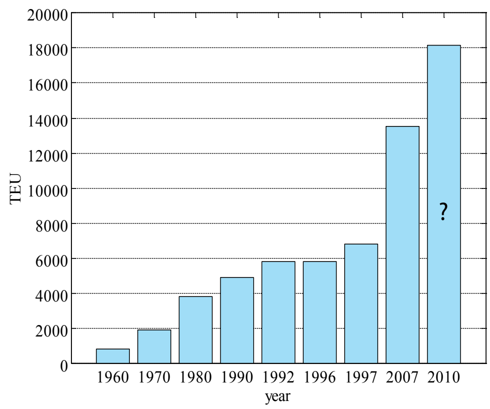


Figure 3.19 The development of TEU capacity per ship

The development of the number of TEU per container ship has shown an impressive growth over the last 10-15 years as is indicated in Figure 3.19.
Whether this increase will continue is very much depending on the markets and the achievable economics of these ships.

3.7 Summary

The increase in ship dimensions has been discussed. Up to 1700 the sailing ship was the mode of transport over seas and oceans. The transfer from sailing to machine propulsion was made possible during the industrial revolution when steam engines were introduced . However, even up to the 19th and 20th centuries the use of sailing ships continued.

These changes in the modes of propulsion and materials used for shipbuilding made it possible to build bigger ships with greater speeds and more cargo loading capacity.
In the past only general cargo ships existed, while today special ships are designed for the transport of oil, ores, LNG and containers; the latter vessels have completely replaced the general cargo ships.
These changes in ship dimensions pose requirements for the layout of ports and harbours, the mooring facilities and the handling of the commodities. These requirements are discussed in the next section.
It is thought that the dimensions of the ocean going ships will be limited to a maximum length of 500 metres, a maximum beam of 70 - 80 metres and a maximum draught of 25 metres.
Bigger ship dimensions pose problems both for ship design and logistic problems in ports and sailing routes.

4. Port layout and the development of cargo handling equipment

4.1 Introduction

The increase in the speed and the dimensions of ships requires that they remain in port for the shortest possible time. This is of economic advantage to both ports and ship owners. This implies that the quay walls must be designed in such a way that the logistic operations can be optimally fulfilled.
Ships have to be loaded and unloaded in ports and the loads exerted on quays by the available loading and unloading facilities can be considerable. Therefore it is necessary to take into account the length, beam, draught and freeboard of the vessels using the port, as well as the development of the type of equipment that is installed. This discussion begins with a description of handling cargo by manpower followed by the introduction of the use of cranes in relation to the cargo or commodity. This overview is not complete, since not all types of cranes are discussed, although the main developments in relation to the loads imposed on the quay wall structure are mentioned.

4.2 Cargo handling before 1800, predating the industrial revolution

Prior to 1800 cargo handling operations in ports had remained unchanged for centuries. In and around 1800 the 200 ton ship was the standard. Most ports had some quays and wharves, although berthing also took place by grounding the ships. The cargo was usually loaded and discharged by the crews of the ships, while incidentally required extra manpower was hired locally when necessary. Most of the cargo handling was carried out manually, but occasionally hand-operated cranes were used to lift the cargo from the ship's holds. During this period the main cargo handling techniques employed human power, which implies that sacks, barrels and piece goods weighing up to 40 kg could be handled. The cargo was often carried in barrels that could be rolled into place and animals were also used to transport goods. However, lifting equipment was developed relatively quickly, using manpower in what were termed 'treadmills'. With this equipment loads of 100 to 200 kg could be lifted. Cranes were also designed; for example the Romans had cranes with a relatively high loading capacity of 500 kg (Figure 4.1).

Like most treadmills, the treadmill shown in Figure 4.2 was moved by manpower, usually supplied by convicts or children. Figures 4.2 and 4.3 show examples of treadmills used in Bruges and Gdansk. The photos indicate that these tread mills could have considerable dimensions. The use of treadmills was widespread in ports, including both sea and river ports and their use in the London docks even continued up to 1910.

Figure 4.1: Replica of Roman treadmill powered crane,replica Bonn [Wikipedia]

Figure 4.2: Treadmill in use in the port of Bruges [De Gijt et al 2003]

Figure 4.3: Treadmill in Gdansk 1500 [Wikipedia]

4.3 Period from 1800 to 1950

The period between 1800 and 1850 was characterized by an increasing throughput in ports. The industrial revolution started at the beginning of this period. This meant that steam and hydro powered machines became available for the quicker and easier handling of goods. Warehouses were also constructed for storage and the handling of the goods and were reasonably common in every port by 1840 – 50. The goods were transported by gantry cranes and cranes operated by horsepower and carried in horse drawn carts. At this time thoughts started to turn to the use of more open storage space. Railways were often used to transport goods to and from the port. By the end of 1850 the average size of seagoing vessels was 210 tons and the average size of the steamship was 250 tons.

Since around 1860 steam engines have been used to lift goods in ports. The steam engines had to compete with hydro powered cranes using the waterpower which were first used at Newcastle upon Tyne in 1846. In approximately 1870 electric cranes came into use. These cranes were very suitable and reliable for the handling of goods. Most harbour cranes moved in both the horizontal and vertical directions and parallel to the front of the quay wall. Their lifting capacity varied between 15 kN to 50 kN, with outreaches varying from 3 to 10 metres, depending on the size of the vessels using the quay. Some typical examples of the harbour cranes used during this period are presented in Figures 4.4 to 4.6.
During this period also great elevator cranes were developed for the transhipment of grain and other dry bulk commodities.

The crane shown in Figure 4.4 is an example of one of the first fixed hydro powered cranes which was used in the port of Venice in1880.

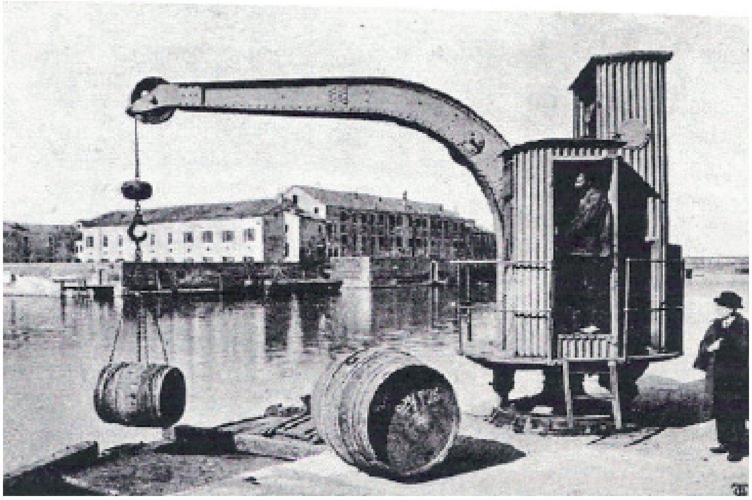


Figure 4.4: One of the first hydro powered cranes Port of Venice 1880 [Cagli, Bernadini 1905]

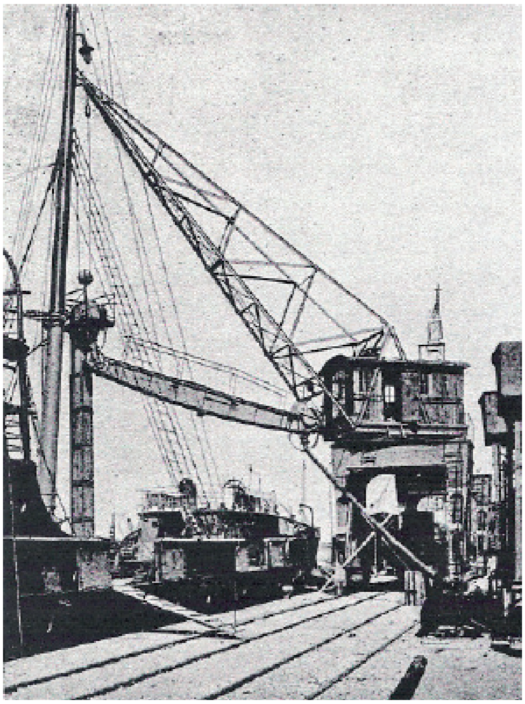


Figure 4.5: Electric crane mounted on a railway in the port of Venice 1900 [Cagli, Bernadini 1905]

In Figure 4.5 a rail-mounted electric crane used in the port of Venice in around 1900 is shown. This crane was used for the unloading of cereals.

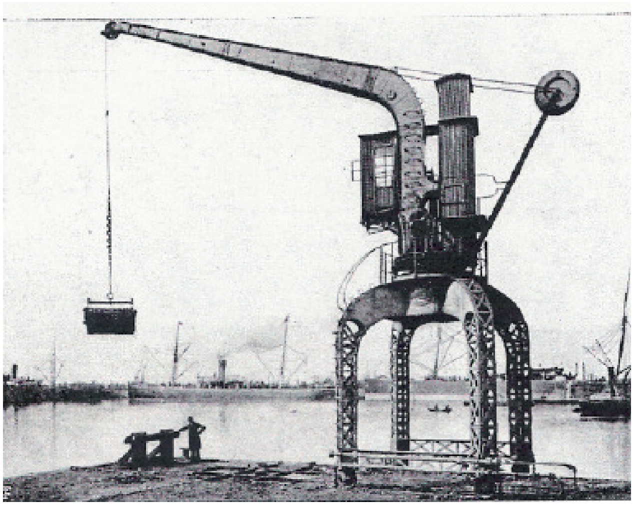


Figure 4.6: An early electric crane used in the port of Venice in around 1900 [Cagli, Bernadini 1905]

This crane was used to unload and load various types of commodities.

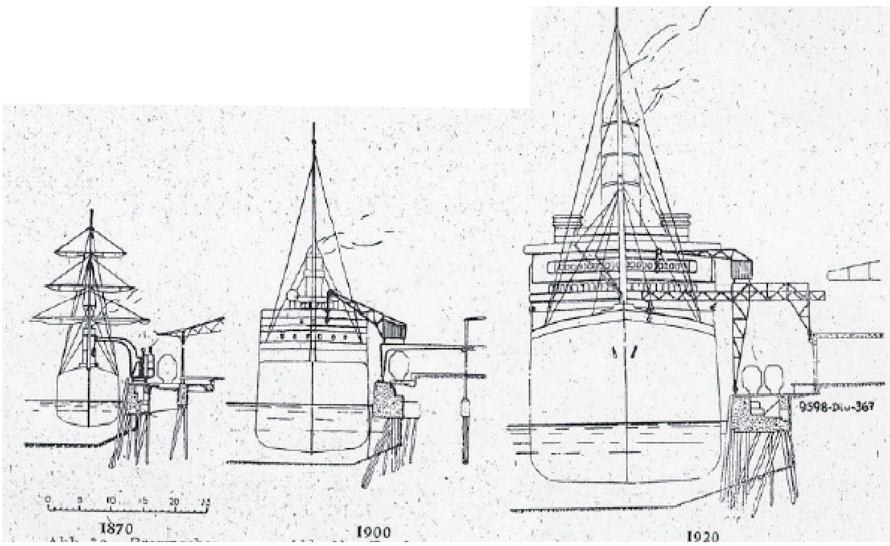


Figure 4.7: The increasing scale of the transhipment of goods between 1870 and 1920 [Buhle 1924]

Figure 4.7 shows the transition of the age of sailing to that of steam and the increase in ship's dimensions in relation to the transhipment of goods.

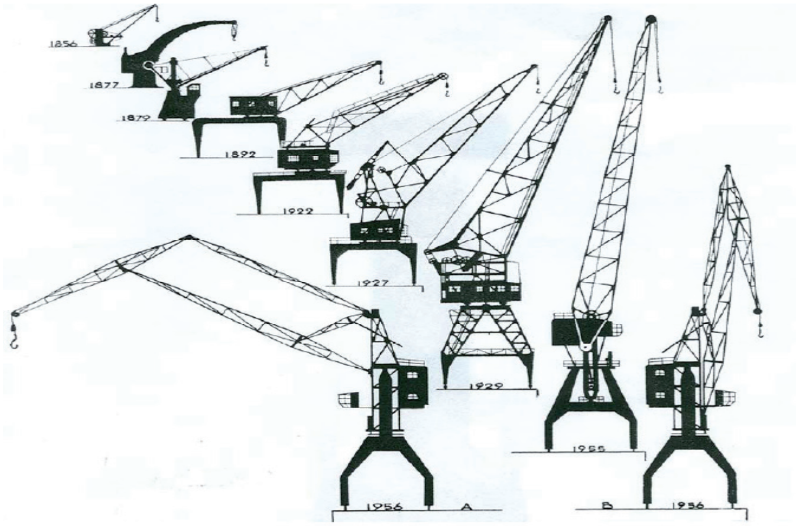


Figure 4.8: Level luffing cranes developed for general cargo handling in the port of Rotterdam 1856-1956

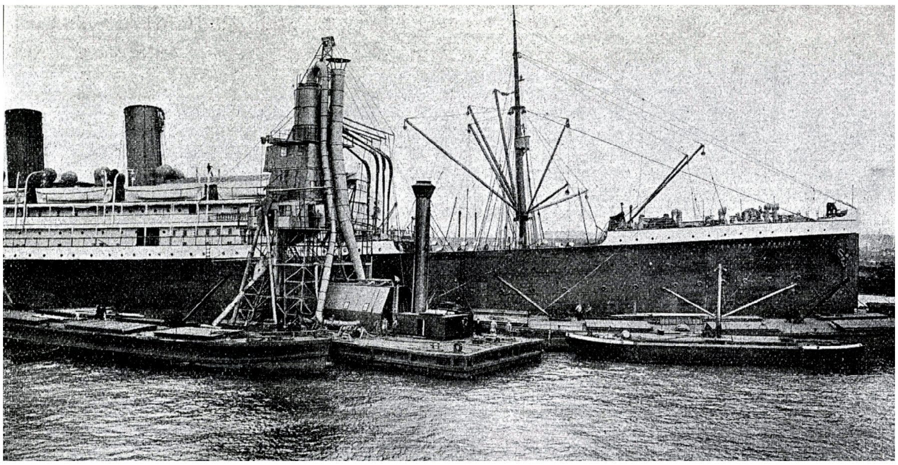


Figure 4.9: Grain elevators in port of Rotterdam 1920 [Driels, Schot 2005]

The invention of the grain elevator in America around 1850 changed the storage and transport of grain dramatically. The grain elevator uses under-pressure to move the grain from the ship's hold and also to transfer it to the barges, which greatly improved the unloading of grain and other bulk material, thus reducing the in-port time of the ships and shortening the delivery time. In Rotterdam, the main grain port in Europe at that time, the grain stored in bales was loaded and unloaded by men as shown in Figure 4.10.

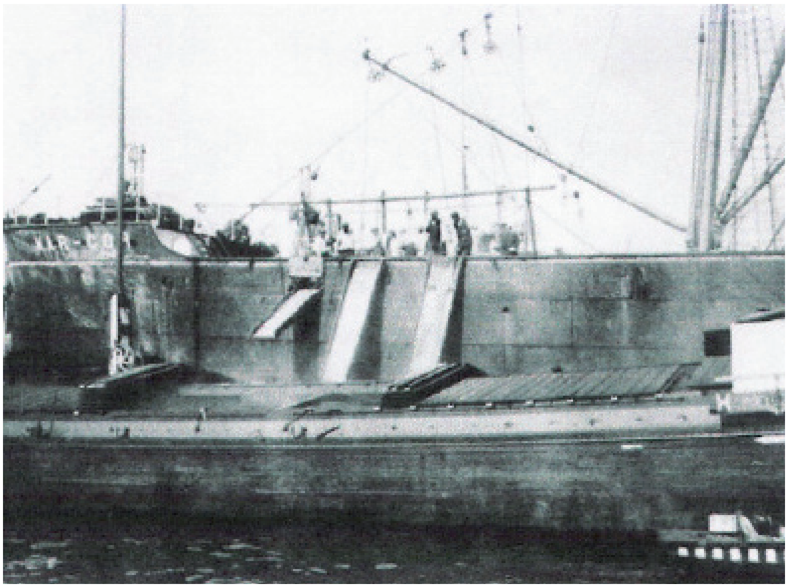


Figure 4.10: Manual unloading of grain [Driels, Schot 2005]

However, from around 1990 the ships sailing from America had started to store the grain in the ship's hold. This way of storage demanded a different system to handle the bulk cargo. Therefore talks were initiated with the stevedoring companies and their clients to improve the grain cargo handling. In 1904 it was decided to use grain elevators. With this new equipment the operation of unloading was accelerated by nearly 100 %. Around 1920 most use was made of floating elevators which could moor alongside of the ships. Only in 1964 did a fixed grain elevator came in to use in Rotterdam [Driel van H, Schot J. 2005].
As the demand for coal rapidly increased after the First World War the transhipment had to be carried out more quickly and therefore very large cranes for the transhipment of coal were developed in Rotterdam in 1925.

This installation is illustrated in Figure 4.11 and at that time was the biggest in the world.

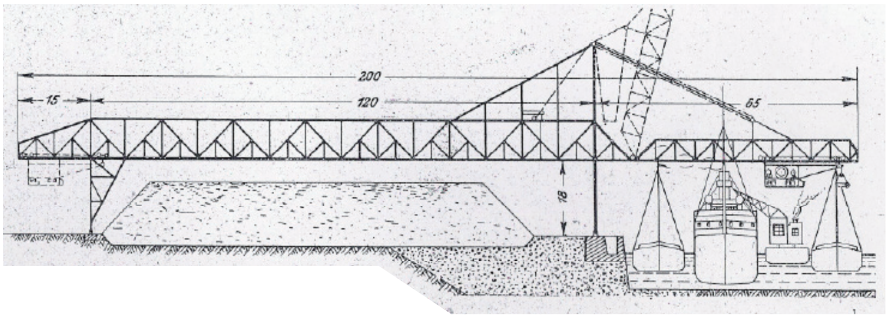


Figure 4.11: Crane bridge for the transhipment of coal in the port of Rotterdam 1925 [Buhle 1924]

4.4 Equipment from 1950-present

Since 1950 the greater utilisation of dry bulk cargoes and the introduction of containers, followed by the standardization of the size of the containers has been in progress. In the 1960s there was a process of gradual evolution as ports adapted to the increase the size of ships and continuous improvement of cargo handling technology.
The development of containerisation and bulk cargoes led to the introduction of more specialised cargo transport vessels such as LNG tankers, ore carriers, oil carriers, and feeders.

This period is characterised by the development of container transport.
At the outset of the introduction of containers, in approximately 1950, the original cranes used for loading and unloading cargo from the ships were gradually replaced by special container-handling cranes.

The lifting capacity of the cranes used for piece goods was formerly limited to 50 kN, with an outreach of about 10 metres. However today the container cranes have an outreach of 50 to 70 metres and lifting capacity of 300 to 1000 kN , as shown by Figures 4.12 and 4.13 for the crane outreach and crane load capacity respectively. These changes introduced higher loads on the quay wall than had previously been experienced. Figure 4.14 illustrates the development of leg loads generated by the container cranes in question.

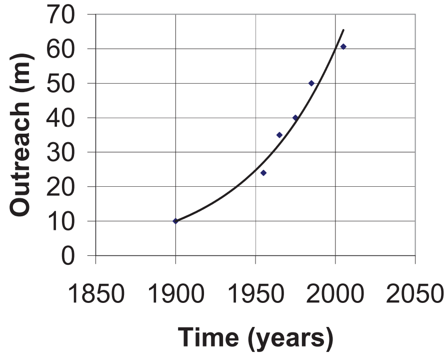


Figure 4.12: Development of the outreach of container cranes versus time

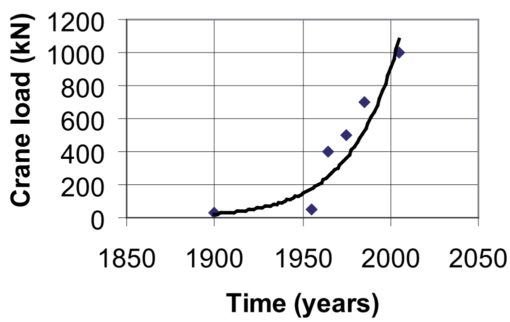


Figure 4.13: Development of the crane load capacity of container cranes versus time

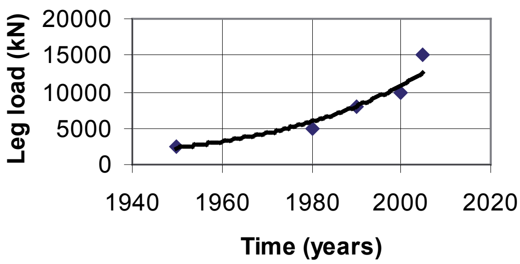


Figure 4.14: Development of the leg load of container cranes

This shows that leg loads have increased by a factor 5 since 1950. These leg loads impose considerable loads on the quay wall or adjacent to the quay, depending on the method used for the foundation of the crane beam supporting the land ward crane rail These are only the vertical loads. However, in normal practice a horizontal force has also to be taken in to account. Usually 10 -15% of the vertical load is taken as horizontal load.

4.5 Storage area development since 1800

In recent years the layout of the terminal area has changed considerably. In the past all quays were multi-purpose terminals. The unloading and loading was carried out with the ship's own cranes. The goods were either loaded to terminal warehouse or to barges for further transport. This situation is shown in Figures 4.15 and 16. Now with the increasing specialisation we have ore terminals, oil terminals, container terminals and combined passenger/freight terminals.

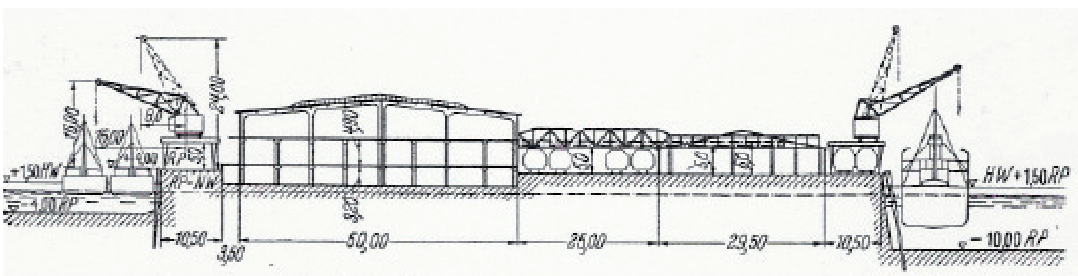
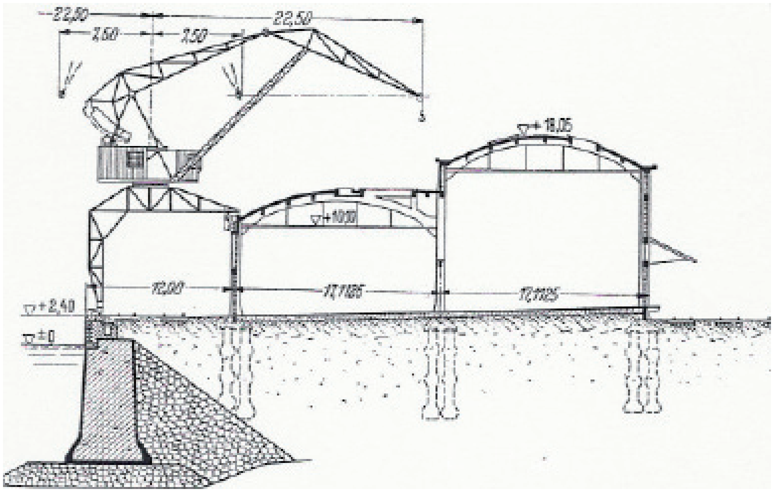


Figure 4.15: Typical terminal in Lekhaven around 1870 in Rotterdam [Bolle1941]

This terminal layout is typical for a river port. Both the river ships and the seagoing vessels moor at the terminal on both sides of the quay walls. In between there are sheds as well as the connection with the railway.



4.16: Typical terminal and storage sheds around 1910 in Naples [Bolle 1941]

This terminal layout, Figure 4.16, differs from the one in Rotterdam in that there is no river and that the goods are transferred to the road or railway via the storage shed. The sheds are founded on insitu made piles within the reclaimed sand area.

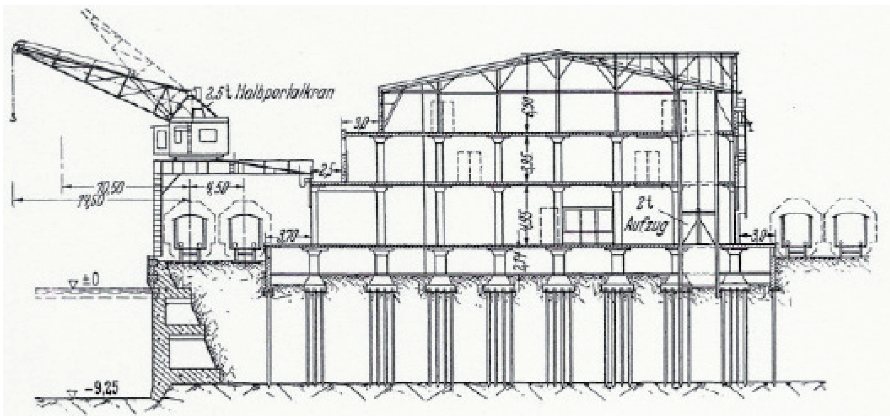


Figure 4.17: Terminal layout in Malmo around 1900 including shed and railway connection [Bolle 1941]

The situation in Malmo, Figure 4.17, is comparable to that in Naples, with the difference that there is a railway connection on both sides of the storage shed.
The sheds are founded on piles resting on the bedrock.

The "Speicher Stadt' (Storage City), built in Hamburg between 1880 and1890, is an excellent example of a dedicated concept for the transport and storage of goods originating from sea and river. The Speicherstadt concept was developed as a result of the shortage of land close to the city.

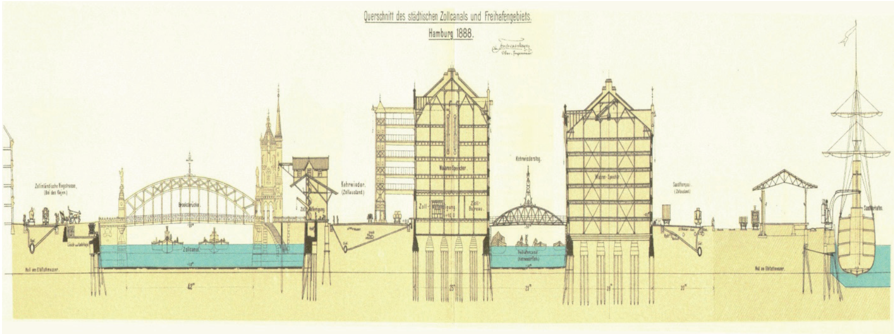


Figure 4.18: Cross-section Speicherstadt Hamburg 1888

Figure 4.19: Terminal operations in the port of Rotterdam around 1960

A typical port scene around 1960 with a number of harbour cranes and forklift trucks for handling the goods is shown in Figure 4.19. Compared to modern terminals the situation on the terminal seems overcrowded and disorganised. Modern terminals and terminal operations are well organized to take into account the current logistic processes.

Figure 4.20: Typical port scene in Rotterdam prior to 1970

In 1966, the container made its debut in the Port of Rotterdam. This spurred some port companies to set up a special company focusing on the handling of containers: ECT. This stevedoring company acquired its own terminal in the Eemhaven. In 1967, the first dedicated container ship, The ' Atlantic Span', owned by the ACL shipping company moored at this quay.

The handling of containers at the start of the container era in 1970 is shown in Figure 4.21. Compared with the present container transport facilities this situation is very simple.

Figure 4.21: Container terminal layout 1990 [ECT Magazine 1992]

The situation at a typical container terminal in 1990 is presented in the above Figure 4.21. Clearly shown is the multi-trailer system developed by ECT in the 1980s. This system ensures that the transport is followed bij predetermined route. Later this multi-trailer system was automated and greatly improved by the installation of transponders in the terrain. The ships were 300 metres long and the outreach of the crane was 50 metres. The total area required for these types of terminal is around 12 hectares.

In 2009 the container terminal has a quay wall length of 500 metres per ship and a land area of 600 by 600 metres for transhipment and stacking. For the transhipment 3 to 4 container cranes are required. In the stacking area 10 -15 straddle carriers are used for the optimal placement and movement of the containers.

The layout of a container terminal and its equipment is shown in 2008 in Figures 4.22 to 4.24.

Figure 4.22: A straddle carrier [de Gijt ea 2003]

The straddle carrier is used to transport of the containers from the ship to location on the terminal. The weight of one full standard container is 300 kN.

Figure 4.23: Container crane terminal Rotterdam [HbR]

Figure 4.24: Maasvlakte 1, Rotterdam the construction of the Euromax terminal [HbR]

Table 4.1: Characteristics of container terminal development in Rotterdam (de Gijt 2010)

Year	Berth length (m)	Crane capacity (kN)	Crane outreach (m)	Depth (m)	Area (ha)
1955	175	50	24	175	3
1965	250	400	35	230	5.7
1985	375	650	50	400	16
2009	500	1000	70	600	30

This table shows the increases in berthing length, crane loads, crane capacity, and depth of the terminal and the area of the terminal. The area of terminals has increased by a factor of approximately 10, the berth length by 2.85 and the crane capacity by a factor of 20.The number of containers stacked on each other has increased from two to five thus a factor 2.5. The limited number of stacked containers is caused by the limitations of the logistic software system. Further improvements are underway to optimize the automated container handling.
It is also interesting to observe that the total stacking area in the warehouses is approximately the same as for the present container terminals.

4.6 Summary

This section shows that already in the past remarkable achievements in the transhipment of goods had been attained. However, recently the speed of port operations has very much increased, as also has the storage capacity, compared to that in the past.
To achieve this improvement more land was required as well as the use of much bigger cranes with very great lifting power. The logistics of terminal operations has also been improved as a result of specialization.
These operational improvements were made possible by the increase in technical knowledge and more specifically by the computerization of the terminal operations
The changes also affect on the design of quay walls, enabling them to accommodate the far higher loads resulting from the cranes and the terrain loads.

5. Materials used in port construction

5.1 Introduction

In principle, all the building materials used by humans are derived from the earth's crust. However in order to obtain an uninterrupted supply of the materials that are required it is necessary to extend the search for these raw materials. The earliest need for construction materials arose during the Stone Age. The exact dates, however, vary considerably in the different parts of the world. In Asia, Africa and Europe the Stone Age started circa two million years ago. In the most advanced parts of the Middle East and Southern Asia it ended around 6000 BC, but in other parts of the world including Europe, the rest of Asia and Africa, Stone Age culture continued until to 4000 BC. In America the Stone Age began some 30 000 years ago and ended in circa 2000 BC. There were enormous changes in climate and in other conditions affecting human culture throughout the Stone Age.

This chapter gives an account of the construction materials used from the very earliest times to present. To date the materials used in the construction of quay walls are stone, brick, wood, steel and concrete. This chapter indicates the availability of the different materials throughout history.

5.2 Period from 6000 BC to 400

The technological development of humans was first directed to making tools for hunting and harvesting and only later to creating structures. Wood, stone or rock were already available for building activities but mankind had to develop tools to work with these materials. In time stone tools became highly polished and more varied. Since 6000 BC pottery and bricks have been produced in the Middle East and India. These materials were first made by drying in the air and only when it was possible to produce higher temperatures use was made of kilns. The early mud and brick making techniques using burned lime and the invention of the use of pozzolanic earth by the Romans dated from the 1st century B C. However, with the decline of the Roman Empire this knowledge vanished and only 1300 years later was the process reinvented in France during the 18th century.
The first use of copper had started in the Middle East. In Thailand bronze has been used for ornaments and weapons since 4500 BC.

In the Middle East from 3000 BC onwards the use of bronze gradually increased. With the introduction of tin in 2000 BC wider use of bronze became possible in this region. Bronze was also used for making tools and weapons. From 1000 BC onwards, raw copper was being pounded into tools and ornaments. Bronze had been used in Greece since 3000 BC, while in China bronze had been in use since 1800 BC. In South America the use of bronze started early in 1000.

The Bronze Age came to an end in the Middle East and Eastern Mediterranean around 1200 BC, when the use of iron making technology became increasingly common.
After 1200 BC, which more or less marked the start of the Iron Age, the manufacture and use of iron became widespread in the early Greek Culture. Furnaces that could reach the high necessary melting temperature of this metal were developed during this period.

Iron had been more generally used in Europe since 500 BC. Early steels were developed by adding small amounts of carbon to iron as it was being hammered over a charcoal fire. The mining operations were also developed and these now included the use of pumps to keep the mines dry. Various metals were used to make cooking pots and dishes, sometimes with disastrous results such as lead poisoning.

In his book De Architectura [Vitruvius 20 BC] describes the characteristics of different construction materials like bricks, sand, lime, pozzolanic earth and quarry stone. For each of these materials Vitruvius indicated their properties such as durability and appropriateness for areas of specific use such as durability and construction methods. His interest in the durability of the materials is illustrated by the information that, once mined, quarried material should be exposed to the weather for a period of two years, after which its suitability for use as foundation material or for other building purposes like port structures could be determined. For timber structures it was recommended that only wood cut in the autumn should be used, since the moisture content was then at its lowest, while the density of the wood was at its highest.

The great Roman civil works such as roads, waterways, aqueduct systems and port structures were also constructed during this period. The advances in building techniques led to the widespread use of the arch by the Romans and the use pozzolanic earth to manufacture cement. Many of the magnificent Roman structures still exist.

5.3 Period 400 to 1800

During this period, of which the beginning coincided with the fall of the Roman Empire, much of the knowledge relating to the development of materials was lost. This was also the case for other disciplines. The period of very retarded scientific development continued up to the Renaissance of 1400-1500, after which a scientific revival commenced that included the development of materials science. Materials that were reinvented or taken into use included cement, pozzolanic earth in Italy and trass (volcanic tuff occurring in the Eiffel region, where it is worked with clay to a hydraulic mortar) in the Netherlands.

5.4 Period 1800 to 1950

The industrial revolution marked a period in human history with a very rapid rate of innovation in technology. The industrial revolution first started in England between 1750 en 1830 and marked a period of change from agricultural life to factory manufacturing. From England the new technologies spread throughout Europe and North America. Great advances were made in developing machinery like spinning machines and steam engines and in railway transport. Since the industrial revolution spread across the world the manufacturing of construction materials has considerably improved. The natural materials like wood and stone were still being used in the same way as in the past, but the scale on which these materials were produced handled and utilised greatly increased.

During this period great progress was made in the manufacture of steel, ranging from charcoal iron to puddle iron, cast iron and the present day extrusion techniques to create beams and sheet-wall elements in every form. Wooden sheet pile elements were used extensively up to the end of 1900 [Roth 1992]. Around that time steel manufacturing had made so much progress that I, Z and U profiles could be manufactured. However the weight of these elements, together with the difficulty of connecting them led Larssen (1902) to search for a new type of sheet pile element. He succeeded in designing the 'Larssen sheet pile element', as displayed in Figure 5.1

Figure 5.1: The Larssen sheet pile element with first the rivetted connection left and the welded connection right

Initially it was not possible to manufacture sheet pile elements with this type of connection, so the first of these interlocks were rivetted to the sheet wall elements. In 1914 it became possible to weld the interlocks to the sheet pile elements. In this way sheet pile elements with good installation capacity, soil tightness and reduction of weight were produced. This development extended the use of sheet pile elements to the wide scope that we know today.
In the port of Rotterdam the first sheet pile wall was constructed in 1927, thus 25 years later then the invention of the Larssen lock.
In 1824, in England, Aspdin patented Portland cement. The raw material for this new material was obtained from a quarry close to the Isle of Portland. He heated the stone from the quarry and thus obtained a type of cement which is still in use. In 1867 Monnier received a patent for the use of steel bars in concrete, which he had used for the first time in1849. This led to the introduction and widespread use of reinforced concrete. With the introduction of reinforced concrete it became possible to build concrete structures that could sustain bending moments. In 1910 Hennebique designed the first integrated concrete structure with columns, beams and floors.
In 1925 Freyssinet introduced the concept of prestressed concrete.

5.5 Period from 1950 to present

Table 5.1 indicates the availability of different construction materials versus the time that people could make use of these materials. Originally stone walls were made by using dry walling techniques, although the gaps were sometimes filled in with lime mortar. However when puzzolanic earth became available bricks could be bonded together. With concrete and steel entirely different structural challenges could be achieved.

Today the developments are leading to improvements in the quality of steel still further to produce higher strengths and special steels for special structures. At the same time much greater attention is paid to the corrosion aspects of steel.

For concrete one might expect that durability will also received more attention, especially in relation to corrosion, and the use of high strength concrete is being introduced in more structures, including quay walls. Developments are also taking place to investigate the use of synthetic textiles as reinforcement and the use of synthetic construction materials in quay wall design may increase.

Table 5.1:Overview of construction materials versus time

Material	Time	
Stone	Always	
Wood	Always	
Copper	6000 BC	- present
ricks	6000 BC	- present
Bronze	4000 BC	- present
Tin	2000 BC	- present
Iron	1200 BC	- present
Pozzolanic earth	300 BC	- present
Trass	1400	- present
Cement	1824	- present
Concrete	1850	- present
Reinforced concrete	1867	- present
Prestressed concrete	1925	- present
High strength concrete	1970	- present
Steel	1880	- present
Synthetics	1980	- present

Since the Second World War understanding of the chemistry of concrete has greatly increased, which has made possible the introduction of high strength concrete and the use of various additives to optimize its characteristics in relation to strength, workability and durability. One could state that since 1900 steel and reinforced concrete have became available throughout the world, which implies that there are challenging structural opportunities.

5.6 Summary

In this section the presence of the different materials and the development of construction materials were discussed.
Stone and wood have been available as construction materials for many centuries. However, when these materials are used only compressive forces can be sustained, although wood does have some limited tensile strength.
With the development from cast iron to steel and later, around 1900, of reinforced concrete it was also possible to sustain bending moments
This implies that slender construction could be built or the span could be increased.
Today the steel and reinforced concrete are around the world the most available and most used construction materials.

6. Development of quay wall structures over time

6.1 Introduction

This chapter considers examples of the different types of quay wall that have been designed and built from the earliest times up to the present. As it would be impossible to include every type of quay wall, the objective is to use a few typical structures to illustrate each period.

6.2 Period from 3000 BC to 400

This period covers a long time span. The reasons for the limited selection that is included is that relatively little information is available and that the descriptions are mainly based on information derived from the Romans and incidental archaeological finds. For example, little is known about quay wall design and construction in China, apart from what can be learned from paintings, even though in early days there was a considerable volume of shipping in and beyond Chinese waters. During this period harbours were protected by moles, the inner sides of which were used as quays, implying that even in those days multi-use was already taking place.

The ancient city of Lothal in India had a big harbour basin which was approximately 4 metres deep and was surrounded by 5 metre high quay walls. Figure 6.1 shows the structure of this harbour. The bricks were sun-dried and subsequently bonded with lime cement.

Figure 6.1: Dock of Lothal, India with brick wall, 2400 BC [ASI 1960]

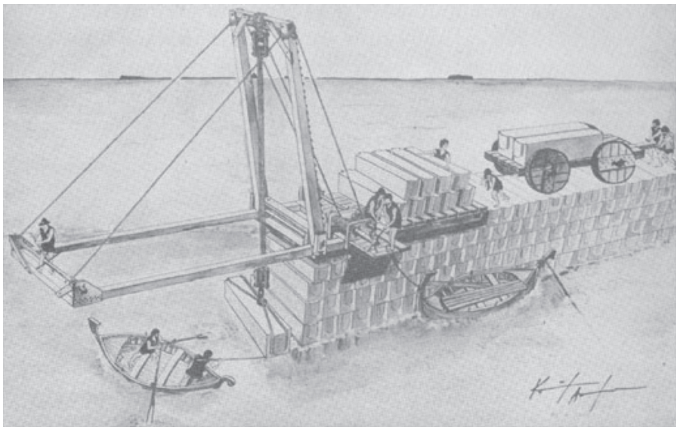


Figure 6.2: The use of a crane to construct a mole from granite blocks in the Hellenic port of Amouthous 1100 BC [Navis]

Figure 6.2 illustrates the mechanism and use of a crane and also the sequence of construction used for a mole in the Hellenic port of Amouthous. The mole is constructed from natural stone that has been sawn to the dimensions required for handling. The columns were next to each other and the spaces between the columns were filled with stones and mortar. The moles were also used as quay wall inside the port.

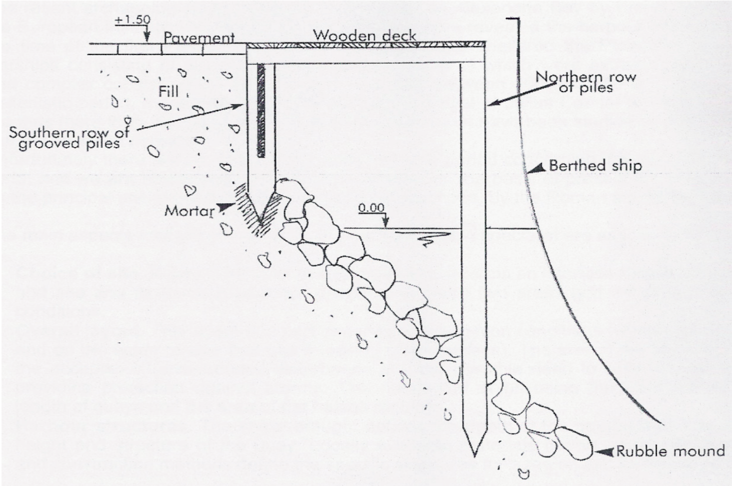


Figure 6.3: Cross-section of Archaic quay consisting of a wooden deck resting on piles, Alexandria 400 BC [De Grauw 2005]

This structure consists of a row of grooved elm piles between which pine planks were installed to prevent the fill from washing out. The elm piles were provided with extra anchorage in the bottom by surrounding the tips with mortar. The northern row of elm piles were installed at a distance of 0.2-0.4 metres and driven to a depth of about 0.5 metres. The retaining height is approximately 3 to 4 metres

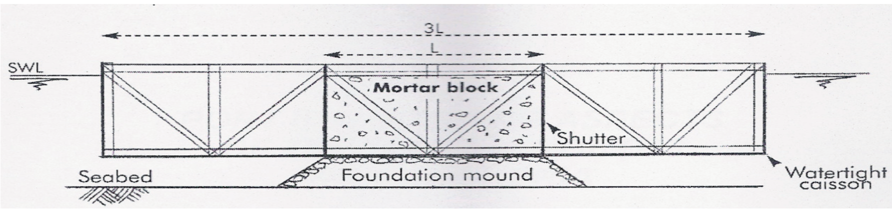


Figure 6.4: Floating caisson used to transport a mortar block, Alexandria 250 BC [De Grauw 2005]

First a wooden mould was constructed as a part of the watertight caisson. Subsequently these blocks were cast in this wooden mould. This mould was then positioned at the required location for the quay wall.

Figure 6.5: The columnar jetty of the middle basin of the harbour of Caesarea 200 BC [Navis]

Figure 6.5 shows the remains of a quay that consisted of stone pillars placed on top of each other. The retaining height was approximately 4 metres. The method of construction used was most probably similar to that described for the quay shown in Figure 6.2.

The retaining walls depicted in Figure 6.6 show types of early retaining walls built by the Romans. The top figure represents a dam structure for a harbour basin. The clay dam inside prevents the loss of water. The middle figure shows an earlier type of cofferdam system. In this case the water tightness is secured by extra planking on the waterside. The cofferdam is filled with clay. The lower figure also shows a cofferdam structure with two rows of planking that was filled in with sand.
The retaining height of these structures varied between 3 and 4 metres.

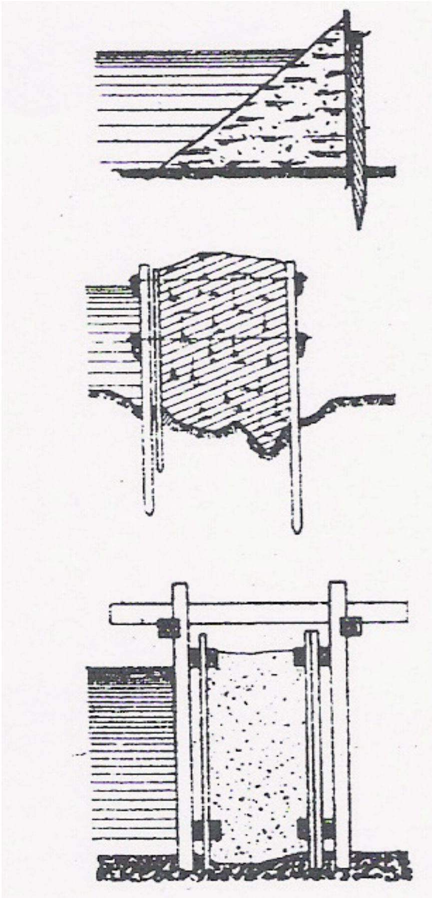


Figure 6.6: Cross-sections of early Roman wooden retaining wall structures 100 BC [Leimdorfer 1976]

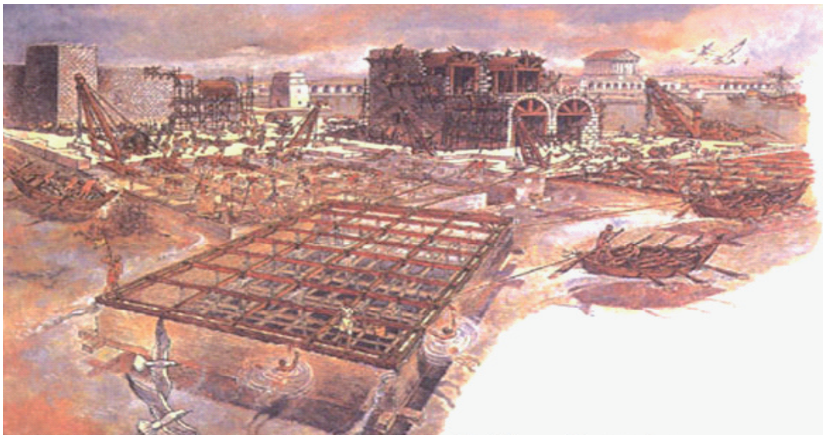


Figure 6.7: Drawing of a caisson wall Caesarea 100 BC [Navis]

Figure 6.7 shows a caisson quay wall. The construction sequence was as follows: first a wooden framework was made then this was filled with pozzolanic mortar with a specific weight of approximately 0.6 kN/m². This permitted the caisson to be floated and towed into the chosen position by a vessel. When the caisson was correctly positioned the mortar was allowed to harden further, eventually reaching a specific weight of 20 kN/m², which ensured that it would remain in place. The connection between the individual caissons was made by means of ropes and mortar.

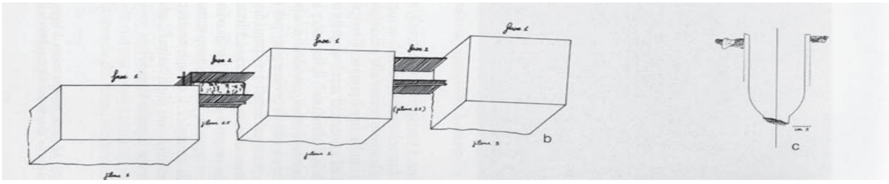


Figure 6.8: Sketch of Mole or quay using mortar blocks with double wooden fencing between them forming a cofferdam type of structure, Cosa 100 BC [Navis]

Figure 6.8 shows the construction of a mole or quay using mortar blocks with double wooden fencing between them, forming a cofferdam type of structure. The space within in the cofferdam was also filled with mortar. In order to secure horizontal stability, the blocks penetrate into the subsoil for a maximum of about 1 metre. One might conclude that this structure is one of the earliest types of combi-wall.

