HANDBOOK OF PORT AND HARBOR ENGINEERING

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GEOTECHNICAL AND STRUCTURAL ASPECTS

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To Nora

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Preface

In past 10 years or so several excellent books and handbooks on "Port and Harbors Engineering" and "Coastal and Ocean Engineering" have been published in Europe and in North America. Reference to these works is made elsewhere in this book.

The authors of the aforementioned works offer a shrewd and comprehensive discussion on the marine environment and its effects on port design, port operation, port hydraulics, coastal geomorphology, littoral drift and sedimentation, port and shipping technology and economics, design and construction of a floating port related structures, and others. However, proportionally the geotechnical and structural aspects of port construction have been given very little attention. This happens, perhaps, because the subject of marine structures engineering is very broad by itself; it is a blend that encompasses the array of engineering disciplines, e.g., civil, structural, geotechnical, hydraulic, strength of materials, corrosion, naval architecture and others knowledge of which is required to produce a sound and economical design of a modern port or marine terminal.

This book has been written to fill a niche in the existing literature on port and harbor engineering and to provide the port designers, and particularly those concerned with the design of a port- and harbor-related marine structures, with state-of-the-art information and common sense guidelines to the design and construction of the basic types of marine structures. This book is a companion volume to my earlier work *Marine Structures Engineering: Specialized Applications* published by Chapman & Hall in 1995. That book covers important subjects such as the evaluation of capacity of the in-service marine structures and methods of their remediation and maintenance, construction and operation of the marine structures in cold regions, design and construction of a shipyard and related marine structures, design of anchored offshore moorings and floating breakwaters, design and construction of marinas (small craft harbors), and design and construction of marine structures that are used in navigable waterways for protecting the bridge piers from ship collision. Conversely, this volume provides the marine structures designer with basic information on the marine environment and its effects on port design and construction (Chapter 1); port elements and their effects on port operation (Chapter 2); design loads and their combinations that are commonly used to design waterfront structures (Chapter 3); information on the phenomenon of soil/structure interaction that explains basic principles that affect soil lateral thrust against rigid and flexible soil retaining structures (Chapter 4); design of gravity quay walls, sheet pile bulkheads, and piled marine structures (Chapters 5, 6 and 7); basic principles of design of the offshore marine terminals (Chapter 8); modernization of the existing waterfront structure that makes them usable in modern port operations (Chapter 9); and design and construction of breakwaters (Chapter 10).

In both books each chapter includes a comprehensive list of relevant cross-references intended to help the interested reader to study the subject in additional depth.

In this book I have attempted to provide the reader with a clear understanding of the phenomenon of interaction between the environmental agents such as waves, currents, and wind as well as harbor soils and backfill materials with bottom-fixed marine structures.

During my long career as a practicing waterfront consultant and port engineer considerable progress has occurred in the field of design and construction of port- and navigation-related marine structures. Progress in port design, and in particular design of waterfront structures, has been strongly influenced by the dramatic changes in vessel sizes and in modes of modern terminal operation. Multipurpose ports have been replaced by more specialized terminals, which result in dramatic effects on both the design of berth structures and layout of the terminal. Furthermore, marine structures for various purposes have been developed using new design and construction principles, and operation of these structures have been significantly improved by the introduction of new and better fendering systems and efficient mooring accessories. New and better structural materials have also been introduced. For example, modern concrete technology now enables the engineer to use durable high-strength concrete, highly resistant to deterioration in harsh marine environments. New and better repair procedures and rehabilitation techniques for port structures have also been introduced.

Progress in development of new marine structures and modernization of existing structures was based on advances in analytical design methods as well as on result of numerous scale-model tests and field investigations conducted all over the world. Today, marine structure design is a unique discipline in the field of civil engineering that is based on the use of highly advanced methods of soil foundation investigation and thorough understanding of the principles of soil/structure interaction in the marine environment.