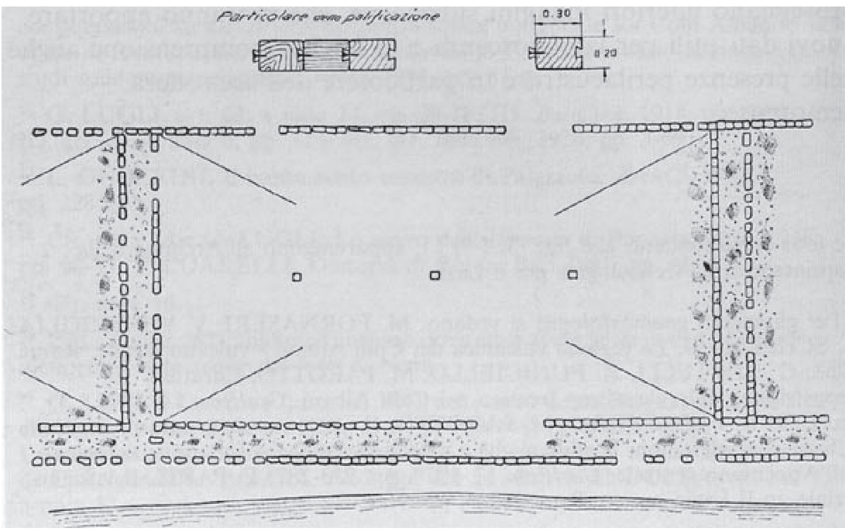


Figure 6.9: Top view of Wooden Cofferdam Lago di Nemi Genzano 40 BC [Navis]

The Lago di Nemi Genzano quay wall, in fact a cofferdam construction, consists of parallel pile rows with planks on the inner side. The inner space was filled with sand.
The waterside is constructed as a double wall filled up with clay to prevent leaking of fine material through the wall.

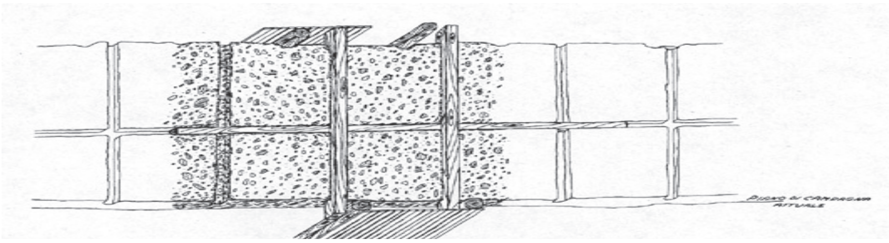


Figure 6.10: Top view of cofferdam constructed by the Romans, Ostia 40 [Navis]

This cofferdam was constructed by first placing two parallel wooden sheet piles walls which are anchored to each by horizontal wooden beams. The space inside was filled up with rubble and mortar. This working method was proposed by [Vitrivius 20].

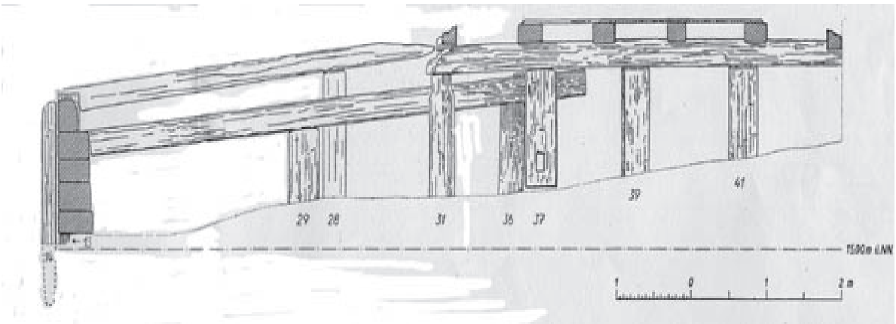


Figure 6.11: Cross-section of a Roman quay, Xanten, Germany 200 [Navis]

In Figure 6.11 the structure of a Roman quay wall found in Xanten, Germany is shown. This quay wall consisted of wooden planking supported by girders and piles. The water-side of the girders is supported by stone columns. The stones were either simply placed on top of each other or were cemented to each other and founded on the subsoil as a mat foundation. The stone walls had retaining heights of more then 3 metres sometimes reaching up to 7 metres. Wood was also used for smaller retaining heights up to approximately 3 metres.

6.3 Period from 400 to 1500

During this period few developments took place in any scientific field until the 14th century. This lack of development included quay walls. Most of the quay walls that were constructed during this period were made of locally available natural materials such as wood and stone.

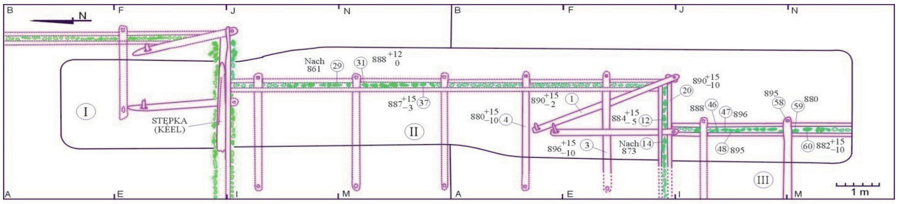


Figure 6.12: Top view of the reconstruction of a quay wall in Wolin Poland, ca 800 [Navis]

Figure 6.12 above, shows the top view of the reconstruction of a quay wall in Wolin, Poland ca. 800. The front wall and the anchoring of the quay wall consist of wood. As can be seen, the front wall is a cofferdam-like structure, which is filled with clayey soil. The aim of using the clayey soil was to prevent the washing out of soil from behind the wall. The retaining height was ca. 5 metres.
The horizontal stability was obtained by installing horizontal wooden anchors. The connections between the structural elements was realized by dowelled connections
The retaining height of this structure was 4 metres.

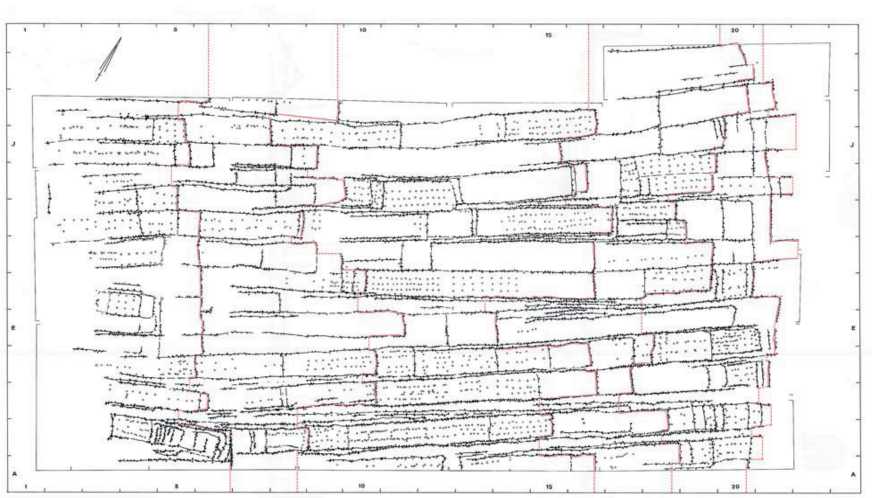


Figure 6.13: Top view of wooden planking of a slipway in Dorestad (near Utrecht) the Netherlands 900 [Van Es 1994]

The slipway structure in Figure 6.13 is interesting as it shows how wood, roughly placed together is used. Between 1000 and 1200 Dorestad was an important trade centre with connections to the hinterland as well with ports overseas (Section 2.3) In Dorestad there were several slipways for the construction and repair of ships.

Figure 6.14: Remains of a dock in Nanking 1300 [Levathes 1954]

Zheng He, the greatest sailor of China, constructed many wooden ships of up to 120 metres in length, some of which were the largest in the history of the port of Nanking. Today still some of these shipyards still exist as is illustrated in Figure 6.15.

Figure 6.15: Schematic cross-section of Nanking dock [Mou 2008]

The banks of the Nanking docks consisted of two or more rows of piles filled up with soil to create depth in the dock.
An illustration of the composition of this wall is presented in Figure 6.16.
The connections of the construction are shown in more detail with the number of piles and planking to create the wall in Figure 6.16.
The space between the piles was filled by rubble. The height of this structure is about 4 metres.
A good example of the use of dowels is also shown.The dock boundary was constructed bydriving two rows of wooden piles by hand as shown in Figure 6.17.

Figure 6.16: Details of retaining structure of Nanking dock 1300 [Mou 2008]

Figure 6.17: Connection of beams by using dowels Nanking Dock1300 [Mou 2008]

The first permanent dry dock in England was built at Portsmouth in 1495-1496. It was rectangular, built of wood and with two sets of gates, the space between them being filled with clay for water tightness when a ship was in dock. To let the ship out when repairs were complete, the clay had to be dug out, and this would take about a month.

This dock took 48 weeks to build and it could take the 'Sovereign', a ship of 600 tons, the biggest warship of the time.

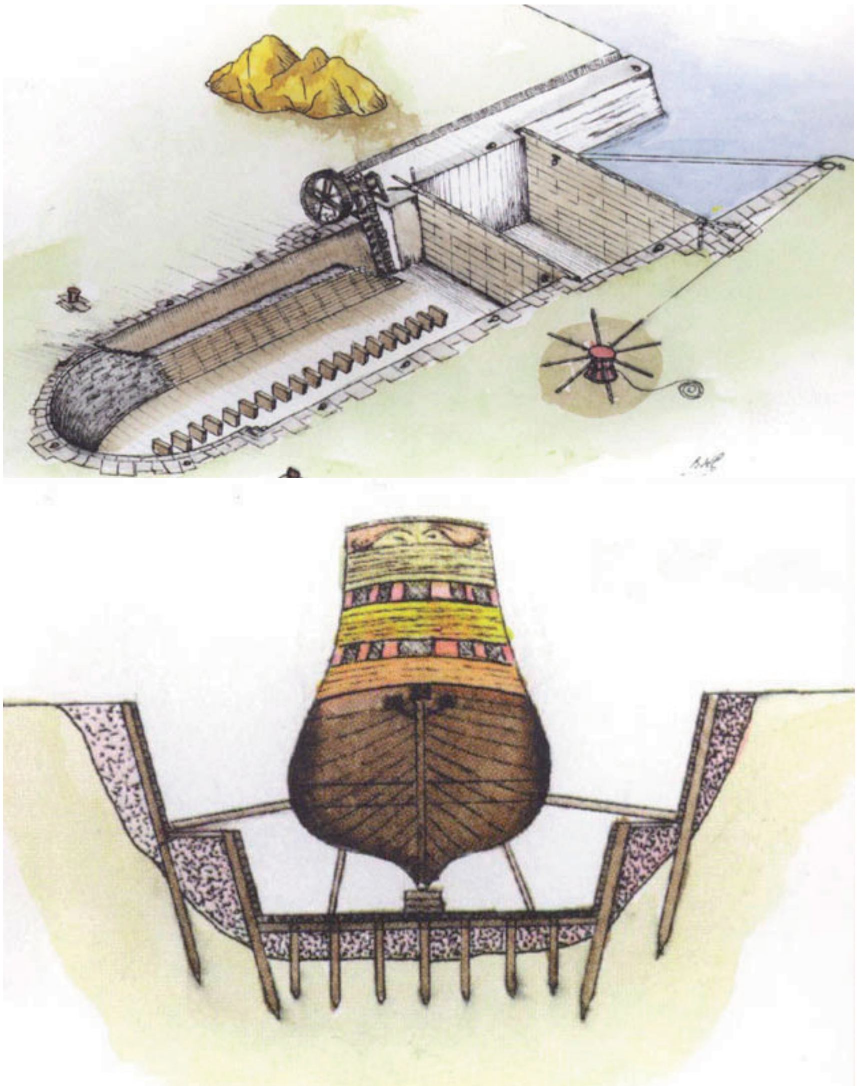


Figure 6.18: Dock built in Portsmouth to accommodate 'The Sovereign', 600 tons 1496 [Portsmouth Royal Dockyard Historic Trust]

6.4 Period 1500 to 1950

This period is characterized by the rapid development of science, the industrial revolution, the renewed invention of concrete and also the invention of reinforced concrete and precast concrete. In addition, steel profiles could be made to replace the wooden sheet piles. An important invention relating to this is the interlock connection for steel sheet piles developed by Larssen (Chapter 4 and 5).

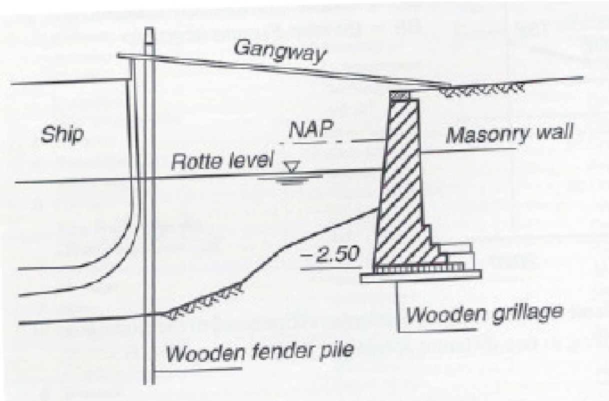


Figure 6.19: Cross-section of the first quay wall built along the Boompjes in the Port of Rotterdam, The Netherlands 1604 [De Gijt et al 2003]

Figure 6.19 shows the first quay wall built in the Port of Rotterdam This gravity quay wall was founded on a wooden framework. A brick wall was constructed on top of the wooden framework. The construction activities took place partly under wet and partly under dry conditions. The retaining height of this structure is 3 metres.

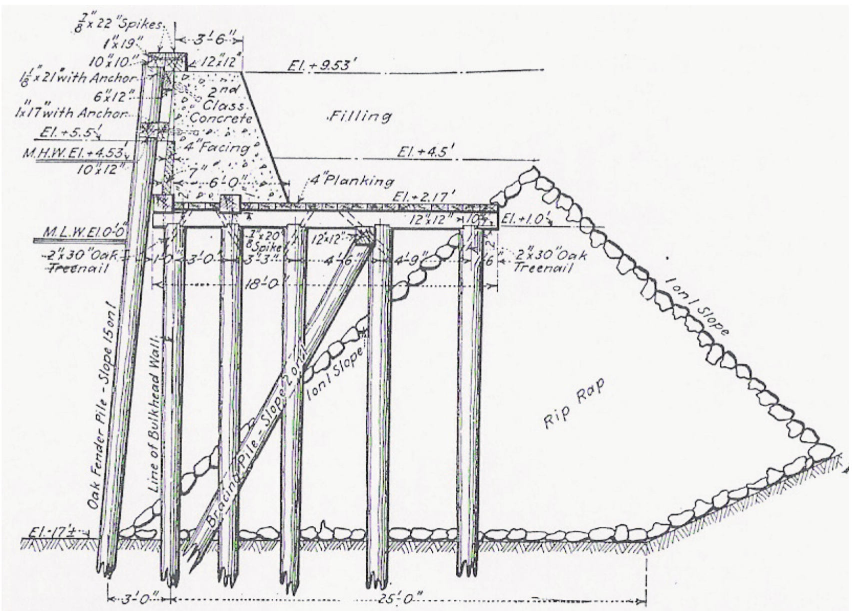


Figure 6.20: Cross-section of platform wall, Gowanus Bay, Brooklyn, New York 1830 [Greene 1917]

Figure 6.20 shows a cross-section of a quay wall built in the port of New York in 1830. The structure consists of a wooden relieving platform with a poured concrete structure on top of it. This ensured that all the wood was situated under water, thus reducing the chance of rotting. Before the wooden piles were driven a riprap bund was placed. The wooden piles were driven through the riprap. The retaining height of this structure is 8 metres.

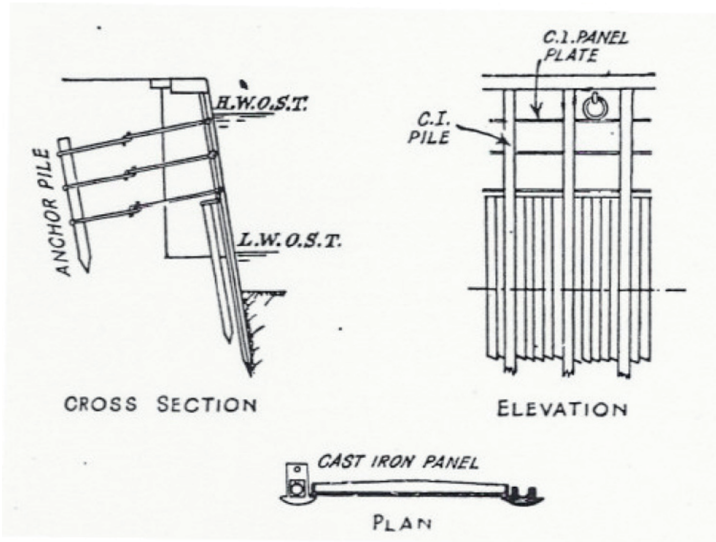


Figure 6.21: Cross-section and elevation of Brunswick wharf, London 1834 [Duplat Taylor 1949]

The Brunswick wharf was the first wharf constructed in cast iron.
This structure consists of cast iron piles, panel plates and anchor rods.
This structure was built by driving the first the main piles and subsequently the planks.
The iron panels fitted into the grooves of the main piles. The retaining height is 5 metres.

The quay wall in Bremen, Figure 6.22, consists of a wooden pile foundation. The piles were driven into the sand layer. The pile bearing capacity is 100 kN. After the installation of the piles the superstructure, made of poured concrete and bricks. The super structure was built under dry conditions. The Altenhafen basin area was built on the initiative of Dutch engineers and businessmen. The use of batter piles in Germany was proposed by Baurath van Ronzelen [Rudolff, Gunther and Claussen 1903] a name which indicates Dutch origin.
The retaining height is approximately 12 metres.

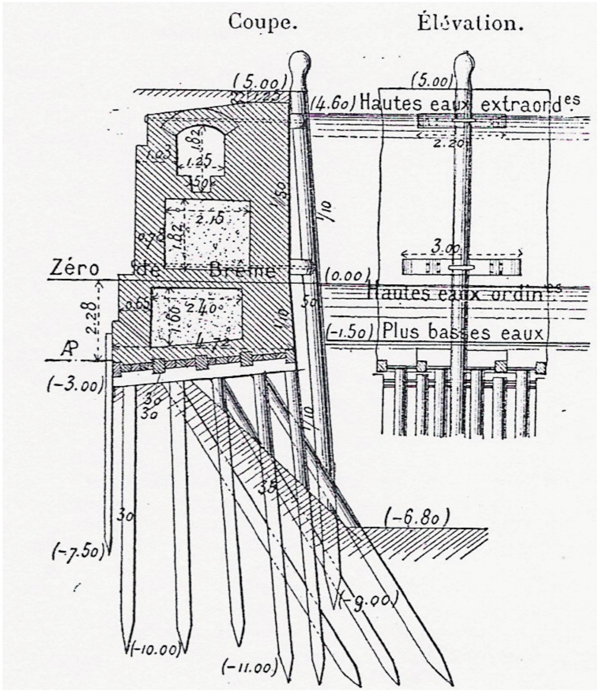


Figure 6.22: Cross-section of Quay wall Bremen 1840 [Rochemont et Desprez 1900]

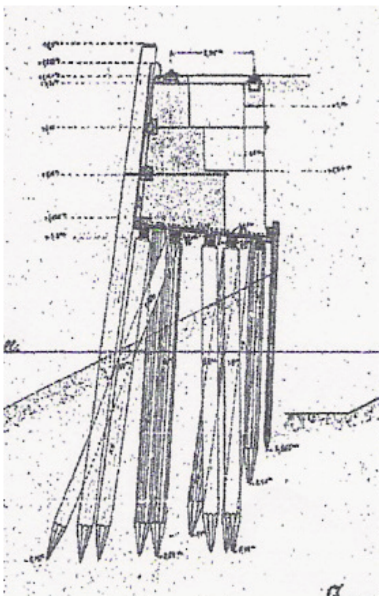


Figure 6.23: Cross-section of a wooden piled structure with a poured concrete element on top. Hamburg 1866 [Miller 2007]

Figure 6.23, shows an example of a wooden piled structure with an unreinforced concrete part on top of the wooden structure with a brick wall facing. This was the first quay wall built in the port of Hamburg (1866). Manually operated pile driving equipment was used to drive the piles to a depth below which they could not penetrate. The concrete was poured between the planking. The wooden parts were placed under water level to prevent rotting. The retaining height is 5 metres.

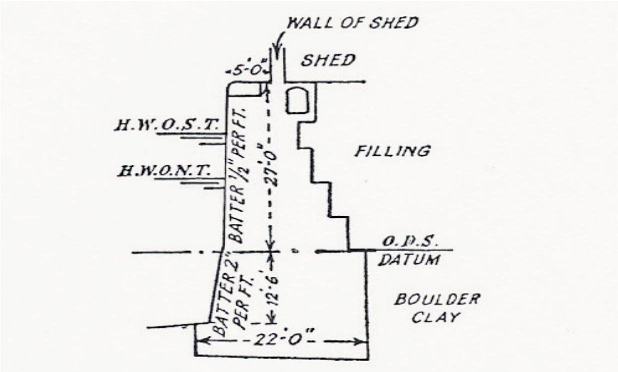


Figure 6.24: Cross-section of Langton Dock Wall, Liverpool 1881 [Duplat Taylor 1949]

The gravity structure shown in Figure 6.24 is a typical example of quay wall construction in Liverpool. This structure, which is of the gravity type, was built in a dry pit and is made of unreinforced concrete. The bearing stratum consists of hard clay layers .It was built between 1873 and 1881, but was actually opened in 1879.The retaining height of this gravity type quay wall is 11.9 metres.

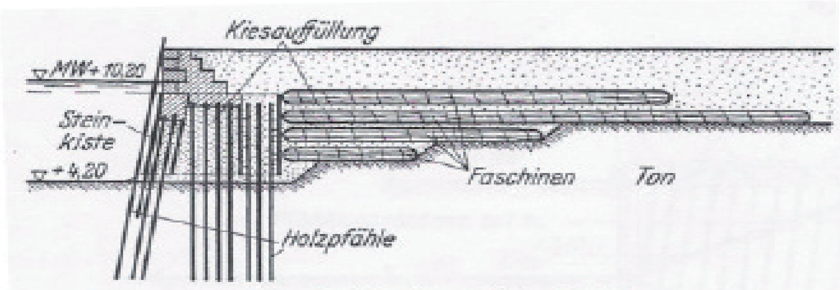


Figure 6.25: Cross-section of Masthuggskaje Gotenburg 1888 [Bergfelt 1955]

The quay wall, Figure 6.25 was built in the port of Gotenborg in 1888. The quay wall consists of an unreinforced concrete superstructure founded on wooden piles. In front of the quay wall a gravel box is placed to permit drainage.
Behind the quay wall fascine mattresses were installed to reduce the active soil pressure behind the quay wall and thus increase the stability of the construction. This quay wall has a retaining height of 7.50 metres.

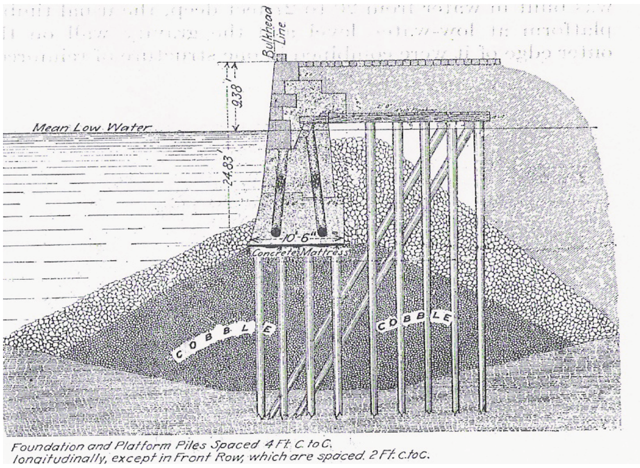


Figure 6.26: Cross-section of combination of retaining and gravity type wall New York 1899 [Greene 1917]

Figure 6.26 shows a quay wall built in New York in 1899, with a retaining height of 7.5 metres of. The wall is a combination of the retaining and gravity types with a relieving floor. A considerable amount of cobbles and stones was used in this structure. The construction sequence started with the placing the cobbles, after which the wooden piles were driven, followed by construction of the floor just above the low water line then the front walls and finally of the relieving floor.

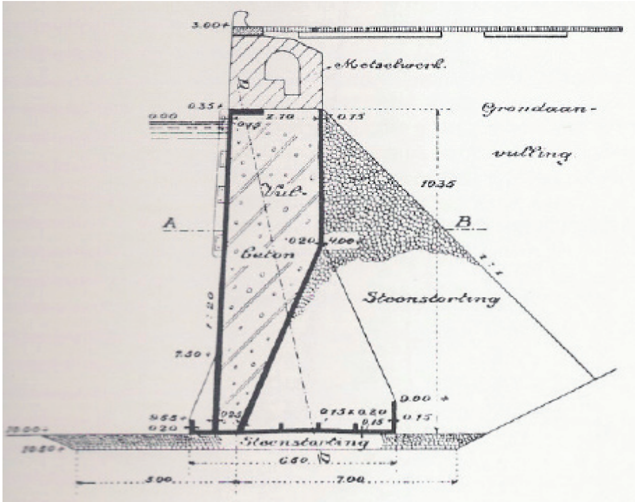


Figure 6.27: Cross-section of reinforced concrete caisson quay wall port of Valparaiso 1903 [HBG 1977]

The earliest caisson-type quay wall was designed by the Dutchman Dr.Krause for the port of Valparaiso.
This structure was built on land and transported by floating to its location. The dotted line indicates the waterline in the floating position. Once at the desired location the caisson

was ballasted and placed in position. The retaining height for this caisson type quay wall is 13.5 metres. This same type was also built in the port of Tandjong Priok in Indonesia in1915. Its dimensions were adjusted to suit the local conditions.

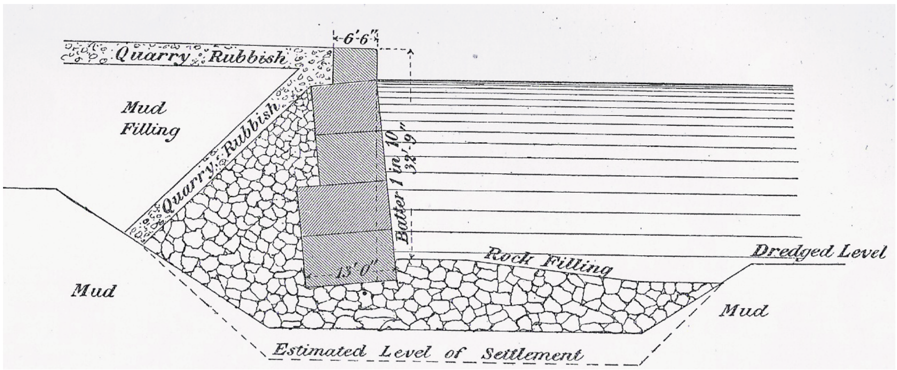


Figure 6.28: Cross-section of unreinforced concrete block wall structure, Bougie, Algeria, 1904 [Duplat Taylor 1949]

Figure 6.28 shows the concrete block wall structure at Bougie, Algeria. This wall is one of the first block walls constructed according to French design. The blocks were fabricated in a yard. Subsequently floating cranes were used to position the blocks on top of each other. The retaining height of this block wall quay is approximately 10 metres

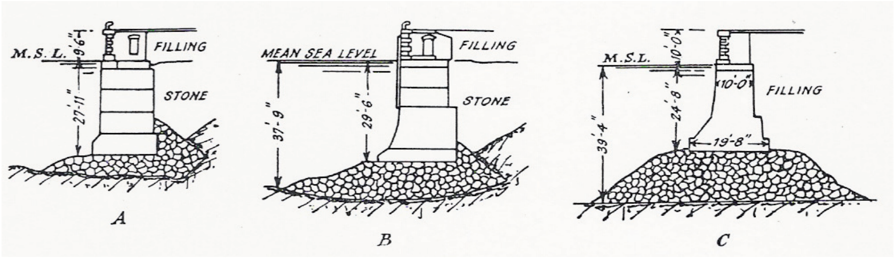


Figure 6.29: Cross-sections of quay walls at Genoa 1905 [Cagli and Bernadini 1905]

Around the Mediterranean most structures are of the gravity type and consist mainly of concrete made in situ or of prefabricated blocks or caissons. Figure 6.29 shows examples of these types of quay walls from the port of Genoa are shown. All the structures are founded on beds of stones. The retaining heights for these structures vary between 7.5 and 12 metres.

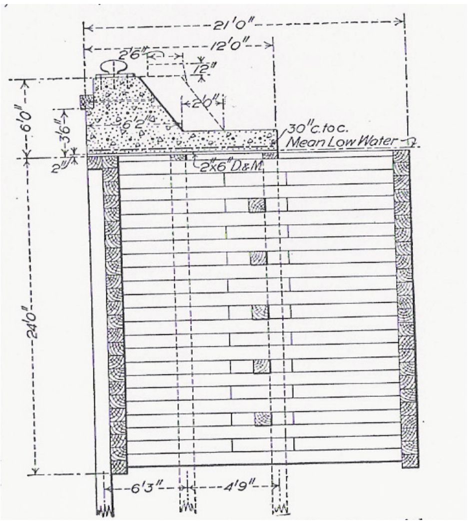


Figure 6.30: Cross-section of crib wall of sawn timber with upper portion of concrete, Duluth, Minn. USA 1909 [Greene 1917]

Figure 6.30 shows a structure consisting of a wooden framework, the crib wall, with a retaining height of 9.3 metres.
A poured concrete structure was placed on top of the crib wall. The concrete super structure was founded on wooden piles by driving the piles through the wooden framework. After the installation of the piles this crib wall was filled up with stones to provide horizontal and vertical stability. These structures were widespread in Canada, USA and Russia where plenty of wood was available. Elsewhere similar crib wall structures were also constructed by making use of concrete beams.

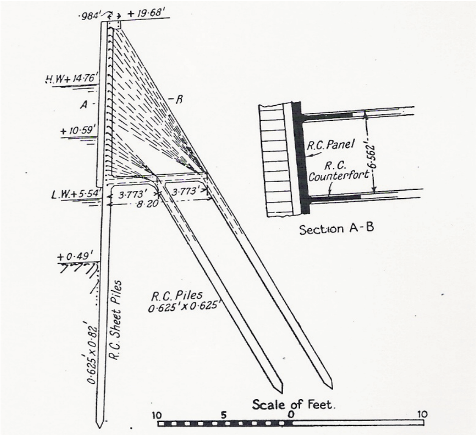


Figure 6.31: Cross-section of reinforced concrete panel wall at Termonde, Belgium 1905 [Duplat Taylor 1949]

The structure built in Termonde, Figure 6.31, is one of first in which precast concrete was used for the quay wall, the bearing piles and the front wall. The anchor forces are taken through the counterforts by the batter piles via tension forces instead of gravity. The construction sequence was to first install the piles and then the platform, followed by the construction of the upper front, the counter forts and the anchoring. The retaining height of this structure is 5.8 metres.

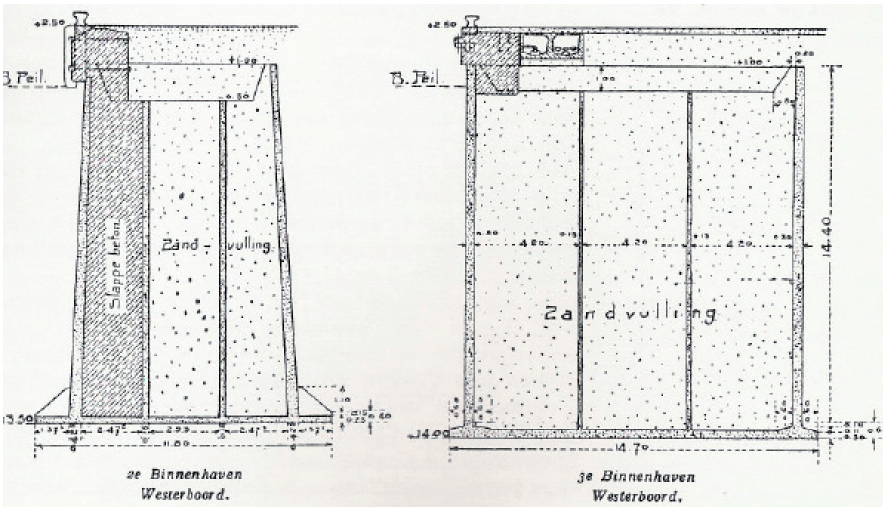


Figure 6.32: Cross-section of caisson type quay walls installed in Tantjong Priok [HBG 1977]

A cross-section of the quay wall of Tantjong Priok (1930) is given in Figure 6.32. Typical are the sloping walls for the ease of concreting. This caisson was later been changed into a shape with vertical walls as that is cheaper to build. The structure at the left was the original Rotterdam caisson and was later modified into the shape indicated in the right cross-section. The retaining height of these caisson-type quay walls is about 16.5 metres. Quay walls of the latter type were built in Rotterdam at the beginning of the nineteen fifties.

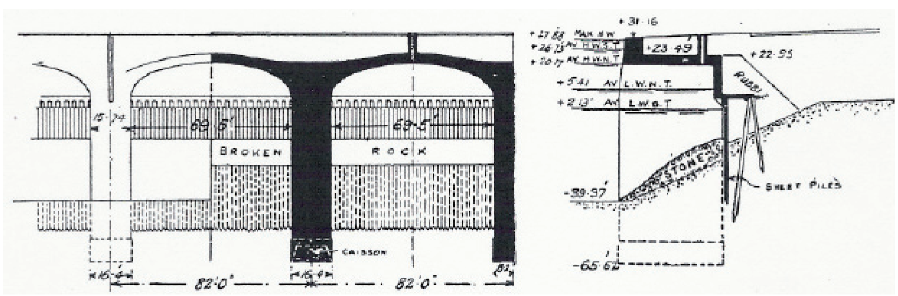


Figure 6.33: Front view and cross-section of quay wall, Le Havre, 1923 [Duplat Taylor 1949]

The structure of a quay wall in the port of Le Havre constructed in 1923 with arches made of bricks and founded on reinforced concrete caissons is shown in Figure 6.33. The span of the arches is approximately 27 metres. The horizontal earth pressure is taken by the sheet pile wall and a filling of broken rock. The retaining height of this structure is 19.5 metres.

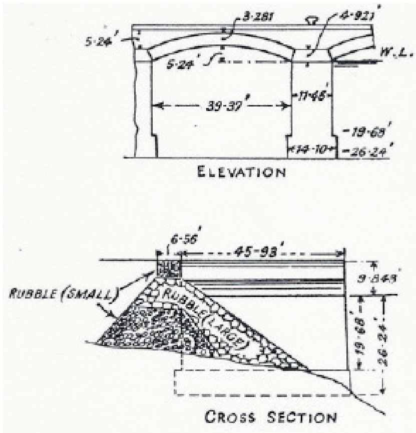


Figure 6.34: Cross-section and front view of quay wall port of Naples 1921 [Duplat Taylor 1949]

This quay wall, which also consists of an arched structure founded on caissons of reinforced concrete, was built in 1923. The distance between the columns is approximately 12 metres and the retaining is height is 9.3 metres. The space between the caissons is filled with a slope of stones of different gradation. The same type of quay wall was built in Naples.

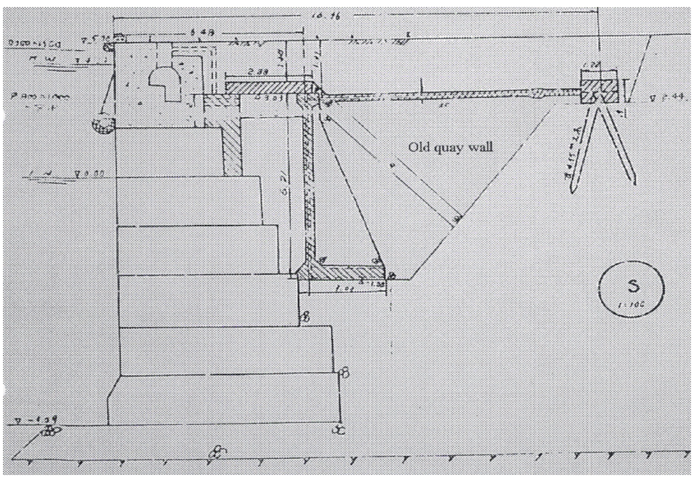


Figure 6.35: Cross-section of two types of quay wall constructed between 1915 and1923 in the port Dalian, China [Peng 2005]

This figure shows the construction of two types of quay wall in the port of Dalian, China. First an L-shaped gravity wall was built, but owing to the increase in the dimensions of ships a block wall was placed in front of this. The old quay wall was already anchored by a concrete beam to a concrete block founded on piles. The retaining height of the block wall is 9.0 metres.

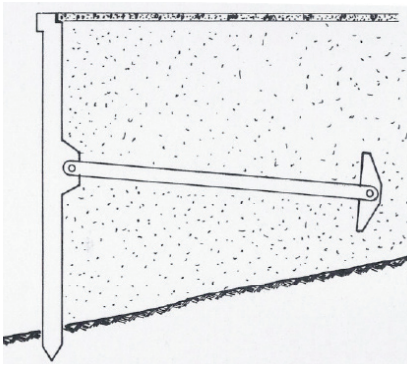


Figure 6.36: Cross-section of quay wall port of Niteroi , Brazil 1929 [Santo Reis and de Bosolo, 1989]

Figure 6.36, shows a quay wall which is approximately 10 metres high and consists of a wall of precast reinforced concrete panels connected to a steel beam by an anchor (flap anchor). The construction was carried out by placing the vertical panels together with the flap anchor. During this process the connection between the elements was secured. The connection between the elements was achieved by a groove connection. This operation is of course very sensitive to the construction sequence. After the installation of the structure the sand filling was placed behind the quay wall.

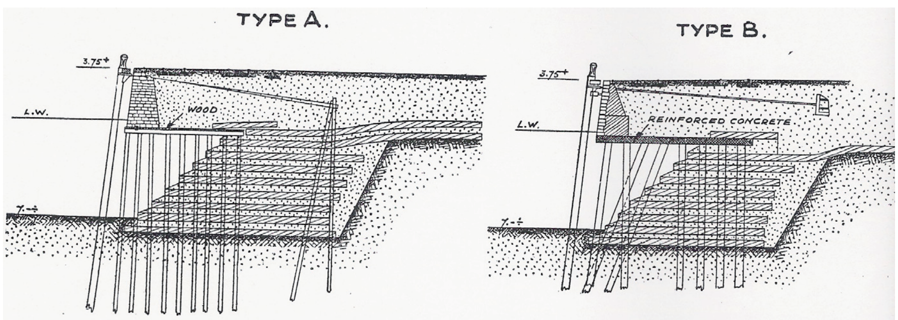


Figure 6.37: Cross-sections of quay walls in Rotterdam 1930

The quay walls shown in Figure 6.37 are examples of quay walls with a retaining height of 10.75 metres, built in Rotterdam in the nineteen thirties. This design shows how it was possible to cope with the very soft clay and peat deposits. These deposits were dredged away and replaced by fascine mattresses. In this way horizontal stability of the dredged trench was obtained. Subsequently the wooden piles were driven through the mattresses and a floor was made of either wood or concrete. Finally the upper part, including

the anchoring, was installed. This upper part initially consisted of bricks. Later reinforced concrete was used.
The difference between the structures A and B is that in A the floor is made of wood while in option B this floor is made of concrete is.

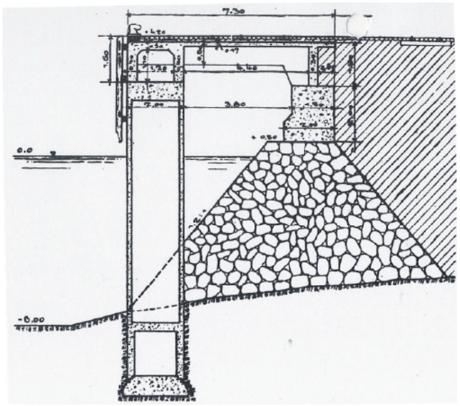


Figure 6.38 Cross-section of quay wall in the port of Seo Sebastio, Brazil 1938 [Santos Reis and De Bosolo. 1989]

The quay wall, Figure 6.38 was constructed from large diameter reinforced concrete columns for a retaining height of 10 metres. The space between the columns was filled with a slope of broken rock. A gravity wall was constructed on top of the broken rock that also forms the foundation for the beams supported on the other end by the columns. The distance between the columns is about 5 metres.

6.5 Period 1950 to 2008

For this period the increase in knowledge and the increased strength of materials became important. Moreover, the lifting capacity of construction cranes increased considerably, as also did pile driving capacities, the latter increase being also attributable to developments in the offshore industry.

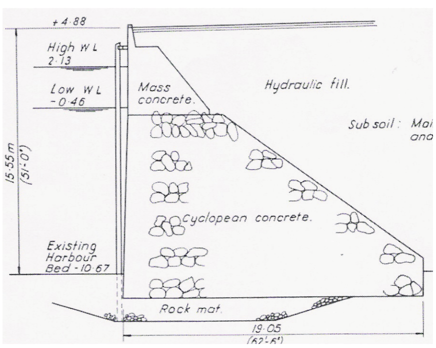


Figure 6.39: Cross-section of quay wall long beach, USA 1959 [Bertlin &Partners 1970]

The quay wall in Figure 6.39, with a retaining height of 4.5 metres, was built by first placing a temporary wooden sheet pile wall and subsequently filling behind with broken rock and mortar on top of which a concrete structure was placed. After the construction of the quay wall hydraulic filling was used to create a terminal terrain.
This quay wall is an example of using much low strength materials without a refined design.

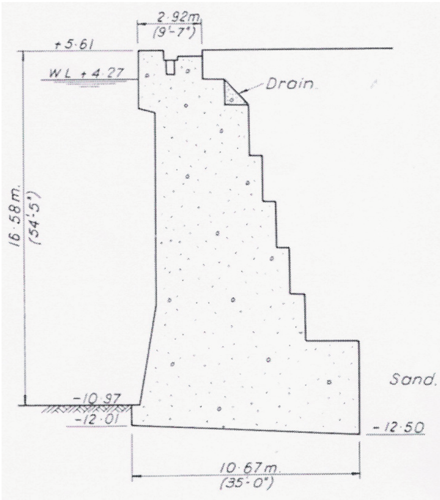


Figure 6.40: Cross-section of quay wall Sixth dock Antwerp 1960 [Bertlin & Partners1970]

This quay wall, retaining height 18 metres, constructed from concrete and bricks in a dry building pit. After the excavation and dewatering of the building pit the concrete was poured in several stages. The structure is founded as a mat foundation on the sand bearing stratum. The front of the quay wall was furnished with a brick panel.

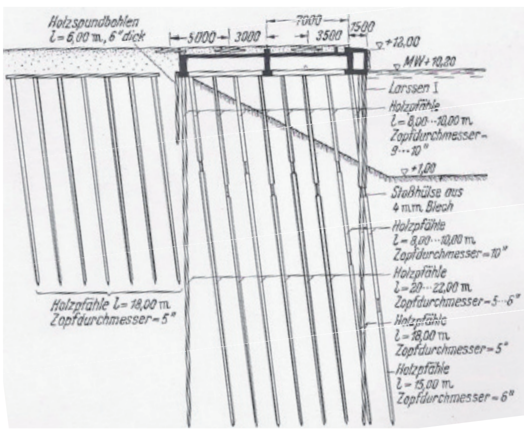


Figure 6.41: Cross-section of quay wall in Goteborg 1950 [Bergfelt, 1955]

This quay walls comprise of a concrete super structure and is founded on wooden piles composed of two sections as the bearing stratum is situated very deep. Further a separate relieving platform is placed behind the quay wall to ensure stability and to prevent excessive settlements. The retaining height is 13.0 metres.

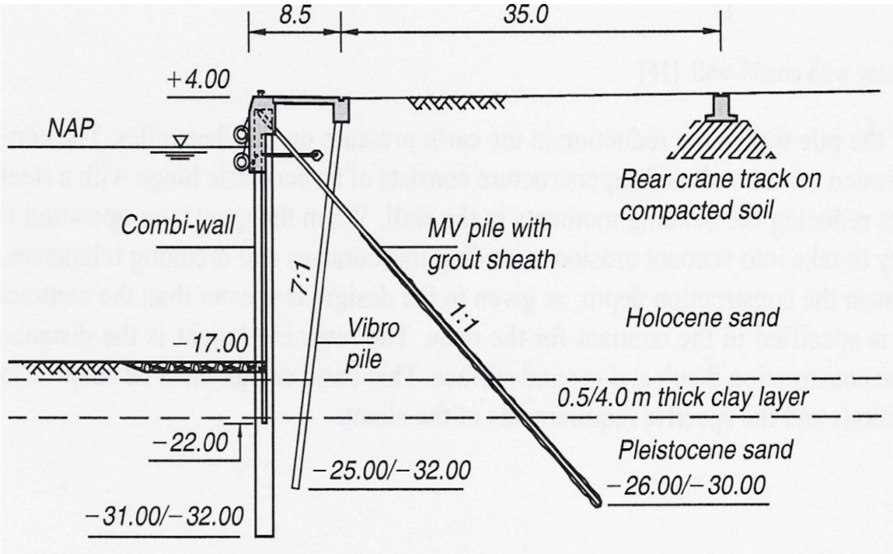


Figure 6.42: Cross-section of quay wall Amazonehaven Rotterdam 1992

This structure of Figure 6.42 is composed of a combi-wall system and the relieving floor is supported by a row a vibro-piles. The quay wall is anchored with MV-piles. This structure was built by using the wet construction method. This implies that the front wall was installed under wet conditions with floating equipment. After the installation of the anchor piles a temporary sheet pile was installed in front of the quay wall to make it possible to construct the concrete cooping. After backfilling the vibro-piles were installed. The retaining height is 22.5 metres.

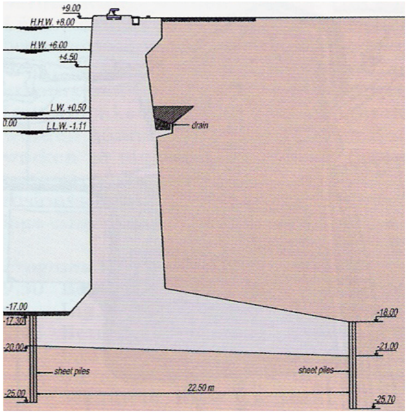


Figure 6.43: Cross-section of quay wall Deurganckdock I, Antwerp 2006 [Hansa 2008]

The Deurganckdock quay wall (2006), Figure 6.43, is a wall of the gravity type and consists of a heavy L-shaped poured in situ reinforced concrete structure. It was constructed in a large dry building pit. The dewatering system of this pit was very impressive, since it involved lowering the groundwater level by 20 m. The construction sequence was first the installation of the seepage cut-off walls at the bottom, followed by pouring a concrete block between the seepage cut-off walls. Next the vertical wall was concreted in two phases. The retaining height of this gravity type quay wall is 28.5 metres.

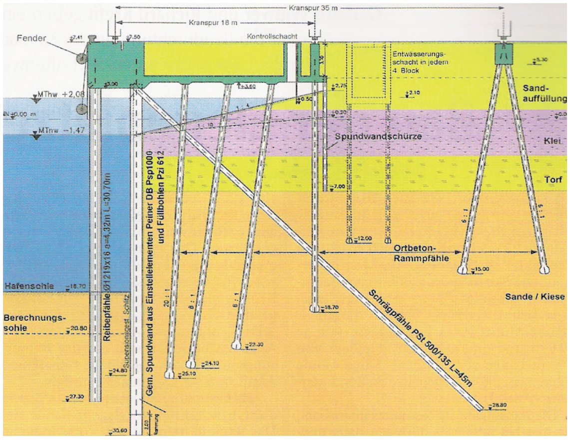


Figure 6.44: Cross-section of quay wall Alterwerder, Hamburg 2006 [Miller 2007]

Figure 6.44 shows the Alterwerder quay wall, retaining height 27.5 metres in Hamburg. This quay wall is also of the retaining wall type. The structure is composed of a heavy reinforced concrete relieving floor founded on 3 rows of Franki-piles. The front is of the combi-wall type. Mooring piles are installed some 2 metres in front of the combi-wall to accommodate the fendering system. The space of 2 metres between the mooring line and the combi-wall is also advantageous during the mooring of the ships. At the front the foundation for the container cranes is provided by the structure itself, while at the rear of the structure a separate pile foundation has been created.

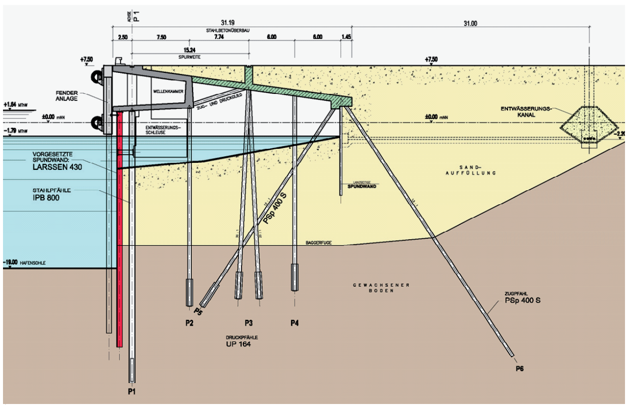


Figure 6.45: Cross-section of quay wall Bremerhaven 2006 [Vollstedt 2008]

As shown in Figure 6.45, this quay wall in Bremenhaven consists of a relieving platform founded on steel I-piles with additional supports at the tips. Very heavy steel I-shaped anchor piles are also included. The front wall is a combi-wall system while the fendering system is movable. Typical of this quay wall is the wave chamber that has been incorporated to reduce the effects of waves and thus providing a relative quite and safe berthing. The retaining height of this structure is 28 metres.

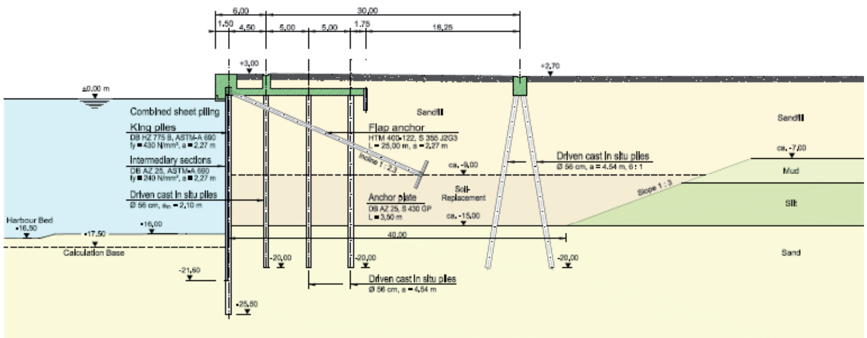


Figure 6.46: Cross-section of quay wall Gdansk 2006 [Tworuschka 2009]

The quay wall, Figure 6.46, with a retaining height of 20, 5 metres was constructed by first removing the soft soil deposits, clay and peat and then installing the front wall. A part of the sand filling has been carried out to make it possible to install the flap anchor. The wall is connected with the flap anchor. Subsequently the additional hydraulic fill was placed, followed by the installation of the in situ made vibro-piles and finally the concrete super structure is made.

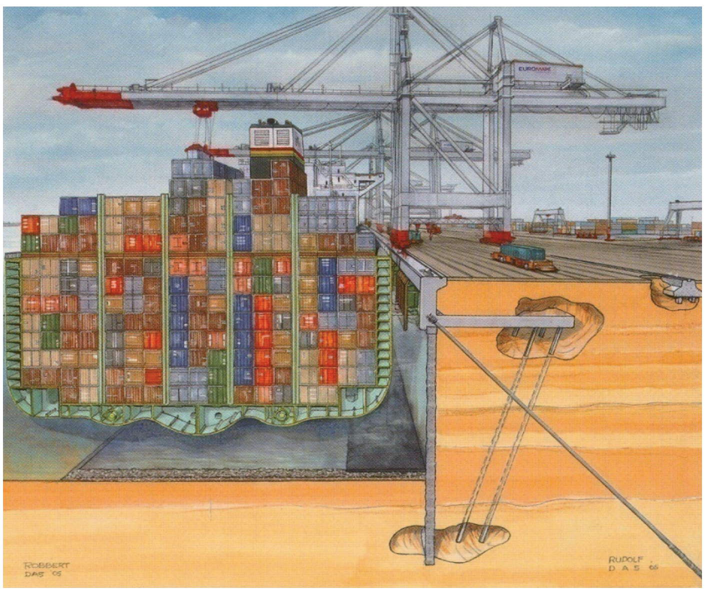


Figure 6.47: Cross-section of quay wall Euromax Terminal, Rotterdam 2007

The Euromax terminal built in the Port of Rotterdam, Figure 6.47, is a retaining type of quay wall with a diaphragm wall as the front wall and an L-shaped reinforced concrete relieving floor founded on vibro-piles. The quay wall is anchored with MV-piles. These MV (Muller-Verfahren) piles are I -shaped steel piles surrounded by grout. The tensile capacity of the MV piles applied here is 6000 kN. The vibro piles each have a bearing capacity of 2000 kN. The retaining height is 26.5 metres.

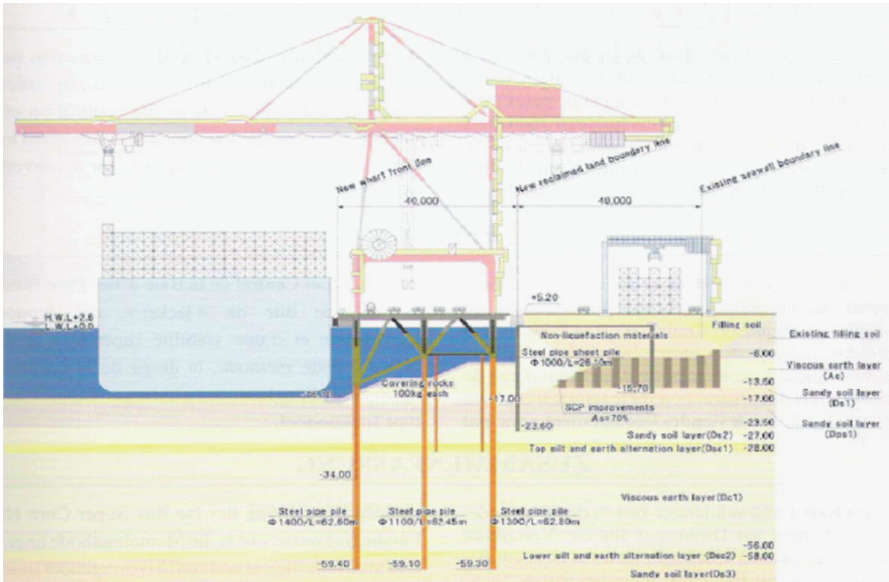


Figure 6.48: Quay wall port of Nagoya in Japan 2008 [Hoshiyama 2009]

The existing berth has a too shallow depth and therefore a new quay wall has been designed with a greater depth, retaining height 21.5 metres. This new quay wall is founded on long (about 63 metres), steel piles. This was necessary to overcome the soft deposits and to take into account earthquake loading. This quay wall consists of template steel structure on top of the steel piles

6.6 Summary

This chapter presented an overview of different type of quay walls built in the world at different locations and at different times. It has been clearly shown that the earlier quay walls were built of wood and stone. In fact in the past the availability of construction materials determined the kind and the use of construction method.
After the industrial revolution iron was introduced as a building material.
Since around 1900 steel and concrete have been the most frequently used construction materials throughout the world. This is because, in principle, every shape can be made with concrete, either in situ or prefab, and very strong reinforcement steel is available.
The shapes and type of quay walls did not change very abruptly but the retaining height increases incessantly However due to improvement of material properties and design techniques is has been possible to design more slender structures which incorporates bending and tension instead of gravity structures where mainly compressive forces have to be transferred.

7. Development of construction techniques

7.1 Introduction

This chapter gives an overview of the development of construction techniques, including aspects such as shallow- and piled foundations, pile driving, lifting capacity, and concreting. The methods of geotechnical investigation that we use today did not exist in ancient times when the selection of the proper foundation method to use was based on trial end error. However in earlier days the construction period was longer so the soil had time to consolidate and accommodate to the loads imposed by the structure. The construction options ands techniques used were heavily dependent on local experience and on the availability of construction materials. This meant that in regions where forests were abundant, such as the USA, Scandinavia and Russia, most structures were built of wood, while in regions with only quarry material available, such as the Mediterranean and England, structures were built in stone.

7.2 Foundations

7.2.1 General

Structures need an appropriate foundation to direct the loads to the subsoil. This can be achieved by making a foundation directly on the soil, which is called a shallow foundation, or by making a foundation supported on piles. With the second foundation method the loads are transferred to lower bearing stratum. The final choice depends on the subsoil conditions and the potential ability of the chosen structure to sustain deformations. Furthermore, two construction methods can be distinguished in relation to the position of the quay wall relative to the water levels. The open pit construction method is used when it is possible to create a dry construction site. This method has several advantages like the logistics, positioning of elements and it is easier to inspect the structure. Usually it is necessary to lower the water table. In this case it is necessary to take into account the variations in the water level. The wet construction method is selected, for example, when there is no alternative such as building the structure in open dry building pit or when there is insufficient space, permeable soil, or there is no time to build the pit to construct under dry conditions. However, if the wet construction method is selected the option for prefabrication of the structural elements must be considered as this can improve the quality of the structure as well as to reduce the construction time. In this way the costs of both equipment and labour are reduced.

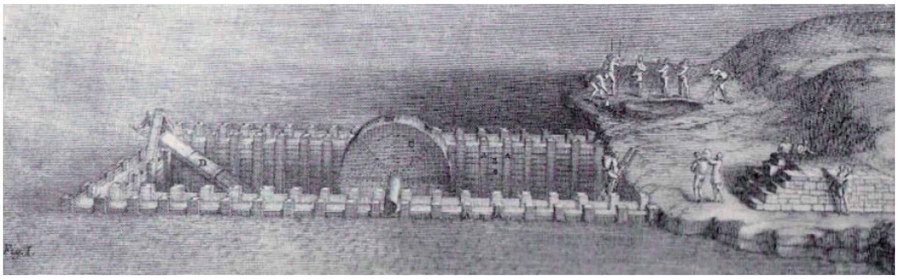


Figure 7.1: The construction of a mole under dry conditions [Vitruvius 20]

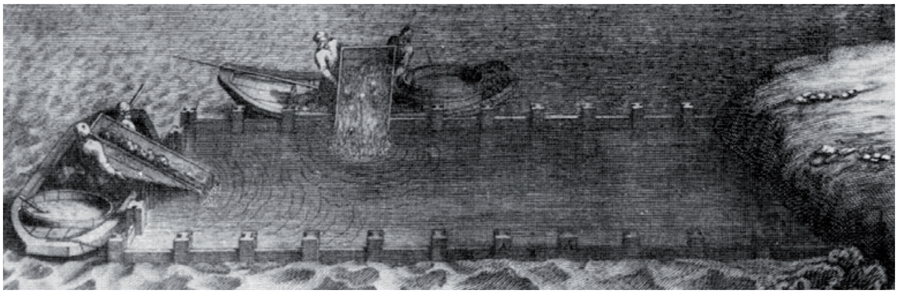


Figure 7.2: The construction of a mole without dewatering, with concreting under water [Vitruvius 20]

7.2.2 Shallow foundations

In the past where possible a shallow foundation was chosen as driving was still primitive. The choice being based on local experience of the behaviour of the subsoil [Vitruvius 20]. When possible the wooden parts of the structure were placed under water to prevent rotting. The first mat foundations were usually made under dry conditions. Depending on local availability, wood, stone and bricks were used as foundation materials. Since 1900 reinforced concrete has been used as mat foundation material.

7.2.3 Pile foundations

When the top soil was very weak and the firmer layers were found deeper down the top layer could be removed or pile foundations could be used to transfer the loads to the firm deeper layers. Pile foundations were used before Roman times [Leimdorfer1976] and in China they were also used for bridge foundations [Tomlinson 1994]. The piles were driven down to the firm layer by hand. The pile in those days driving process has evolved from hand driving to the use of modern driving equipment with enormous capacities. Although pile foundations have already existed for a very long time, and this is not a new technique, the methods used in the past were very different from those used at present. Before Roman times the driving of piles was carried out by one or two men each lifting by hand a weight of approximately 30 kg and dropping that weight onto the pile head from a height of 1 metre.

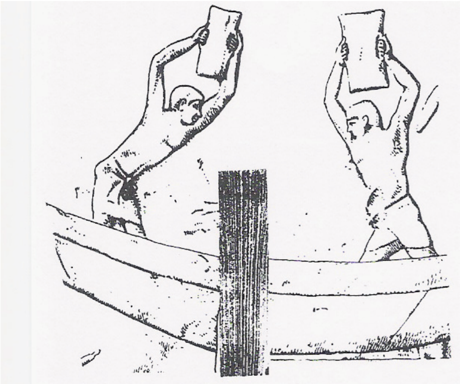


Figure 7.3: Ancient pile-driving system [Leimdorfer 1976]

This process was continued up to refusal, which is the point when the pile can be driven no further. The use of this method continued for many years but in the 15th century the weight used was increased to 50 kg. The work then was done by four men , although the drop-height was still limited to by the size of the human body around 1 metre.

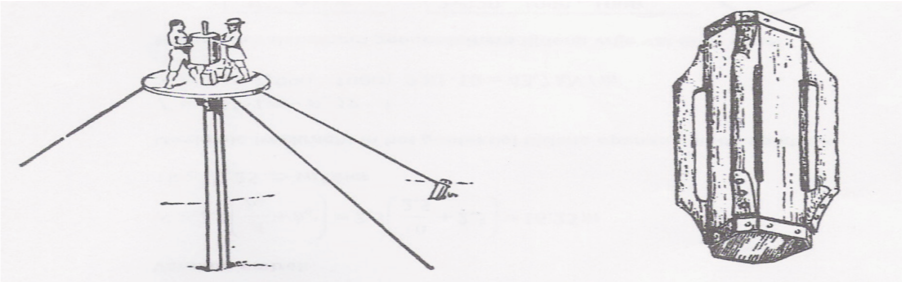


Figure 7.4: Hand driving equipment in 1400 [Huizinga 1985]

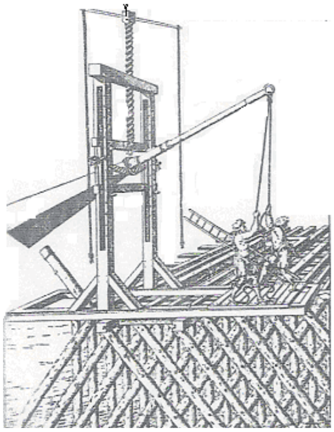


Figure 7.5: The driving of wooden batter piles in the 16th century [Belidor 1783]

Later the weight was increased to 80 kg and then to 160 kg and the falling height was 2 m. This method of driving required the effort of 16 men. This way of pile driving was carried out by pulling up the weight via the cords from the men to the dropping weight. To harmonize the process the men sang ‘driving ballads’ (Huizinga 1985).

Batter pile driving was already possible in 16th century (Fig. 7.5). In Holland around 1700 the Dutch piling frame was developed.

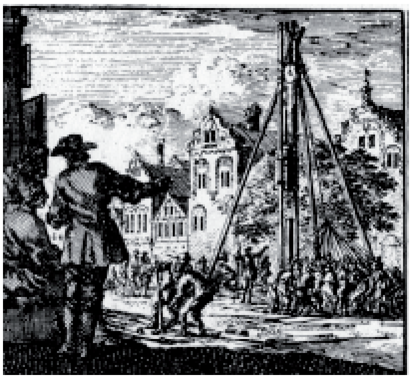


Figure 7.6 Dutch pile driving equipment (Huizinga 1985)

With this equipment the falling height could be increased to 2-3 metres and the weight of the driving block was increased to between 400 and 1,000 kg. Similar developments, initiated by the growth of Venice, took place in Italy at that time.

In Bremen (1850) the triple pile driver was developed to increases the rate of the pile driving operations. With this machine three piles could be driven simultaneously.

Over time many kinds of different pile driving formulas have been derived in several countries, mainly to predict the bearing capacity of the piles and to plan the piling operations better. However the accuracy and the reliability of these formulas are not very high. Since the nineteen seventies the wave equation theory has been applied to the driving of piles. This has made it possible to perform pile driving analyses and to predict the bearing capacity of piles much more accurately than before.

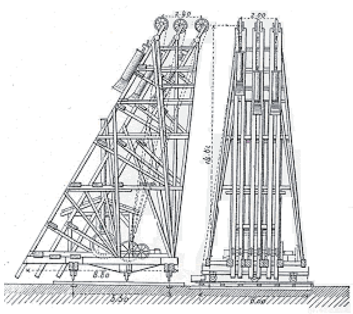


Figure 7.7: The Sonnette triple pile driving system used in Bremen, 1850 [Rochemont and Desprez 1900]

Although some improvements during time already had been achieved in the piling equipment, however a big improvement took place around 1868. In that year the German company Menck and Hambrock designed the first steam-powered pile driving equipment. The falling weight was pulled up by the means of a valve in the cylinder. The steam boilers were initially fed by burning coal. After 1945 however, diesel power was used. In Germany in 1926 the Demag Company developed the first diesel hammers with a falling weight of 500 kg with an air-benzol mixture.

In 1936 Demag succeeded in designing the first hammer which was lifted by the explosion of diesel oil. Later, around 1950, the double acting steam hammer was introduced which generates more energy per blow to the piles. The number of blows for a single acting diesel hammer is approximately 50 blows per minute while for the double acting hammer 90 blows per minute are achieved.
A great step forward in relation to pile driving was made in the nineteen seventies, when the first hydraulic hammers were designed by two Dutch companies, first HBG and later by IHC between 1960 and 1970. The efficiency of these hydraulic hammers is circa 50% greater than that of diesel hammers and in addition it is also possible to use these hammers for driving piles underwater. This development coincided with the need for heavier pile driving equipment required for the offshore structures built in North Sea.
In the Port of Rotterdam the steel pipe piles in the combi-wall system of the quay walls were driven by a hydraulic hammer with an energy of 2400 kNm per-blow.
In Figure 7.5 the development of the energy per blow versus time is indicated.

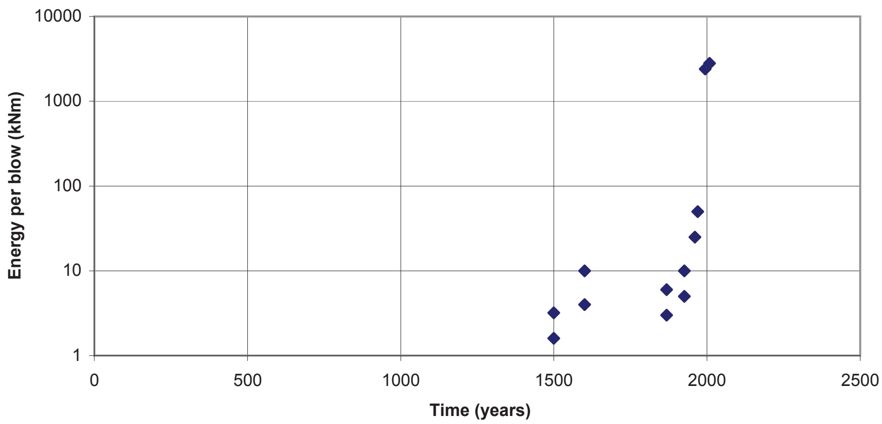


Figure 7.8: The development of pile driving energy versus time

The increase of pile driving energy of the present driving equipment has made it possible to drive heavier and longer piles and thus increase the scale of the foundation of quay walls.

7.3 Construction methods

7.3.1 Constructing under dry conditions

By using the construction method the structure is built under dry conditions.
First a construction pit is excavated and it is often necessary to lower the groundwater table. To ensure that this building pit remains dry a dewatering installation is necessary.

Figure 7.9: Construction pit for a gravity wall in a dry pit, Glasgow 1850 [The Glasgow Story]

In the port of Glasgow a gravity type quay wall was constructed by using prefabricated concrete elements.
This building pit could be excavated under dry conditions without the use of a dewatering system which was made possible by the impermeable soil conditions.
Subsequently the prefab elements were on top of each other.

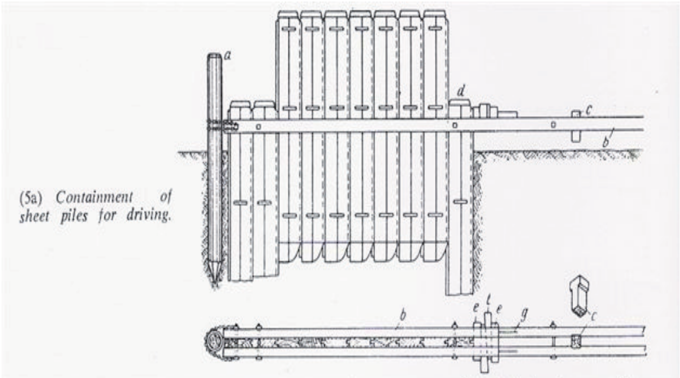


Figure 7.10: The installation sequence for wooden sheet pile wall [Leimdorfer 1876]

This figure illustrates the installation sequence for a wooden sheet pile wall.
Today a guiding frame (Figure 7.11) is used for the installation of steel combi-wall systems to ensure the accurate installation of the combi-wall elements. This guiding frame must secure the position of the piles as otherwise the sheet pile elements cannot be installed.
If pipe piles are used the turning of spiral welded piles must be prevented.

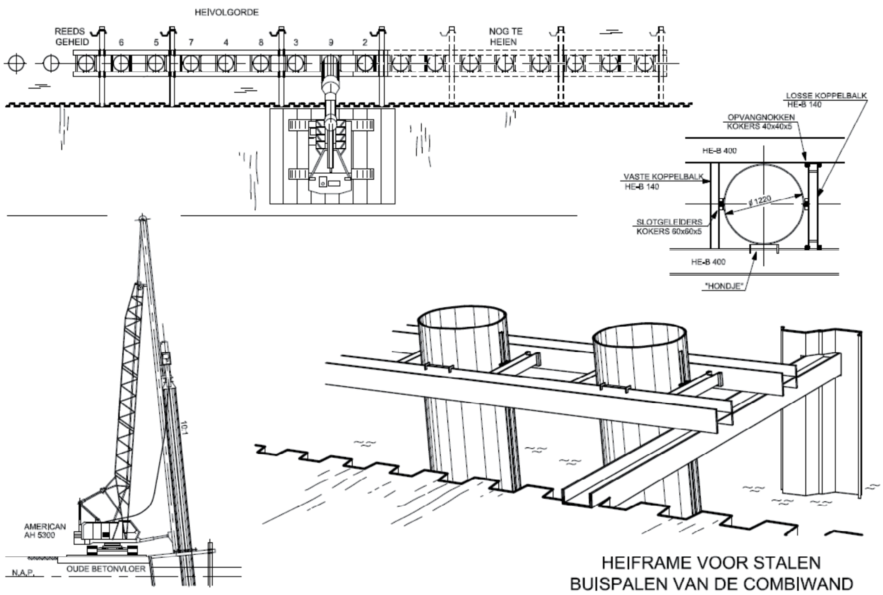


Figure 7.11: Guiding frame for the installation of combi wall system [de Gijt 1996]

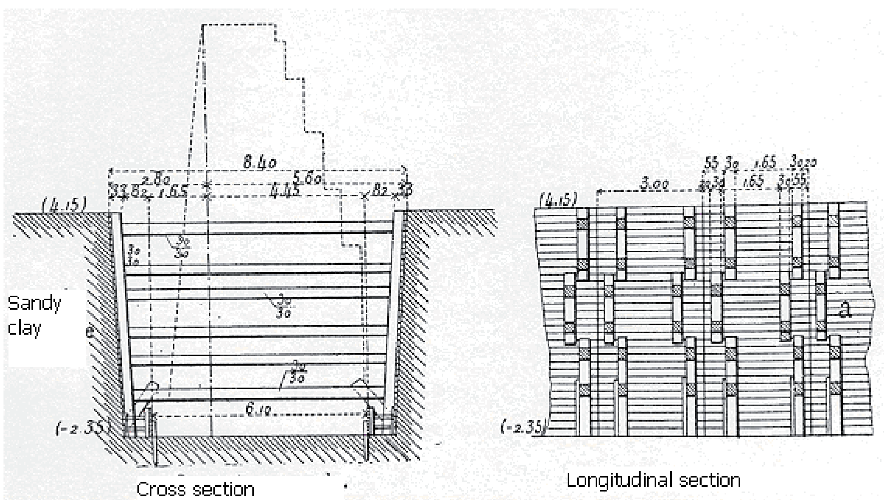


Figure 7.12: Cross and longitudinal sections showing strutted excavation 1890 [Rochemont et Desprez 1900]

In Figure 7.12 the execution of the technique used around 1890 is shown. This figure illustrates the construction of a gravity type unreinforced concrete quay wall with impermeable soils under dry conditions in a braced building pit.

Figure 7.13: Quay wall constructed under dry conditions in a building pit with a dewatering system [De Gijt et al 2003]

The building pit in excavation in sand, Figure 7.13, was kept dry by a dewatering system that lowered the water table by 20 metres. The lowering of the ground water table necessitated that measures were taken to prevent settlements in the surroundings. The area affected by the lowering of the ground water table was limited by installing injection wells and also by building a slurry wall.

7.3.2 Constructing using the wet construction method

In this case all the construction activities are carried out from floating equipment. This working method requires that variations in water level be taken into account, which means that some construction activities are tide-dependent. In order to ensure the accurate execution of the work great attention must be paid to the positioning of the floating equipment.

In Figure 7.14 the subsoil consists of rock, the profile of which is very irregularly overlain by very soft clay (Vase) is shown. Explosives were used to remove the rock in order to create an adequate foundation for the caisson. This was done in 1-1.5 metre thick layers. Subsequently the rock debris was removed by digging. The caisson was 9-12 metres high and had a diameter of 11.40 metres. The weight of each caisson was 20000 kN.

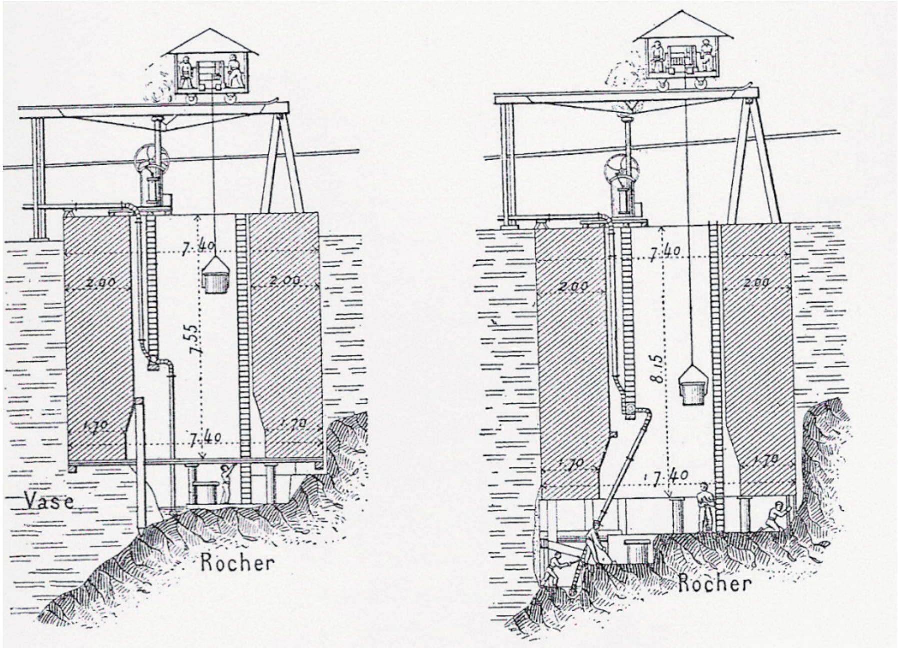


Figure 7.14: Construction with the wet construction method 1850 as used in St Nazaire [Rochemont and Desprez 1900]

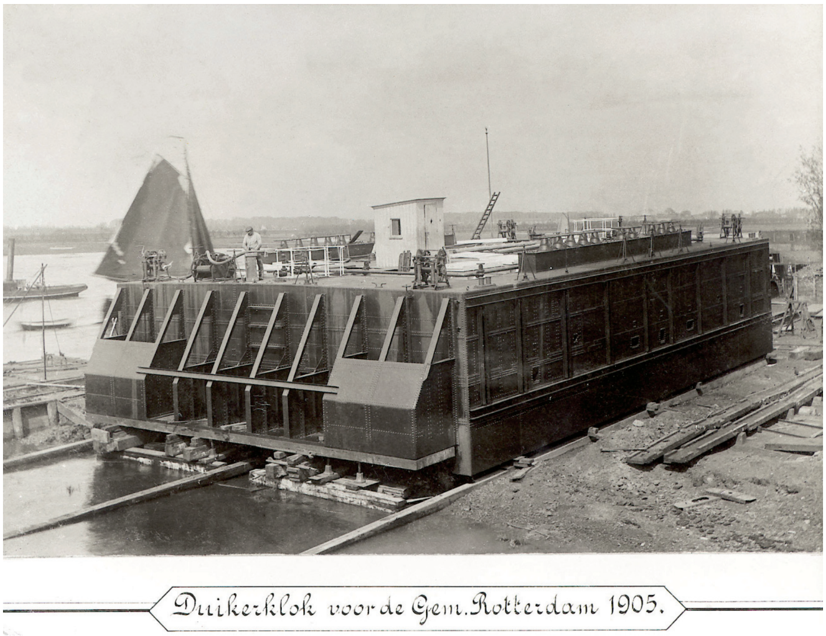


Figure 7.15: Diving bell of the Municipality of Rotterdam 1905 [De Gijt et al 2003]

The figure shows the use of a steel diving bell in the Port of Rotterdam. This was used to ensure that the construction activities were independent of the tidal variations.
It was possible to work continuously under increased air pressure. The water level is lowered by the increasing the air pressure. All the workers had to be protected from the caisson disease and therefore they could work only for short periods.

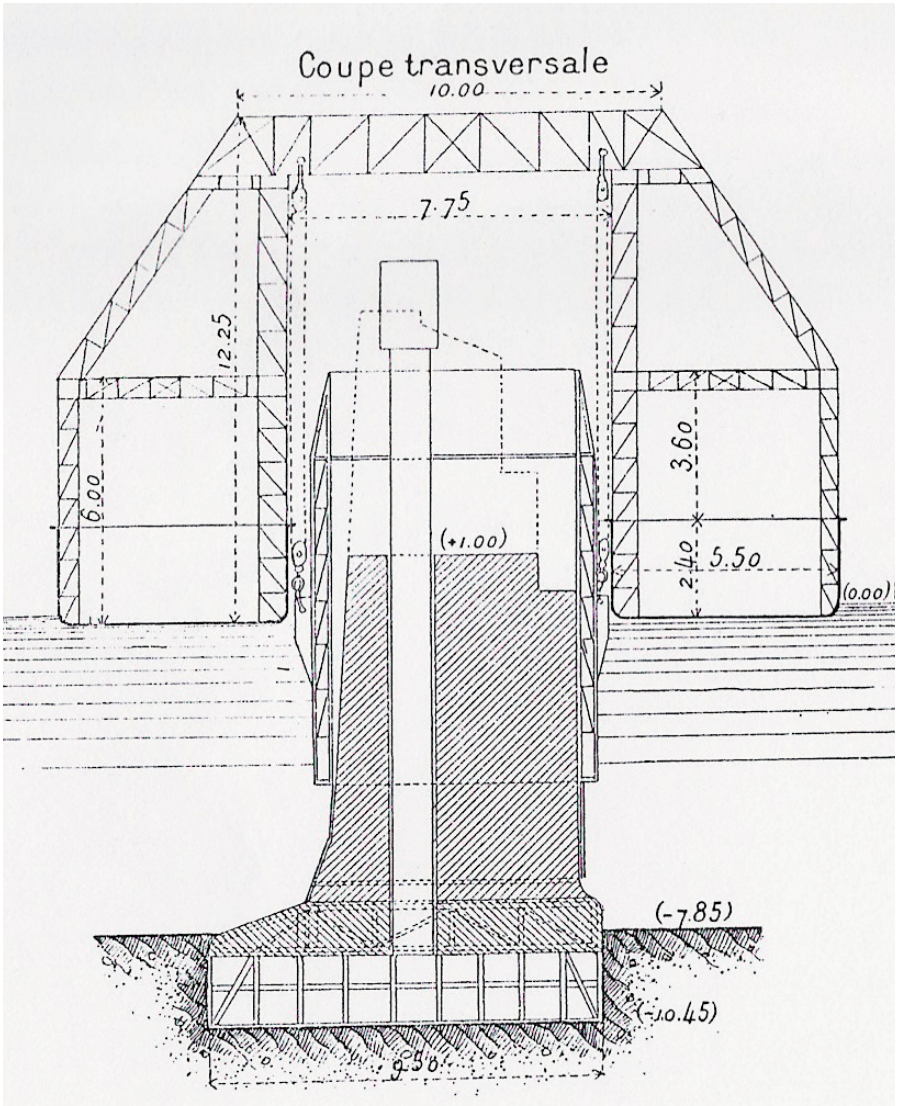


Figure 7.16: Cross-section of a quay wall constructed in Antwerp 1890 [Rochemont and Desprez 1900]

The construction of the gravity walls in the port of Antwerp was carried out by making a caisson-type of structure with the aid of a steel diving bell that was attached to the foundation, after which the concrete part above this was made by using a floating framework.

The construction sequence of this gravity wall was first excavated to the foundation level with the aid of compressed air and subsequently to position the steel structure on the foundation, after which the concreting of the upper part was completed. The total system was secured in place with two ships along side of the structure.

The total length of one section is 30 metres , the width is 9.5 metres and the height 3.25 metres. The height of the foundation section was 3.25 metre while the height of the working chamber is 1.70 metres. The working chamber was constructed in steel. On top of the working chamber a cylindrical steel mantle was attached to transport people and materials.
The building of this structure was made possible by the aid of a steel structure that acted as guiding and casting for the concrete to be placed.
After excavation to the required level was completed the section above the foundation level was made by lowering the formwork with the guiding frame. The space occupied by the working chamber was then filled with concrete. Subsequently the following sections were installed.

7.3.3 Combined methods

If caissons or similar structures are selected it is a great advantage if a dry dock can be used for their construction. After construction the caissons are floated to the site and carefully sunk into position.
The construction of quay walls can also be carried out from the landside with subsequent transport either by floating or by lifting materials onto the site.

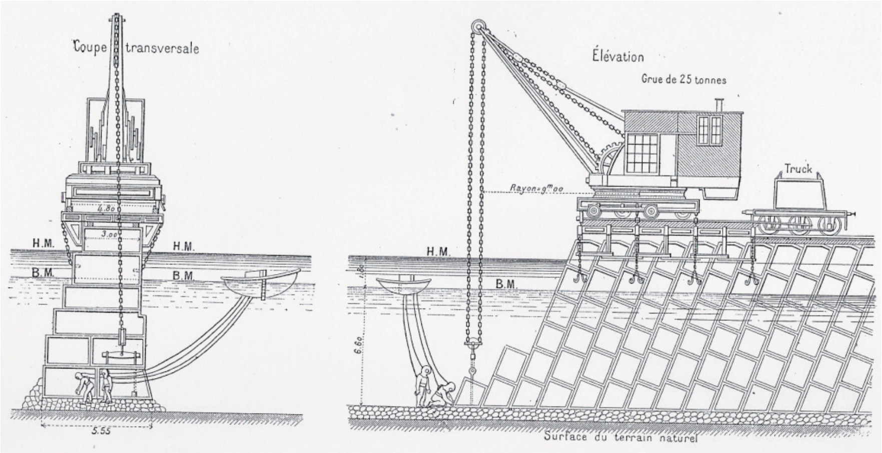


Figure 7.17: Placing of a sloping bond block wall 1870 [Rochemont and Desprez 1900]

In the port of Rotterdam, Figure 7.18, the subsoils consist of very weak peat and clay layers (untrained shear strength of 10 kN/m2). In this case the option selected was to excavate the soft deposits and then to backfill and preload the site before building the quay wall.

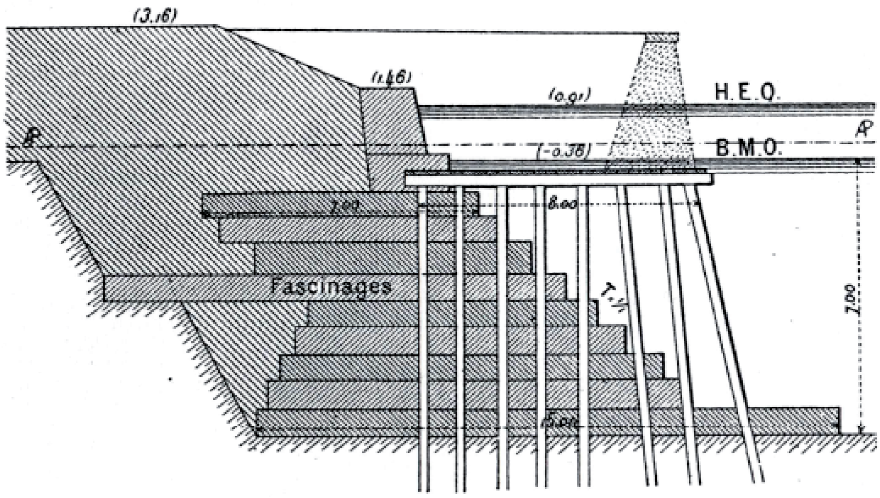


Figure 7.18: Quay wall structure, Rotterdam1870 [Rochemont and Desprez [1900]

For the structure shown in Figure 7.19 in Amsterdam, a 25 metre thick sand layer was used to preload the area to minimize settlement. This working method was necessary to improve the strength of the very weak soils consisting of very soft peat and clay layers. The preloading took about one year. Subsequently the quay wall structure was built. This preload method was selected as excavation of all the soft deposits would have been too expensive

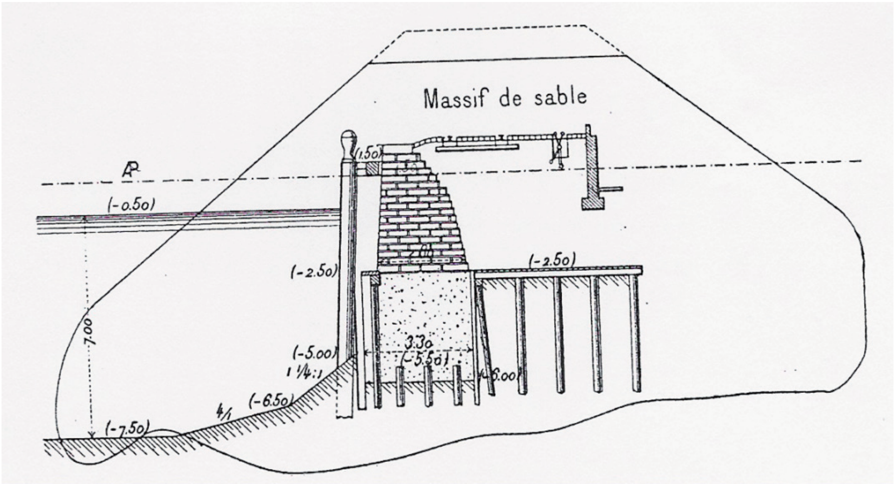


Figure 7.19 :Quay wall structure in Amsterdam with preloaded site [Rochemont, Desprez 1900]

7.4 Pouring concrete

Under water concreting was already used by the Romans [Vitruvius 20]. Although this technique has improved, the principle is the same. An example of the underwater concreting that was carried out around 1880 is presented in Figure 7.25. The wooden supporting framework is a structure of considerable size. In the water the concrete was carefully lowered by means of a bucket to prevent segregation of the mixture. Today Tremy pipes are used to prevent segregation.

Concrete needs a curing time to develop its strength. During this period the fresh concrete must be supported by the formwork system. These systems have recently evolved from material-intensive wooden support structures to sophisticated movable steel formwork systems. If necessary a cooling installation is also incorporated.

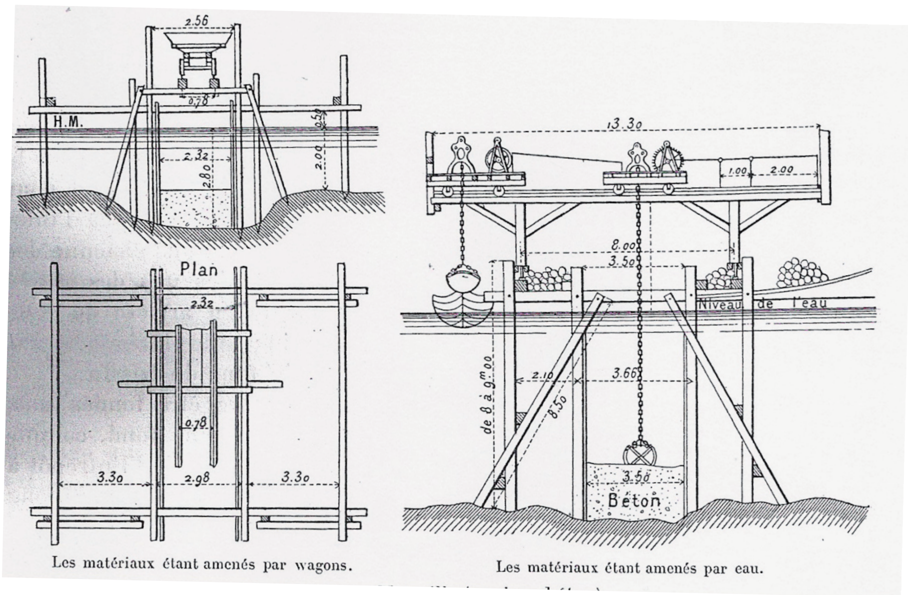


Figure 7.20: Placing concrete under water around 1890 [Rochemont and Desprez 1900]

7.5 Cooling of concrete

A cooling system is used when relatively thick (1.5-2 metres) concrete structures are built. The use of a cooling system removes the heat generated by the chemical reaction of the hardening of cement and water and ensures a better control of the hardening process while the development of cracks is prevented.

Figure 7.21: The cooling system used in the construction of a concrete quay wall [de Gijt et al 2003]

7.6 Lifting machinery

The use of cranes and other equipment is vital to reduce the construction time and to working in a manner that ensures the safety of those working on the construction site. Today large cranes are used to handle the pile driving equipment, concrete installations and concrete framework. However in the past too, heavy equipment was developed, especially after the industrial revolution when steam and later machines using other forms of power became available. Figure 7.22 shows equipment used to place concrete blocks and a floating crane used for heavy lifting activities.

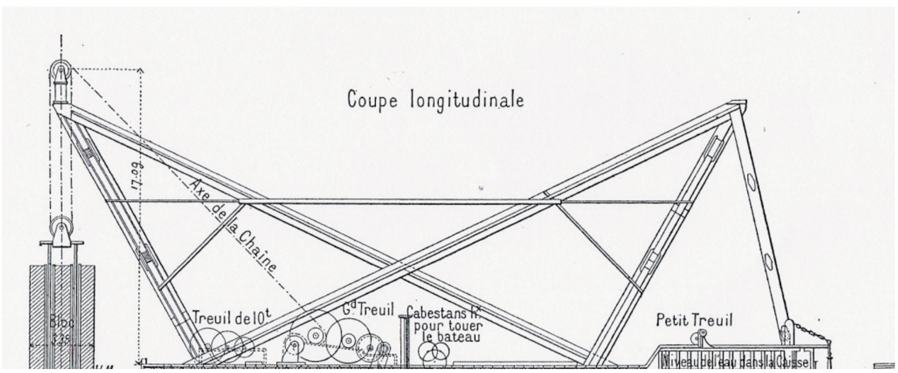


Figure 7.22: Lifting machinery specially designed for placing concrete blocks [Rochemont and Desprez 1900]

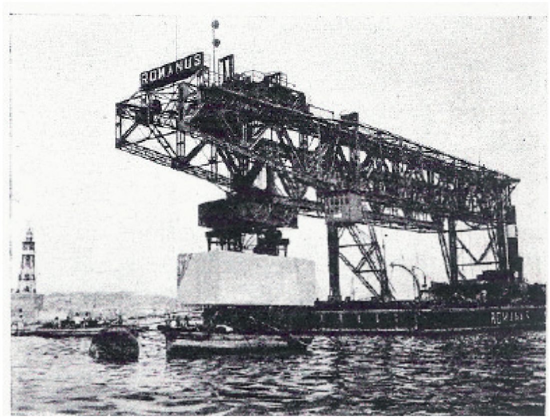


Figure 7.23: Crane for placing the blocks of gravity type quay wall in Venice [Cagli and Bernadini 1905]

These types of cranes were built especially for the placing of the prefabricated blocks of the quay wall structure. The weight of the blocks the dimensions of which were 2 metres wide by 2 metres high and 4 metres long is approximately 320 kN.

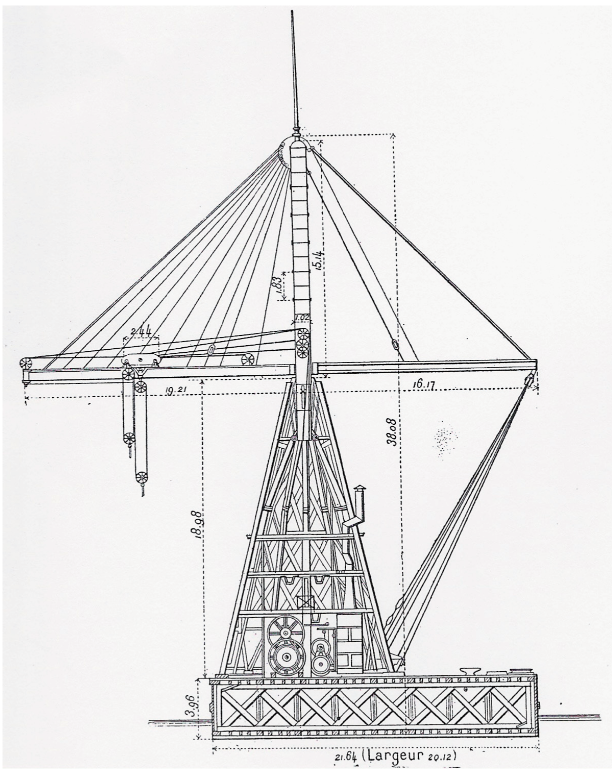


Figure 7.24: Floating derrick structure used in the United States around 1870 [Rochemond et Desprez 1900]

This floating derrick crane, shown in Figure 7.24, could lift 1000 kN and was used to transport and lift heavy elements like piles and concrete blocks for the construction of quay walls.

Figure 7.25 Handling of a caisson type quay wall in Japan

The first concrete caissons were designed by Dr. Krause in Chile. These caissons were built on land and then floated to their final position (Section 6). During the period between 1920 and 1940 concrete caissons were built in Rotterdam in an excavated construction dock. This method made it possible to build the caissons completely under dry conditions. Once the caissons were finished the dock was flooded and the caissons could be floated to their final location. At this location the upper part was finished.

In Japan since their introduction by the Dutch in around 1920, quite a large number of quay walls of the caisson type have been built. This is partly in response to the need for earthquake loading and partly due the fact that extension harbour areas are made in open water and then caissons are installed as quay wall, while the area behind the quay wall is filled with sand to create the port area. Heavy cranes as shown in Figure 7.25 are used to transport and place the caissons in their final position.