Recently sophisticated computational procedures and mathematical models have been developed and used for design of various marine structures. It must be stressed, however, that in many cases the diverse and complex geology at various port locations results in a wide variety of geotechnical environments. Such conditions require a careful approach to selection of structure type and use of the appropriate design method, which should not necessarily be highly sophisticated. It is a misconception that sophisticated computer analysis, with its greater accuracy, will automatically lead to better design. Despite the highly sophisticated analytical methods available today, the marine structural designer must be aware that the design is not merely a stress analysis process. Use of computers has not diminished the value of some hand calculations. In fact, many questions about marine structure engineering are still best answered with simple, often empirically based, but practical formulas.

Computers have revolutionized the process of structural engineering and greatly increased productivity of engineering firms. Computer-aided analyses are of great help when used in the proper context, for example, when modeling of the structure is correct, the real boundary conditions are taken into account and most of all when the output is examined and interpreted by an experienced engineer. However, some critics observed a "rapid deteriorating competency on the part of the engineering community as a consequence of using computers" and found "a serious lack of critical evaluation ability in many of the young engineers... (which) put an inordinate amount of faith in the computer" (ENR, October 28, 1991).

The worrisome trend in the present design and construction practices is that some inexperienced, however, highly competent in the use of computers, engineers consider themselves "instant experts" ready to analyze and design anything.

The marine structures designer should realize that formulation of the mathematical approach used for structural analysis must be practical and compatible with available engineering data, for example, shearing strength and consolidation characteristics of the foundation and backfill soils, environmental and live loads, etc. However, sometimes even when analytically correct results are obtained, the inexperienced engineer can make errors by neglecting some practical aspects related to constructibility, for example, how to fabricate or how to get the structural component in place.

To avoid the disastrous consequences of such designs experienced engineers must spend sufficient time helping their less experienced colleagues to prepare the mathematical models and review the computer output.

The 1980s and 1990s have become known for global modernization of existing ports and construction of new high capacity specialized marine terminals. During the same period of time the nature of port traffic has changed markedly rendering some older facilities unsuitable for today's operations.

The obvious example is the emphatic shift to containerization of literally all types of cargoes and transportation of containerized goods in ever larger vessels. Similar developments have occurred in transporting of huge volumes of liquid and dry bulk commodities; sizes of the vessels that now transport these cargoes reached 500,000 DWT and more. Obviously, these giant vessels require deeper approach channels; larger harbor basins; deep water quays; gantry cranes with greater height clearance, outreach, and lifting capacity; specialized terminals with appropriate handling equipment; and so on. This gives obvious impetus to global modernization of existing ports as well as to construction of new ports and terminals that can accommodate the modern maritime traffic.

Large capital investments into ports development have been made in 1960s through 1980s and many experts predict that this trend will continue through 1990s and far beyond into the 21st century.

Much of the capital spent on port development is allocated for construction, operation, and maintenance of its marine facilities. Therefore, economical design of these facilities can save a lot of money needed for port development.

Successful design of any project is based on three pillars; they are

- intelligence
- education
- experience.

The latter two assume thorough knowledge of a subject matter and the most recent developments in the area of interest. Unfortunately, all too frequently good and less costly engineering solutions are not used because of the lack of familiarity on a part of the designer. On the other hand, use of a "text book" solution to solve the problem may also be counterproductive.

The subject of marine engineering is a field where ingenuity can achieve considerable savings. Every project is site specific and therefore no engineer should be content merely to follow anothers designs but should study such designs and use them as a starting point for developing his or her own ideas that are best suitable for the particular site conditions.

As noted earlier the science and practice of port and harbor engineering draw from various disciplines and cover a broad area of interrelated subjects. This book offers basically geotechnical and structural aspects of port and harbor engineering, and no attempt has been made to include all detailed analytical procedures from these interrelated disciplines, for example, dredging, port operation and maintenance, etc. However, where relevant, all efforts have been made to provide the reader with a considerable cross-reference on the interrelated subjects; this includes the most recently published books, papers from the journals of professional engineering societies, and the proceedings of specialty conferences.