Heavy lifting equipment, Figure 7.26, was used to place the steel on top of previously installed piles to construct a new quay wall in front of an older one (see also Figure 6.48)

Figure 7.26 Heavy lifting crane used for placing the steel top on the installed piles [Hoshiyama 2009]

7.7 Summary

In this section the development of construction methods and techniques was discussed. This development shows that even in the past people could already construct enormous quay walls while their equipment which was relatively simple compared to modern equipment.
It was also shown that working conditions are now much better than in earlier times. The evolution of equipment, together with progress in the development of materials, permitted the construction of higher and more extensive quay walls.
With the development in cargo handling facilities and the improvement in quay wall design the logistics of the port activities was improved.

8. Factors that determine the design and construction of quay walls

8.1 Introduction

The design and construction of quay walls is a complex process that is influenced by a number of sometimes conflicting factors. First the factors that determine the design of quay walls are discussed .Subsequently functional requirements of quay walls are discussed. This chapter describes the functions that a quay wall must to fulfil.
After establishing the programme of functional requirements a technical programme of requirements is composed. In this the technical aspects needed for the design are described in detail.
The two programmes of requirements, functional and technical, are essential to good communication between client and builder /designer.

8.2 Factors that determine design and construction of quay walls

8.2.1 Soil and subsoil conditions

For every civil engineering design it is important to have a through understanding of the soil conditions; for quay design this is crucial. The subsoil condition poses limitations and challenges for the designer who has to cope with the soil material encountered. The forces, resistance and loads generated by the various types of soil types can be very different.

8.2.2 Tidal variation

The tidal variations in the area play an important role, as does the response to these variations in the groundwater regime at the land side, since this determines the differences in the water level over the structure. This difference may be very significant and may amount to 30 - 50% of the total force to be resisted. The tidal range varies greatly with location ranging from 0.5 metres to more than 8 metres. However, wave loading is not usually taken into account in harbour basins except when they are in exposed locations.

8.2.3 Crane loads

The crane loads depend on the type of terminal to be constructed, for example, whether it is as an ore terminal or a container terminal. Crane loads are transferred directly to the subsoil via a pile or mat foundation or indirectly via the quay wall structure. The magnitude of the loads transferred to the quay depends on whether they are transferred directly or indirectly.

8.2.4 Terrain loads

Like the crane loads mentioned in 9.5, the terrain loads are also terminal-type dependent. In most cases these loads are transferred directly to the subsoil. In the case of soft soils this may create high excess pore pressure, resulting in extra forces on the quay wall.
The surface loads may vary from 40 kN/m² up to 300 kN/m² for a container terminal and an ore terminal respectively.

8.2.5 Construction materials

The quay wall structure can be made of wood, concrete, steel or combinations of these. Nowadays the most frequently used materials are concrete and steel, while in the past wood and stone were the principle materials used. Today and in the future the ecological aspects of the manufacturing processes for the different materials and the use of these construction materials must evaluated within the design process.

8.2.6 Construction methods

The cost of a quay is largely dependent on the size of the structure and the construction method used. In principal two methods of construction are distinguished: building from the landside and building from the waterside. Each method requires special construction equipment. In some cases this equipment may be specially designed for the project.

8.2.7 Availability of construction materials

The availability of construction materials may govern the design. This was certainly the case in the past when the transport potential and the knowledge transfer were limited compared to those of today. Wood was much used in Northern Europe, Russia and North America, where abundant supplies were available. In Southern Europe more use was made of stone and later of concrete elements. At locations with very high temperature and water with a high salt content concrete block structures are most commonly used to minimize the effects of corrosion.

8.2.8 Experience

As with all things in human life, experience also plays an important role in quay wall design. In earlier times, when there was little understanding of the mechanical behaviour of materials and structures, building was often a process of trial end error. Nowadays, even though we are able to calculate forces, moments and loads, local conditions sometimes impose severe restrictions on the type of structure built. Experience may help to advance the design of a new structure if it is modelled properly to make predictions and the predictions are verified by tests. At the very least mistakes made elsewhere, hopefully by others, can be avoided.

8.2.9 Design recommendations

In the past there were several design codes or rules (see Chapter 9 for an overview) based on understanding of the behaviour of the structures, acceptable risk level, and experience, and these differ from country to country. With the introduction of the Eurocodes, probably in 2010, it is necessary to discuss the differences within the several design codes as they result in different solutions. Since the introduction of the Eurocodes it is crucial that in the initial phase that all the relevant codes and design rules are taken into consideration in relation to the proposed programmes of requirements for the quay wall in question.

8.3 Functional requirements

The quay walls must fulfil the following basic requirements:

Retaining function
Bearing function
Mooring function
Protecting function.

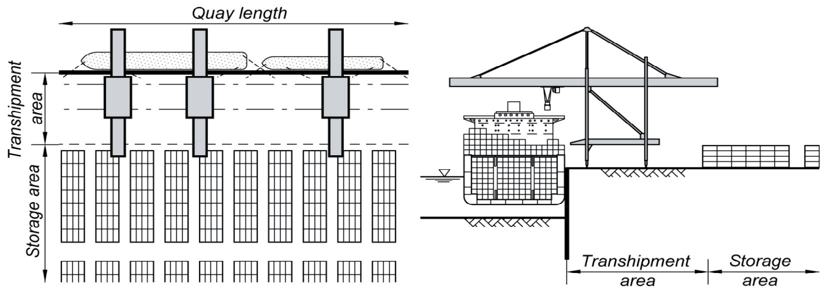


Figure 8.1 Functional design of quay wall

Retaining function
The structure has to safely retain soil and water. Typical for this aspect is that the retaining height must be agreed and therefore the levels of both the top and bottom of structure must be established. This assessment follows from the requirements of the anticipated mooring of ships and the minimum anticipated water level.

Bearing function
The quay wall must safely sustain the loads imposed by cranes, vehicles and the stored goods. It is essential that the handling equipment for the goods is safe.
The time taken to load and unload the ships is also important.
Due the requirement for high handling speeds, extra horizontal forces may be generated due to acceleration of the cranes.
In some cases separate storage areas and transhipment areas are incorporated in the design of the terminal for buffering.

Mooring function
The structure must be able to ensure that the ships can be safely moored at their berths and subsequently ensure that their cargoes are loaded and unloaded efficiently. Therefore the space required depends on the number and dimensions of the ships using the quay and on the wind, waves and currents. To this end suitable mooring bollards are required and in special circumstances storm bollards are necessary

Protecting function
This function is related to the safe berthing of ships. To avoid damage to ships and possibly to the quay, fendering may be needed. It may also be necessary to ensure the stability of the quay by installing protection against scouring of the bottom in front of the quay. The need for scour-protection depends on the dimensions of the ship's propellers and their power.

8.4 Programme of project requirements

8.4.1 Introduction

Today it is standard practice to formulate terms of reference in advance of the design and construction phase. Generally two types of terms of reference are distinguished: functional terms of reference and technical terms of reference. Both are necessary and depending on the contract specifications, the composition of each may vary for each project.

Within this project requirements also the life cycle concept of the structure has to be considered as this might have implications for the design. For example, fit for purpose only, adaptable, multifunctional and possible re-use.
However, it is of paramount importance that these terms of reference are carefully formulated. This document, which defines what is to be built is very important in the communication between client and designer.
An example of the functional requirements are listed in Chapter 8.4.2 and an example of the technical requirements are listed in Section 8.4.3

8.4.2 Functional Programme of requirements

1. **Introduction:**
   This gives a brief description of the project
2. **Boundary conditions**
   - 2.1. Determination of the existing situation
   - 2.2. Natural conditions such as water levels and wind
   - 2.3. Existing operational situation
3. **Requirements**
   - 3.1 Nautical requirements
     Types of ship, plus characteristic parameters, including length, beam and draught, number and length of berths
   - 3.2 Bearing requirements
     Width of the apron area
     Number and types of cranes, plus characteristic parameters
     Dimensions of the storage zone
     Sort and volume of freight to be handled and storage method
   - 3.3 Retaining requirements
     Height of the upper surface of the quay
     Depth of the water
   - 3.4 Protective function
     Berthing facilities
     Bottom protection

8.4.3 Technical requirements

This document provides all the information required to make the technical computations, for example, steel quality, concrete quality.

Contents of Programme of Technical Requirements

1. **Introduction**

This gives a brief description of the requirements. The objective of the project, the organisation, planning, and possible phasing and functional requirements are described.

2. **Boundary conditions**
   - 2.1 Description of existing situation
   - 2.2 Natural conditions
     - 2.2.1 Topographical conditions
     - 2.2.2 Hydro graphic conditions
     - 2.2.3 Geotechnical conditions
     - 2.2.4 Hydraulic conditions
     - 2.2.5 Meteorological conditions
     - 2.2.6 Environmental conditions

2.2.7 Disturbance to substrata
2.3 The presence of cables and pipelines
2.4 Existing operational situation
3. Nautical function
3.1 Nautical basis
3.1.1 Usable length of berths
3.1.2 Type of vessel
3.1.3 Details of main propellers
3.1.4 Details of bow thrusters
3.2 Dimensions of quay wall
4. Retaining function
4.1 Structure of the quay wall
5. Bearing function
5.1 Data on freight
5.2 Data on cranes and vehicles
5.3 Crane track equipment
5.3.1 Details of crane track
5.3.2 Criteria for use
6. Protective function
6.1 Mooring facilities
6.2 Harbour bottom
6.3 Harbour bed protection
6.4 Bank protection
6.5 Maintenance requirements and management plan
7. Diverse
Public utilities, lighting, drainage, signage
8. Safety aspects/reporting and permits

8.5 Summary

This section has described the functional and technical project requirements for building a quay wall including aspects like maintenance and life cycle approach. Furthermore each subject that it is necessary to consider when designing a quay wall is discussed.
The detailed specification of the functional and technical programme requirements is very much dependent on the type of contract selected.
If this subject and specifications are not discussed in sufficient detail in advance there may be serious consequences with regard to time and costs.

9. Development design aspects for quay walls

9.1 Introduction

These days when designing structures we have several design tools at our disposal. However in the past things were very different. To understand the problems encountered by the engineers in the past it is necessary to have some insight into the development of the relevant design methods. For this reason an overview of the development of the design tools is presented in the following sections.

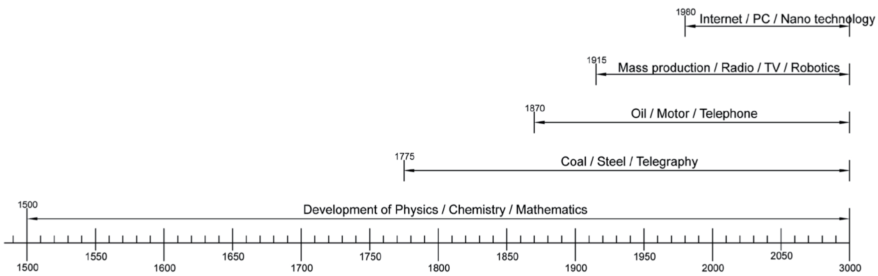


Figure 9.1: Phases of the Industrial Revolution

The industrial revolution was initiated in Great Britain in 1770. However, since that time further technical revolutions with big impacts on society have taken place. The first phase of this Industrial Revolution started with the invention of the steam engine that was quickly followed by the diesel motor. The first phase of the industrial revolution made the production of steel and cement possible followed by that of the telegraph, radio, telex and telephone.

After the Second World War the inventions in the field of electronics enabled us to develop the computer which generates wide ranging possibilities for analyzing and computing. Today we are in the nanotechnology phase which will possibly permit even more detailed measurement of the behaviour of port structures.

9.2 Scientific disciplines required for the design of quay walls

In Chapter 8 the requirements for the layout of harbours are discussed in relation to the quay wall design. This section discusses the technical disciplines necessary for the design. The forces acting on a quay wall are presented in Figure 9.2.

The loads imposed on a quay wall that are shown in Figure 9.2 are generated by:
Water : waves and currents, groundwater;
Soil : soil pressures including the effects of surface loads;
Equipment : container cranes, ore cranes,
Morphology : sedimentation and erosion
For the design of quay walls understanding of the following disciplines is necessary.

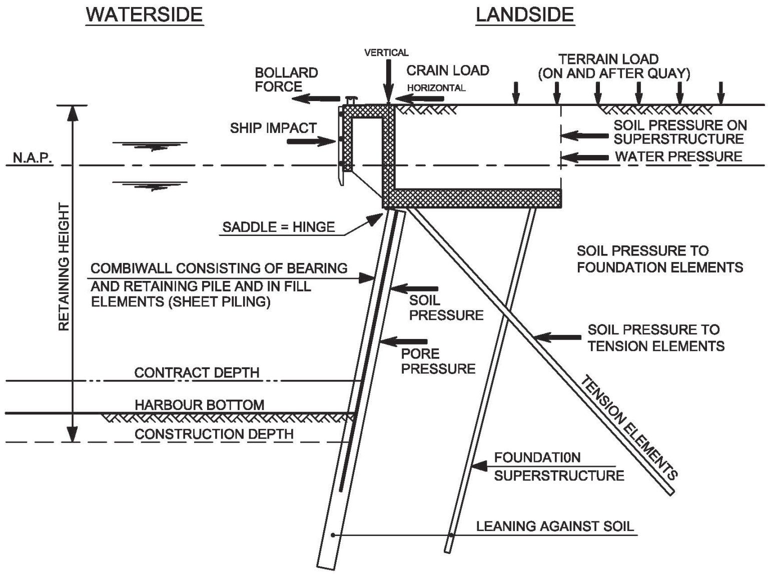


Figure 9.2: Principle design features and imposed loads on a quay wall

Structural mechanics:
During the 16th and 18th centuries tremendous progress was made in the understanding of mechanical behaviour of materials. In this respect the contributions of Leonardo da Vinci, Newton, Hooke and Coulomb were most remarkable, while the contribution of Vitruvius (20), who described the construction techniques used by the Romans, should also be remembered. Vitruvius considered that structures must be designed in such a way that they are in harmony with the surrounding world and that the dimensions are correlated with each other. Today we rely on this previous theoretical and experimental work and the experience gained by practical construction to improve the computerised computation techniques.
From structural mechanics the imposed loads inherent in the design can be schematized to determine the internal end external equilibrium conditions and to obtain cross-sections of the different parts of the quay wall structure.
The theory of elasticity is used. However in certain circumstances, such as when redesigning older existing structures in which some yielding is accepted, the theory of plasticity is applied.

Fluid mechanics:
The discipline of fluid mechanics comes into play when it is necessary to assess the impact of waves and currents on the structure. It is obviously important to assess the impact of waves and currents in exposed locations and in order to reduce the movements of the berthed ships and thus increase the working time of cranes most harbour basins are protected from wave attack.

Those who made major contributions to the development of the theoretical framework of fluid mechanics include Navier, Stokes, Bernoulli, Chezy and Isbash.
In quay wall design fluid mechanics is important in relation to the design of bottom protection structures and slope protection underneath jetties.

Soil mechanics
The birth of soil mechanics is generally considered to have occurred with the introduction of the effective stress concept, two phase medium, soil skeleton and fluid that was formulated by Terzaghi (1925). With this model the time dependent phenomena of soil behaviour, consolidation, are described.
However, even before that the physicists, Coulomb (1776) and Rankine (1857) were thinking about the forces exerted by earth pressure on structures to be built. The discipline of soil mechanics provides tools to assess the impact of soil and water forces generated by the own weight of the soil as well the surcharge loads on the structural elements of the quay wall in the case of both gravity and retaining wall structures.

It is also necessary to have a thorough knowledge of materials science and the structural materials that are available in the 21st century:
steel
concrete
wood
synthetics materials

For all these materials it is necessary to have a clear understanding of the methods used to produce them, their structural properties and the quality control processes and monitoring systems used during and after construction. In addition, the costs involved for designing and constructing a quay wall must be assessed.

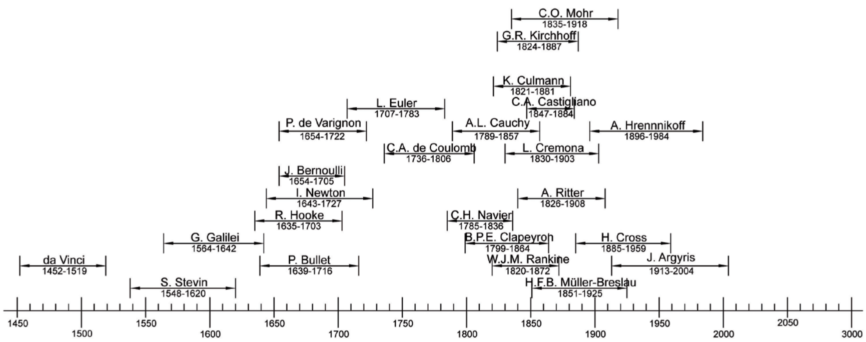


Figure 9.3: Selection of people who contributed to the development and understanding of structural-, fluid- and soil mechanics [Straub 1975]

9.3 Construction materials

9.3.1 Steel
Steel plays an important role in modern quay wall structures. It is used in bearing structures like combi-wall systems and as reinforcement in concrete, so understanding of the typical behaviour of steel is required in relation to the production process and its quality. Steel structures in particular are sensitive to different types of corrosion, so the designer certainly has to consider how to deal with these aspects that affect the life cycle of such structures.

For example, to repair damaged interlock openings underwater it is necessary to weld them. Reductions in strength of more than 50% have been measured in underwater welds.

9.3.2 Concrete

Concrete is one of the oldest construction materials. The Romans used concrete based on pozzolanic earth and trass, a mixture of lime and clay that has been extensively used in the Netherlands since 1500. The use of modern steel reinforced concrete started around 1900.
Today the development of the strength of concrete and the addition of chemicals to improve its characteristics are both very important and the subject of research.
In Figure 9.4 the development of strength over time is indicated. A considerable increase in strength has been obtained over the last hundred years. Whether high strength concrete will be used in future quay wall design is still a topic for further research.

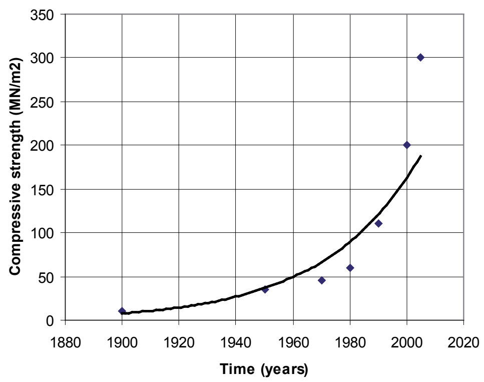


Figure 9.4: The compressive strength of concrete versus time

The compressive strength of concrete has increased by a factor of 15 in 100 years. This allows the designer to use less concrete and to build 'slimmer' designs. However, to prevent the occurrence of high temperatures, and thus cracking problems that might change the design lifetime of the structure , considerable attention must be paid to the fabrication and construction phases.

9.4 Retaining wall design methods

Coulomb (1776) was the first to consider the problem of earth pressure and he was followed by Rankine (1857). A CIRIA study (1974) reveals for the first time that considerable differences may occur in the dimensioning of sheet pile element structures in response to the design standards or recommendations applied. These differences in the results obtained can be in the order of 20 %. Thus the computation of sheet pile walls is still prone to a great scatter in the computational results.

Leimdorfer (1978) and DeLattre (2001) made comparisons between anchored sheet pile designs for a retaining height of 10 metres using 6 different methods based on the available earth pressure theories.
The six methods used in this comparison are discussed briefly below.

Free earth support:
This method is based on the assumption that the wall is installed down to the depth at which it mobilizes no negative bending moments. This means that there is no resilience in the system. In addition the use of materials is not optimized. This method is also known as the 'American Method' as it is widely used in North America.

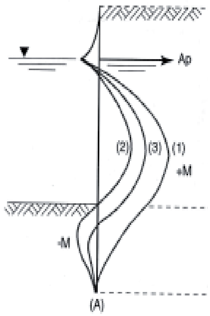


Figure 9.5: The influence of fixity of the wall on the bending moments

Number 1 in Figure 9.5 indicate no fixity (freely supported wall), while number 2 is 100% fixity,(fully embedded) and number 3 is the condition in between complete fixity and free support.

Fixed earth support:
This method uses the fact that with greater penetration into the subsoil a negative moment develops. This reduces the moment and thus reduces the amount of construction material that is required. This type of structure also has more resilience. This method is called the 'European method' as this design approach is generally used in Europe and is in contrast with the American approach which assumes freely supported walls .

Rowe’s method (1952, 1955):
Rowe proposed a method that takes the rigidity of the wall into account. This method reduces the maximum moment. The degree of flexibility is expressed by a coefficient that includes the height and the bending stiffness of the wall. The Norwegian method is analogous with Rowe’s method.

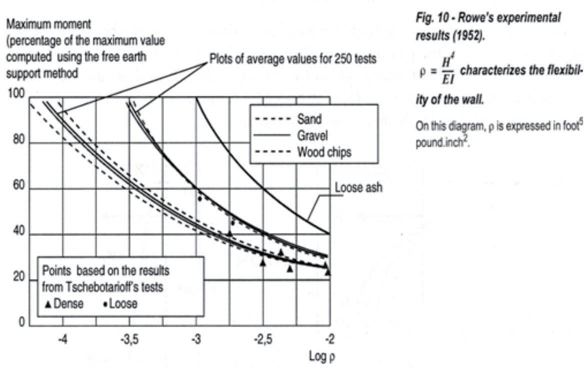


Figure 9.6: Reduction factors for the computed moments according to Rowe’s theory

Blum method or equivalent beam method (1931):
This method of fixed earth support is simplified by assuming a relation between the angle of internal friction and the distance from the point of contra-flexure near the point where the pressure is zero.

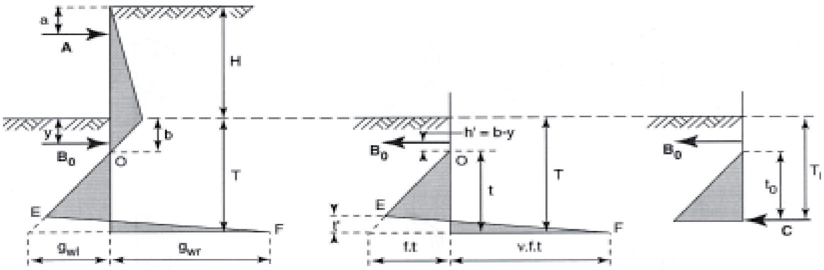


Figure 9.7: The approach of the Blum method 1931

Graphical method:
With this method the penetration can be determined from forces and polygons, thus by using this method one can compute both free and fixed support structures.

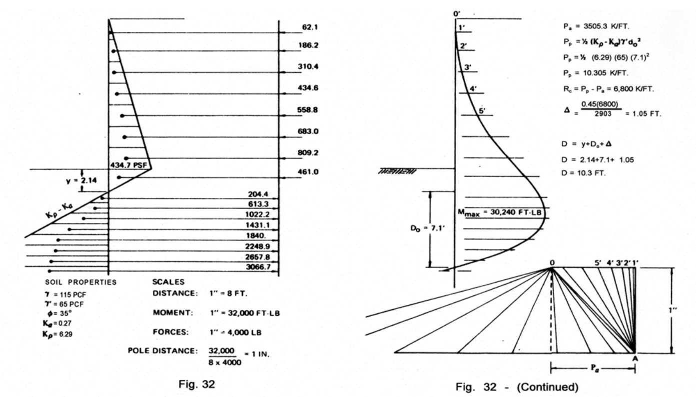


Figure 9.8: Graphical approach with force polygon 1900

- Danish method:
This is a purely observational method. Its basis is the observation of the distribution of lateral pressure against a retaining wall in an arching phenomenon of the backfill as well as the flexibility of the wall. The purely empirical equation assumes sandy backfill and zero wall friction. Both the latter assumptions are open to discussion.

This method involves the computation of the earth pressures according the classical earth pressure theories. The computed earth pressures are corrected by assuming a parabolic reduction based on observations of quay walls. The results of this comparison show that for this case there are significant differences between anchor loads and moments when these methods are used, varying between 30 to 40%.

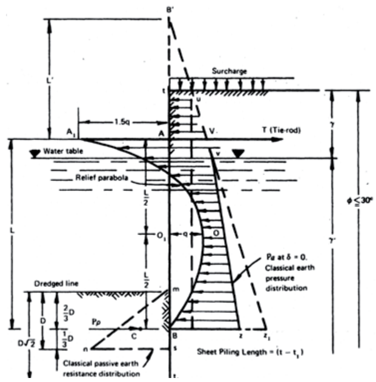


Figure 9.9 Danish approach 1920

The computation of a sheet pile as an elastic beam was introduced in 1970 when the personal computer made it possible to solve the equations numerically. The advantage of this method is that deformation can be computed and that staged excavation can be modelled.

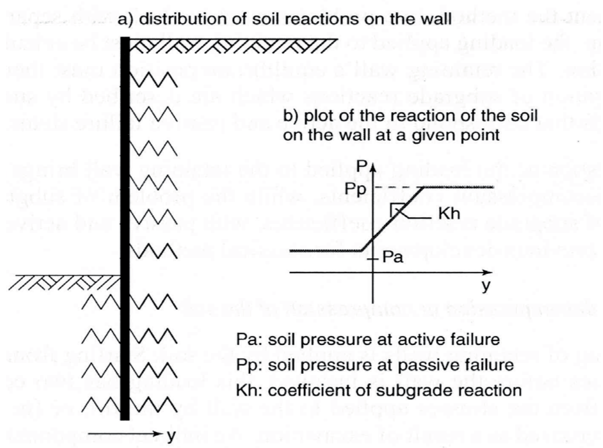


Figure 9.10: Interaction model used for the subgrade reaction method

Since 1980 several finite element programmes have been available (e.g. PLAXIS). The great advantage of using finite element modelling is that the structure and soil are incorporated in one model and that the deformation patterns are visualized. However, it is still very difficult to predict the deformations of sheet pile walls accurately because soil is a non linear elastic material.

9.5 Effects of construction methods used

Glimm and Morgen (2004) compared quay walls built according to two different construction methods. They compared two options for building a quay wall, namely first constructing the quay wall on land in a building pit and subsequently dredging the harbour basin and secondly the method of first building the quay wall under wet circumstances and then backfilling behind the quay.

These two cases were analysed by using the Blum method (1931) and various finite element computer programs. For both cases the results of these computations for the dry construction and wet construction methods are presented in Figures 9.11 and 9.12 respectively.

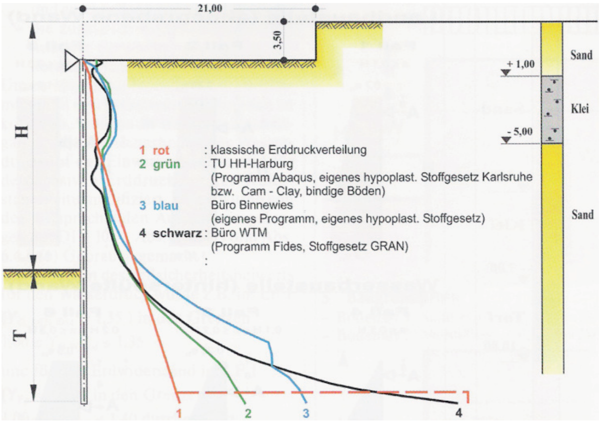


Figure 9.11: Earth pressure after construction in a building pit and dredging

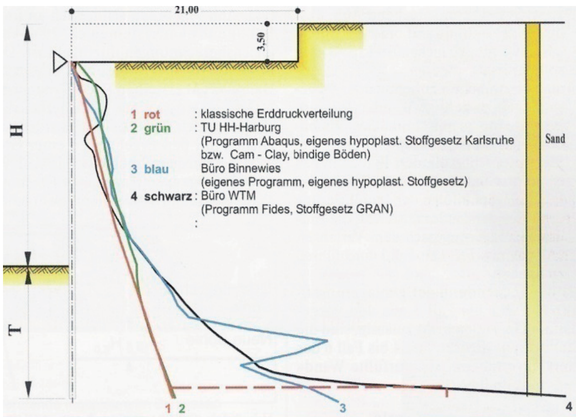


Figure 9.12: Earth pressure after construction in water with backfilling

The comparison between the finite elements methods and the Blum method is reasonable. It is clearly shown that arching occurs when constructing in a building pit in the original soil and that no arching occurs when building under wet conditions and the soil is backfilled.

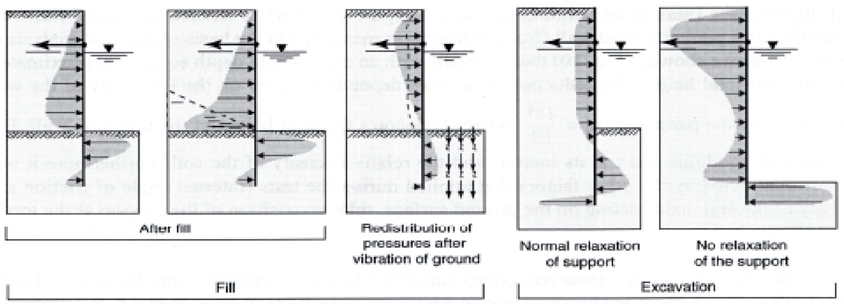


Figure 9.13: Results of measured stress distributions depending on the construction method [Tschebotarioff and Brown 1948]

Tschebotarioff and Brown (1948) performed model tests to investigate the distribution of soil pressures on a flexible wall with one anchor for two different construction methods, namely in excavation and with backfilling.
The results of these measurements are presented in Figure 9.13. They show that in the case of backfilling considerably less arching occurs than in the excavated situation. This figure also indicates that vibration after backfilling reduces the pressure on the wall and the arching effect is nearly completely disappeared

9.6 Scour

When designing quay walls scour is a very important threat that must be considered-because the effects of scouring can be disastrous. If scouring occurs at the toe of the wall the stability of the wall will decrease, which might lead to collapse as a result of the movement of the toe of the wall. Soil transport may also be initiated by scouring, which might lead to settlements in the terrain behind the quay wall. These include the flowing of sand from behind the quay wall, terrain settlements and eventually failure of the structure. Therefore the effects of scour on the stability must be studied and properly evaluated. Roubos (2006) proposes a probabilistic approach for the design of scour protecting structures in front of quay walls. The proposed design process is presented in Figure 9.14.

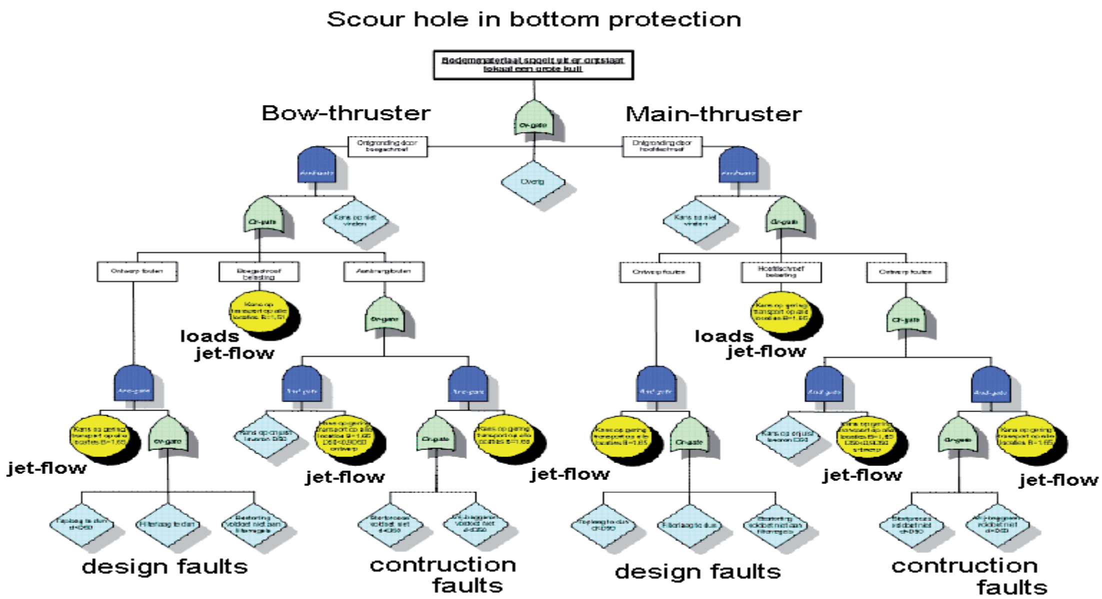


Figure 9.14: Design process for scour protection measures [Roubos 2006]

9.7 Effect of removing soil by dredging

When a quay wall is constructed in a dry building pit the effect of subsequently dredging the harbour basin must be assessed against two arguments:
Deformations of the quay wall
Dredging of the basin removes soil up to thickness of 30 metres.
During this process the underlying soil is relieved, which in turn results in heave of the soil layers and also of the quay wall structure as indicated in Figure 9.15.

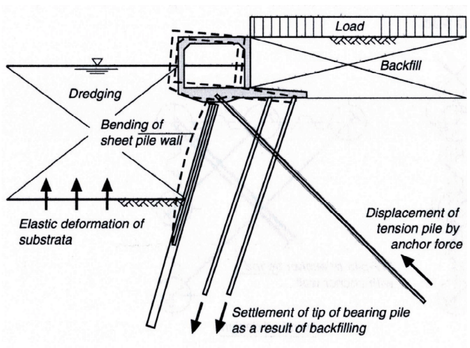


Figure 9.15: Effect of dredging the harbour basin to the deformation of the quay wall

This heave may cause vertical uplifting of the quay wall of 20 to 50 millimetres and horizontal deformations of 50 to 100 millimetres. This deformation must be considered as it may have great implications for the crane rail installation Therefore it recommended that the crane rail should be installed after the dredging of the basin in front of the quay wall.

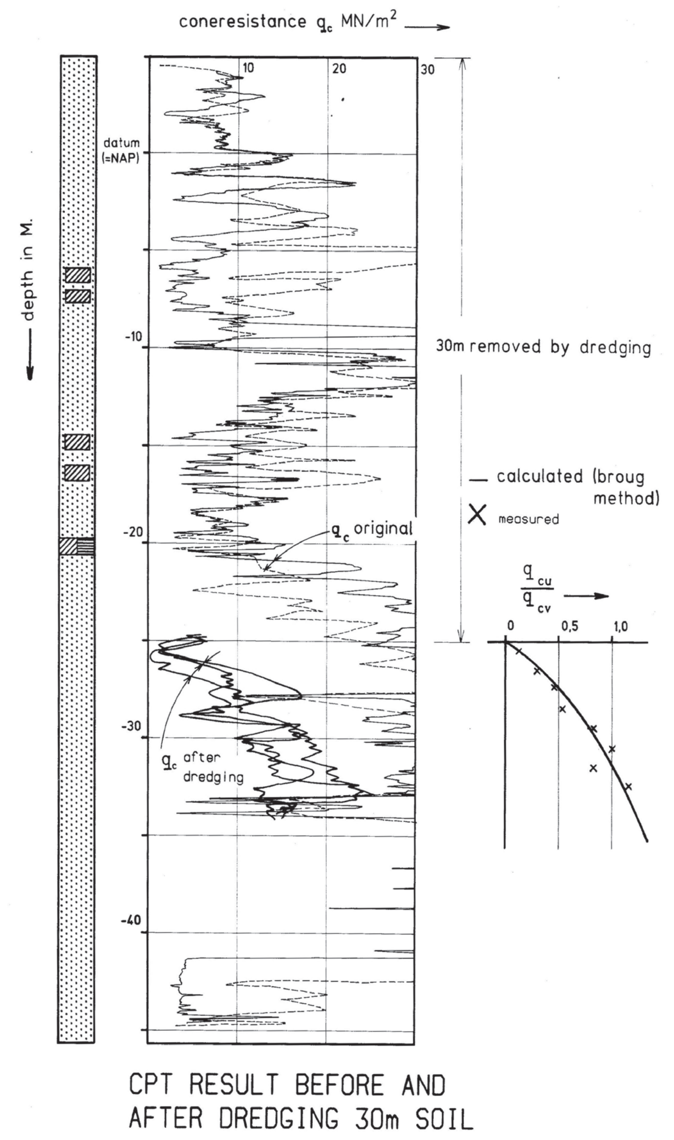


Figure 9.16: Effect of dredging on cone resistance

This effect of stress reduction by the removal of overburden has been studied [de Gijt and Brassinga 1992]. Dredging of the harbour basin considerably reduces the cone resistances as indicated in Figure 9.16. In this case removing 30 metres of soil affected the horizontal stability and the pile bearing capacities of the structure.

9.8 Interlock openings with combi-wall systems

When a quay wall structure is composed of several elements, such as caissons or combi-walls, in order to prevent loss of soil the connection between these elements must be secured.

The problem of combi-wall connections was investigated by [de Gijt and Heijndijk 1996]. In this study the three components pile, sheet wall element and the interlock connection were investigated.

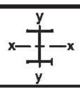
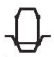
Type of pile	Rigidity Ix	Rigidity Iy	Torsion	Buckling	Dimensional stability	Instal-lation	Costs
	3	1	1	3	4	3	2
	5	3	3	4	4	4	1
 Without reinforce-ment rib	4	3	3	2	3	3	3
 With reinforcement rib	5	3	3	3	4	3	3
 Welded along seam	5	5	5	5	5	5	4
 Welded with spiral seam	5	5	5	5	4	4	5

Figure 9.18: Evaluation of the types of combi-wall system

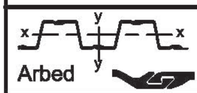
Type of sheetpile	Rigidity x	Rigidity y	Distorsion capacity	Dimensional stability	Instal-lation	Costs
 Arbed	4	4	5	4	4	3
 Krupp	3	3	3	3	3	2
 Larssen	2	2	1	4	4	3
 Larssen	3	3	3	3	4	4
 Larssen	4	4	5	3	4	5

Figure 9.19: Evaluation of sheet pile interlocks for combi wall system

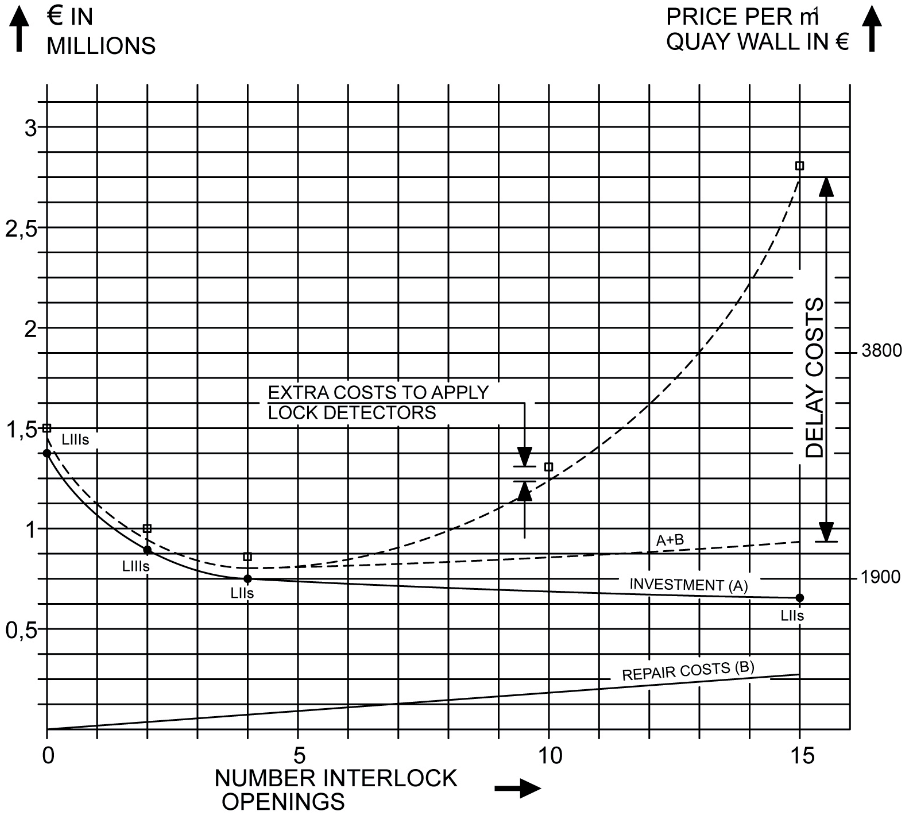
The piles were analysed with regard to bending stiffness in both directions, deformation capacity, dimensional stability, ultimate strength, installation aspects and costs and scored between 1 (poor) to 5 (excellent). The results of the evaluation are presented in Figure 9.19.
Based on this evaluation, preference is given to longitudinally welded pipe piles as the spirally welded piles turn during the driving process, which makes it necessary to use a heavy guiding frame during the installation of the piles.

The sheet wall elements were also considered in relation to bending stiffness in both directions, deformation capacity, dimensional stability, installation aspects and costs. From this evaluation it was concluded that the Larssen element is the preferred one.

Type of lock	Plugging	Dimensional stability	Hooking	Strength	Lock-friction	Costs
 Peiner	3	3	2	3	2	1
 Larssen	3	4	4	3	3	3
 Larssen	3	3	3	2	4	4
 Larssen	3	3	4	4	4	5
 Hoesch	3	3	5	4	2	2

Figure 9.20: Available interlock connection for combi-wall system

The interlock connections were evaluated with regard to the following aspects: prop building, fabrication tolerances, locking strength, lock friction and costs.
This evaluation has shown that the available interlock connections should be modified by the addition of a nock (GW IH nok). This connection prevents the occurrence of interlock openings, provided the proper installation method is selected.
The results of this investigation showed that to prevent the occurrence of plugging in the interlock connection, sheet pile elements in a combi-wall system should be installed by vibration and by simultaneously jetting. For this reason driving the sheet pile elements is not permitted.
From the evaluation it was concluded that the longitudinally welded pipe is the best pile element and that the Larssen sheet pile element with the modified interlock is the preferred type of connection.



ASSUMPTIONS:
- LENGTH QUAY WALL 500 M
- COSTS INTERLOCK REPAIR € 30.000,- EACH

Figure 9.21: Indication of extra investments needed to prevent interlock opening and to reduce service costs

The repairing of interlock openings under water is very time consuming and very expensive operation. It may be necessary to weld steel plates under water or to bolt them. The cost of repairing one interlock opening is 30 000 euro. There is a heavy financial loss if the quay wall is not in service during the repair of interlock openings including the considerable loss of harbour dues and port dues and delay of the transport of goods. This warrants investing in additional strength and strict control of the installation procedure to avoid the occurrence of interlock openings.

9.9 Design recommendations

Recently Meijer (2006) and Meijer, De Gijt (2007) made an inventory of available design recommendations. The results of their comparison are presented in Table 9.1.

Table 9.1: Overview of available design recommendations

	G = Good, good information and/or good design rules and diagrams (G+ = very good) **A** = Adequate, adequate information and/or some design values and design rules **B** = Basis, basis information and/or only design values **D** = Only descriptive - = No description **Subjects**	CUR 211	CUR 166	Eurocode 7-1	BS 6349 - 1 & 2	EAU 2004	ROM 0.2-90	Technical Standards In Japan	MIL-HDBK-1025/4	EM 1110-2-2504
1	**Index**	G	G	G	G	G	G	G	G	G
2	**Symbol list**	-	G	G	G	G	G+	-	-	-
3	**Clarifying wordlist**	G	G	B	A	-	G	-	B	B
4	**Safety philosophy**	G+	G+	G	B	A	A/G	D	-	B
5	**Ship information**	A	-	-	A	A	A	A	-	-
6	**Environmental criteria:**									
6 a	Wind	D	-	-	D	B	B/A	D	-	D
6 b	Ice	B	A	D	D	G	D	-	-	D
6 c	Waves	D	A	D	G+	G	B	G+	D	D
6 d	Tide	G	B	D	D	G	A	B	D	D
6 e	Currents	D	-	-	D	-	B/A	B/A	-	-
6 f	Geotechnics	A	G	D	B	A	B	B	-	A
7	**Design aspects:**									
7 a	Loading	A/G	A	-	B/A	G	G	D	-	G
7 b	Earth pressures	A	G	G	A	G	G	A	B	G
7 c	Groundwater(flows)	G	G	D	D	G	A	-	-	D
7 d	Dredging works	D	D	-	-	A	-	-	-	-
7 e	Sheet piling	G	G+	B	A	G+	-	A	B	G
7 f	Piling	G	-	D	B	G	-	A/G	-	-
7 g	Anchoring	G	G+	D	B/A	G	A	A	B	G+
7 h	Relieving platform	G	A	-	B	A	B/A	B/A	B	-
7 i	Dolphins	-	-	-	B/A	G	-	D/B	-	-
7 j	Breakwaters	-	-	-	B	A	-	G	D	-
7 k	Embankments	-	-	D	D	G	-	-	D	-
7 l	Mooring	B	B/A	D	A	A	A	A	-	D
7 m	Quay wall equipment	D	-	-	B	G	-	B	-	-
7 n	Quay wall geometry	A	D	-	B	A/G	-	D	-	-
7 o	Seismic	D	B	D	D	A	-	A	-	D
7 p	Stability	G	G	D	B	G	-	B	-	A
8	**Type of quay wall treated:**									
8 a	Block wall	D	-	D	B	A	B	A	D	-
8 b	L-wall	D	-	D	B	-	B	A	D	-
8 c	Caisson	D	-	D	B	A	B	A	D	-
8 d	Cellular wall	D	D	D	B	B	-	A	D	-
8 e	Earth structure (Terre Armee wall)	D	D	D	-	-	-	-	D	-
8 f	Sheet pile structure	G	G+	D	A	G+	-	A	B	G
8 g	Cofferdam	D	G+	D	B	A	-	A	-	-
8 h	Sheet pile wall with relieving structure	G+	A	-	B	A	B	B/A	B	-
8 i	Open berth quay	D	-	-	A	G	-	A	D	-
9	**Construction**	G	G+	-	B	G+	-	-	-	B/A
10	**Cost**	B	B	-	-	-	-	-	-	-
11	**Monitoring**	D	D	D	D	A	-	-	-	D
12	**Maintenance**	G	G	D	D	A	-	B	D	D
13	**Experience**	G	A	-	-	G	-	-	-	-
14	**Examples**	G	G	-	-	-	-	-	-	-

This inventory shows that there are considerable differences between design rules. These specifically concern the proposed safety approaches such as the overall safety approach and the probabilistic design approach. Based on this comparison, computations for quay walls were performed for a retaining height according to three methods [EAU (2004), CUR 211(2005), CUR 166 (2005)].
The EAU (Emphelungen des Arbeitsausschusses "Ufereinfassungen und Wasserstrassen) is a German committee founded in 1950 that since its establishment publishes recommendations for port related structures about every five years. These recommendations include the latest experience in port construction.
The CUR (Civieltechnisch Centrum Uitvoering Research en Regelgeving) is a Dutch non-profit organisation that publishes recommendations in the field of civil engineering. Handbook Damwandconstructies (CUR166) presents recommendations for the design of sheet piles for building pits. The Handbook Quay walls (CUR211) includes the recommendations for quay wall design with special emphasis on quay walls with relieving floors.
In order to stimulate fair competition within the European member states the Euro code is now the generally accepted design code within the European community.
The BS (British Standard) is the United Kingdom's standard organisation which publishes recommendations for several civil engineering structures and also for port engineering.
The Spanish Port Organisation presents Recommendations for Maritime Structures (ROM 2002). The Technical Standards of Japan (1995) include recommendations and instructions based on the Japanese experience of port engineering. In this respect earthquake loading is a very important aspect in that region.
The NAVFAC documents are design documents compiled by the US Corps of engineers and the US Navy.

These design approaches were selected because they describe the design methods most extensively and clearly. These methods also anticipate future design methods that incorporate the probabilistic approach. The results show that there are differences between the various design approaches, ranging from 10% to 30% depending on the results that are considered: anchor force, bending moment and driving depth.