The design procedures and guidelines contained in this book are intended to point out the complexity of the particular problem and illustrate factors that should be considered and included in an appropriate design scenario. They should not be used indiscriminately and particularly not for the detailed design, and should always be combined with good engineering judgment. As noted earlier, this work has been conceived as a two-part treatise in which I have attempted to provide marine structures designers with state-of-the-art information and common sense guidelines to the design of basic types of marine structures associated with port activities.

This book is designed to serve as both a guide and a reference for practicing marine and geotechnical engineers and a text for graduate students and others seeking to enter the field of marine engineering.

This book has been 7 years in preparation. I have drawn from more than 40 years of my own experience as a marine engineer and scientist involved with research and all practical aspects of structural design, construction, and project management. Also, worldwide experience has been examined and the best of it is included in this work. Subsequently, acknowledgments of material used in this book are given in the appropriate places in the text and figures. I wish to extend my deepest gratitude to all the publishers, authors, and organizations from whom material for this work has been drawn.

This volume is not a one-man job. I am deeply indebted to many experienced individuals who have contributed material and comments to this project. In attempting to make this work most helpful and useful I have drawn from sources including the knowledge and experience of my former colleagues at Acres International Limited, who assisted in a variety of ways: Dr. W. S. Dunbar contributed information on seismic-induced loads, potentials for soil liquefaction, soil dynamic loads upon retaining structures, design of a soil retaining structures for seismic loading and also reviewed several chapters and helped in editing the book; Mr. R. G. Tanner has reviewed several chapters and offered useful comments; special gratitude goes to Mr. D. Protulipac who dedicated a great deal of his time to editing most of the text.

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GREGORY P. TSINKER

Introduction

Ports — Their Past, Present, and Future

Maritime transportation has generally been the most convenient and least expensive means of transporting goods, and this is why mankind, since ancient times, has been steadily extending its activities into this area.

The history of maritime transportation and port development dates back to the year 3500 B.C. and beyond. Over centuries, transport of goods by means of water transportation has been evolved in steps with the needs of world trade and technical capabilities to build larger ships and ship/cargo handling facilities.

Initially, waterborne traffic has existed on a local basis where small ships sailed out of river ports for other nearby river ports located in the same river system. With advancing navigational skills the merchants ventured greater and greater distances. Thus, larger ships transporting larger quantities of goods have emerged. As ship traffic increased, the existing river ports became overcrowded, and in order to permit more ships to berth and at the same time to keep the river usable for more ships, piers had to be constructed along river banks.

This stage may be seen as the beginning of the development of modern ports. The ever-increasing demand for shipping and port facilities resulted in construction of the first open-sea ports. Four to five thousand years ago the Phoenicians established open-sea ports along the Mediterranean coastline, and the Romans built the famous naval port near Rome on the Tiber River at Ostia. By the end of the first century A.D. a number of large ports had been constructed in the Mediterranean, the Red Sea, and the Persian Gulf.

Unfortunately, many of these old ports and harbors have disappeared, either being destroyed during the wars, buried by earthquakes, or just through neglect and decadence. Some of these ports are known from old documents and others have been discovered by archaeologists. As pointed out by DuPlat Taylor (1949), these ports have been well planned and effectively executed.

The description of different methods of port construction in earlier centuries, specifically in the Roman Empire, that include the use of tongue and grooved, laminated, and various other types of sheet piling, and large stone blocks are found in treaties by Roman architects (Leimdorfer, 1979).

As ship navigators developed more skill and fears of unknown waters gradually disappeared, merchant mariners, in addition to trade between river ports on their own coasts, started sailing the high seas, bringing goods from country to country and from continent to continent. The interchange of goods and later of raw materials between countries and continents reached by maritime traffic as well as the development of powerful navy fleets brought about development of large sea ports; this subsequently gave birth to large cities built around these ports.

Many modern cities have been built and expanded around medieval ports located on the open sea, bays, estuaries, sounds, and rivers. Examples are London, Rotterdam, Hamburg, and many others. However, it was not until the 1880s that a revival of interest in port works reappeared.

Port developments and their evolution has started, motivated by both economic and technological pressures that resulted from the global industrial revolution. At this time, the size, diversity, and complexity of ports changed dramatically. To a great extent this have been influenced by the changing nature of ships, for example, the transition from ships made from wood to steel and the introduction and rapid development of steamboats, and by the demand that greater volumes of cargo be handled at ports more rapidly. The latter stimulated the development of more and more efficient methods and technologies for handling and hauling of miscellaneous cargoes. However, in the 1880s many kinds of cargos were still handled manually as it had been for centuries. Cargoes that consisted basically of bags, bales, bundles, barrels, cases, cartons, drums, pieces of timber, steel, and so forth have been moved manually in the ship, on the quay, in the shed, and in the warehouse, sometimes "humped" on the back. This created a heavy demand for labor which fluctuated greatly with the arrival and departure of ships. Thus, if the ships were to be turned round efficiently and economically, a big pool of casual laborers was necessary.

In the late 1880s, ships still continued their transition from sail to steam engine. The capacity of these vessels was a few thousand tonnes and their draft less than 6 m. As ships changed, so did the ports that served them.

In many ports, the finger pier was the most characteristic type of berth construction. Typically, goods were stored there in warehouses located in close proximity to the berth line and were taken in and out of port by horse and cart.

The shift to mechanized handling of cargoes in ports began in the early 1900s. This was largely dictated by the growing volume of maritime traffic and changing size of ships. By the 1920s most of the general cargo ships were using onboard booms to move cargo by the sling-load method. The trend toward the growth of ship size coincided with construction of vessels specialized in transporting a certain type of cargo (e.g., general purpose commodities, dry and liquid bulk cargoes, and others). Naturally, new developments in a ship industry inevitably brought about innovations in cargo handling and hauling technologies, the most radical of which was introduction of a quay edge cranes.

World War II-inspired inventiveness took mechanization of cargo handling one step forward by the introduction of forklift trucks and pallets that enabled the general-purpose cargoes to be moved faster. In postwar years, pallets have been standardized internationally by International Standard Organization (ISO) (1992). The ISO Committee stipulated that the maximum permissible width of road vehicles (then mostly flat and open) must be about 245 cm; thus, all standard pallets had one dimension, of which 245 cm was a multiple, so that they could be stowed across open vehicles without wasting space. The use of forklift vehicles and pallets was very rapidly developed in industry all over the world, and palletized loads occupied the steadily increasing volume of ship holds. This, however, changed drastically in the not too distant future.

The shift to new technologies occurred in the 1950s with the introduction of container ships built to transport large freight containers.

Containers were soon standardized by ISO internationally to 20 or 40 ft in length (6.06 m or 12.19 m) with the outside width and height being 8 ft (2.44 m). At the present time, the empty weight of a modern 20-ft container ranges from 19 to 22 kN with maximum permitted total weight of 240 kN. The empty weight of a 40-ft container ranges from 28 to 36 kN with a maximum permitted total weight of 305 kN.

Initially, containers have been handled by conventional quay edge cranes. The first specially designed container crane was introduced in 1959, and over the last 30 years, container handling cranes have grown in size and handling capacity. The need for efficient handling of containers stimulated the development of new equipment, such as straddle carriers, heavy lift forklift trucks, gantry cranes, special tractors, and others. Older forklift trucks used for handling general cargo and pallets had lifting capacities of 30–80 kN. In contrast, today's new forklifts for container handling have capacities up to 450 kN.

During the last 25 years, the roll-on/roll-off method of handling containers have been developed and used extensively. This method allows containers, but also cars, tracks, trains, and so forth, to roll on ships via large stern or side ramps.