The results of the studies mentioned show considerable variation in computational results, both in the length of the wall, anchor forces and moments in the wall. This variation is mainly attributable to the different factors used and to a lesser extent to differences in soil parameters. The differences lead to different dimensions for the structural elements and thus also to different costs.
These studies also indicate that despite the increasing understanding of soil behaviour during the last 300 years, considerable differences (approximately 20%) still exist between the computational results. Exact solutions cannot be obtained owing to uncertainties in loading conditions, soil characteristics and the modelling of the structural behaviour. Thus in this area more research is necessary.

9.10 Summary

This chapter has discussed the evolution of the disciplines necessary for the design of quay walls with special emphasis to the design of retaining structures.
Furthermore some problem areas including the reduction of cone resistance due to dredging and the movement of quay walls as a result of dredging the harbour basin are addressed.
In addition an overview of current design rules is presented.

10. Classification of quay walls

10.1 Introduction

Today so many quay wall structures have been built around the world that it has become necessary to make a systematic classification of the different types.
This classification is needed to increase understanding of the mechanical behaviour of the different types of quay walls and for comparisons. For educational purposes it is also relevant as an illustration of the differences in behaviour of the available types of quay wall constructed in the past and those of today. This chapter proposes such a classification and also includes older structures such as those built by the Romans and Egyptians. In addition some developments are described in relation to structural elements involved in quay wall design and construction as well as developments of quay wall types.

10.2 Classification of types of quay wall

A proposal for the classification of quay wall structures was made by Tsinker (1997). However this proposal did not indicate the construction dates or the most recently designed types. Thus De Gijt (2010) proposes the extension of the original classification to include the times at which different types of quay wall structures were introduced and also the inclusion of the new types. This improved classification of quay wall structures is shown in Figures 10.1 to 10.5 and Tables 10.1and 10.2. The tables show when different types of structural elements and the different types of quay walls were designed.

The available types of sheet pile quay walls are presented in Figure 10.1 Wood, steel and concrete can be used to construct these structures. For limited retaining heights (less than 3 metres) no anchor is required. For greater retaining heights an anchor is necessary to limit the deformations and to improve the stability of these systems. These types of quay walls can only be constructed if the soil conditions are such that pile driving is possible.

For these structures the same materials are used as for the sheet pile walls, however, for these structures natural stone may also be used. These structures are built when the soil conditions has proper bearing capacity and stiffness properties These structures can either be built in a construction yard, as in the case of caissons, and subsequently transported to the desired location or constructed on site.

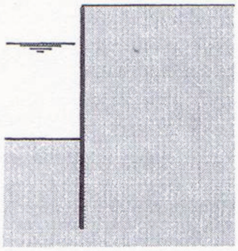
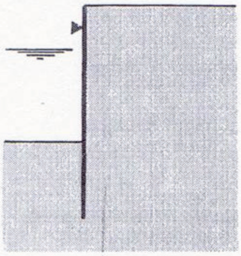
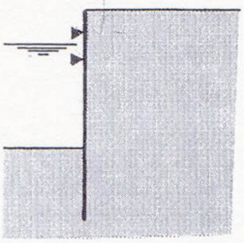
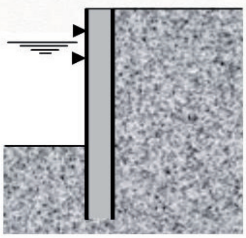
	Cantilever Bulkhead	Steel or Reinforced Concrete Piles
	Single Anchor Bulkhead	Steel or Reinforced Concrete Piles. Anchors: Regular Steel Tieback with Deadman, Ground Anchor, Anchor pile, Pile system, Screw Anchor, M.V.-pile, Others
	Multi Anchored Bulkhead	Same as Single Anchor Bulkhead
	Slurry wall Single/multi anchored	Steel or Reinforced Concrete Piles. Anchors: Regular Steel Tieback with Deadman, Ground Anchor, Anchor pile, Pile system, Screw Anchor, M.V.-pile, Others

Figure 10.1: Overview of sheet pile quay walls

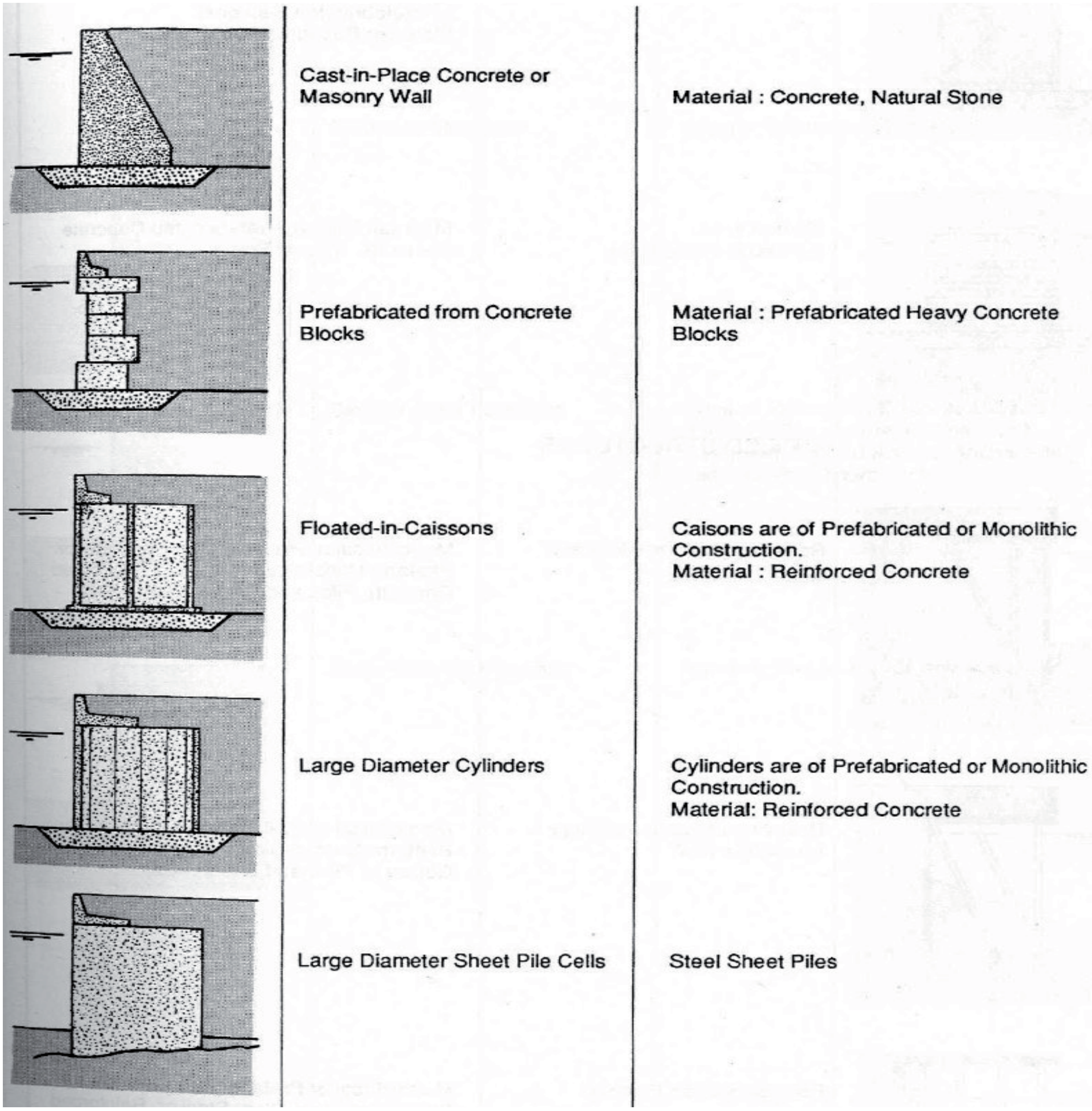


Figure 10.2: Overview types of gravity quay walls

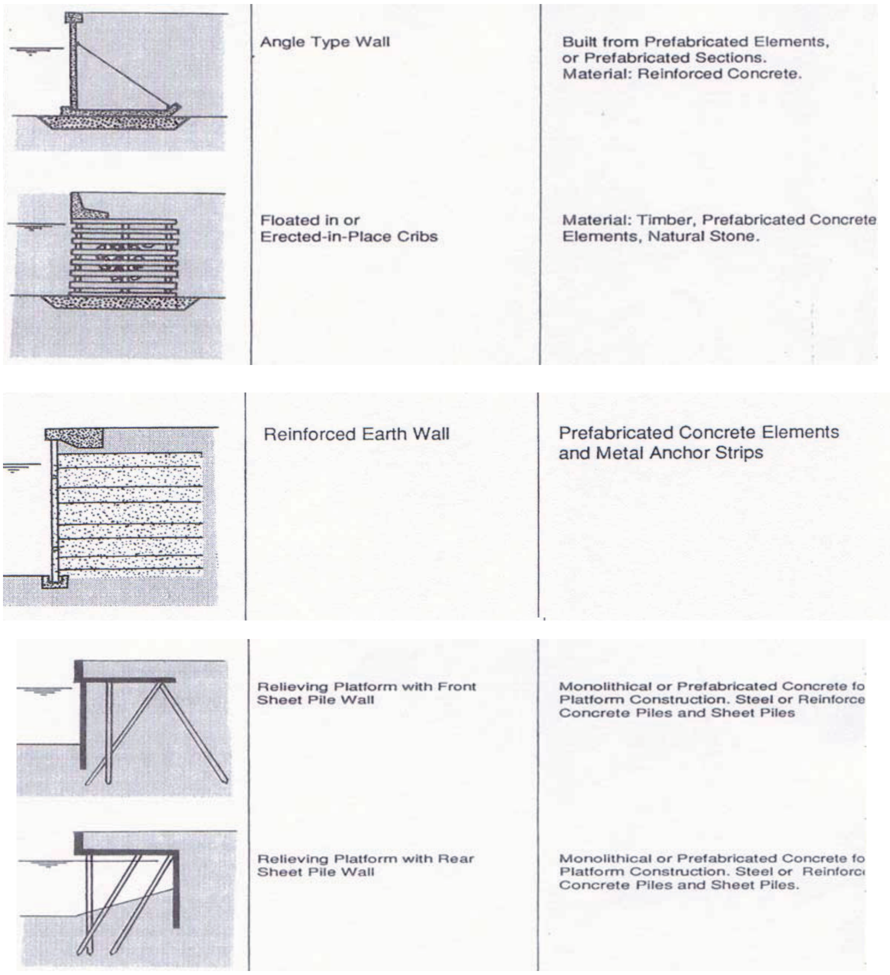


Figure 10.3: Overvieuw of sheet pile with relieving platforms

Relieving platforms are most often used where soil conditions are the same as for sheet pile walls. The advantage of a relieving type quay wall is that, depending on the length and depth of the relieving floor, the forces generated on the front wall by the soil and the surcharge are considerably reduced. As a result less material is required.

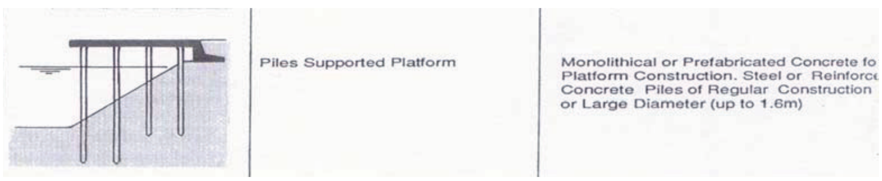


Figure 10.4:Pile supported platforms(jetty)

These platform -types of structure are generally used if the soil conditions are poor and/or reclamation is very expensive. They derive their stability from the piles. However, if great horizontal forces occur pile tressle systems have to be incorporated into the structure. In earthquake prone areas, to reduce the stiffness of the structure only vertical piles are used.

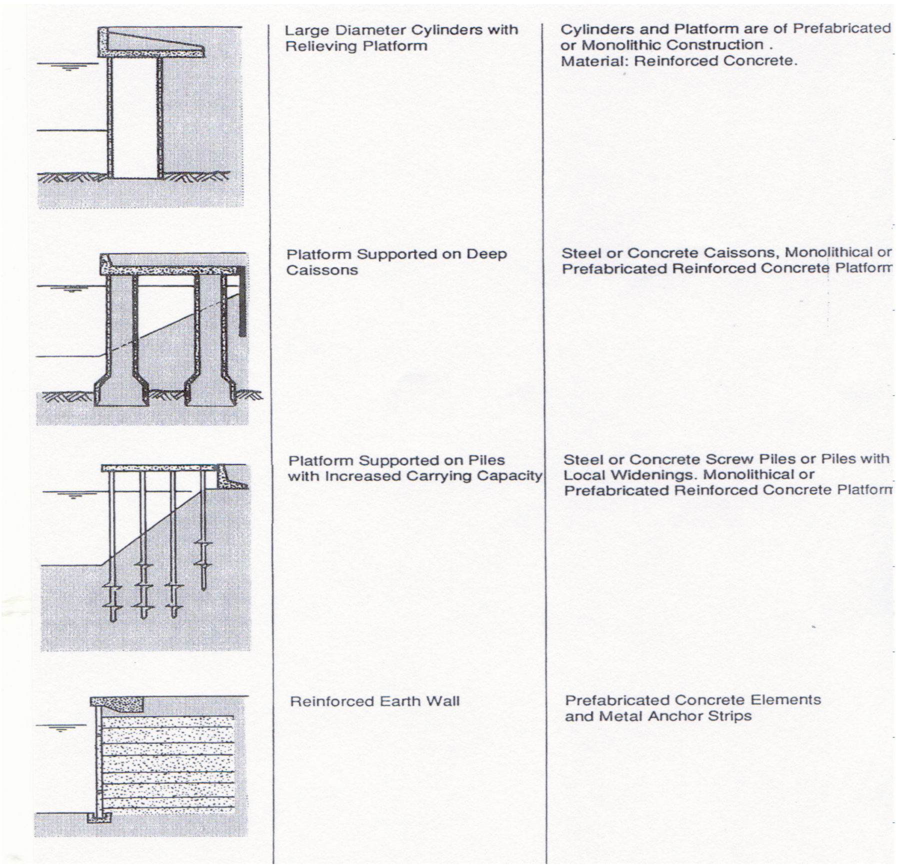


Figure 10.5: Special types of quay walls

Figure 10.5 shows special types of quay walls. These structures were designed to meet specific local soil conditions like very soft clay deposits. For these structures various kinds of materials are used.

The classification of quay walls presented in Figures 10.1 to 10.5 is based on long-term experience. The specific characteristics of the various types of quay wall relate to load transfer. When the transfer of loads and forces on the quay wall structure is considered, three principle types of structure can be distinguished, these being: the gravity structure , the sheet pile structure and pile supported platform structures.

In the case of gravity structures all the forces and loads, both horizontal and vertical, have to be transferred to a good bearing stratum. The friction between the structure and the bearing stratum has to sustain the horizontal forces. The vertical forces and the weight of the structure itself are directly transmitted to the subsoil. The horizontal forces on the structure also generate a moment which must also be taken by the bearing stratum with only compressive stresses.

In a sheet pile structure the transfer of loads through to subsoil is achieved by fixing the sheet pile wall with an anchor both in the soil and at the top. The anchor can be positioned horizontally or inclined. In the latter case the anchor initiates a vertical load on the sheet pile wall. The sheet pile design in Europe usually assumes a fixed sheet pile wall support at the tip while in America a free support system is assumed.
With the relieving floor type of structure the vertical loads are taken by piles while the horizontal loads are resisted by the sheet pile wall or combi-wall and anchor.
The platform types of quay wall derive their stability in the same manner as the relieving platform type with the only distinction that no front wall is present.

At the end of the 19th century reinforced concrete was invented and this greatly increased the options for the use of concrete in construction. So since 1900 reinforced concrete quay walls have been constructed, while about the same time the design of sheet piling also made progress, thus stimulating its use. Since circa 1920 most types of quay wall have been designed and constructed, the most frequently used materials being reinforced concrete and steel. At present about 70 % of the quay walls constructed throughout the world are gravity structures and 30% are retaining structures. In the Netherlands and Germany steel combi-wall systems are much favoured as alluvial soils are suited for sheet pile types of structure, while in Belgium and France more concrete structures are built.

10.3 Structural types

The following overview derives from historical listing of when the main types of structure were first built and this is indicated in Table 10.1.

Table 10.1: Types of quay walls/time

Wooden sheet piling	always	
Block wall	always	
Brick wall	2400 BC - present	
Caisson	Roman	
Steel sheet pile	1834	- present
Relieving platform	1850	- present
Pneumatic foundation	1886	- present
Caisson wall modern	1886	- present
Diaphragm wall	1960	- present

As this table shows, the first wooden walls that were constructed were followed by stone walls, (either block or masonry structures). Depending on the required retaining height, such walls may be still built. Sheet pile structures with wooden planks have already been used for a very long time.

The first types of quay walls built were jetty type structures. The materials used to construct them were wood, bricks, stones and later concrete.
Brick structures came into use in northern Europe around 1500. They were founded on wooden piles and supported by a wooden deck on top of which the brick wall was constructed. The first wrought iron quay wall was built in 1834 in Brunswick (see Chapters 5 and 6). At the beginning of the next century these quay walls were followed by walls with concrete planks.
The principle of the relieving floor was first employed in the USA around 1850.
The caisson quay or mole construction technique was already known to the Romans (Chapter 6).

This method of construction was reinvented in 1886. In that year the foundation of the Brooklyn Bridge was constructed by using steel caissons.
In this project caisson disease took its toll for the first time: 30 people died during the construction of this bridge.
When Portland cement concrete became available in around 1870 it was possible to use reinforced concrete caissons as construction elements. The first concrete caisson quay walls were built in the port of Valparaiso 1900 (see Figure 6. 28). Between 1920 and 1940 this system of building the caissons in a dock and then floating them to the location was used to construct the Waalhaven in Rotterdam. Although the caisson wall system has been replaced by other structures in ports like Hamburg and Rotterdam, this type of structure is still used in many ports around the world especially in Japan.
The first diaphragm wall was tested and built for the Milan metro in 1950 [Puller, 1996]. It was another ten years before the technique was first used in the construction of quay walls. The first quay wall of this type was constructed in the port of Le Havre around 1960. This diaphragm wall technique is one of the most recent developments in quay wall design, although the other techniques continued to be used for a considerable time as is shown in Chapter 10, Table 1.

10.4 Structural elements

10.4.1 Introduction

Quay wall structures are composed of various structural elements. The time line when these elements were used for the first time is presented in Table10.2.

Table 10.2 Development of structural elements of quay walls

Structural element	Time
Wooden piles	200 BC - present
Wooden sheet piles	Roman - present
Deadman anchors	1440 - present
Pile trestle systems	1500 - present
Steel sheet piles	1834 - present
Klap anchor	1900 - present
Reinforced concrete sheet piles	1910 - present
Reinforced concrete piles	1920 - present
Prestressed reinforced concrete piles	1950 - present
Steel piles	1950 - present
MV piles	1970 - present
Screw anchors	1990 - present

10.4.2 Piles

Up to 1920 only wooden piles were available for the construction of piled foundations. However, after 1920 the concrete pile and the steel pile came into use as bearing elements. Later, in 1950, the prefabricated prestressed concrete pile was designed for both tubular and rectangular shapes. Further development took place with the introduction of Franki-piles and vibro-piles which are piles made in situ by using a steel casing. Steel piles and I-beams were also used as bearing elements. These developments over the past 90 years have resulted in the introduction of a wide variety of piles that can be used to construct the foundations of jetties and platforms (Table 7.1).

Table 10.3: Overview of types of pile used for quay wall design in 2005 [De Gijt et al 2005]

	Pile type/ material		System name	Pile shape	Soil displacement	Soil removal	Installation method	Tension	Bearing	Inclination up to
1	Timber		Timber pile	Round	X		Driven		X	3:1
2	Prefab concrete	a	Reinforced concrete pile	Square	X		Driven	X	X	3:1
		b	Built-up pile, or coupled pile	Square/ round	X		Driven		X	5:1
		c	Prestressed concrete pile	Square, right-angled	X		Driven	X	X	3:1
		d	Prestressed concrete pile	Round, hollow	X		Driven	X	X	3:1
		e	Euro pile	Round, hollow	X		Screwed	X	X	3:1
3	In situ concrete	a	Vibro pile	Round	X		Driven	X	X	3:1
		b	Franki pile	Round	X		Driven (Internally)	X	X	3:1
		c	Fundex pile	Round	X		Screwed	X	X	3:1
		d	Fluidization pile	Round	X		Vibration fluidization	X	X	6:1
		e	Grouted screw pile	Round		X	Screwed		X	4:1
		f	Tubular screw pile	Round	X	X	Screwed	X	X	4:1
		g	Auger grout pile	Round		X	Drilled	X	X	5:1
		h	Diaphragm wall pile	Variable		X	Excavated	X	X	None
4	Steel	a	Steel tubular pile	Round, open or closed	X		Driven	X	X	1:1
		b	Steel tubular pile	Round, open	X	X	Pulsed	X	X	None
		c	Tubex pile	Round	X		Screwed	X	X	1:1
		d	Steel H-pile	H-shaped	X		Driven	X	X	1:1
		e	MV-pile	Variable (post grouted)	X		Driven	X	X	1:1
5	Combination piles: Prestressed prefabricated concrete elements placed in the steel casing of the pile systems 3 a, b, c, d, f, g and h									
6	Casing piles: Concrete piles cast in situ with permanent casing of the pile systems. 3 a, b, c, d, and g									

10.4.3 Wooden walls

Before the invention of steel and concrete sheet pile elements wood and possibly rock was the most commonly used material for this type of structure. The configurations of some wooden sheet pile elements are shown in Figure 10.6.

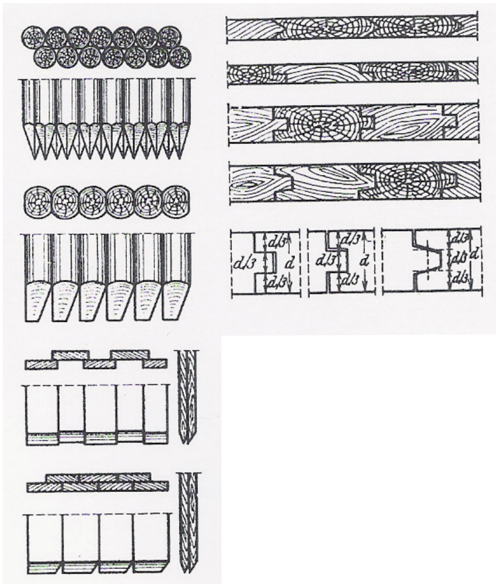


Figure 10.6: Sections showing the structure of early wooden sheet pile systems [Leimdorfer 1976]

The wooden sheet pile wall has evolved from the initial placing of two, or sometimes three, rows of piles to a system in which two wooden plank systems are connected to each other (Section 6.2).

10.4.4 Steel Sheet pile- and Combi-walls

The first combi-walls were built by the Romans and they used stone as the bearing element and wooden planks as intermediate elements. (See Chapter 6, Figure 6.9)
The first iron sheet pile wall was built in England 1834, while in the Port of Rotterdam the first sheet pile wall was built in 1927 [De Gijt, Van Kleef 2003]. After the Second World War the combined systems of steel piles and sheet piles were introduced. This culminated in the system of pipe piles with 3 sheet pile elements in between. This system has been in use in the Port of Rotterdam since 1985.
The combi-wall system consists of a combination of bearing elements in both vertical and horizontal directions and of intermediate elements that transfer the horizontal loads to the bearing elements.

Modern combi-wall systems built up from steel elements Figure10.9.
In Figure 10.10 the development of the combi-wall system in Rotterdam over time is shown [De Gijt, Heijndijk 1996].

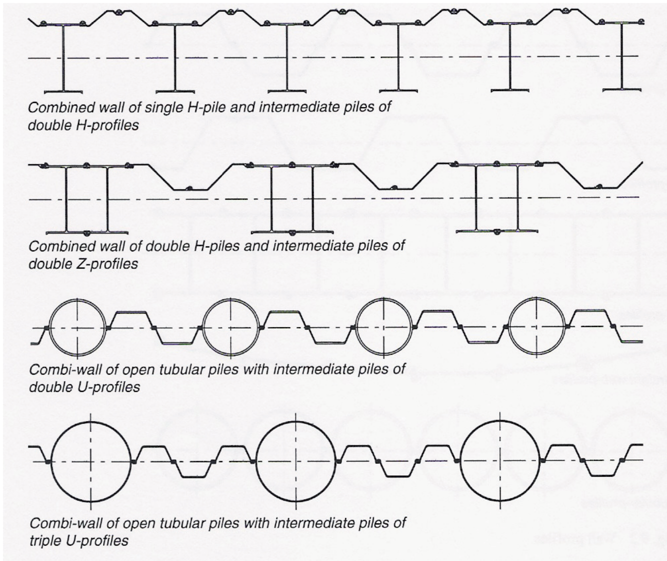


Figure 10.9: Overview of modern steel combi-wall systems [de Gijt et al 2003]

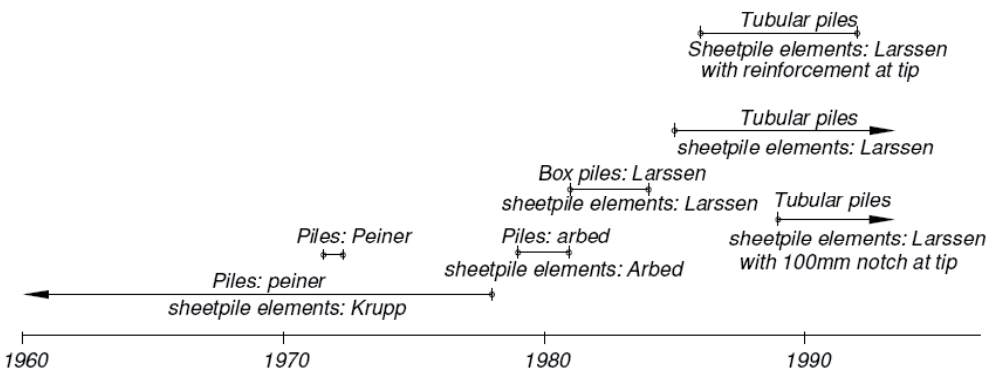


Figure 10.10: The use of combi-wall systems in the Port of Rotterdam

The sheet pile wall or combi-wall can be constructed of wood, concrete or steel. The principal materials used today are steel and concrete, since only with these materials can a considerable retaining heights be achieved.

10.4.5 Concrete walls

Since the beginning of 19th century concrete wall elements have also been used [Hennibique system 1920]. The Hennebique system was still used up to 1950, after which it was seldom used until to 1990, when once again concrete sheet pile elements were used to build some structures. The use of concrete sheet piles is still limited because of installation problems.

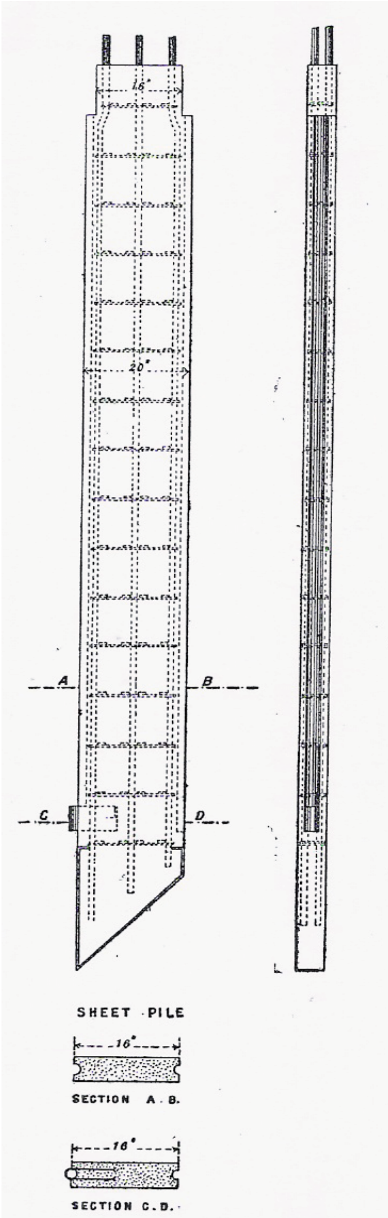


Figure 10.7: Hennebique concrete sheet pile system [Duplat Taylor 1949]

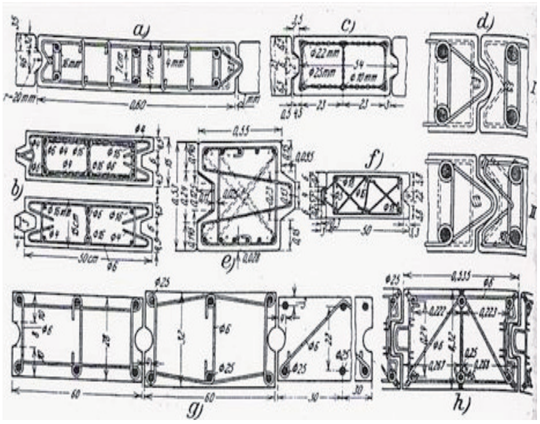


Figure 10.8: Cross-sections of different concrete wall panels [Leimdorfer 1976]

10.5 Summary

A complete overview of types of quay wall has been presented. This shows the availability of the different type of quay wall structures over time
The different structural elements used to build a quay wall are also indicated together with the first appearance of the different types.
In each part of the world ideas that can be used to build new types of quay walls or make use of new techniques have been developed. However the principles of constructing a quay wall and the functional aspects have remained the same throughout. Improvements were made especially during the last 50 years in relation to material consumption, drivability and other construction equipment.

11. A model for construction costs comparison versus time

11.1 Introduction

The cost of building port infrastructure depends on several components which have already been briefly described and discussed from the functional and technical points of view in Chapter 8. The translation of these technical factors into economic factors and finally into the total building costs is obtained by pricing the structural elements. For the decision maker it is important that, in addition to technical considerations, an economic evaluation of the different technical options from which to select the most economic option can be made. To perform this economic evaluation several methods are available. The most frequently used methods are listed below in Table 11.1.

Table 11.1: Economic evaluation methods

- Present Discounted cash flow: This method considers the predictions of the future cash flows transferred to present day value. No cost are considered
- Net present value method (NPV): This method discounts the costs and revenue flows for a project are computed for a selected life time and interest rate at the present value. This method is sensitive for the chosen interest rate and time considered.
- Internal rate of return method: This method is equal to the NPV method, however, the interest rate of the project is calculated by assuming the NPV =0. In this way the internal interest rate can be calculated.
- Cost /benefit analysis: This method compares the benefits and the costs of the project. This includes not only the financial aspects of the project values but also other aspects such as like employment and social considerations.

For this study the ‘Net Present Value Method’ has been chosen because only the costs are considered and this method is widely used to evaluate the financial aspects of infra-structural projects. This method involves considering the construction, maintenance and demolition costs during the life cycle of a structure as well as the revenues generated by this structure.

Today designs must fulfil their function for a design life of 50 years but for different-structures and situations a different time span may be agreed. In this thesis attention is focused on the lifetime costs and not on the revenues. The revenues include items like harbour dues, quay wall dues and pilot dues. These types of costs are not considered. However the decision to build a quay wall structure in a port is based on the comparison of costs and revenues according the "Net Present Value Method".

In the following equation

NPV = PV(R) - PV(C)

NPV= Σ (R(t)-C(t))/(1+r)t

NPV = Net Present Value (€)
R = Revenues (€)
C = Costs (€)
r = interest (-)
t = time span considered (years

When NPV is > 0 a profit is generated, while if the NPV is <0 a loss occurs. This method provides a means to evaluate the financial feasibility of alternative projects.

When considering the costs during the entire life cycle of a structure, the following costs or investment components can be distinguished: Planning, Design and Engineering (PDE), Construction Costs (C) Maintenance Costs (M) and Demolition Costs (D). The planning-, design-, engineering and construction costs are the initial costs of building a structure and are therefore called the initial costs of the project. The maintenance costs are those costs which must be met to ensure that the required functionality is maintained. These maintenance costs are spread over the lifetime of the structure. The demolition costs arise when it becomes necessary to remove the structure. These components are elaborated and discussed in the next section.

11.2 The model of investments

The total project costs are composed of the initial construction costs, the maintenance costs and the demolition costs. These are illustrated graphically in Figure 11.1.

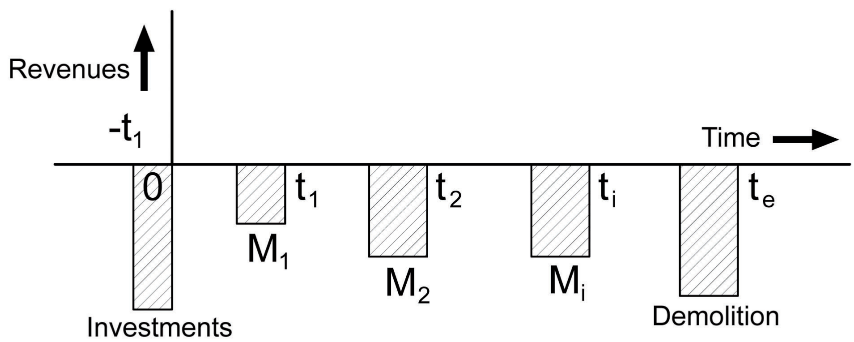


Figure 11.1: Costs versus time

The Total Costs (TC) are:

$$TC = I_0 + M_1 + M_2 + M_i + D$$

Where:
TC = Total Costs
M1, M2, Mi = Maintenance costs in year i
D = Demolition costs

Experience in the Port of Rotterdam has indicated that, on average, the following relation between construction costs, maintenance costs and demolition costs is valid for quay walls.

Table 11.1:Maintenance and demolition costs as a function of construction costs

Investments I %	**Maintenance % I_0/per year**	**Demolition % I_0**	**Source I_0**
100	0.5-1.5	15-20	Gemeentewerken Rotterdam
100*	1-2	--	Thoresen 2003

The maintenance and demolition costs may be expressed as a percentage of the construction costs shown in Table 11.1.

$$TC = I_0 + 0.010 I_0 + 0.175 I_O \quad (3)$$

Equation (3) can be translated into PV -value by the equation

$$PV = I_O + (0.010 I_O / r)\left(1 - 1/(1+r)^t\right) + 0.175 I_O / (1+r)^t$$

For investment decisions it is recommended that 1.0% of the initial construction costs be allocated to cover maintenance and 15-20% to cover demolition.

Assuming an interest rate of 4% per year and a lifetime of 50 years, the relation for PV becomes PV = 1.24 I_0. This excludes the planning, design and engineering costs (PDE).

Experience indicates that the PDE costs vary with the level of construction costs. Depending on the extent of the project these costs may vary between 4 and 8% with an average of 6% of capital expenditure I_0 [De Gijt 2003]. The PV relation then changes into: PV=1.30 I_0.
Recently other contract options such as Design and Construct, Design, Construct and Maintain and possibly also Finance, tend to be used more frequently. Despite these changes in contracting the use of the above expression for PV to establish the total costs over the life time period it is still applicable.

11.3 Indexing

It is both interesting and important to make a comparison of costs versus time when making decisions for future projects. Indeed, if a project is to be successful it is important that knowledge based on past experience is included, since this will certainly assist in the evaluation of the financial decisions relating to the proposed project. Knowing the price fluctuations and the price developments over time may enable one to predict the cost of future investments, although the uncertainties tend to increase when one looks far back and far ahead in time.

These uncertainties are caused by lack of information about:

- construction habits : habits may change slowly or abruptly.
- technical developments : over time alternative construction methods and designs may become available and also new materials or different ways of using existing ones may be found. Such innovations tend to reduce the costs.
- changing social interests: the community may change its behaviour and thus the demand for certain structures will also change.
- changes in the use of materials or shortages of specific materials: it is possible that the supply of construction materials is limited and, depending on the economic developments, shortages of materials may occur and these materials will be substituted by other materials which are more available.
- inflation and deflation rates: over time the value of money changes. This may be caused by wars or natural disasters or by an imbalance between supply and demand.

All these aspects differ over time and will also differ from each other.

Economists have developed methods to measure these changes in prices by defining 'index numbers'. The best known and most widely used of these is the consumer price index (CPI), which is also the index that has been the longest in use. This index presents the changes in the prices of consumer goods (such those relating to housing and the cost of living) over time. Economists use this index to attempt to predict and explain the trends in the market. An overview of the most frequently used index methods is presented below and the relevance of these indexes to each other is shown.

11.4 Indexing methods

By using index numbers one is able to follow the price changes over time for a defined commodity or a defined group of commodities. To compute indexes one must define a base year for comparison and one must make assumptions of improvement and changes within the originally assumed group, the basket.
At present the following indexing methods [Gaeremynck en de Broeck 2001] are mostly frequently used to compute the indexes:

- Laspeyres index
- Van Paassche index
- Fisher index
- Tornquist index, Chain index.

The Laspeyres index assumes that the quality remains the same over the period considered. This implies that no technological improvements of products over time are considered.
The Van Paasche index compares the current prices with the prices of the base year. This index takes into consideration the quality or the improvements in quality. In both the Fisher index and the Tornquist index the two former indexes are combined. The purpose of chaining is to take into account the differences occurring over the period that is under consideration by adjusting the indexes over several recent years.

It will not be surprising that each of the indexes gives a different number. The Laspeyres index over estimates inflation while the Van Paassche index indicates lower rates of inflation. The Fisher and Tornquist indexes give intermediate values.
In Gaeremynck and de Broek (2001) an overview of these formulas is presented with some comparative computations that show that the differences between the methods used are rather limited. The difference between the computed index numbers varies by less than 1%.This margin is considered acceptable for this study, so the greater problem is how to obtain sufficient data and to define the basket rather than how to refine the method of indexing.

11.5 Available data

During the period of this study the following databases were used in the preparation of the indexes:
- Consumer Price Index of the Netherlands 1450-2008 (Neha)
- Consumer Price Index of the USA 1500-2008 (EH Net)
- Consumer Price Index of England 1750-2008 (Statistics Gov. England)
- Wage Index of the Netherlands 1800-2005 (Spek 1961)
- Consumer Price Indexes of USA, Canada, Japan, Australia, Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom 1950-2008 (US Department of Labour, Bureau of Labour Statistics 2008)
- Construction Index 1996 (Mc Conville 1996]
- Developments in the prices of Stone 1900-2008, Cement 1900-2008, Sand and Gravel 1900-2008, Steel 1900-2008 of the (USGS 2008)
- Oil price index 1900-2008 (BP 2008)
- Indexes for hydraulic engineering works 1995-2008 (CROW 2008)

The base years from the data have been adjusted to 2008 (base year 2008=1).

11.6 Wage index

Spek [1971] studied the prices and wages in the Netherlands from 1620 to 1971. This data has been completed up to 2008 using the consumer price index (CBS 2008) and extended by the inclusion of a data study [Posthumus 1964] back to 1450. Comparable data is available from the USA and England, although for a shorter time. This data gives the same order of magnitude as the data for the Netherlands. Despite these limitations the data can be used to extrapolate over time, taking into account a variation of 10%. This study indicates that in 1859 the average wage was about 5 - 7 euro per week; rising to 280-330 euro per week in 2008. This implies that the increase over the last 149 years varies by a factor between 47 and 56.

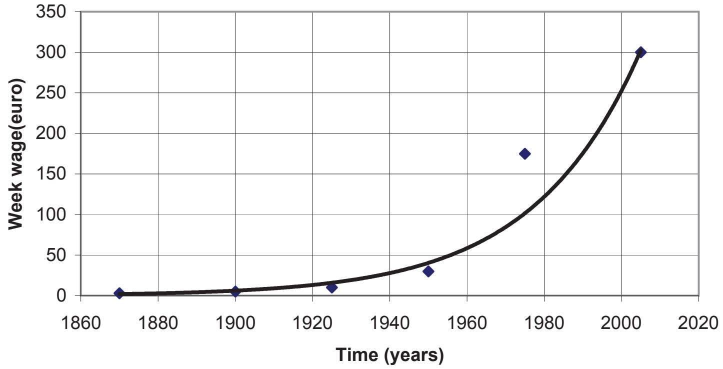


Figure 11.2: Minimum Wage per week in The Netherlands versus time expressed in Euros of 2008

11.7 Indexes of materials

From the material indexes it is possible to index the individual components of which the structure is composed.
The material indexes which are valid for quay wall structures are:
- Steel index
- Stone (riprap, rock) index
- Sand and gravel index
- Cement index
- Oil index; required for the operation of equipment

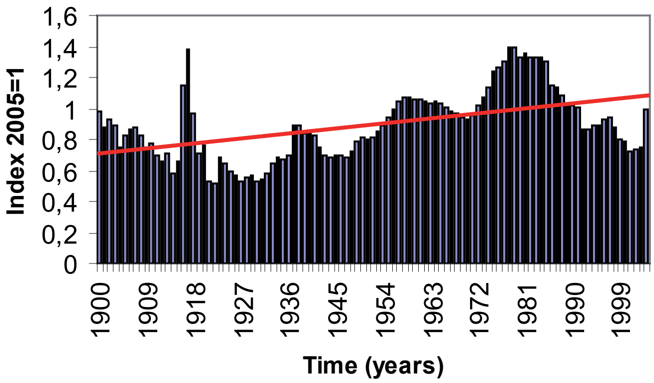


Figure 11.3: Steel index versus time

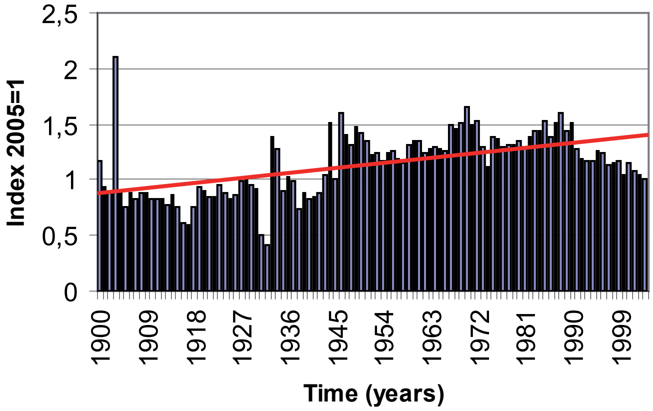


Figure 11.4: Stone and riprap index versus time

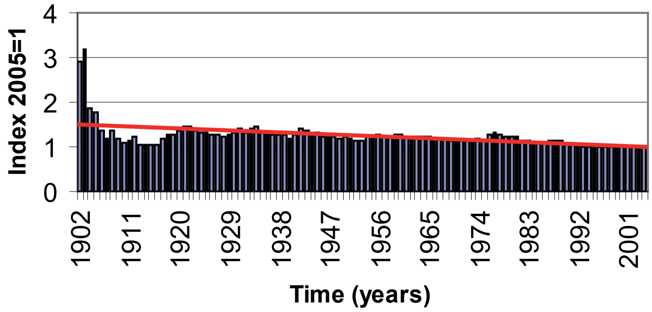


Figure 11.5: Sand and gravel index versus time

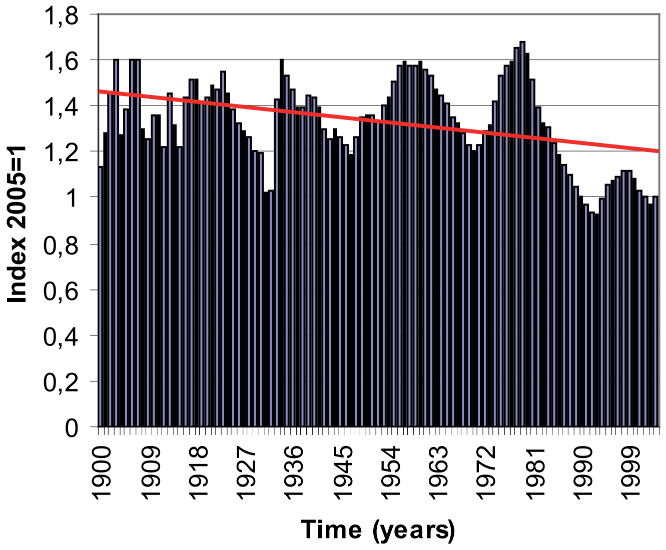


Figure 11.6: Cement index versus time

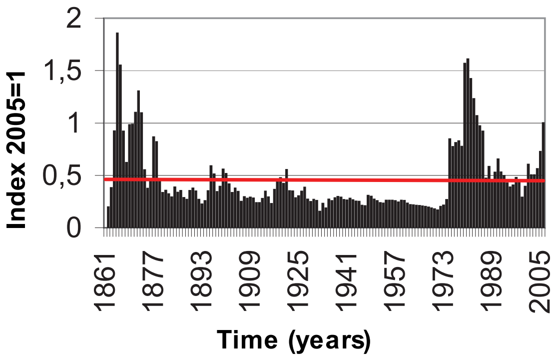


Figure 11.7: Oil price index versus time

The Figures 11.3 to 11.7 indicate that the price of oil has scarcely increased, while that of steel and stone has increased and the prices of cement, sand and gravel have decreased.

11.8 Construction cost index

Research into the cost of constructing housing and industrial complexes was carried out for 30 countries [McConville1996]. The cost components per country vary considerably owing to factors like import dues or equipment and labour costs. Sometimes the industry can use local staff and materials, but often materials must be imported. When local staff is not available it is not always easy to work out the cost estimate for working abroad, so it is difficult to make comparisons. In addition to these factors, the levels of education are very different from one country to another.

Based on these influencing factors and taking into account the costs of commodities like cement, steel, wood, stone, sand, gravel and oil (Section 11.9) the data obtained is found in Table 11.2.

The original data was related to the USA as reference level. This reference level has been adjusted to the Netherlands and given the index 1. The data shows a variation of the index structure between 0.71 and 1.34 while the average is 0.9 to 1.0. This variation results partly from some countries being richer and also some countries being economically in the development phase, which might coincide with a relatively high inflation

Table 11.2: Construction cost index. The Netherlands = 1 (1996)

	Housing	Industrial complexes
Australia	1.07	1.04
Brazil	0.83	0.73
Canada	1.07	1.04
China	0.89	0.71
Czech Republic	1.06	0.92
Denmark	1.14	1.09
Egypt	1.00	0.76
England	1.06	1.04
France	0.89	0.89
Germany	0.97	0.97
Hungary	1.05	0.92
Indonesia	0.87	0.73
Ireland	0.89	0.87
Italy	0.88	0.86
Japan	1.06	1.04

	Housing	Industrial complexes
Kuwait	1.18	1.04
Malaysia	0.83	0.78
Mexico	0.86	0.83
Nigeria	1.34	1.17
Norway	1.31	1.17
Poland	1.07	0.92
Portugal	0.87	0.85
Saudi Arabia	1.20	1.12
South Africa	1.00	0.94
South Korea	0.86	0.83
Spain	0.89	0.85
Sweden	1.15	1.12
Turkey	1.00	0.87
USA	0.93	0.97

11.9 Effects of construction time and the material used.

The ship dimensions and especially the draught of the ships have increased over the last hundred years see figure 3.16.

This implies that the depth and thus the retaining height of the quay walls must also be increased to make it possible for the ships to moor. The result is that during the last 100-150 years the retaining height has increased from approximately 5 m to a maximum of 30m.

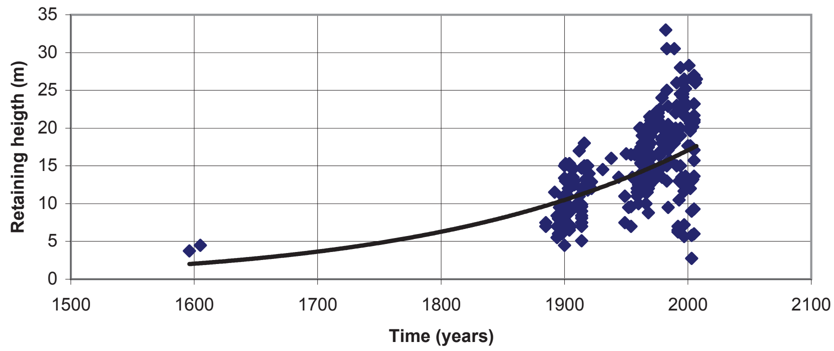


Figure 11.8: Retaining height development versus time

The retaining height has increased by a factor 7.5 from a height of 4 m in 1600 to 30 m at present.
The rate of construction expressed in per m² of quay wall, length times the retaining height, built per year is presented in Figure 11.9.
The increase is per m² per year gives a factor of 200 in the 150 years since 1850. However since 1900 this factor has been 60 which corresponds with 3.9 % increase in the rate of construction per year.

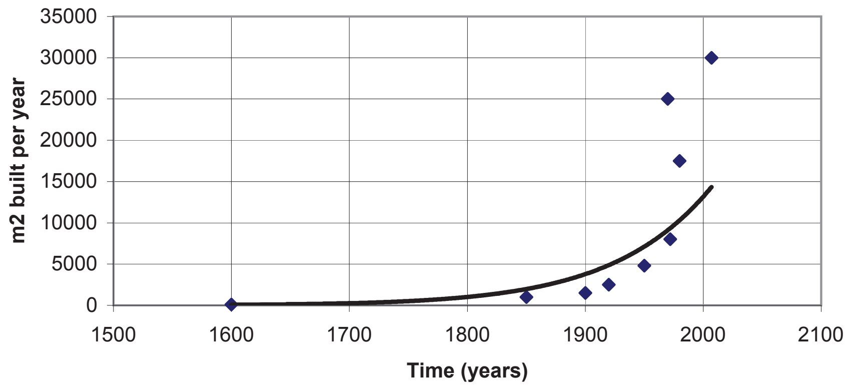


Figure 11.9: Rate of construction expressed in m2 per year versus time

In the Port of Rotterdam a cost comparison based on the use of concrete in quay walls was made. This comparison considered four quay walls in the period 1974-1991 [Van Ast 1992]. The results are presented in Table 11.3.

Table 11.3: Comparison of the man hours per unit of concrete in quay walls in Rotterdam 1974-1991

Materials used for quay walls	***Concrete m-h/m²***	***Formwork m-h/m²***	***Formwork m-h/m³***	***Concrete m-h/m³***
EMO 1974	100	100	100	100
ECT 1981	75	65	50	45
Euro terminal 1989	35	50	20	30
ARCO 1991	25	40	10	25

The above table (11.3) shows that a reduction in labour and concrete used of 75% was achieved during this period.
This implies a decrease of 7 to 8 % per year.

These reductions were achieved by the following actions [Van Ast 1992]:
- increase in production speed;
- involving equipment;
- simpler shapes;
- improvements in logistics.

The costs of a quay wall are composed of the costs of material, equipment and wages. The improvement in productivity has been a factor 60 while on average the wages increased by a factor of 52. When corrected for inflation this resulted in a relatively constant price.

11.10 Consumer Price Index (CPI)

In Figure 11.10 all CPI data is summarized in a graph showing the index number on the vertical axis and time on the horizontal axis. The results derived from the individual data from each index are presented in Appendix A.

From this graph it can be clearly observed that, apart from some small changes in periods around wars, the index number remains relatively constant between 1450 and 1950. During this period The average price change per year was 1.02 %. However, after the Second World War a dramatic increase can be observed. Between shortly after the Second World War (1950) and 2005 the average change per year was 3.6 % per year. During the period after the Second World War the growth became a factor 7 greater than in the period before 1950.
In appendix B a comparison of 6 different types of construction indexes versus the CPI index is presented. The results of this comparison are that the variation in relation to the CPI-index is +/-20%.

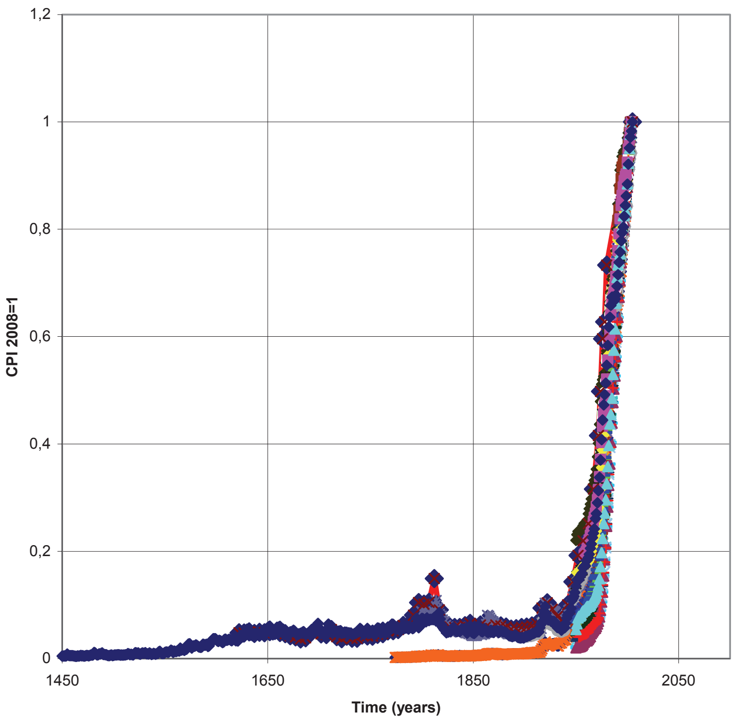


Figure 11.10: Consumer Price Index (CPI) for 19 countries (see appendix A for details)

Regarding this variation it can be concluded that CPI index is a good index to predict future costs since this reflects the wealth of people which will also finally be included in other specially developed indexes, such as those for concrete or other building materials or construction indexes.
The modern economy is very different from that of the period 1850-1900. Due to international trade the economies of all countries in the world are much more closely interrelated, and more dependent on each other. This has led to the principle of the controlled market mixed economy with opportunities for everybody. This has also resulted in an inflation rate varying between 1% and 2% that is considered acceptable for human wellbeing. This period is also characterized by the absence of world wars, which in a historical context is rather exceptional. World War Two was this last such war. However, price fluctuations do occur, for example, as a result of the closing of the Suez Canal in 1956, the oil crises of 1972, and local wars like the Gulf War. Periods during which greater inflation also occurred because of the lack of equilibrium between supply and demand in the market for commodities and, to a lesser extent, labour. Further examples include the growth of India and especially China since 1995. This growth is expected to continue.

11.11 The analysis of construction costs versus time

11.11.1 Introduction

The costs of building quay walls depend on several factors that have been indicated and discussed in Chapter 8. Experience from the Port of Rotterdam indicates that 75% of the construction costs of a quay walls are determined by the retaining height and 25% by other factors like soil conditions and tidal differences. This breakdown of costs is based on cost evaluations of quay wall projects in Rotterdam and expert judgement. This is illustrated in Figure 11.11

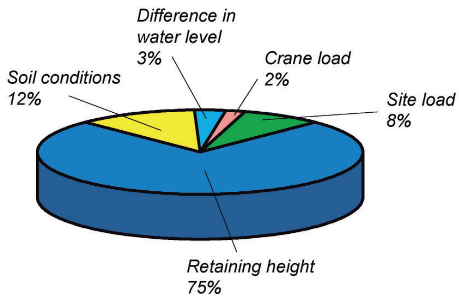


Figure 11.11: Analysis of factors driving the costs of quay walls in Rotterdam [De Gijt ea 2003]

The increase of retaining height up to 30 metres was made possible by the use of steel piles and combi walls. It could be argued that quays with this 30 m retaining height could also be constructed from wood, however although that would be possible such a huge wooden structure would most probably be very costly owing to the cost of material and the labour requirements. The designers always aim to construct a quay wall to the minimum costs and to fulfil the project requirements. The availability of construction materials, delivery times for material and equipment and the costs govern in general the design. Today the design must also comply with the environmental requirements and also incorporate the life cycle approach.

The aim is a cost reduction which can be only achieved by optimizing the design and construction process, including the reduction of labour, the use of new materials and new construction techniques. The latter include equipment and improvement of the logistics at the construction yard.

11.11.2 The Method of Individual Indexing (MII-method)

The MII-method, uses a weighted index composed of other indexes, incorporates factors such as material, equipment and labour and the contribution and changes of value over time, which is expressed in the formula:

$$Cn = \alpha\, W(1+w)^t + ß\, Br\,(1+br)^t + \gamma\, S\,(1+s)^t + \delta\, Cn\,(1+cn)^t + \varepsilon\, C\,(1+c)^t + \xi\, St\,(1+st)^t + \eta\, Sw\,(1+sw)^t + \theta\, E\,(1+e)^t + \iota\, M\,(1+m)^t$$

in which

$$\alpha + \beta + \gamma + \delta + \varepsilon + \xi + \eta + \theta + \iota = 1$$

These are the factors for the contribution of each kind of material, equipment and labour as a ratio to the total costs.

W = wood
Br = brick
S = stone
Cn = poured concrete
C = reinforced concrete
St = steel
Sw = reinforcement steel
E = equipment
M = man-hours
W = wood index
Br = brick index
S = stone index
Cn = poured concrete index
C = reinforced concrete index
St = steel index
Sw = reinforcement steel index
E = equipment index
M = hour index
T = time

The components in this formula comprise the proportions of the various materials used, the equipment and the labour. For example, if the quay wall structure is entirely constructed from wood the formula is reduced to:

$$Cn = \alpha\, W\, (1+w)^t + E\, (1+e)^t + \iota\, (1+m)^t$$

$$\alpha + \theta + \iota = 1$$

This means that for each item in the equation an index number should be available to determine the influence of each component on the total construction costs. If this data is available the above formula can be used.

11.11.3 The Method of Total Indexing (MTI-method)

However if insufficient data is available, as is usually the case, and certainly if historical situations are under consideration, the costs may be estimated according to the equation of the MTI -Method.

$$C_n = (\alpha\, W + \beta\, Br + \gamma\, S + \delta\, Cn + \varepsilon\, C + \xi\, St + \eta\, Sw + \theta\, E + \iota\, M)\,(1+CPI)^t$$

in which

$$\alpha + \beta + \gamma + \delta + \varepsilon + \xi + \eta + \theta + \iota = 1$$

Cn = future costs
CPI = Consumer Price Index
t = time

11.11.4 Comparison of the MII and MTI methods

The results of these methods are compared by using the data of the indexes [CROW 2005] for the period of 1995 to 2005 (see Appendix C). This data has been selected because it covers a long period.

In this example two typical quay wall structures have been selected: a gravity quay wall, Deurganckdok, Antwerp, Figure 11.14, and a retaining quay wall that is a combi-wall with a relieving floor, Amazonehaven Rotterdam, Figure 11.15.
These quay walls were selected for comparison of the costs of quay walls for the two methods, MTI and MMI, as these types of structures have a completely different composition and the building methods used also differ significantly.

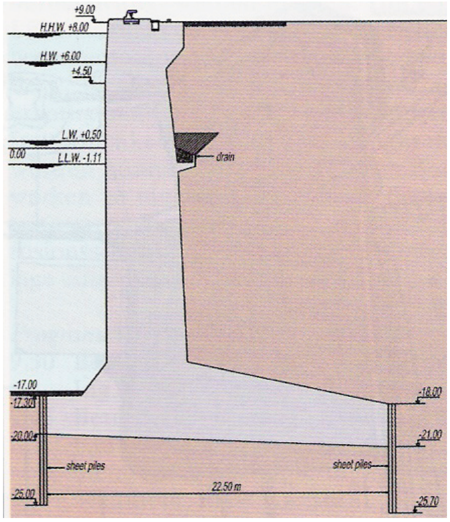


Figure 11.12: Quay wall Deurganckdok, Belgium

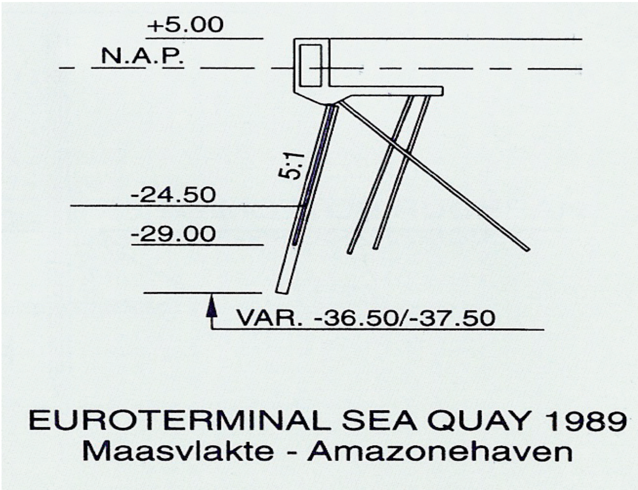


Figure 11.13: Quay wall Amazonehaven Rotterdam

The typical distribution of the costs of these quay walls is presented in Table 11.4.

Table 11.4: Typical distribution of costs

	Deurganckdok	**Amazonehaven**
Concrete	60%	20%
Steel	10%	40%
Wages and groundwork	30%	40%

Comparing the two methods, MMI and MTI, for these two types of quay wall structures, Deurganckdok and Amazonehaven which are composed of 60% and 20% concrete and steel 10 % and 40% respectively. The groundwork contributions in both cases are 30% and 40% for the Deurgangckdok and Amazonehaven.
The increase in costs during 1995 en 2005 is a factor 1.50 and 1.59 for the MII method and for the MTI values a value of 1.48 was computed in both cases
The results of this comparison are presented in Table 11.5.

Table 11.5: Results of computations according the MMI-and MTI methods

Method	**Deurganckdok**	**Amazonehaven**
MII	1.50	1.59
MTI	1.48	1.48
Ratio MTI/MII	0.99	0.93

In Appendix B the detailed comparison of both methods is presented.
The **MII method** gives the highest increase in cost and the **MTI method** the lowest. If the **MTI method** is considered as the reference method a difference of 1-7% is found between the two methods. Therefore making the comparison based on the **MTI method** when using the CPI index seems to be justified.

If the market is demanding extremely high quantities of steel, as has been the case in China during recent years, the average indexing is not applicable. However on a long term basis in case of rather stable price development the MTI method gives sufficient accuracy for first cost estimates and involves less effort.

11.12 Construction costs of quay walls

11.12.1 Introduction

In this section the costs of quay walls are presented. The total database includes approximately 300 quay walls around the world (see Appendix D). The costs of the quay walls for 2008 are presented in Euros. The costs of quay walls from other countries are calculated by using the exchange rates between the country and the Netherlands and the MTI method.

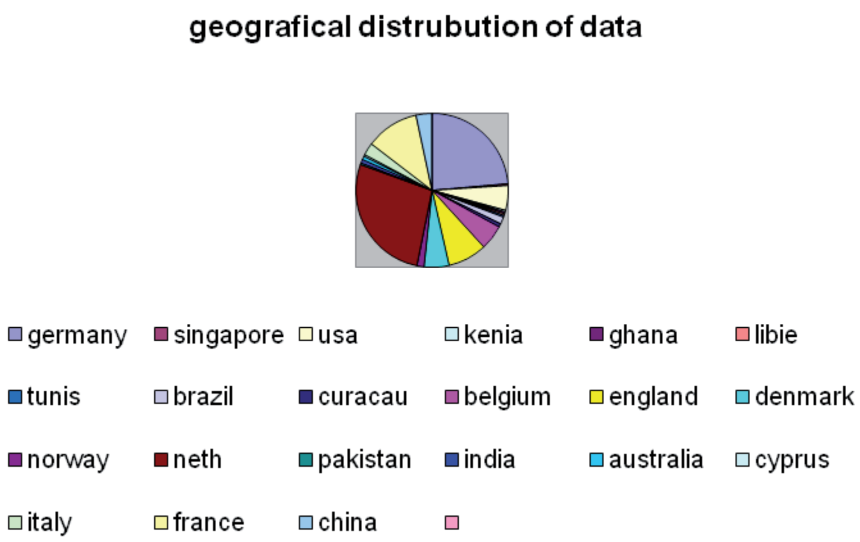


Figure 11.14: Geographical distribution of the data

In Figure 11.14 the distribution of the available data from many parts of the world is presented. Most of this data derives from Europe, although data from other continents, including Asia, Africa and America is also included. The data from Europe is about 70% of the total.

The data was obtained from several Port Authorities (Rotterdam, Antwerpen, Hamburg, Dalian, Shanghai), personal communication, and various journals including HANSA and Dock and Harbour Engineering and from text books This data provided sufficient information to formulate conclusions that are also valid outside Europe. In Appendix C the full data set is presented.

11.12.2 Costs of quay walls around the world

In Figure 11.15 the costs per running metre versus retaining height are presented for the quay walls around the world.

When considering the costs of quay walls it was already stated that the contribution of the retaining height to the total costs is more than 75 % of the total cost. This can also be illustrated as follows.

Gravity structures derive their stability by resisting the horizontal loads to the subsoil by horizontal equilibrium and the moment at toe at the waterside.

Sheet pile structures derive the stability from resisting the moment in the beam.

This results in an expected formula for the costs in relation to the retaining height:

$$C = \text{factor } H^{1\text{-}3}$$

In which C = costs
H = retaining height

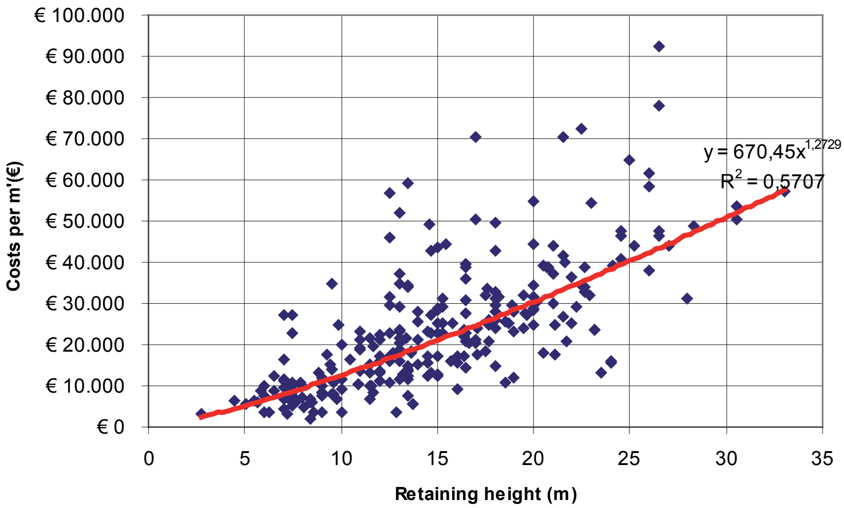


Figure 11.15: Costs of quay walls in euro (2008 values) around the world as a function the retaining height (data from ports in the countries shown in Figure 11. 14 has been used)

The correlation coefficient is 0.57, which indicates a relatively strong relationship between retaining height and costs.
This graph includes all available data though some anomalies can be observed. These anomalies are attributable to special circumstances like very difficult soil conditions and or special structures, which is the case for a few quay walls in France and England.
In other situations the time at which the quay wall had to be built may have coincided with unfavourable market conditions. The costs of quay walls vary within a band width of approximately +/-25 %, irrespective of the soil conditions, tidal ranges and types of structures.
This analysis is based on comparing the costs of a running metre of quay wall up to 2008. However, it is very interesting and also challenging to predict the costs of quay walls for future projects.

This prediction is made by the formula:
C_x = $(1+0.035)^t \, . \, 566H^{1.3}$
C_x = costs (Euro) in year (2008 values)
H = retaining height in metres

The results of these computations are shown in Figure 11.16.
This exercise is made possible by supposing that the change in the CPI index will remain the same for the coming hundred years as that which was found for the past fifty years. This assumption is, of course, open of discussion as the composition of the CPI index might alter as living conditions will change. If, however, we assume a future without great disasters, like wars and natural disasters this approach may be selected. Major natural disasters and the effects of climate change are not taken into account since they may be considered as normal fluctuations within the geological time frame. The contribution of humans to the increase in CO_2 is also of limited importance in the geological time scale.

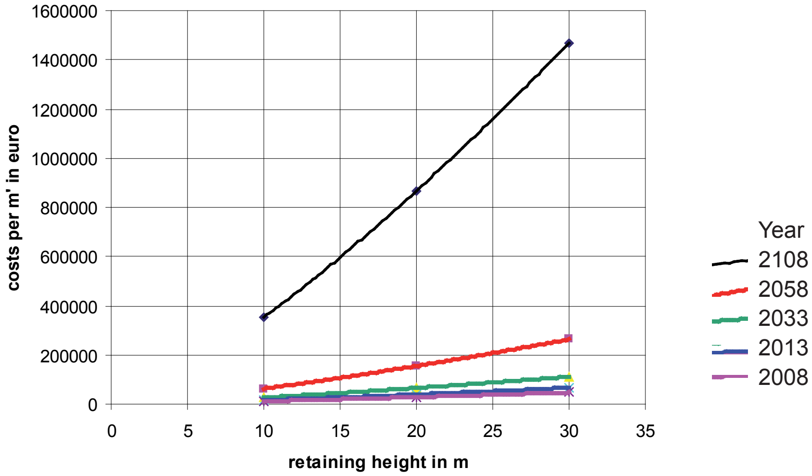


Figure 11.16 Cost in euro (2008 values) versus time as a function of retaining heights

Looking far into the future and making predictions is in itself a risky operation. Thus the applicability of the graph of Figure 11.16 is possibly limited to a period of 50 years.

11.12.3 Economics of scale

The costs of quay walls versus time are shown Figure 11.17 as a function of retaining heights. It can be observed that the decrease in costs is about 25% for the retaining heights greater than 25 metres, while this reduction is reduced almost to zero to 5%, for retaining heights up to 4.9 metres. This is because for quay walls with greater retaining heights the improvement in logistics and the development of special equipment is warranted, while for lower retaining heights these improvements are not feasible. Thus with high and long quay walls advantages are obtained from the scale effects.

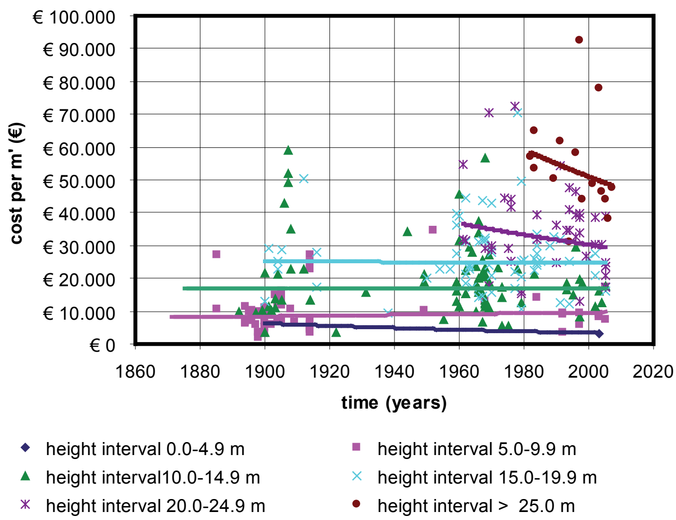


Figure 11.17: Cost of quay walls in euro (2008 values) versus time.

Figure 11.17 implies that when adjusted for inflation the costs of quay wall construction are relatively constant with time. If we compare the increase in the rate of production during the construction process and realize (see Sections 11.6 and 11.9) that this is balanced by the increased wages, the constant costs are then entirely due to greater and better use of equipment, serial production, efficient material use and improvements in construction logistics.

So with larger quantities the costs are reduced, a situation which is comparable to that for the production of manufactured goods such computers and cars. However, the scale advantages for quay construction tend to be limited, since the construction of a quay wall is not a continuous production process. In every port within a single contract quay wall construction lengths of 500-1000 metres are relatively commonly encountered and sometimes quays of 2000 to 3000 metres long are being constructed. This means that in fact no optimum repetition effect can be achieved.

11.12.4 Costs comparison for gravity and sheet pile quay walls

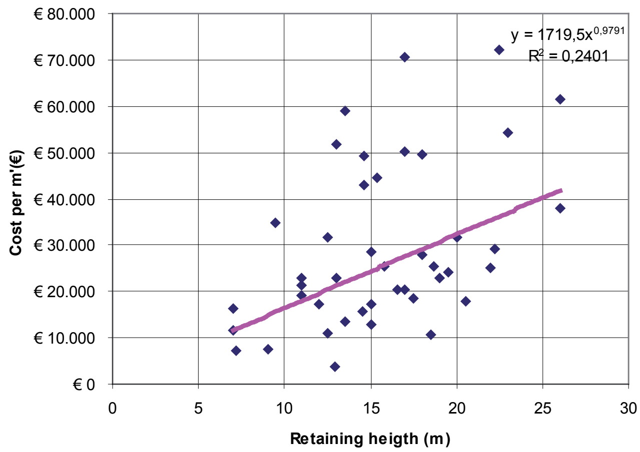


Figure 11.18: Costs for gravity structures in euro (2008 values)

Figure 11.19 indicates that there is a considerable variation in the cost of gravity structures. This can be explained by the fact that these structures are built of concrete and steel. To build these structures a construction pit is often required, which of course will increase the costs. In such cases the distance between the construction pit and the final location is important as this determines the transport costs and may contribute considerably in the total costs.

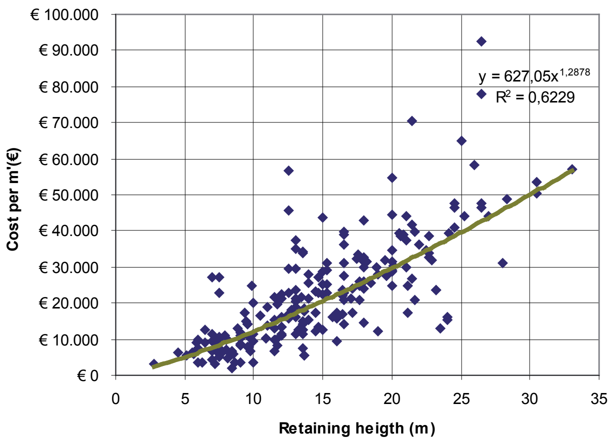


Figure 11.19: Costs of sheet piles and piled structures in euros (2008 values)

For sheet pile wall like structures the relation is considered fairly good and is explained by the fact that these types of structure are not dependent on construction pits and transport.

11.12.5 Influence of tidal range on costs

The costs in relation to the tidal difference are depicted in Figure 11.20. The increase in costs as a result of tidal difference is presented for retaining heights of 10 metres, 20 metres and 30 metres. The increase in costs in the range of 1 to 5 metres tidal difference is approximately 4000 euro for a retaining height of 10 metres and 5000 euro for a retaining height of 30 metres.
These extra costs are considered relatively minor since as the tidal range increases the retaining height of the quay wall also has increase to accommodate the ships.

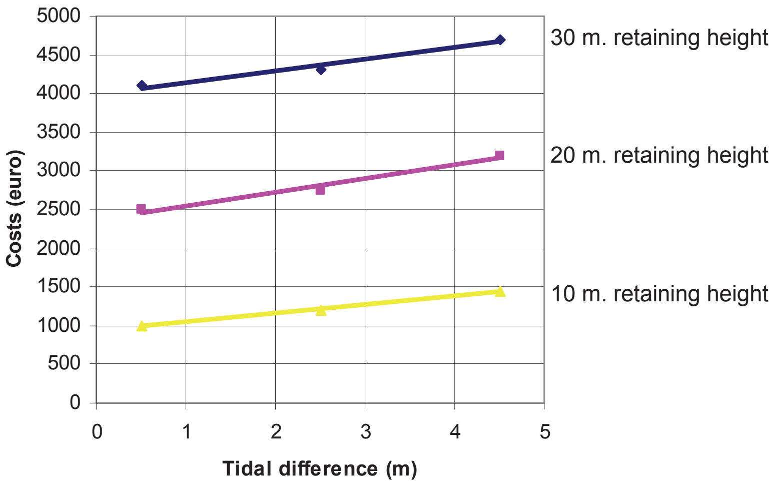


Figure 11.20: Costs increase due tidal difference in euros (2008 values)

11.12.6 Additional costs relations

In the previous subsections the costs of the quay walls in general and a comparison between gravity and sheet pile wall structures and the influence of the tidal range have been discussed. More graphs have been compiled, for example graphs for a particular port or country. This additional information is presented in Appendix E.

11.13 Summary

This section has presented an overview of different index numbers used to analyse and predicted future costs.
This study uses the MTI method to predict construction costs for quay walls by making use of the CPI index. The CPI index reflects human consumer behaviour which is finally also reflected in specific indexes.

The construction costs per running metre of about 300 quay walls around the world have been analysed. This analysis shows that there is a strong relation between the costs per running metre and retaining height. For gravity structures this relation is less pronounced than for piled structures. Comparisons indicate that gravity structures show a greater variability than piled structures.
Moreover, it has been shown that if corrected for inflation the costs are more or less constant.
Certain types of structure could not have been built until the materials and equipment in use today became available. As a result of improvements in the logistics of the construction process it has been shown that with retaining heights in excess of 25 metres it is still possible to reduce costs.

12. Future developments in quay wall design and construction

12.1 Introduction

Although looking into the future is more speculative than scientific, nevertheless it is necessary that port authorities and port designers acquire insight into possible future developments, since they will have to cope with competition and trends in ports development. This also implies that these changes might influence the designs of quay walls, so some consideration is given to how quay walls and other berthing and mooring facilities might develop in relation to the anticipated trends in world maritime trade. For this it is implicit that developments in ship and cargo handling are also considered. Possible changes in the construction materials are also discussed. All these developments have financial consequences, so some attention is also devoted to costs.

12.2 Development of ships

Until approximately 1900 all commercial ships were general cargo vessels. During the 20th century, however, ships were designed to transport specific types of cargo such as coal, petroleum products, grain, frozen meat, fruit and ores and ports and handling facilities were designed to accommodate specific types of ship. At present most cargoes in the western world tare transported in ships such as, for example, bulk carriers for ore and oil, LNG-tankers and container carriers. This trend is expected to continue.

The development of container traffic and of oil tankers is the most remarkable of these trends. However, how the developments, especially in ship dimensions, will continue is open to discussion. The expectation is that for traditionally designed ships the dimensions will be restricted to a maximum length of 500 m, a maximum width of 70 m and a maximum draught of 25 m. The reasons for this expectation is that due nautical constraints like depth of the sea or dimensions of sea straits and the presence of small islands (Strait of Malacca), bigger ships cannot pass through these areas Another argument is that the economics of bigger ships is not necessarily improved by bigger engines and or for example the use of double propellers. Figures 12.1 and 12.2 indicate how this could apply to both bulk carriers and container vessels.

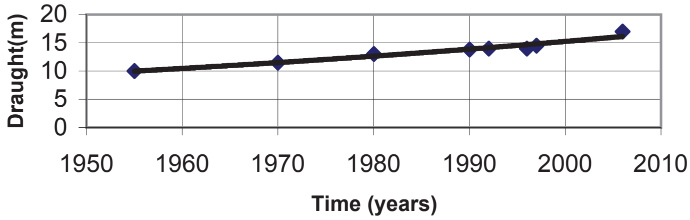


Figure 12.1: Increase in the draught of vessels and tankers

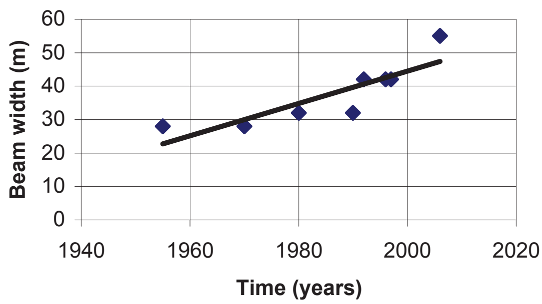


Figure 12.2: Increase in the beam of container vessels

The speed of these vessels at sea is typically 24 km/h for ore carriers and 45 to 54 km/h for containerships.

Today investigations are taking place into whether containerships of 15000 TEU capacity or more might be designed with two main propellers to ensure that at least the present speed level at sea can be maintained. So far it seems that the limit of speed has been reached. Considering the above, it is anticipated that the carrying capacity of containerships, expressed in TEU, will reach a maximum of around
25.000 TEU

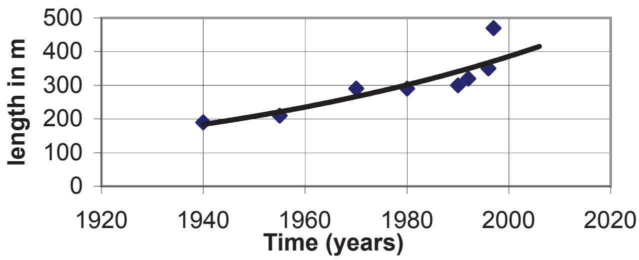


Figure 12.3: Increase in TEU carried by container vessels

Another trend could be toward the use of twin-hulled vessels which may reach speeds of 30 to 40 knots at sea, however at this stage they do not exist. In addition the use of such vessels must be investigated in relation to the type of cargo and the transhipment facilities required.

12.3 Development of cargo handling facilities

The present cargo handling facilities, especially those for bulk goods like liquids, ore and coal, include pipelines for liquids, while for ore and coal mobile or fixed cranes are used. These methods of transhipment fulfil the present needs. For the near future no dramatic changes are foreseen, although for container handling one might expect a greater outreach, extending to about 75 m, and the use of a double cat to permit the simultaneous transhipment of two containers. This development implies higher crane loads on the quays.

Another possibility could be to use cranes on each side of the vessels, as is done at the Ceres terminal in Amsterdam, Figure 12.4.

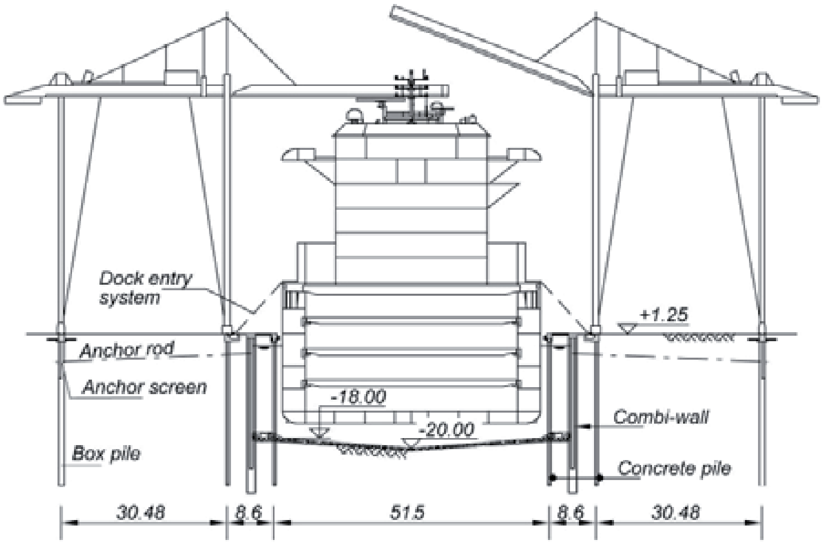


Figure 12.4: Cranes used on both sides of the vessel, Ceres harbour, Amsterdam [De Gijt et al 2003]

The benefits of such quay wall configurations are still limited and certainly the unloading and unloading capacity is not doubled by their use (Hollebrands, 2002).
This is because container ships sail to different ports where different volumes of containers are transhipped. Only when nearly 100% of the cargo is transhipped in one port does this system present advantages.

An entirely different option could be to use floating terminals at sea, with transport systems linking them to the shore. For container vessels an alternative to floating terminals is a floating transhipment facility [De Gijt, Plugge 1996], as presented in Figure 12.5.
With this facility the ships are handled on-stream and the stacking area is considerably reduced, while quay wall extensions will be limited.
For the Dutch situation this does not seem to be viable because of the high costs involved (Section12.8), compared with the costs of expanding seawards by using sand for land reclamation. However with the possible climate changes and especially the anticipated rise in sea level this might be an option.

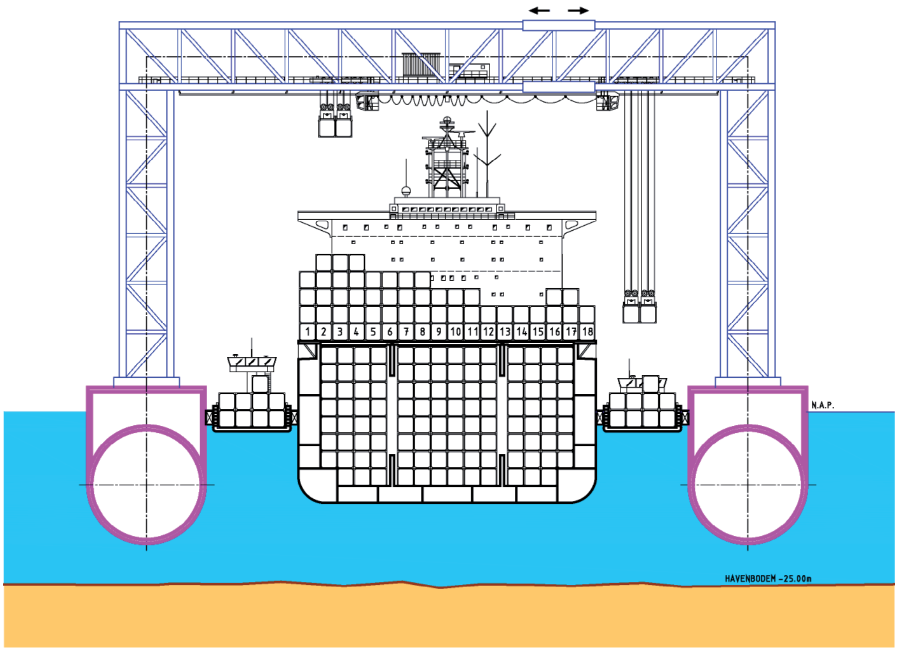


Figure 12.5: Moveable transhipment installation [de Gijt, Plugge 1996]

12.4 Construction materials

Nowadays the materials predominantly used for quay wall construction are steel and concrete because these materials can be used to produce any desired shape and they are both still available in abundance. At present there are no indications that there will be a rapid change in the near future. Some designs [van Breughel 2002] that are still in the study phase have incorporated synthetic construction materials as indicated in Figures 12.6 and 12.7. The aim of these studies is to investigate whether these types of solution will reduce the construction time and construction costs and increase the durability and flexibility. However, at this stage these solutions appear to be very expensive and without clear advantages.

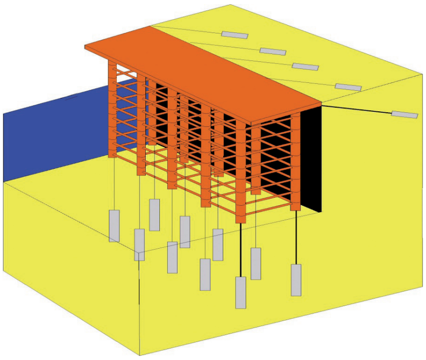


Figure 12.6: Hybrid quay wall concept comprising steel and synthetic elements

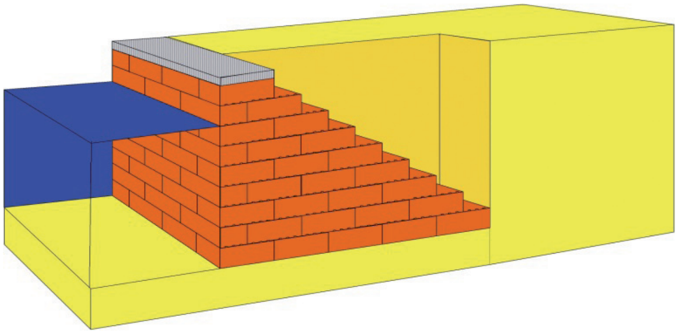


Figure 12.7: Synthetic block quay wall concept

It may be possible that a combination of synthetic and steel structures could be used, for example to reduce the corrosion problems. Another approach could be to design flexible structures in order to optimize the technical design lifetime, service life time and the economic lifetime of a quay wall. This approach is an attempt to design for an economic life time which is about equal to the design life time and thus reduce the costs. If the anticipated duration of the service life is approximately 10 years then the frozen quay wall concept [de Gijt 2005] might be feasible. Preliminary studies indicate that the energy costs for this period are favourable compared with the traditional construction costs of a quay wall.

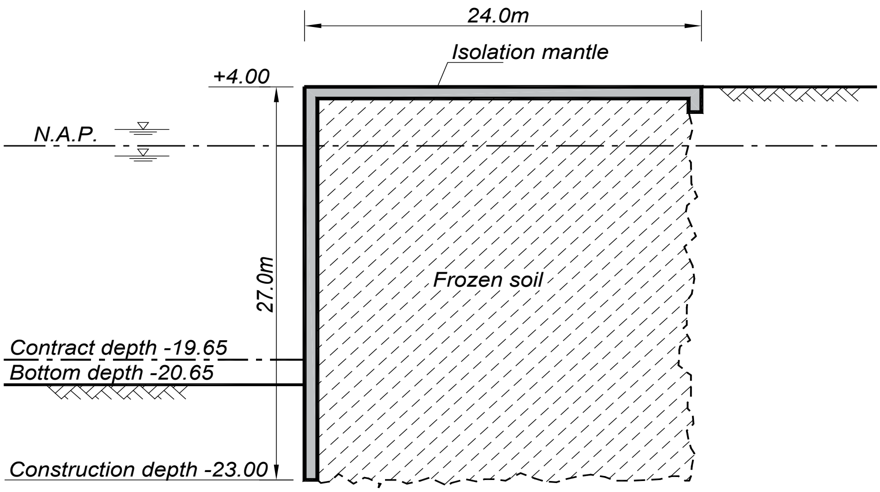


Figure 12.8: Frozen quay wall concept

Up to now quay walls are constructed in 40 metre long sections with a joint between each section. As joints always pose structural and construction problems like unexpected cracking, difficulties arise during construction.
Recently the container terminal in Bremenhaven was constructed without joints [Morgen, Vollstedt 2008].

The use of high-strength concrete might reduce the dimensions of a quay wall considerably, therefore the use of high strength concrete combined with a jointless quay wall was investigated [Dudok Van Heel, 2007].

An indication of this structure is given in Figure 12.9. Because of the danger of the development of cracking it would be possible to construct such a high-strength concrete wall only if it could be ensured that the concrete part of the structure could move independently of the foundations piles. Figure 12.9 shows this new sliding construction.

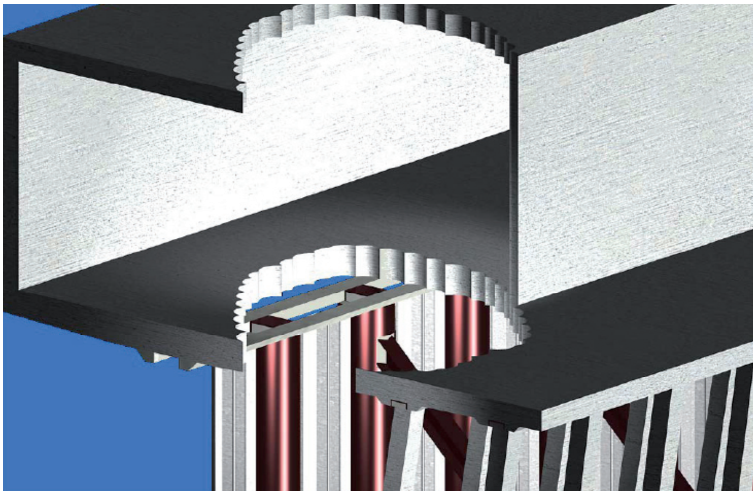


Figure 12.9: Detail of sliding construction between upper and lower parts of a quay wall

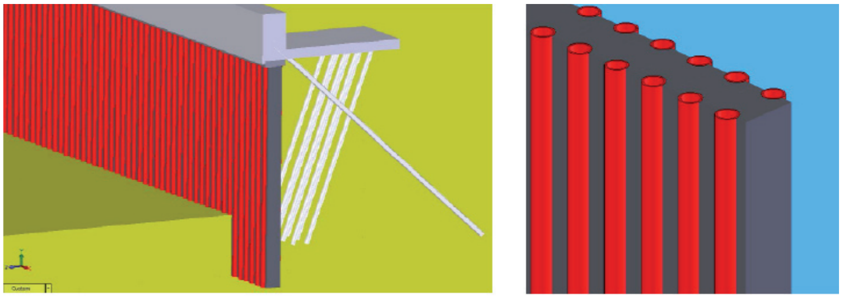


Figure 12.10: Hybrid wall structure consisting of two rows of pipe piles with concrete between.

This hybrid wall structure was designed for an MSc study [Bonte, 2006] investigating possible alternative quay wall structures.

Another possible option would be to construct floating structures, the advantage of these being that when necessary they can be moved to different locations to accommodate to changing port layouts. However, when considering the dimensions of quay wall structures, as in the case of other structures, a minimum dimension is required to sustain the imposed forces. This will also limit the reduction in the material required, even when high strength concrete and high strength steel are to be used (Section 12.8).

12.5 Design philosophy

Today most quay walls are still designed according the overall safety approach. This means that all uncertainties relating to actions and reactions as well modelling uncertainties are reflected in one number, the overall safety factor.
However, it is expected that in the near future a fully or semi-probabilistic design approach will be used more often and this will permit the risks in both time and money to be better quantified. A first approach to using semi-probabilistic design for quay walls with a relieving floor has already been proposed [de Gijt et al. 2003].
Subsequently [De Grave, De Gijt and Vrijling 2003] performed a study to determine partial factors for three other quay walls with a relieving floor. This study has shown that the partial factors originally proposed were also applicable to these structures.
The determination of the water levels requires more attention as the forces generated by the differences in water level are directly transferred to the structure.
Finally the study also recommended that the concrete superstructure should be incorporated into the fault tree in order to obtain a total probabilistic design of the whole structure.

The design of quay walls is not only a technical process but also a commercial, financial and social process. This process has its ownstrengths and weaknesses.
Within the design of quay walls several phases are distinguished and each phase has its own inherent uncertainties with their effects on costs as indicated in Table 12.1.

Table 12.1: Uncertainties in quay wall design

Phase	Uncertainties	Effects on Costs
Initiative	- Changes in consumer markets	+/-
	- Changing logistics concepts	+/-
	- Port ownership	+/-
	- Port layout	+
	- Ship properties	-
	- Cargo handling facilities	+
	- Boundary conditions	+/-
	- Berthing length	+
	- Draft	+
	- Human error	+/-
Design	- Design methods	+/-
	- Local experience	+
	- Available materials	+
	- Life cycle concepts	+/-
	- Contracting method	+/-
	- Legal aspects	-
	- Design models	+/-
	- Determination of soil parameters	+
	- Computational model	+
	- Human error	+/-

Phase	Uncertainties	Effects on Costs
Construction	- Selection of equipment	+
	- Working sequence	+
	- Human error	+/-
Service	- Real loads	+/-
	- Real deformations	+/-
	- Maintenance	+/-
	- Deformations of crane rails	-
	- Human error	+/-
Demolition	- Diaphragm wall	-
	- Combi wall system with relieving floor	+
	- Sheet pile system	+
	- Gravity wall (block wall)	+
	- Gravity wall (monolith)	-
	-Human error	+/-
	-legal aspects	-

Note: + positive effect on costs (lower costs),
- negative effects on costs (higher costs)

Therefore de Gijt and Vrijling (2009) propose to make use of a decision and fault tree analysis to create an open and objective decision process which considers the responsibility of the parties involved.
In Table 12.2 a proposal for a combined decision- and fault tree is presented.
This decision- and fault tree combines all the phases in the project and illustrates the influence of the decisions made in each phase and the effects of these decisions on the other phases.
With this approach an open and objective quantification of all the risks is obtained and also the effects of the decisions are made clear to the parties involved.

Table 12.2: A Proposal for a combined decision and fault tree

Decision tree initiative phase: e.g. scenarios for ship development , cargo handling, port dues, commodity development
Fault tree design phase: e.g. calibration/ improvement in modelling, improvement of obtaining material characteristics
Fault tree construction phase: e.g. reduction of incorrect installation methods and the improper use of materials
Fault tree service phase: e.g. comparison predicted and real loads and deformations, real use

12.6 Types of structure

If there are no significant changes in the cargo handling techniques it is not anticipated that there will be any significant changes in the types of quay wall that are constructed. However if such changes do occur the mooring facilities will have to be adapted to these new requirements, since the quay wall design must follow the development of the logistic facilities. It may be possible that in the future quay walls will also be used for storage activities, although at this stage these options do not seem to be financially viable at this stage of development.

12.7 Costs

Based on the evaluation of costs described in Chapter 11, it is not anticipated that the cost of constructing quay walls will increase drastically. It might indeed be possible that in certain periods one type of quay wall will become more expensive, depending on the relative cost of one or more construction materials, but it is thought that in the long term this effect will be redressed by technological development. Considering the overall changes, which are predominantly influenced by inflation over a longer period of time, the short-term price changes may be considered to be minor fluctuations. However, if entirely different loading/unloading facilities are going to be designed and used, we will have to design different types of structures and the cost of these new types of port infrastructure will certainly change. This will be achieved by continuous improvement of the logistics of the building process, reduction of manpower, increasing use of equipment and the development and use of new structural elements.

Scenario's:	Single use quay				Adaptable quay				Reusable quay			
	No change	Depth increase	Load increase	**Overall**	No change	Depth incr.	Load incrase	**Overall**	No change	Depth incr.	Load inc.	**Overall**
Construction costs	36	36	36	36	40	40	40	40	60	60	60	60
Maintenance costs	5,8	5,8	5,8	5,8	6,4	6,4	6,4	6,4	6	6	6	6
Upgrade costs	-	18	10	5,6	-	8	4	2,4	-	12	-	2,4
Demolition costs	-	5	2	1,4	-	-	-	0	-	-	-	0
Indirect costs:												
Loss of rental	-	2,3	1,2	,7	-	,7	,3	,2	-	1,6	1	,4
Loss of dues	-	1,2	,6	,3	-	,3	,2	,1	-	0,8	,5	,2
PV Asset at 25 yr.	-2,3	-2,3	-2,3	-2,3	-4,6	-4,6	-4,6	-4,6	-6,9	-6,9	-6,9	-6,9
Scenario probability (%)	*60*	*20*	*20*	⤴	*60*	*20*	*20*	⤴	*60*	*20*	*20*	⤴
Total:				**47,5**				**44,5**				**62,2**

Figure 12.11: Comparison of alternative quay wall designs

The results of a study into a quay wall for the future by [Wijnants, de Gijt et al 2005 and Wijnants, de Gijt et al 2006] are presented in Figure 12.11.
A comparison was made of the life cycle cost for a standard quay wall (single use quay), an adaptable quay wall (upgradable to a certain extent) and a reusable quay wall (transferable to different locations). The results indicate that the total investment for these options range between 44.5 and 62.2 million euro .The reusable quay wall is far the most expensive option. The single-use quay wall and adaptable quay wall have the same order of magnitude of investment, only a difference of 6 %. However, the present value after 25 years for these options is -2.3 and -4.6 milliton a difference of 100%.

Of course these types of computations are sensitive to the interest rate used, the time frame considered and the technical possibilities.
On the basis of this study it seems that the idea of building reusable structures does not seem to be viable when the costs are concerned. Adaptable quay walls might give a small advantage.

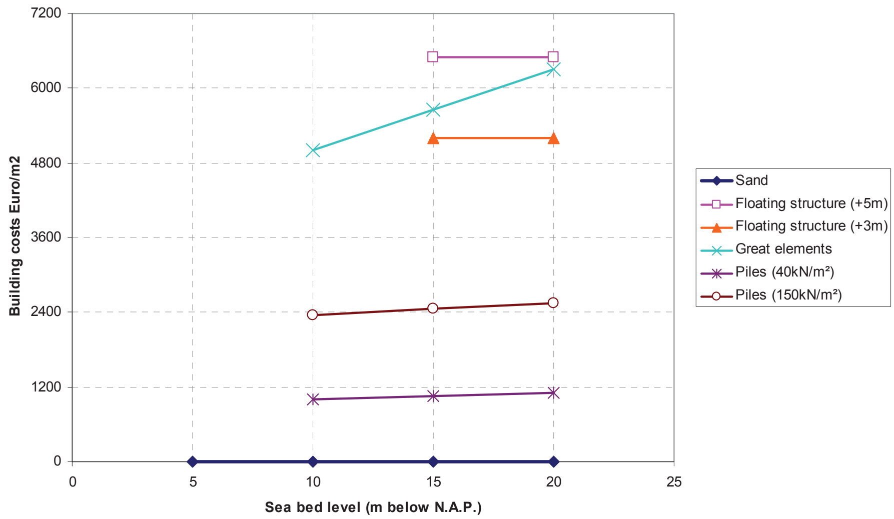


Figure 12.12 Comparison of different options to create land

In the performed work of the Maasvlakte 2 extension project in the Port of Rotterdam there have been performed several studies of how to create new land. The results of a study [Eversdijk, de Gijt et al 1997] are presented in Figure 12.12
For different levels of the sea bed ranging from N.A.P -5 to -20 metres the following options have been analysed: sand fill structures on piles, floating structures composed of steel or concrete, large prefab elements like caissons and cofferdam structures. The results are presented in Figure 12.2, which shows the relation between to seabed level and square metre price in Euros for the several options.
It is evident that the sand option is by far the cheapest solution for this location.
The results of these studies show that building floating structures and reusable quay walls at these locations are very expensive options. Only in the case of deep water, for example more than 800 to 1200 metres are the floating options economically feasible.

12.8 Summary

This chapter has discussed possible important future developments for the design of quay walls. Based on the available information, it is not expected that ships will have a greater length than 500 metres or a beam exceeding 70 metres. Owing to the water depths in coastal regions the maximum draught will not exceed 25 metres.
The logistics of the terminal impose requirements on the quay wall and the quay wall has to be adapted to change, but no dramatic changes are expected in this respect.
In relation to alternative quay wall designs there will be opportunities for the use of new materials and improvements in the construction process.
Studies of flexible structures for the Dutch situation have shown that compared to the present designs these are very expensive.

13. Conclusions and recommendations

13.1 Introduction

This study involved making a comprehensive inventory of the way sea trade has developed in different parts of the world over the last 5000 years. The increase in sea trade was made possible by the enormous developments in shipbuilding and transhipment facilities such as cranes and quay walls during this period. The study has focussed on the design methods and construction techniques used and in particular on the construction costs of quay walls versus time. Although this study is relatively comprehensive, some areas still remain to be investigated and researched in greater detail so this chapter is subdivided into a section giving conclusions that have arisen from this study and a section containing recommendations for further research.

13.2 Conclusions

- The developments of knowledge occurred in several parts of the world at different times. The gains in knowledge gave advantages to the people in those parts of the world where the first practical applications took place.

- Trade, and especially sea trade, has changed considerably if one compares the volume of trade and the speed of shipment in earlier ages with that of today.

- The equipment for the transhipment of goods has increased enormously in running capacity and size.

- The shapes and types of quay wall structure have remained relatively unchanged during the last 4000 years. However the size has increased by a factor of ten or more.

- The quality of the materials used to build quay walls has improved considerably, especially since 1900 when the use of concrete, reinforced concrete and steel made it possible to built bigger structures that withstand higher loads.

- The knowledge required for designing and building quay walls was obtained by using the results of the developments in structural mechanics, soil mechanics and, to a lesser extent, fluid mechanics.

- People who made major contributions to develop design theories include Leonardo da Vinci, Newton, Galileo, Coulomb, Rankine, Simon Stevin, and Terzaghi.

- It has been proposed that the MTI method (Method of Total Indexing) should be used to determine the construction costs of quay walls versus time.

- The world economy in the Western World has changed since the Second World War from purely capitalism or mercantile systems to what is termed a controlled, mixed economy. This seems to imply an acceptable inflation rate of 1 to 3 % per year.

- This study has shown that when the construction costs per running metre of quay wall are corrected for inflation they remain constant over time.

- Over the last hundred years the speed of quay wall construction has increased by a factor of 40 to 60, thus reducing the relative costs of construction. On the other hand wages increased with about the same order of magnitude as the reduction of construction time, resulting in an overall constant cost.

- As ship dimensions largely determine the dimensions of quay walls some considerations relating to the future development of ships and quay walls are included. From these considerations it is expected that ships will have a maximum length of 500 metres, a width 70 metres and a draft of 25 metres.

- The number of quay walls to be built around the world is small if compared to consumer goods like personal computers and cars, so the options for cost reduction are limited. In addition the circumstances, such as geotechnical and hydraulic aspects, in which quay walls are built are different.
  However, for quay walls with high retaining heights and greater lengths a cost reduction of 20 % and 30 % may be achieved by improvement of the logistics of the construction process.

- As possibilities to achieve cost-saving are rather limited, regardless of the type of quay wall design and the differences in cost between various locations are limited to around 20%, one might consider that the design of a quay wall is not a competitive component between competing ports.

13.3 Recommendations

- The proposed model for converting costs versus time is also applicable to other types of infrastructure such as tunnels and bridges. It is therefore proposed that data relating to these types of structure should be gathered and used to create a database.

- Studying the past assists in understanding why existing structures have their present form. For this reason it is recommended that this type of study should be conducted in relation to other branches of civil engineering and maybe even to other engineering disciplines.

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Appendix A
CPI-index data 19 countries

Year	United States	Canada	Japan	Australia	Austria	Belgium	Denmark	France	Germany	Italy		Netherlands		Norway	Spain	Sweden	Switzerland	United Kingdom
	I (2)	I (3)	I	I (4)	I	I (5)	I (6)	I (7)	I(8)	I	II	I	II(9)	I(10)		II	I	I(11) I
1950	24,1	21,6	14,8	12,6		24,0	12,3	11,1			8,3		21,4	13,6	5,5	13,4	33,2	9,8
1951	26,0	23,9	17,2	15,1		26,3	13,5	13,0			9,1		23,5	15,7	6,0	15,5	34,8	10,7
1952	26,5	24,5	18,0	17,7		26,5	14,0	14,6			9,5		23,8	17,1	5,9	16,7	35,7	11,7
1953	26,7	24,2	19,2	18,4		26,4	14,1	14,4		10,3	9,6		23,8	17,5	6,0	16,9	35,4	12,1
1954	26,9	24,4	20,5	18,5		26,9	14,2	14,3		10,6	9,9		24,7	18,2	6,1	17,1	35,7	12,3
1955	26,8	24,4	20,2	18,9		26,8	15,0	14,5		10,9	10,2		25,2	18,4	6,3	17,5	36,0	12,9
1956	27,2	24,8	20,3	20,1		27,4	15,8	14,8		11,2	10,7		25,4	19,1	6,7	18,4	36,5	13,5
1957	28,1	25,6	20,9	20,6		28,2	16,1	15,3		11,4	10,9		27,1	19,6	7,4	19,2	37,3	14,0
1958	28,9	26,3	20,8	20,9	31,6	28,6	16,3	17,6		11,7	11,4		27,5	20,6	8,4	20,0	37,9	14,4
1959	29,1	26,6	21,1	21,3	32,0	29,0	16,5	18,7		11,7	11,4		27,8	21,0	9,0	20,2	37,7	14,5
1960	29,6	26,9	21,8	22,1	32,6	29,1	16,7	19,4		11,9	11,7		28,6	21,1	9,1	21,0	38,2	14,6
1961	29,9	27,1	23,0	22,6	33,8	29,3	17,4	20,0		12,2	12,0		28,9	21,6	9,2	21,5	38,9	15,1
1962	30,2	27,4	24,6	22,6	35,3	29,8	18,8	21,0		12,7	12,6		29,6	22,8	9,7	22,5	40,6	15,8
1963	30,6	27,9	26,4	22,7	36,2	30,4	19,8	22,0		13,7	13,6		30,5	23,4	10,6	23,2	42,0	16,1
1964	31,0	28,4	27,4	23,2	37,6	31,7	20,5	22,7		14,5	14,4		32,3	24,7	11,3	23,9	43,3	16,6
1965	31,5	29,1	29,5	24,1	39,5	32,9	21,8	23,3		15,2	15,0		33,6	25,7	12,8	25,1	44,8	17,4
1966	32,4	30,2	31,0	24,9	40,3	34,3	23,3	23,9		15,5	15,3		35,5	26,6	13,6	26,8	46,9	18,1
1967	33,4	31,3	32,3	25,7	41,9	35,3	25,0	24,6		16,1	15,6		36,8	27,8	14,5	27,9	48,8	18,5
1968	34,8	32,5	34,0	26,3	43,1	36,3	27,0	25,7		16,3	15,8		38,1	28,7	15,2	28,4	50,0	19,4
1969	36,7	34,0	35,8	27,1	44,4	37,6	27,9	27,3		16,7	16,3	40,6	41,0	29,6	15,5	29,2	51,3	20,5
1970	38,8	35,1	38,5	28,2	46,4	39,1	29,8	28,8		17,5	17,1	42,1	42,5	32,8	16,4	31,3	53,1	21,8
1971	40,5	36,2	40,9	29,9	48,5	40,8	31,5	30,3		18,4	17,9	45,3	45,6	34,8	17,7	33,6	56,6	23,8
1972	41,8	37,9	42,9	31,6	51,6	43,0	33,6	32,2		19,4	18,9	48,9	49,2	37,3	19,2	35,6	60,4	25,5
1973	44,4	40,7	47,9	34,6	55,5	46,0	36,7	34,6		21,6	20,9	52,9	53,1	40,1	21,4	38,0	65,7	27,9
1974	49,3	45,2	59,1	39,9	60,8	51,9	42,3	39,3		25,7	25,0	58,1	58,3	43,8	24,8	41,7	72,1	32,3
1975	53,8	50,1	66,0	45,9	65,9	58,5	46,4	43,9		30,0	29,3	63,8	64,2	49,0	29,0	45,8	76,9	40,1
1976	56,9	53,8	72,2	52,1	70,8	63,8	50,5	48,2		35,1	34,1	69,6	69,9	53,5	34,1	50,5	78,2	46,8
1977	60,6	58,1	78,1	58,5	74,6	68,4	56,1	52,7		41,0	40,3	74,1	74,4	58,3	42,4	56,3	79,2	54,2
1978	65,2	63,3	81,4	63,1	77,3	71,4	61,8	57,5		46,0	45,3	77,2	77,4	63,1	50,8	61,9	80,1	58,7
1979	72,6	69,1	84,4	68,8	80,2	74,6	67,7	63,6		52,8	52,4	80,5	80,6	66,1	58,8	66,4	83,0	66,6
1980	82,4	76,1	90,9	75,8	85,3	79,6	76,1	72,3		64,0	63,5	86,1	85,9	73,3	67,9	75,5	86,3	78,5
1981	90,9	85,6	95,4	83,2	91,1	85,6	85,0	82,0		75,4	75,4	91,9	91,7	83,3	77,8	84,6	91,9	87,9
1982	96,5	94,9	98,0	92,4	96,0	93,1	93,6	91,6		87,8	87,7	97,2	97,1	92,7	89,0	91,9	97,1	95,4
1983	99,6	100,4	99,8	101,8	99,2	100,3	100,0	100,5		100,7	100,8	99,8	99,8	100,5	99,9	100,0	100,0	99,8
1984	103,9	104,7	102,1	105,8	104,8	106,6	106,4	107,9		111,5	111,5	103,0	103,1	106,8	111,1	108,1	102,9	104,8
1985	107,6	108,9	104,2	112,9	108,2	111,8	111,4	114,2		121,8	121,1	105,3	105,4	112,9	120,9	116,0	106,4	111,1
1986	109,6	113,4	104,8	123,2	110,0	113,3	115,4	117,2		129,0	128,5	105,6	105,5	121,0	131,5	121,0	107,2	114,9
1987	113,6	118,4	104,9	133,7	111,6	115,0	120,0	120,9		135,1	134,4	105,1	104,8	131,6	138,5	126,1	108,8	119,7
1988	118,3	123,2	105,7	142,9	113,8	116,4	125,5	124,2		141,9	141,1	106,1	105,5	140,4	145,1	133,4	110,8	125,6
1989	124,0	129,3	108,1	154,1	116,6	120,0	131,5	128,6		150,8	150,4	107,1	106,7	146,8	155,0	142,0	114,3	135,4

	Year	United States	Canada	Japan	Australia	Austria	Belgium	Denmark	France	Ger-many	Italy		Nether-lands		Norway	Spain	Sweden	Switzer-land	United King-dom
d																			
I		I (2)	I (3)	I	I (4)	I	I (5)	I (6)	I (7)	I(8)	I II	I	II(9)	I(10)		II	I	I(11)	I
	1990	130,7	135,5	111,4	165,3	120,5	124,1	135,0	133,0		160,5	159,6	109,9	109,3	152,8	165,4	156,7	120,5	148,2
	1991	136,2	143,1	115,1	170,7	124,4	128,1	138,2	137,2	81,9	170,6	169,8	113,3	112,7	158,0	175,2	171,5	127,5	156,9
	1992	140,3	145,3	117,0	172,4	129,5	131,2	141,1	140,6	86,1	179,4	179,0	116,9	116,2	161,7	185,6	175,6	132,7	162,7
	1993	144,5	147,9	118,5	175,5	134,1	134,8	142,9	143,5	89,9	187,5	186,5	120,0	119,2	165,4	194,1	183,9	137,0	165,3
	1994	148,2	148,2	119,3	178,8	138,2	138,0	145,8	145,9	92,3	195,0	193,8	123,3	122,4	167,7	203,3	187,8	138,3	169,3
	1995	152,4	151,4	119,2	187,1	141,3	140,1	148,8	148,4	93,9	205,1	204,2	125,7	124,6	171,8	212,8	192,4	140,8	175,2
	1996	156,9	153,8	119,3	192,0	143,9	142,9	151,9	151,3	95,3	213,4	212,2	128,2	127,0	174,0	220,3	193,5	141,9	179,4
	1997	160,5	156,2	121,5	192,5	145,8	145,3	155,3	153,2	97,1	217,7	216,0	131,0	129,7	178,5	224,8	194,8	142,5	185,1
	1998	163,0	157,7	122,2	194,1	147,1	146,7	158,2	154,3	98,0	222,0	219,9	133,6	132,2	182,5	228,8	194,2	142,7	191,4
	1999	166,6	160,5	121,8	197,0	147,9	148,3	162,0	155,0	98,6	225,7	223,6	136,5	135,1	186,7	234,2	195,1	143,8	194,3
	2000	172,2	164,8	121,0	205,8	151,4	152,1	166,8	157,7	100,0	231,4	229,1	140,0	138,4	192,5	242,1	196,9	146,0	200,1
	2001	177,1	169,0	120,1	214,8	155,5	155,8	170,8	160,3	102,0	237,8	235,4	145,9	144,1	198,4	250,8	201,6	147,4	203,6
	2002	179,9	172,8	119,1	221,2	158,2	158,4	174,8	163,4	103,4	243,7	241,0	150,7	148,7	200,9	259,6	206,0	148,4	207,0
	2003	184,0	177,6	118,7	227,4	160,3	160,9	178,5	166,8	104,5	250,3	247,0	153,9	151,7	205,9	267,6	209,9	149,3	213,0
	2004	188,9	180,9	118,7	232,7	163,7	164,3	180,7	170,3	106,2	255,8	252,6	155,7	153,5	206,8	275,7	210,0	150,5	219,4

Year		USA	canada	japan	italy	germany	uk	swiss	sweden	spain	norway	neth	nethy	italy	france	denmark	belgium	austria	australia
1950	24,1	0,12758	0,1194	0,12468	0,03286		0,04467	0,2206	0,06381	0,01995	0,06576	0,13941			0,06518	0,06807	0,14607		0,05415
1951	26,0	0,13764	0,13212	0,1449	0,03603		0,04877	0,23123	0,07381	0,02176	0,07592	0,15309			0,07634	0,07471	0,16007		0,06489
1952	26,5	0,14029	0,13543	0,15164	0,03761		0,05333	0,23721	0,07952	0,0214	0,08269	0,15505			0,08573	0,07748	0,16129		0,07606
1953	26,7	0,14134	0,13378	0,16175	0,038		0,05515	0,23522	0,08048	0,02176	0,08462	0,15505		0,04027	0,08456	0,07803	0,16068		0,07907
1954	26,9	0,1424	0,13488	0,1727	0,03919		0,05606	0,23721	0,08143	0,02213	0,08801	0,16091		0,04144	0,08397	0,07858	0,16372		0,0795
1955	26,8	0,14187	0,13488	0,17018	0,04038		0,0588	0,2392	0,08333	0,02285	0,08897	0,16417		0,04261	0,08514	0,08301	0,16312		0,08122
1956	27,2	0,14399	0,13709	0,17102	0,04236		0,06153	0,24252	0,08762	0,0243	0,09236	0,16547		0,04378	0,08691	0,08744	0,16677		0,08638
1957	28,1	0,14876	0,14151	0,17607	0,04315		0,06381	0,24784	0,09143	0,02684	0,09478	0,17655		0,04457	0,08984	0,0891	0,17164		0,08853
1958	28,9	0,15299	0,14538	0,17523	0,04513		0,06563	0,25183	0,09524	0,03047	0,09961	0,17915		0,04574	0,10335	0,0902	0,17407	0,19304	0,08982
1959	29,1	0,15405	0,14704	0,17776	0,04513		0,06609	0,2505	0,09619	0,03264	0,10155	0,18111		0,04574	0,10981	0,09131	0,17651	0,19548	0,09153
		0	0	0	0		0	0	0	0	0	0		0	0	0	0	0	0
1960	29,6	0,1567	0,1487	0,18366	0,04632		0,06655	0,25382	0,1	0,03301	0,10203	0,18632		0,04652	0,11392	0,09242	0,17712	0,19914	0,09497
1961	29,9	0,15828	0,14981	0,19377	0,04751		0,06882	0,25847	0,10238	0,03337	0,10445	0,18827		0,04769	0,11744	0,09629	0,17833	0,20648	0,09712
1962	30,2	0,15987	0,15146	0,20725	0,04988		0,07201	0,26977	0,10714	0,03518	0,11025	0,19283		0,04965	0,12331	0,10404	0,18138	0,21564	0,09712
1963	30,6	0,16199	0,15423	0,22241	0,05384		0,07338	0,27907	0,11048	0,03845	0,11315	0,1987		0,05356	0,12918	0,10957	0,18503	0,22114	0,09755
1964	31,0	0,16411	0,15699	0,23083	0,05701		0,07566	0,28771	0,11381	0,04099	0,11944	0,21042		0,05668	0,13329	0,11345	0,19294	0,22969	0,0997
1965	31,5	0,16675	0,16086	0,24853	0,05938		0,07931	0,29767	0,11952	0,04643	0,12427	0,21889		0,05942	0,13682	0,12064	0,20024	0,2413	0,10357
1966	32,4	0,17152	0,16694	0,26116	0,06057		0,0825	0,31163	0,12762	0,04933	0,12863	0,23127		0,06059	0,14034	0,12894	0,20876	0,24618	0,107
1967	33,4	0,17681	0,17302	0,27211	0,06176		0,08432	0,32425	0,13286	0,05259	0,13443	0,23974		0,06294	0,14445	0,13835	0,21485	0,25596	0,11044
1968	34,8	0,18422	0,17966	0,28644	0,06255		0,08842	0,33223	0,13524	0,05513	0,13878	0,24821		0,06372	0,15091	0,14942	0,22094	0,26329	0,11302
1969	36,7	0,19428	0,18795	0,3016	0,06453		0,09344	0,34086	0,13905	0,05622	0,14313	0,2671	0,26076	0,06529	0,16031	0,1544	0,22885	0,27123	0,11646
		0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0
1970	38,8	0,2054	0,19403	0,32435	0,0677		0,09936	0,35282	0,14905	0,05948	0,15861	0,27687	0,27039	0,06841	0,16911	0,16491	0,23798	0,28345	0,12119
1971	40,5	0,2144	0,20011	0,34457	0,07086		0,10848	0,37608	0,16	0,0642	0,16828	0,29707	0,29094	0,07193	0,17792	0,17432	0,24833	0,29627	0,12849
1972	41,8	0,22128	0,20951	0,36142	0,07482		0,11623	0,40133	0,16952	0,06964	0,18037	0,32052	0,31407	0,07584	0,18908	0,18594	0,26172	0,31521	0,1358
1973	44,4	0,23504	0,22499	0,40354	0,08274		0,12716	0,43654	0,18095	0,07762	0,19391	0,34593	0,33976	0,08444	0,20317	0,2031	0,27998	0,33903	0,14869
1974	49,3	0,26098	0,24986	0,49789	0,09897		0,14722	0,47907	0,19857	0,08995	0,2118	0,3798	0,37315	0,10047	0,23077	0,23409	0,31589	0,37141	0,17147
1975	53,8	0,28481	0,27695	0,55602	0,11599		0,18277	0,51096	0,2181	0,10519	0,23694	0,41824	0,40976	0,11728	0,25778	0,25678	0,35606	0,40257	0,19725
1976	56,9	0,30122	0,2974	0,60826	0,135		0,21331	0,5196	0,24048	0,12369	0,2587	0,45537	0,44701	0,13722	0,28303	0,27947	0,38831	0,4325	0,22389
1977	60,6	0,3208	0,32117	0,65796	0,15954		0,24704	0,52625	0,2681	0,15379	0,28191	0,48469	0,47592	0,16028	0,30945	0,31046	0,41631	0,45571	0,2514
1978	65,2	0,34516	0,34992	0,68576	0,17933		0,26755	0,53223	0,29476	0,18426	0,30513	0,50423	0,49583	0,17983	0,33764	0,342	0,43457	0,47221	0,27116
1979	72,6	0,38433	0,38198	0,71104	0,20744		0,30356	0,5515	0,31619	0,21328	0,31963	0,52508	0,51702	0,20641	0,37346	0,37465	0,45405	0,48992	0,29566
		0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0
1980	82,4	0,43621	0,42067	0,7658	0,25139		0,35779	0,57342	0,35952	0,24628	0,35445	0,55961	0,55299	0,2502	0,42454	0,42114	0,48448	0,52108	0,32574
1981	90,9	0,48121	0,47319	0,80371	0,2985		0,40064	0,61063	0,40286	0,28219	0,4028	0,59739	0,59024	0,29476	0,4815	0,47039	0,521	0,55651	0,35754
1982	96,5	0,51085	0,5246	0,82561	0,34719		0,43482	0,64518	0,43762	0,32281	0,44826	0,63257	0,62428	0,34324	0,53787	0,51799	0,56665	0,58644	0,39708

1983	99,6	0,52726	0,555	0,84078	0,39905		0,45488	0,66445	0,47619	0,36235	0,48598	0,65016	0,64098	0,39367	0,59014	0,5534	0,61047	0,60599	0,43747
1984	103,9	0,55003	0,57877	0,86015	0,44141		0,47767	0,68372	0,51476	0,40297	0,51644	0,67166	0,66153	0,43589	0,63359	0,58882	0,64881	0,6402	0,45466
1985	107,6	0,56961	0,60199	0,87784	0,47941		0,50638	0,70698	0,55238	0,43852	0,54594	0,68664	0,6763	0,47615	0,67058	0,61649	0,68046	0,66097	0,48517
1986	109,6	0,5802	0,62687	0,8829	0,50871		0,5237	0,71229	0,57619	0,47697	0,58511	0,6873	0,67823	0,5043	0,6882	0,63863	0,68959	0,67196	0,52944
1987	113,6	0,60138	0,65451	0,88374	0,53207		0,54558	0,72292	0,60048	0,50236	0,63636	0,68274	0,67502	0,52815	0,70992	0,66408	0,69994	0,68173	0,57456
1988	118,3	0,62626	0,68104	0,89048	0,55859		0,57247	0,73621	0,63524	0,5263	0,67892	0,6873	0,68144	0,55473	0,7293	0,69452	0,70846	0,69517	0,6141
1989	124,0	0,65643	0,71476	0,9107	0,59541		0,61714	0,75947	0,67619	0,56221	0,70986	0,69511	0,68786	0,58952	0,75514	0,72773	0,73037	0,71228	0,66223
		0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0
1990	130,7	0,6919	0,74903	0,9385	0,63183		0,67548	0,80066	0,74619	0,59993	0,73888	0,71205	0,70584	0,62744	0,78097	0,74709	0,75533	0,7361	0,71036
1991	136,2	0,72102	0,79104	0,96967	0,67221	0,77119	0,71513	0,84718	0,81667	0,63547	0,76402	0,7342	0,72768	0,66693	0,80564	0,7648	0,77967	0,75993	0,73356
1992	140,3	0,74272	0,80321	0,98568	0,70863	0,81073	0,74157	0,88173	0,83619	0,6732	0,78191	0,757	0,7508	0,70133	0,8256	0,78085	0,79854	0,79108	0,74087
1993	144,5	0,76496	0,81758	0,99832	0,73832	0,84652	0,75342	0,9103	0,87571	0,70403	0,79981	0,77655	0,77071	0,73299	0,84263	0,79081	0,82045	0,81918	0,75419
1994	148,2	0,78454	0,81924	1,00505	0,76722	0,86911	0,77165	0,91894	0,89429	0,7374	0,81093	0,79739	0,79191	0,76231	0,85672	0,80686	0,83993	0,84423	0,76837
1995	152,4	0,80678	0,83693	1,00421	0,80839	0,88418	0,79854	0,93555	0,91619	0,77185	0,83075	0,81173	0,80732	0,8018	0,8714	0,82346	0,85271	0,86316	0,80404
1996	156,9	0,8306	0,85019	1,00505	0,84006	0,89736	0,81768	0,94286	0,92143	0,79906	0,84139	0,82736	0,82338	0,83425	0,88843	0,84062	0,86975	0,87905	0,8251
1997	160,5	0,84966	0,86346	1,02359	0,85511	0,91431	0,84366	0,94684	0,92762	0,81538	0,86315	0,84495	0,84136	0,85106	0,89959	0,85944	0,88436	0,89065	0,82725
1998	163,0	0,86289	0,87175	1,02949	0,87055	0,92279	0,87238	0,94817	0,92476	0,82989	0,8825	0,86124	0,85806	0,86787	0,90605	0,87548	0,89288	0,89859	0,83412
1999	166,6	0,88195	0,88723	1,02612	0,88519	0,92844	0,8856	0,95548	0,92905	0,84947	0,9028	0,88013	0,87669	0,88233	0,91016	0,89651	0,90262	0,90348	0,84658
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2000	172,2	0,91159	0,911	1,01938	0,90697	0,94162	0,91203	0,9701	0,93762	0,87813	0,93085	0,90163	0,89917	0,90461	0,92601	0,92308	0,92575	0,92486	0,8844
2001	177,1	0,93753	0,93422	1,01179	0,93191	0,96045	0,92799	0,9794	0,96	0,90968	0,95938	0,93876	0,93706	0,92963	0,94128	0,94521	0,94827	0,94991	0,92308
2002	179,9	0,95236	0,95522	1,00337	0,95408	0,97363	0,94348	0,98605	0,98095	0,9416	0,97147	0,96873	0,96789	0,9527	0,95948	0,96735	0,96409	0,9664	0,95058
2003	184,0	0,97406	0,98176	1	0,97783	0,98399	0,97083	0,99203	0,99952	0,97062	0,99565	0,98827	0,98844	0,9785	0,97945	0,98783	0,97931	0,97923	0,97722
2004	188,9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

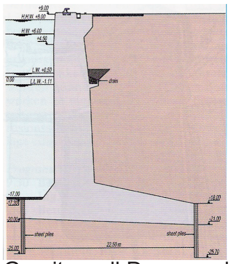
Appendix B
Comparison different construction indexes

Year	ENR CCI (%)		ENR BCI (%)		Boeckh (%)		Lee Saylor (%)		Turner (%)		R.S. Means (%)		USA CPI (%)		Neth CPI %		
1980	0		0		0		0		0		0			0		0	
1981	9,2	0,8440367	8	0,733945	9,9	0,908257	8,1	0,743119	10,3	0,944954	11,3	1,036697	91	10,9	0,56	0,04	13,3
1982	18,2	0,99453552	15,1	0,825137	19,1	1,043716	9,4	0,513661	19	1,038251	21	1,147541	97	18,3	0,59	0,07	23,3
1983	25,6	1,16894977	22,8	1,041096	25,1	1,146119	19,7	0,899543	25,3	1,155251	27,5	1,255708	100	21,9	0,61	0,09	30
1984	28,1	1,04850746	24,5	0,914179	30	1,119403	22,9	0,854478	31,9	1,190299	30,4	1,34328	104	26,8	0,63	0,11	36,7
1985	29,6	0,93375394	25,1	0,791798	32,2	1,015773	26,1	0,823344	37	1,167192	31,3	0,987382	108	31,7	0,65	0,13	43,3
1986	32,7	0,95614035	27,9	0,815789	34,3	1,002924	28,4	0,830409	40,7	1,190058	33,9	0,991228	110	34,2	0,65	0,13	43,3
1987	36,1	0,92564103	30,9	0,792308	37,1	0,951282	31	0,794872	45,4	1,164103	39,4	1,010256	114	39	0,64	0,12	40
1988	39,6	0,90205011	33,8	0,769932	42,1	0,958998	35,2	0,801822	50,9	1,159453	42,9	0,977221	118	43,9	0,64	0,12	40
1989	42,6	0,83365949	35,7	0,69863	48,4	0,947162	38,6	0,755382	56	1,09589	46,4	0,908023	124	51,1	0,65	0,13	43,3
1990	46,2	0,77516779	39,2	0,657718	52,1	0,874161	40,7	0,682886	61,5	1,031879	49,9	0,837248	131	59,6	0,67	0,17	59,7
1991	49,4	0,75075988	41,7	0,633739	57	0,866261	42,3	0,642857	64,1	0,974164	53,9	0,819149	136	65,8	0,69	0,19	63,3
1992	54	0,76379066	46	0,650636	61,1	0,864215	44,5	0,62942	64,8	0,916549	58	0,820368	140	70,7	0,71	0,21	70
1993	61	0,79427083	54,4	0,708333	66	0,859375	49	0,638021	68,5	0,891927	61,7	0,803385	145	76,8	0,73	0,23	76,7
1994	67,1	0,83354037	60,3	0,749068	70,8	0,879503	55,4	0,688199	71,1	0,88323	66	0,819876	148	80,5	0,75	0,25	83,3
1995	69	0,80796253	60,3	0,707089	74,4	0,871194	60,5	0,708431	73,6	0,861827	71,1	0,832553	152	85,4	0,76	0,26	86,7
1996	73,6	0,80525164	65	0,71116	79,1	0,865427	64,1	0,701313	85	0,929978	75,2	0,822757	157	91,4	0,77	0,27	90
1997	80	0,83073728	73,3	0,761163	84,8	0,880582	67,8	0,70405	92,3	0,958463	79,3	0,823468	161	96,3	0,79	0,29	91,7
1998	82,9	0,83991895	74,7	0,756839	87,5	0,886525	71	0,719352	101.1	1,024316	83	0,840932	163	98,7	0,80	0,30	1

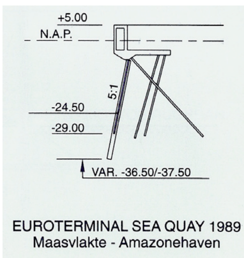
Appendix C
Comparison of the costs of two type of quay walls using the MTI-method (method total indexing) and the MII-method (method with individual indexing)

Comparison of the costs of two type of quay walls using the CPI-index (method total indexing) and the MII-method(method with individual indexing)

For this example two different quay wall types have been selected one type is a gravity wall type from the port of Antwerp and concerns the quay wall of the Deurganck dok . The other quay wall is from the port of Rotterdam and concerns a combi wall type quay wall, the ore terminal in the Amazonehaven .



Gravity wall Deurganck dok ,Antwerpen
60% concrete
10% steel
30% wages ,groundwork



Combi wall Amazonehaven,Rotterdam
40% steel
20% concrete
15% groundwork
25% wages

Using these data the following results are obtained.
Antwerp costs using MMI method :
0,60(1 + 0,04) ^10+0,10(1+0,059)^10 +0,30(1 +0,04)^10=1,50
Using the CPI-method we find.
(1+0,04)^10=1,48

Rotterdam costs using MMI-method:
0,4(1 +0,059)^10 +0,2(1+0,04)^10 +0,15(1+0,04)^10 +0,25(1+0,04)^10=1,59
Using the CPI-method we find
(1+0,04)^10=1,48
If we use the CPI-methods as reference then we find a difference of 1 to 7% for respectively Antwerp and Rotterdam.

De Raadscommissie Risicoregeling GWW, ingesteld door CROW op 15 november 1991, heeft ten behoeve van de Risicoregeling GWW 1995 de indexen voor maart 2006 vastgesteld, die samen met de reeds vanaf augustus 1999 gepubliceerde indexen hieronder zijn vermeld.

	Loon-kosten	Grind en industrie-zand	Steenslag en brekerzand	Beton-mortel	Beton-producten	Cement	Breuk-steen	Beton-staal	staal excl. beton-taal
1-8-1999	116,8	111,0	106,1	109,6	107,2	104,2	106,1	97,4	89,5
1-9-1999	116,8	111,0	106,1	109,6	107,0	104,2	106,9	100,8	91,9
1-10-1999	116,8	111,2	106,1	109,6	106,8	104,2	106,9	101,8	93,0
1-11-1999	116,8	111,2	106,1	109,6	107,0	104,2	106,9	102,3	95,3
1-12-1999	116,8	111,2	103,0	109,6	108,1	104,2	106,9	101,9	96,5
1-1-2000	118,8	117,2	108,1	113,2	108,6	105,3	109,5	93,7	96,5
1-2-2000	118,8	117,6	108,3	113,2	108,6	105,3	111,4	94,3	97,7
1-3-2000	118,8	117,7	108,3	113,2	108,6	105,8	113,0	94,7	100,0
1-4-2000	118,8	117,7	108,3	114,0	110,2	104,8	113,0	97,8	102,3
1-5-2000	120,6	117,7	108,3	113,2	110,2	104,8	113,0	98,1	104,7
1-6-2000	120,6	117,7	108,3	113,2	110,2	104,8	113,0	96,9	107,0
1-7-2000	122,4	117,7	108,3	114,0	110,2	104,8	112,2	96,4	105,8
1-8-2000	122,4	117,9	108,3	113,2	110,2	104,8	112,2	96,4	107,0
1-9-2000	122,4	117,9	108,3	114,0	110,2	104,8	112,2	95,7	107,0
1-10-2000	122,4	119,0	109,5	114,0	110,2	104,8	113,7	93,9	107,0
1-11-2000	122,4	119,0	109,5	114,0	110,2	104,8	113,7	92,7	105,8
1-12-2000	122,4	119,0	109,5	114,0	110,6	104,8	113,7	91,9	105,8
1-1-2001	122,4	123,1	112,1	121,1	114,0	106,7	117,6	92,7	104,7
1-2-2001	122,4	123,1	113,9	121,1	114,9	106,7	118,3	92,7	103,5
1-3-2001	122,5	123,4	114,5	121,1	115,6	107,2	119,9	94,7	103,5
1-4-2001	126,2	123,3	114,5	120,2	116,5	107,2	119,9	96,6	103,5
1-5-2001	126,8	123,3	114,5	120,2	116,3	107,2	119,9	97,8	103,5
1-6-2001	127,7	123,3	114,5	121,1	116,3	107,2	119,9	97,8	103,5
1-7-2001	128,8	123,5	115,6	121,1	116,3	107,7	119,9	99,3	103,5
1-8-2001	128,8	124,1	115,6	121,1	116,7	107,2	119,9	100,5	103,5
1-9-2001	128,8	124,1	116,3	121,1	116,5	107,2	119,9	102,2	103,5
1-10-2001	128,8	124,0	115,1	121,1	116,9	107,2	119,9	102,2	105,8
1-11-2001	128,8	124,0	115,1	121,1	116,9	107,2	119,9	101,0	105,8
1-12-2001	128,8	124,0	115,1	121,1	116,9	107,2	119,9	99,9	108,1
1-1-2002	130,5	128,7	118,4	128,9	119,6	110,0	123,2	96,1	104,7
1-2-2002	130,5	128,4	117,8	128,9	120,3	110,0	124,0	96,1	105,8
1-3-2002	131,1	128,4	120,2	128,9	120,5	110,5	124,0	96,1	104,7
1-4-2002	131,1	128,8	120,2	128,9	121,6	110,5	124,0	101,4	105,8
1-5-2002	131,1	129,3	120,2	128,9	121,2	110,5	124,0	102,5	105,8
1-6-2002	131,2	129,6	122,0	128,9	120,9	110,5	127,1	102,9	108,0
1-7-2002	134,7	129,5	121,4	128,9	122,1	110,5	127,1	104,1	107,0
1-8-2002	134,7	129,8	120,8	128,9	122,1	111,6	124,8	106,4	109,3
1-9-2002	134,7	129,8	120,8	128,9	122,5	111,6	124,8	105,2	109,3
1-10-2002	134,7	130,0	121,4	128,9	121,4	111,6	124,0	104,8	110,5
1-11-2002	134,7	130,0	121,4	128,9	120,9	111,6	124,0	104,8	111,6
1-12-2002	134,7	130,0	121,4	128,9	121,2	111,6	124,0	105,9	111,6

	Loon-kosten	Grind en industrie-zand	Steenslag en brekerzand	Beton-mortel	Beton-producten	Cement	Breuk-steen	Beton-staal	staal excl. beton-taal
1-1-2003	136,5	134,3	124,8	131,6	122,8	112,0	127,3	110,1	112,8
1-2-2003	136,5	134,5	124,8	131,6	123,3	112,0	127,3	110,1	112,8
1-3-2003	136,5	134,1	125,4	131,6	123,3	112,0	127,3	114,3	114,0
1-4-2003	136,8	134,0	124,2	130,7	123,3	112,0	127,3	115,4	115,1
1-5-2003	136,8	134,0	130,2	130,7	123,5	112,0	127,3	118,4	116,3
1-6-2003	136,9	134,0	123,9	130,7	123,0	112,0	127,3	117,3	116,3
1-7-2003	139,4	134,4	124,8	130,7	122,6	112,0	128,0	115,8	116,3
1-8-2003	139,4	134,4	124,8	130,7	122,6	112,0	128,0	115,8	116,3
1-9-2003	139,4	134,4	124,8	130,7	122,8	112,0	128,0	114,9	116,3
1-10-2003	139,4	133,9	124,8	130,7	122,6	112,0	128,0	114,9	116,3
1-11-2003	139,4	134,1	125,4	131,6	122,5	112,0	127,3	114,9	117,4
1-12-2003	139,4	134,1	125,4	131,6	122,5	112,0	127,3	114,9	117,4
1-1-2004	138,9	135,6	125,4	132,7	123,5	112,2	127,5	116,7	120,3
1-2-2004	139,3	135,6	122,4	132,7	123,1	112,2	123,8	140,6	126,2
1-3-2004	139,3	135,6	125,4	132,7	123,1	112,2	127,5	190,9	142,2
1-4-2004	139,6	135,8	122,8	132,8	123,1	112,2	124,8	202,2	159,4
1-5-2004	139,6	135,8	123,5	132,7	123,5	112,2	125,0	203,4	162,8
1-6-2004	139,6	135,8	123,7	132,7	124,0	112,2	125,1	203,6	165,2
1-7-2004	140,0	135,8	123,8	132,4	123,6	110,9	125,3	197,5	162,8
1-8-2004	140,0	136,2	122,8	132,5	123,5	111,2	123,3	193,6	168,9
1-9-2004	140,0	136,2	122,8	132,5	123,2	111,2	123,3	194,4	176,5
1-10-2004	140,0	135,9	124,8	132,3	123,1	111,2	126,1	192,5	178,3
1-11-2004	140,0	135,8	123,4	132,3	123,1	111,2	124,6	176,5	174,1
1-12-2004	140,0	135,8	123,8	132,1	122,9	111,2	124,8	166,9	172,2
1-1-2005	138,5	138,0	132,6	132,7	120,8	111,2	136,0	160,4	166,6
1-2-2005	138,8	138,0	125,8	132,7	120,4	111,8	127,7	155,7	170,2
1-3-2005	138,8	138,0	130,0	132,8	120,2	111,7	132,9	150,2	167,6
1-4-2005	138,8	138,1	127,6	132,4	120,2	111,8	129,8	143,4	160,1
1-5-2005	138,8	138,1	124,6	132,4	120,2	111,8	125,7	136,6	155,6
1-6-2005	138,8	138,1	131,2	132,4	120,4	111,8	134,1	128,7	148,6
1-7-2005	143,6	138,9	126,9	132,1	120,8	111,8	128,6	133,2	145,7
1-8-2005	143,6	138,7	128,0	132,3	120,9	111,8	129,8	142,4	152,3
1-9-2005	143,6	138,7	127,3	132,3	121,0	110,2	128,9	156,0	159,4
1-10-2005	143,6	140,4	129,3	132,5	121,2	111,1	131,6	161,3	159,5
1-11-2005	143,6	140,4	129,6	132,5	120,9	111,1	131,6	153,8	158,4
1-12-2005	143,6	140,9	129,6	132,5	121,3	111,1	131,6	148,2	159,4

Average
Last 10 years
Wages :143,6- 100=43,6 or 4,36%/year
Concrete :132,5-100=32,5 or 3,25 %/year
Cement:111,1-100=11,1 or 1,11%/year
Concrete steel: 148,2-100=48,2 or 4,82%/year
Steel:159,4 -110=59,4 or 5,94 %/year

Appendix D Basic Costs Data

kademuren in duitsland			euro2008		
hamburg	d1	1e liegeplatz burchardkai	1996	24,5	€ 46.410
	d2	4e liegeplatz euopakai	1996	24,1	€ 39.270
	d3	7e liegeplatz predolhlai	1998	25,2	€ 44.030
	d4	2e ba alterwerder	2001	28,3	€ 48.790
	d5	1e liegeplatz predohlkai	2004	26,5	€ 46.410
	d6	4e liegeplatz burchartdkai	1968	18,2	€ 31.533
	d7	burchardtkai	1973	13,5	€ 14.181
	d8	predohlkkai	1968	18,2	€ 31.533
	d9	oswaldkai	1954	16,5	€ 22.848
	d10	kronprinzkai	1984	22,9	€ 32.035
	d11	ellerhoft/stoltenkai	1984	18,9	€ 29.746
	d12	kameroenkai	1964	16	€ 17.326
	d13	1eliegeplatz predohlkai	1938	16	€ 9.325
	d14	versmankai	1984	17,7	€ 24.965
	d15	hachmankai	1984	17,1	€ 23.909
	d16	sudkai	1984	19,6	€ 27.406
	d17	steinwerderkai	1984	17,6	€ 33.456
	d18	parkhafen	1994	19	€ 12.075
	d19	10e liegeplatz burchardkai	1994	24,5	€ 47.640
	d20	hoft burchardkai	1994	15	€ 25.228
	d21	block11 burchardkai	1994	24,5	€ 40.996
	d22	seawall	1914	14,7	€ 13.221
kiel	d31	sudmolen	1912	17	€ 50.342
	d32	sudmolen	1912	11	€ 23.009
	d33	nordmolen	1916	18	€ 27.935
	d34	sudmolen	1916	15	€ 17.128
bremen			1983	25	€ 64.909
	d36	containerkai ct2	1997	26,5	€ 92.387
			2003	26,5	€ 77.999
			2007	26,5	€ 47.708
	d37	konigsberg	1903	9,4	€ 15.118
	d38	emden	1904	15,3	€ 25.126
	d39	pillau	1908	9,6	€ 10.805
	d40	harburg	1909	9,8	€ 6.829
	d41	rinteln	1900	7,2	€ 3.192
	d42	kosel	1894	8,4	€ 6.789
	d43	neufahrwasser	1894	7	€ 11.359
	d44	berlin	1897	7,6	€ 5.963
	d45	berlin	1895	8	€ 7.072
	d46	gluckstadt	1896	8	€ 10.075
	d47	gluckstadt	1898	8	€ 9.831
	d48	ruhrort	1896	9,5	€ 7.952
	d49	stolpmunde	1900	7,5	€ 5.193
	d50	sassnitz	1898	8,4	€ 2.136
	d51	berlin	1901	7,2	€ 9.439

	d52	berlin	1900	7,2	€ 9.439
	d53	berlin	1899	7,2	€ 9.452
	d54	berlin	1900	7	€ 6.681
	d55	berlin	1900	7,2	€ 9.588
	d56	gluckstadt	1902	8,5	€ 6.071
	d57	friedrichstadt	1900	4,5	€ 6.315
	d58	kosel	1904	6,5	€ 12.455
	d59	berlin	1898	8,6	€ 3.421
	d60	geestmunde	1899	10,9	€ 10.251
	d61	geestmunde	1902	10,9	€ 10.251
	d62	emden	1901	15,3	€ 29.262
	d63	emden	1904	15,3	€ 22.678
kademuur singapore	si1	new eastt w	1962	15,3	€ 31.178
kademuren usa	usa1	contaquay new york	1963	15	
	usa2	quayw long beach	1959	16,5	€ 36.059
	usa3	pier c and d long beach	1959	16,5	€ 27.532
	usa4	gencargoquay long beach	1959	16,5	€ 39.720
	usa5	boston, 60*390ft	1953	14,1	
	usa6	cri wall chicago	1871	9	
	usa7	new yorksw	1914	12	€ 13.414
	usa8	nysw	1914	9	€ 3.506
	usa9	nybargec	1914	8,4	€ 6.045
	usa10	nyoswego	1914	9,6	€ 8.029
	usa11	wallsorelin	1914	7	€ 4.426
	usa12	bcwny	1914	5,1	€ 5.529
	usa13	gwanusby	1914	8,1	€ 4.858
	usa14	20nw	1914	9,9	€ 24.923
	usa15	21ny	1914	7,5	€ 22.803
kademuren afrika	usa16	ny44 47	1914	7,5	€ 27.019
	k2	berth7 en 8	1944	13,5	€ 34.439
	l1	new wall benhhazi libie	1965	13	€ 23.631
	g1	n1ext ghana	1960	12,5	€ 31.675
	l1	apapaw lagos	1966	13,5	€ 33.988
	t1	boogie tunis	1904	7,2	€ 7.336
	br4	riogrande delsol	1907	13,5	€ 59.101
	br5	bahia	1907	13	€ 51.886
	br6	rio dejaneiro	1907	14,6	€ 49.123
	br7	riopracamauro	1950	16,6	€ 20.275
kademuren curacau	cu 1	cellelar wall senel	1949	11	€ 19.046
	cu2	block wall	1949	11	€ 21.182

kademuren in belgie	b1	verrebrouckdok	1994	28	€ 31.065
antwerpen	b2	deurganckdok	2006	26	€ 38.080
	b3	noordzeeterminal	1996	26	€ 58.287
	b4	europaterminal	1991	26	€ 61.616
	b5	sixthdok	1962	17,5	€ 18.541
	b9	willemdoknz	1899	10	
	b10	willemdokzen noz	1875	10	
	b17	scheldkai antwerpen	1906	14,65	€ 42.840
zeebrugge					
	b11	containerkaai	1991	23	€ 54.275
gent					
	b12		1966	16,5	€ 14.279
	b13	sifferdock	1952	9,5	€ 34.730
	b14	kluizendok	1999	21,5	€ 26.706
	b15	large dok	1922	12,9	€ 3.721
	b16	port arthurkaai	1985	15,8	€ 25.390
kademuren in engeland	e1	no28 berth southampton	1960	10	€ 11.424
	e2	crossberth grimsby	1967	11,5	€ 6.833
	e3	p-berthlondon	1965	11,6	€ 9.996
	e4	quay aberdeen	1968	13	€ 20.325
	e5	containerberth felixstowe	1967	18	€ 31.321
	e6	no4 berth rvcd lonon	1959	11,5	€ 13.042
	e7	n4berthlondonrvcn	1959	11	€ 18.850
	e8	timberp immingham	1968	12	€ 13.347
	e9	berth29/30can dlondon	1959	12	€ 15.956
	e10	berth27/28 can dlondon	1962	12	€ 22.467
	e11	ellesmere manchester	1966	13	€ 37.380
	e12	blaikiequay aberdeen	1969	13	€ 18.735
	e13	no3berth southampton	1967	14	€ 25.514
	e14	s-e arm hull	1968	14	€ 21.134
	e15	no8 berth avonmouth	1964	14	€ 27.989
	e16	croswall tilb dlondon	1969	14,7	€ 27.351
	e17	sinclair wharf belfast	1957	16,5	€ 22.658
	e18	western d ext southampton	1968	17,5	€ 32.140
	e19	new quay se side kingslynn	1966	10	€ 20.037
	e20	new wharf new port s wales	1967	15	€ 43.641
	e21	stormont wharf belfast	1962	17	€ 21.325
	e22	n1 quay tees and hartlepool	1962	20	€ 31.435
	e23	container quay greenock	1969	21,5	€ 70.389
	e24	north quay birkenhead	1960	12,5	€ 45.853
	e25	se wal rec liverpool	1967	11,5	€ 21.706
	e26	leith	1967	18	€ 14.756
	e27	eastwall mercd liverp	1970	20	€ 28.560
	e28	west waal mercd liverp	1970	19	€ 27.894

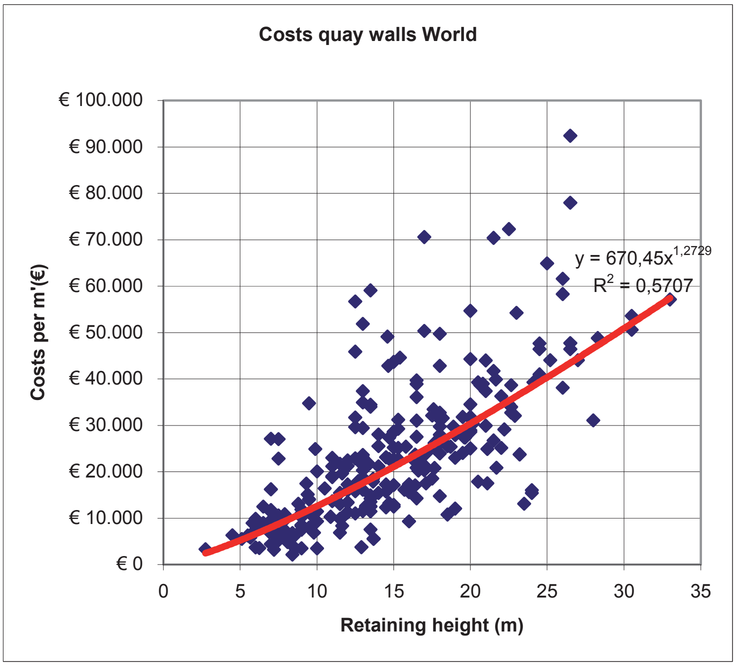
	e31	north quay x hull	1963	13	€ 29.393
	e32	dublin	1904	12	€ 21.208
	e34	felixstowe dooleyterminal	1983	17,9	
	e35	felixstowe landguardterminal	1983	17,9	
kademuren in denemarken	de1	levantwharf kopenhagen	1968	14,5	€ 12.268
	de2	berths75/77aarhus	1968	13,5	€ 12.469
	de3	berth no70 aarhus	1968	13,5	€ 11.463
	de4	berths no124,126,128 aarhus	1955	13,5	€ 7.522
	de5	vestkraft wharf esjberg	1970	16	€ 15.566
	de6	aalborg, glevel6,4ft	1949	7,5	€ 10.186
	de7			7,5	€ 8.488
	de8			7,5	€ 7.640
	de9			7,5	€ 7.130
	de10			7,5	€ 5.942
	de11			9	€ 11.883
	de12			9	€ 11.035
	de13			9	€ 10.186
	de14			9	€ 8.487
kademuren in noorwegen	n1	cargo wharf tonsberg	1968	8,8	€ 13.072
	n2	sorengapier oslo	1965	12,7	€ 17.980
	n3	640w skandiah gothenburg	1970	15	€ 28.558
	n4	industrwharf oslo	1962	14	€ 15.386
kademuren cyprus	c1	gencargoberth larnaca	1969	12,5	€ 10.980
kademuren rotterdam	nl1	eecv uitbreiding	1982	33	€ 57.120
	nl2	deka	1983	13	€ 21.420
	nl3	ekom uitbreiding	1983	30,5	€ 53.550
	nl4	seaportterm1efase	1983	15	€ 22.610
	nl5	seaportterm1efase	1983	18	€ 26.180
	nl6	zeekade ect delta1	1984	20,5	€ 39.270
	nl7	binnenkade ect delta 1	1984	9,5	€ 13.983
	nl8	unit centre 1e fase	1988	18	€ 29.750
	nl9	emo zeekade	1989	30,5	€ 50.575
	nl10	emo bewerkingskade	1989	18	€ 32.725
	nl11	arco	1990	20	€ 24.990
	nl12	ect delta2	1990	22	€ 36.295
	nl13	unit centre fase 2	1991	19,5	€ 31.833
	nl14	steinweg handelsveem	1991	15	€ 12.495
	nl15	maaskade oostzijde	1992	6,5	€ 8.925
	nl16	peperklip	1992	7	€ 9.520

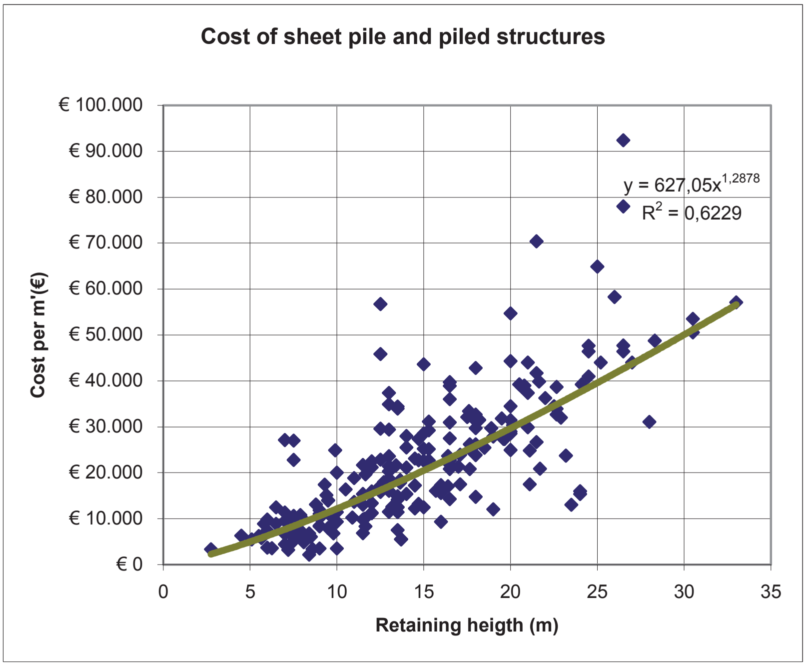
nl17	hewi	1993	13	€ 18.445
nl18	zekadeplan2008 1e fase	1993	22,5	€ 34.510
nl19	botlek handelsveem	1994	20	€ 34.510
nl20	avr	1993	10,5	€ 16.363
nl21	wilhelminakade	1996	12,5	€ 29.631
nl22	plan2008 1b	1996	22,65	€ 32.725
nl23	plan2008 2a	1997	22,65	€ 33.915
nl24	plan2008 2b	1997	22,65	€ 38.675
nl25	plan 2008 fase 4	1997	11,65	€ 19.635
nl26	sproorweghaven zz	1997	7,2	€ 9.520
nl27	mot	1997	11,65	€ 8.330
nl28	tanisbaai	1997	5,65	€ 5.831
nl29	verlenginght	1998	13,65	€ 18.445
nl30	hanno	2000	17,65	€ 26.180
nl31	waalhaven verbreding	2002	12	€ 11.305
nl32	bulkkade eecv	2003	13	€ 16.065
nl33	kopkade amazonehaven	2002	17,65	€ 20.825
nl34	dfdstorline	2002	20,65	€ 38.675
nl35	margriethaven 1e fase	2002	19,65	€ 27.370
nl36	margriethaven 2e fase	2002	20,15	€ 30.345
nl37	pcs	2005	13,65	€ 17.850
nl38	euromax	2005	27	€ 44.030
nl39	swarttouwkade rotterdam	1968	20	€ 28.960
nl40	boompjes	1885	7,5	€ 10.603
nl41	boerengat	1885	7	€ 27.106
nl42	wilhelminakade	1892	11,5	€ 9.842
nl43	admiraliteitskade	1894	5,5	€ 6.251
nl44	1e katendrechtsehaven	1897	10	€ 9.324
nl45	ren nassaukade	1895	6	€ 9.845
nl46	nassauhaven/kade	1898	6	€ 3.681
nl47	westbank rijnkade	1900	7,9	€ 10.844
nl48	1e/2e katendrechtse haven	1900	10	€ 3.502
nl49	rijnhaven	1901	13	€ 11.480
nl50	2e katendrechtse haven	1903	11	€ 13.643
nl51	parkhaven	1903	12	€ 11.169
nl52	parkhaven oost	1905	9,5	€ 14.047
nl53	maashaven	1908	12,5	€ 22.848
nl54	rijnhaven	1908	13	€ 34.909
nl55	eemhaven caison	1962	15,4	€ 44.563
nl56	eemhaven ontasl	1963	16,4	€ 23.680

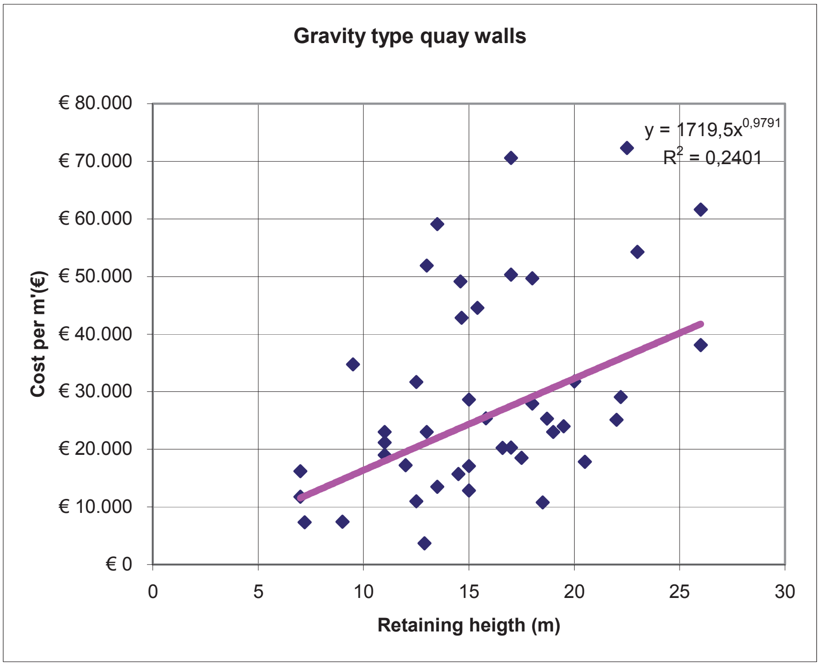
kademuren in Nederland	nl57	suezhaven amsterdam	1966	12,5	€ 17.105
	nl58	contquay amsterdam	1968	14,5	€ 23.128
	nl59	neptunushav amsterdam	1966	12,5	€ 15.803
	nl60	hornhaven amsterdam	1967	11,5	€ 15.384
	nl61	kade meppel	1992	6,25	€ 3.570
	nl62	frima harlingen	1995	13,5	€ 14.875
	nl63	handelkade delfzijl	1997	21,65	€ 39.865
	nl64	groningen seaports	2004	20,15	€ 30.345
	nl65	vlaardingen	2003	5,8	€ 8.925
	nl66	vlaardingen 2	2003	9	€ 8.330
	nl67	boskoop	2003	2,75	€ 3.332
	nl68	amsterdam texa en amerikah		11,5	
	nl69	drachten	2005	6	€ 7.438
	nl70	delfzijl jul haven		21	€ 37.399
	nl71	shortseadelfzijl 1e fse		15	
kademuren in vlissingen	nl73	xx	1997	23,5	€ 13.068
kademuren delfzijl	nl74	puttenkad	1900	15	€ 12.846
harlingen	nl75	industriehaven	2004	13,2	€ 12.624
	nl76	industriehaven	2004	13,2	€ 12.402
kademuren in pakistan	p1	eastwhrfk	1960	16,5	€ 38.914
kademuren indai	i1	alexdoeter	1970	16,5	€ 20.855
	i2	ballardpierbombay	1970	18	€ 42.816
kademuren australie	au1	bulkhandlingb adelaide	1966	16,5	€ 30.980
	au1	victoria portlandharbour	1968	12,5	€ 56.713
kademuren indonesie		caisson soerabaja	1917	13,2	
kademuren italie		catani	1905	9	€ 7.438
		giano	1905	15	€ 28.641
		trapani	1905	7	€ 16.227
		messina		12	€ 17.238
		boccardi	1931	14,5	€ 15.727
		genes	1905	13,5	€ 13.522
		messina	1905	7	€ 11.764
kademuren in frankrijk		brest	1979	24	€ 16.030
	fr1	sixth dok	1961	20	€ 31.775
	fr2	ore quay	1961	20	€ 54.702
		bordeaux	1976	22	€ 25.155
	france	dunkerque	1977	22,5	€ 72.308
		marseille	1969	20,5	€ 17.849
		lorient	1975	22,2	€ 29.087
		rouen	1974	20	€ 44.294
		brest	1979	24	€ 15.418

fr3	dunkerque	1970	21	€ 29.918
	nantesstna	1976	21	€ 43.976
	nantestnaz	1976	21,5	€ 41.692
	lehavre	1963	18	€ 23.887
	roscoff	1979	18	€ 49.707
	marseillef	1979	18,7	€ 25.355
	bayonne	1980	18,5	€ 25.474
	rochelle	1969	19,5	€ 24.028
	guadeloupe	1977	16,4	€ 17.071
	guadeloupe	1977	16,4	€ 22.186
	dunkerque	1963	19	€ 23.017
	marseillef	1979	17	€ 20.303
	natesstnaz	1978	17	€ 70.566
	marseillef	1979	18,5	€ 10.774
	bordeax	1900	13,4	€ 21.635
	caen	1979	13,5	€ 12.520
	lehavre	1973	14,5	€ 17.265
	caen	1972	13	€ 23.034
	bordeaux	1978	14,7	€ 22.739
	cherbourg	1973	13,7	€ 5.512
	cherbourg	1975	13,7	€ 5.547
china	11	2005	9,3	€ 17.424
	2	2005	17,1	€ 17.494
	3	2005	15,7	€ 16.061
	7	2005	21,1	€ 17.466
	5	2005	23,2	€ 23.735
	9	2005	21,1	€ 24.871
	10	2005	20,8	€ 38.969
	4	2005	21,7	€ 20.870
	1	2005	23,2	€ 23.735

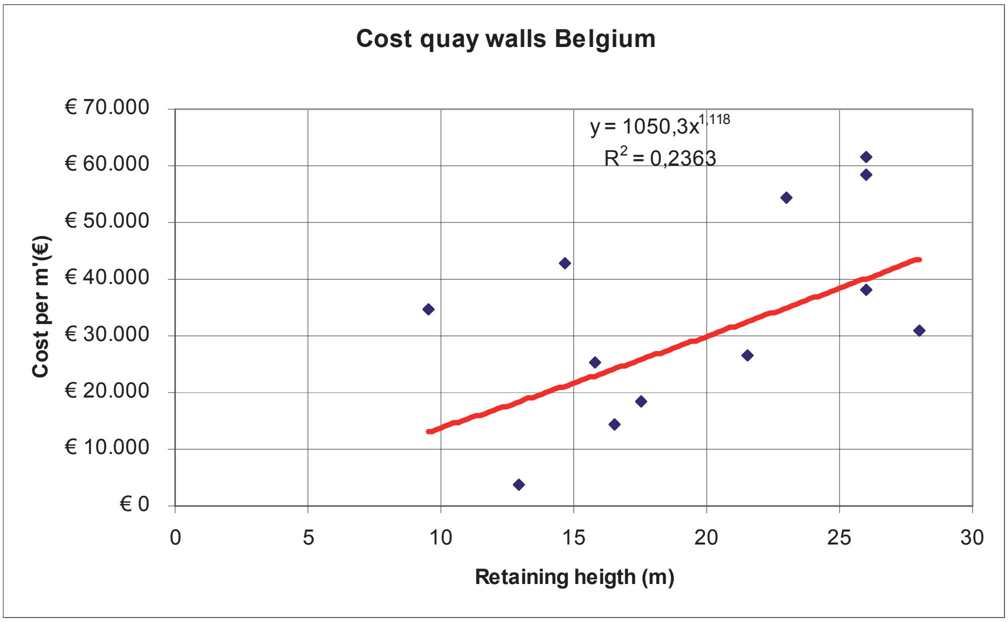
Appendix E
Additional Cost graphs


Costs quay walls World
€ 100.000
€ 90.000
€ 80.000
€ 70.000
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Costs per m'(€)
0
5
10
15
20
25
30
35
Retaining height (m)
y = 670,45x1,2729
R2 = 0,5707

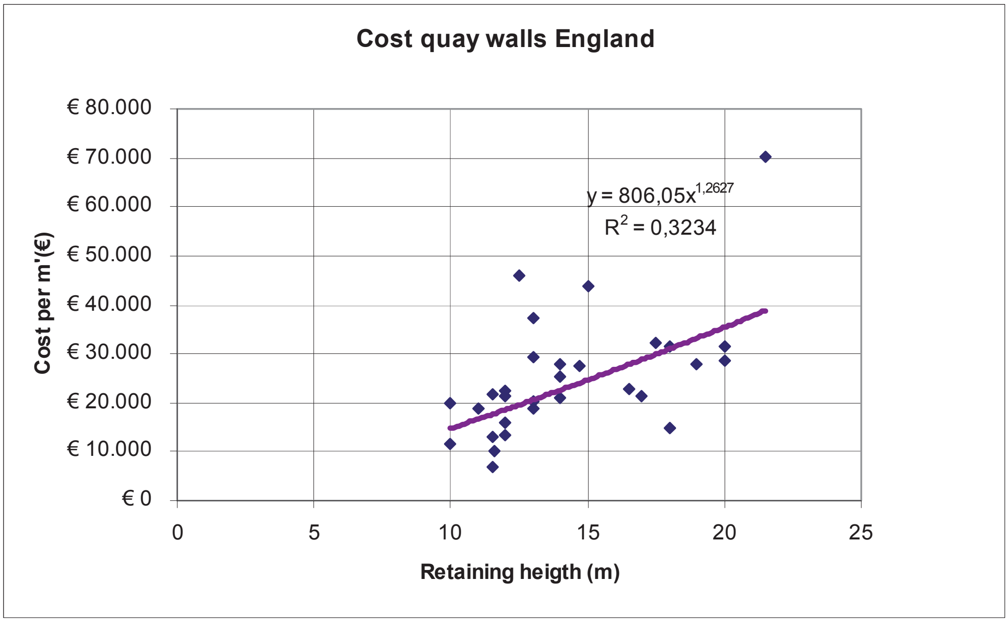

Cost of sheet pile and piled structures
€ 100.000
€ 90.000
€ 80.000
€ 70.000
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost per m'(€)
0
5
10
15
20
25
30
35
Retaining heigth (m)
y = 627,05x1,2878
R2 = 0,6229

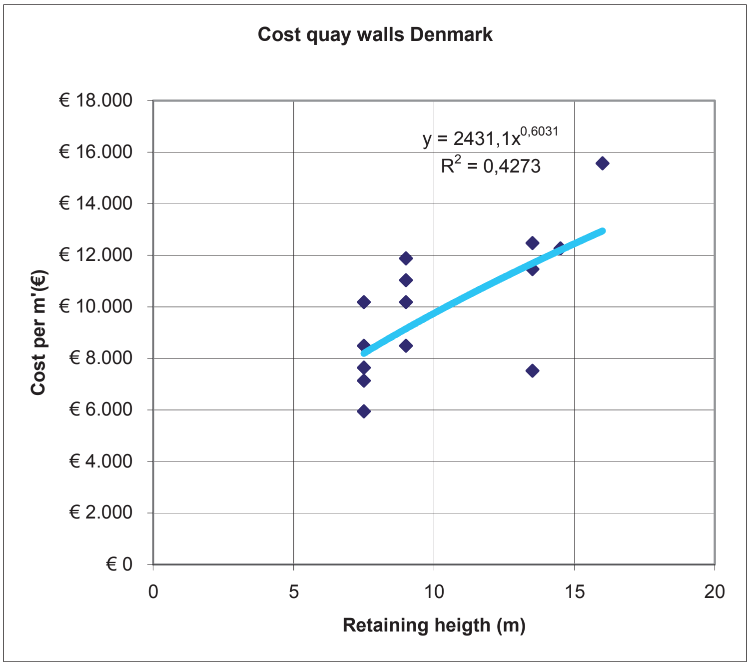


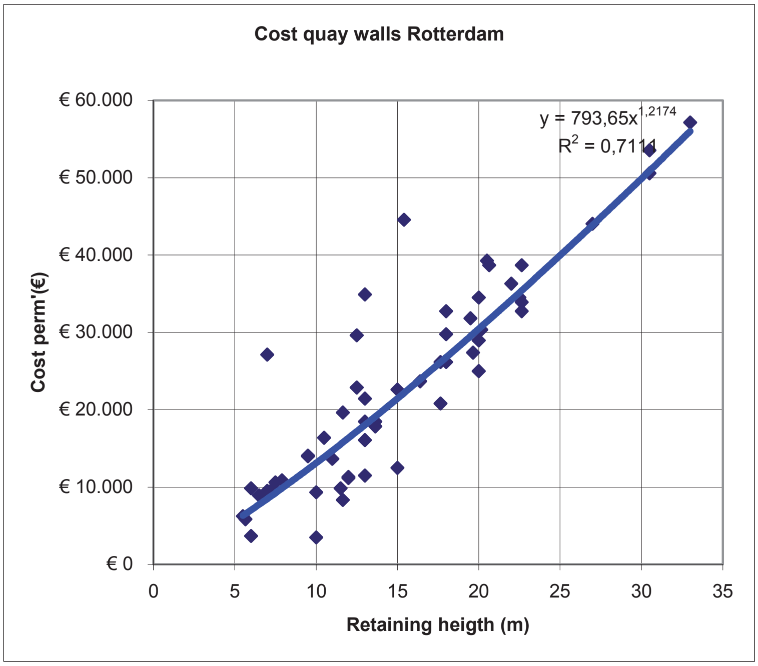
Gravity type quay walls
y = 1719,5x0,9791
R2 = 0,2401
€ 80.000
€ 70.000
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost per m'(€)
0
5
10
15
20
25
30
Retaining heigth (m)

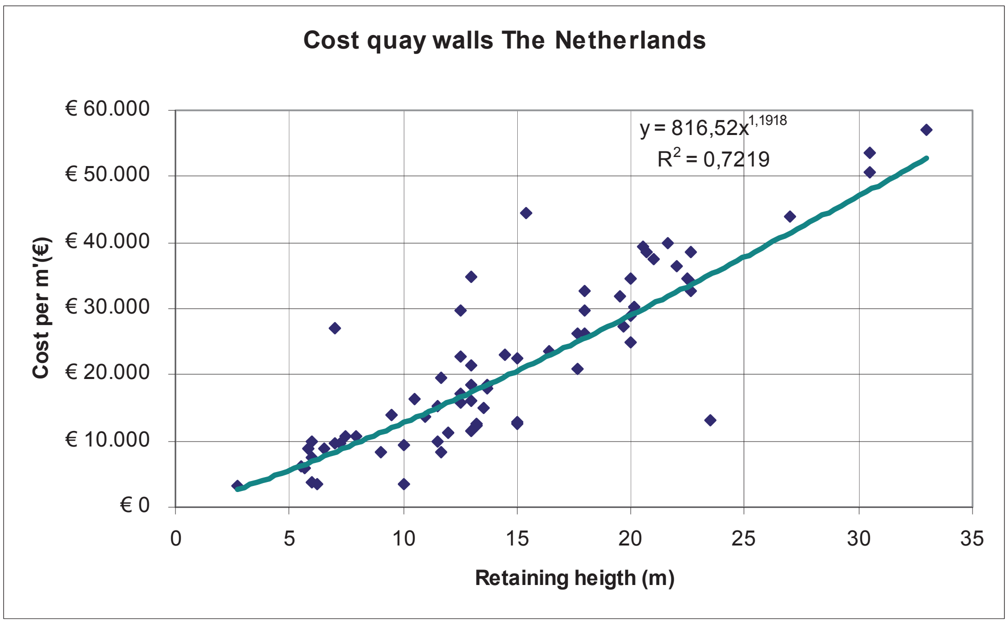


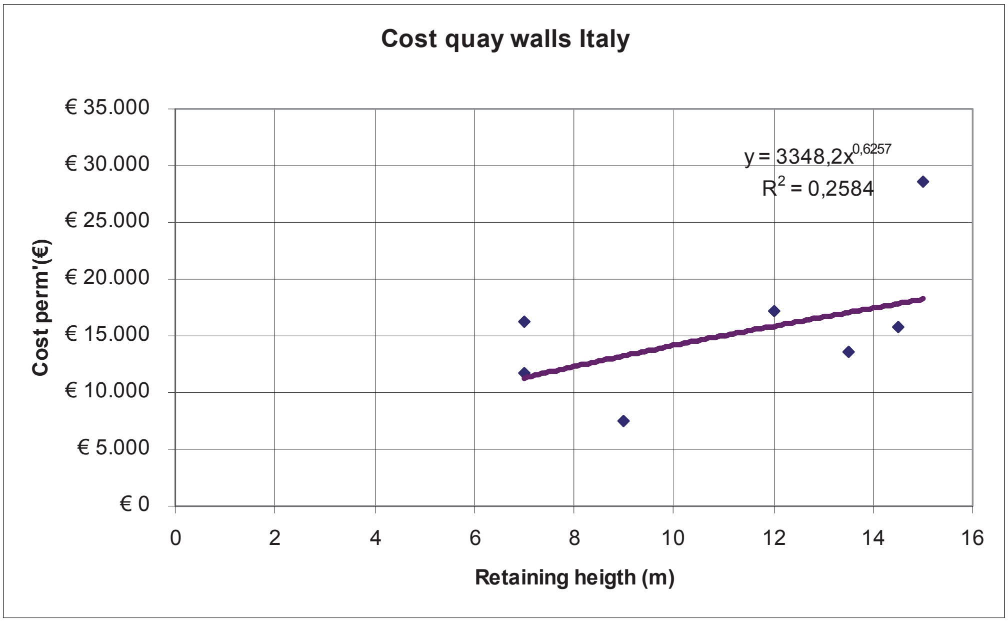
Cost quay walls Belgium
y = 1050,3x1,118
R2 = 0,2363
€ 70.000
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost per m'(€)
0
5
10
15
20
25
30
Retaining heigth (m)

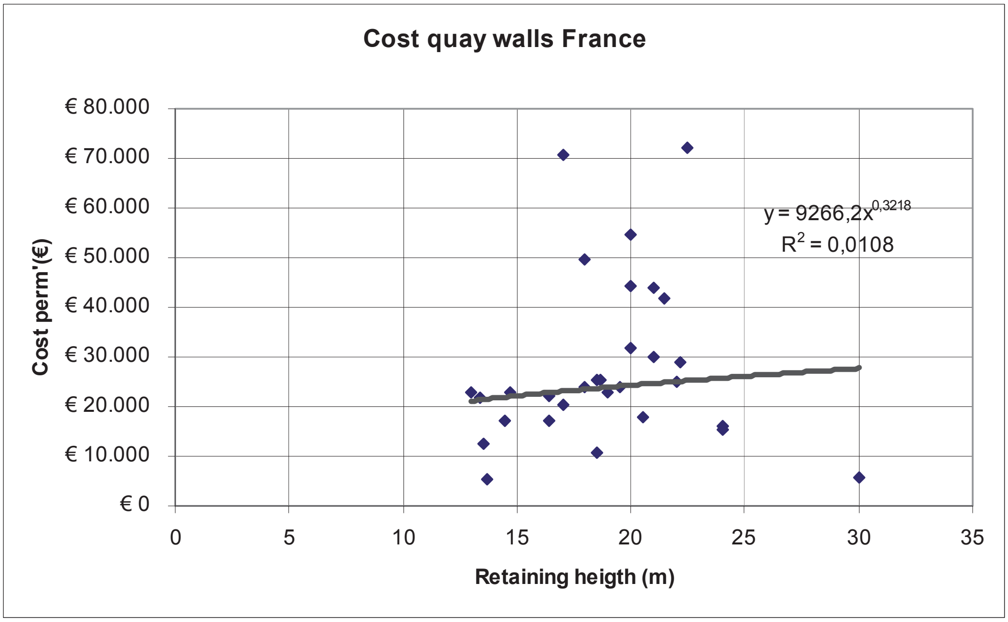

Cost quay walls England
€ 80.000
€ 70.000
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost per m'(€)
y = 806,05x^1,2627
R^2 = 0,3234
0
5
10
15
20
25
Retaining heigth (m)

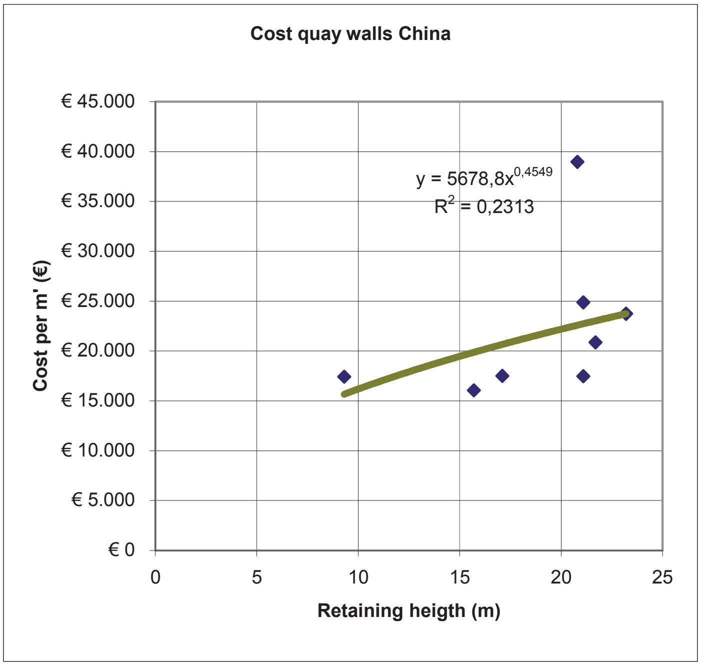

Cost quay walls Denmark
€ 18.000
€ 16.000
€ 14.000
€ 12.000
€ 10.000
€ 8.000
€ 6.000
€ 4.000
€ 2.000
€ 0
Cost per m'(€)
y = 2431,1x^0,6031
R^2 = 0,4273
0
5
10
15
20
Retaining heigth (m)

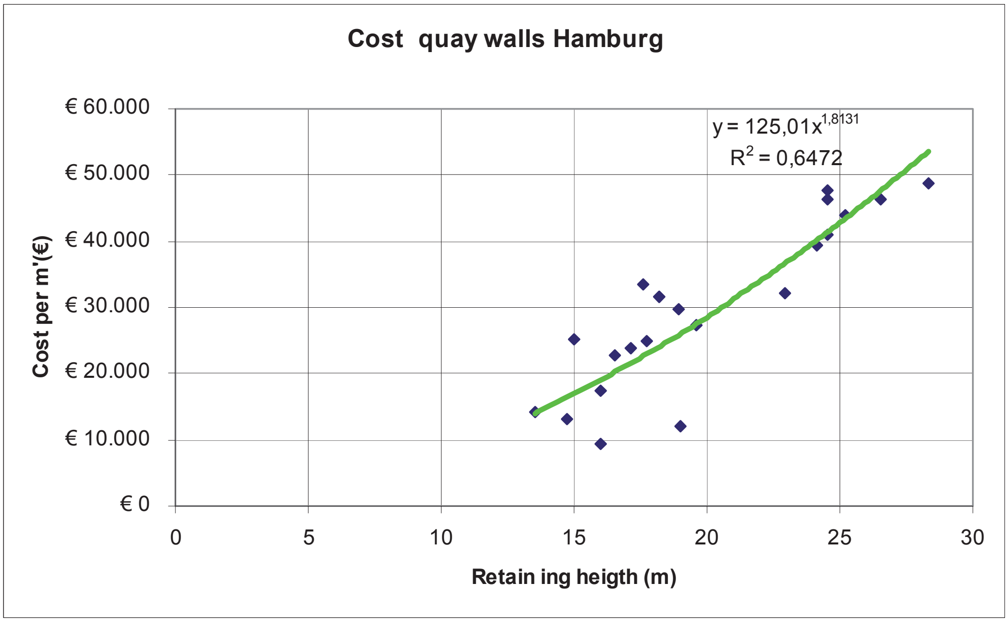

Cost quay walls Rotterdam
y = 793,65x^1,2174
R^2 = 0,7114
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost perm'(€)
0
5
10
15
20
25
30
35
Retaining heigth (m)

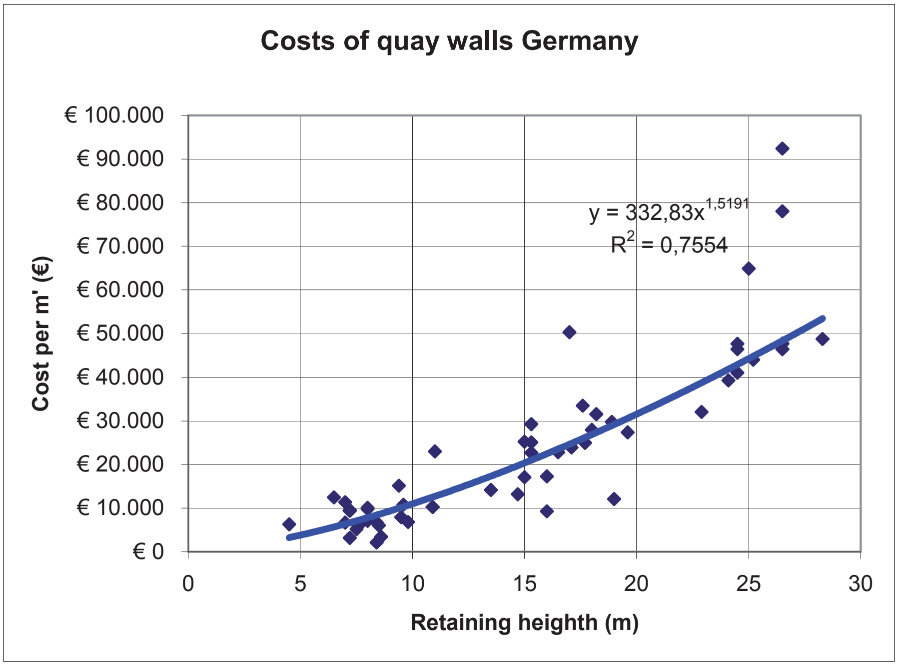

Cost quay walls The Netherlands
y = 816,52x^1,1918
R^2 = 0,7219
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost per m'(€)
0
5
10
15
20
25
30
35
Retaining heigth (m)

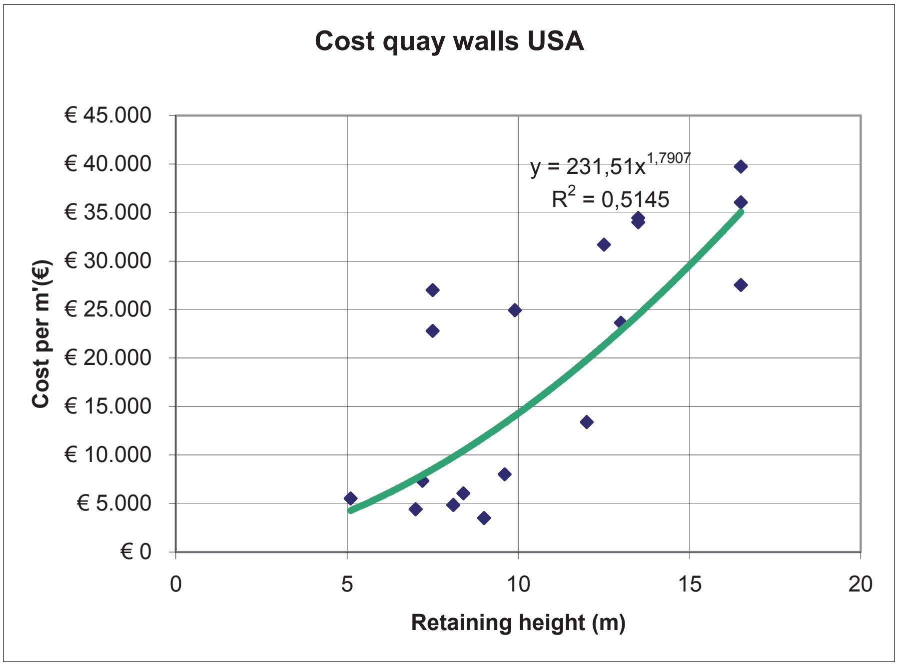

Cost quay walls Italy
€ 35.000
€ 30.000
€ 25.000
€ 20.000
€ 15.000
€ 10.000
€ 5.000
€ 0
Cost perm'(€)
0
2
4
6
8
10
12
14
16
Retaining heigth (m)
y = 3348,2x^0,6257
R^2 = 0,2584


Cost quay walls France
€ 80.000
€ 70.000
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost perm'(€)
0
5
10
15
20
25
30
35
Retaining heigth (m)
y = 9266,2x^0,3218
R^2 = 0,0108

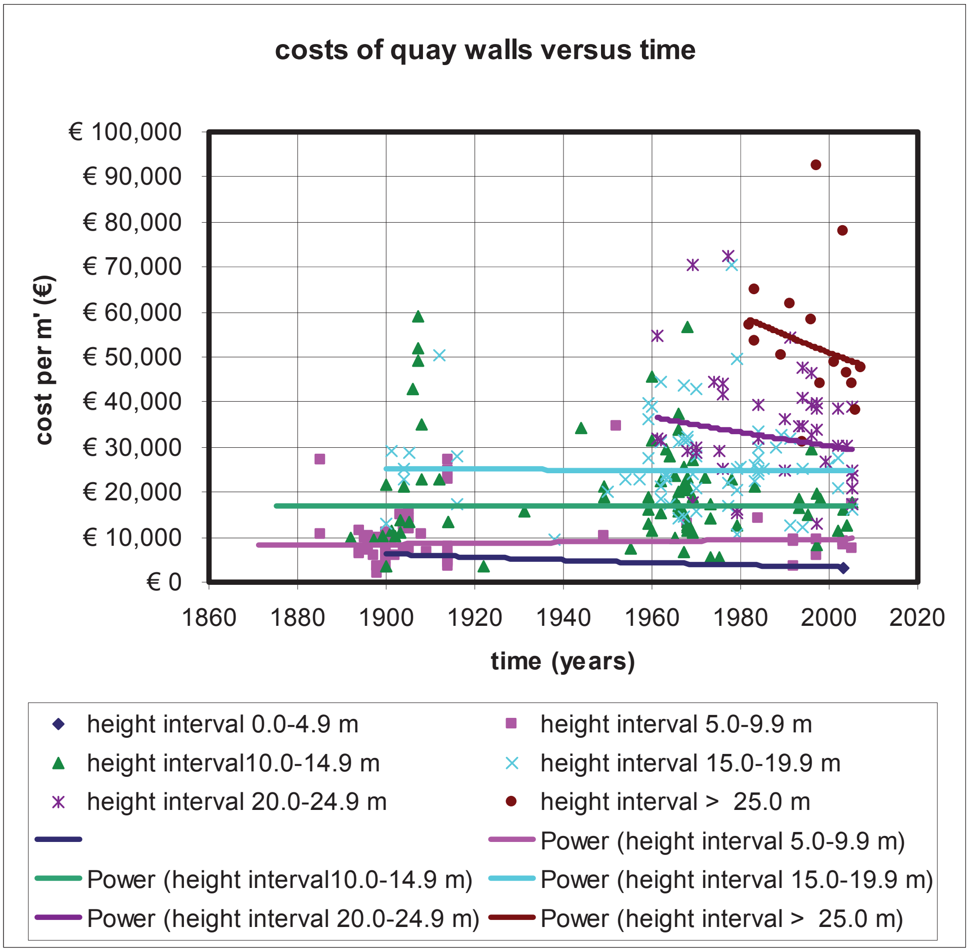

Cost quay walls China
€ 45.000
€ 40.000
€ 35.000
€ 30.000
€ 25.000
€ 20.000
€ 15.000
€ 10.000
€ 5.000
€ 0
Cost per m' (€)
y = 5678,8x^0,4549
R2 = 0,2313
0
5
10
15
20
25
Retaining heigth (m)


Cost quay walls Hamburg
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
Cost per m'(€)
y = 125,01x^1,8131
R2 = 0,6472
0
5
10
15
20
25
30
Retain ing heigth (m)


Costs of quay walls Germany
€ 100.000
€ 90.000
€ 80.000
€ 70.000
€ 60.000
€ 50.000
€ 40.000
€ 30.000
€ 20.000
€ 10.000
€ 0
0
5
10
15
20
25
30
Cost per m' (€)
Retaining heighth (m)
y = 332,83x^1,5191
R^2 = 0,7554


Cost quay walls USA
€ 45.000
€ 40.000
€ 35.000
€ 30.000
€ 25.000
€ 20.000
€ 15.000
€ 10.000
€ 5.000
€ 0
0
5
10
15
20
Cost per m'(€)
Retaining height (m)
y = 231,51x^1,7907
R^2 = 0,5145

x


costs of quay walls versus time
€ 100,000
€ 90,000
€ 80,000
€ 70,000
€ 60,000
€ 50,000
€ 40,000
€ 30,000
€ 20,000
€ 10,000
€ 0
cost per m' (€)
1860
1880
1900
1920
1940
1960
1980
2000
2020
time (years)
height interval 0.0-4.9 m
height interval 5.0-9.9 m
height interval10.0-14.9 m
height interval 15.0-19.9 m
height interval 20.0-24.9 m
height interval > 25.0 m
Power (height interval 5.0-9.9 m)
Power (height interval10.0-14.9 m)
Power (height interval 15.0-19.9 m)
Power (height interval 20.0-24.9 m)
Power (height interval > 25.0 m)

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CV J.G. de Gijt

Jarit de Gijt was born (1947) in Ede(Gld). After leaving the high school, Marnix College Ede,in 1965 he studied Civil Engineering at the Delft University of Technology. He graduated in 1976 and was award the degree of MSc. His graduation thesis included the design both the dewatering pumping station for a polder and the dike systems for this. During the course of his studies he worked as student assistent with the PAO from 1972-1975 and fulfilled his military service from 1969 to 1971.
He joined in Fugro 1975 and worked there up to 1987. He was in this period involved both in onshore and offshore geotechnical consultancy work as well as environmental and hydrological aspects.
Since 1987 de Gijt joined Rotterdam Public Works with the engineering section and has been involved since then with all types of port infrastructure consultancy, quay walls, jetties, reclamation, dredging.
De Gijt acted as account manager for the Port of Rotterdam and was member of the management team of the Harbour and Transport Group of Public Works Rotterdam.
Since 2004 de Gijt is part time working at TU Delft with the Hydraulic Engineering Section and is lecturing on port infrastructures and coaching MSc students.
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De Gijt published about 70 articles and made contributions to several books.