The advent of containers completely overshadowed cargo handling on pallets. The introduction of container systems for transporting goods revolutionized sea and land transport and cargo handling methods; ship turnaround time was reduced spectacularly and speed, efficiency, and safety of handling all types of containerized cargoes increased dramatically. This new technology drastically changed the approach to port planning. In most ports, a previously very effective pier system was disused as general cargo operations have been moved to the usually remote, high-volume container facilities with their large paved container storage areas and relatively few berths. These modern specialized ports and terminals tie directly into upland staging areas (marshalling yards) with multimodal links to several cities, a region, or the entire country.

Traditionally, ports have been developed in natural habors and, as mentioned earlier, have formed the nuclei for many cities. Today, ports and marine terminals are built wherever they can be economically justified. The need for large open areas to accommodate a modern container facility has induced ports to move to the periphery of cities and often on poor quality land. The latter usually presents a challenge to port designers and has been an area of major controversy related mostly to dredging and disposal of the contaminated dredged soils. Alternatives to dredging have been found in constructing offshore island ports and moving the up-river shallow draft ports down river, to deeper waters.

Dramatic changes have also occurred in the handling of liquid and dry bulk cargoes. Movements of liquid bulk petroleum products by ship started in the 1880s when special tanks were mounted onto existing vessels. Prior to this, the only means of moving liquids was in barrels, which was not a very efficient way of transporting ever-increasing quantities as mankind moved into the petroleum age.

Since the introduction of the first tank-mounted vessels, the procedure and method of liquid bulk handling has not changed in principle 100 years later; however, technical improvements in this area have been spectacular. The capacity of liquid bulk carriers (tankers) in the 1940s has reached 22,000 DWT and at the present time 500,000-DWT tankers ply the oceans. Today, several shipyards in Europe and Asia have the capacity to build 1,000,000-DWT tankers.

Similar developments have occurred in the transportation of dry bulk materials. Bulk carriers have lagged but tracked tanker growth, and, similarly, tankers may also be expected to grow in the future. The use of large and very large deep draft ships for transporting liquid and dry bulk materials and the material hauling innovations have changed the nature of the modern port. Ports actually become a highly specialized terminals able to handle the one specific cargo at very high rates; for example, loading of up to 20,000 tonnes/h and more of dry bulk, and 220,000 m^3 of crude oil per day; thus, annual throughput of tens of millions of tonnes has been achieved.

Deep draft vessels need deep water ports. It has been learned, however, that the conventional approach to construction of such ports, involving dredging of large quantities of sometimes contaminated sediments, can be prohibitively expensive. The solution has been found in the construction of offshore marine facilities not protected from the effects of environmental forces such as waves and currents. At these facilities, the low berth occupancy due to rough sea conditions has been compensated for by a very high rate of material handling on calm days. These facilities have been constructed far enough offshore where sufficiently deep water is found and no maintenance dredging is needed. In some instances the terminals have been moved as far as 2 km or more offshore and have been linked to the shore either by a bridgelike trestle, designed to support pipe lines or conveyor systems and to provide access to the terminal for lightweight vehicular traffic or by submarine pipelines. In some instances, particularly in heavily populated areas where local residents object to the construction of conventional trestles as an unacceptable "visual pollution," submarine tunnels have been constructed as a solution to the problem.

The modern port is developed as an important link in a total transportation system and planners of such multimodal systems seek to optimize the total network, not just one of its components.

Construction of a new port, or expansion or modernization of an existing one, is usually carried out to increase port capacity and its effectiveness. Traditionally, this has been focused on the sea, and, consequently, construction of new berths and modernization and expansion of existing ones was the prime area of interest. However, as urban coastal areas, particularly in developed countries, have substantially expanded over the last five decades, while concurrently international trade has increased and continue to expand, making the world more and more economically interdependent, the port land-side capacity to transfer the cargo from the wharf to the end user has become increasingly critical. In some densely populated areas, the available transportation network (e.g., highway and rail) is limited to moving a certain amount of cargo and cannot be expanded further. Under these conditions there is no logic in increasing the existing port capacity, unless the land-side transportation infrastructure is equally capable of moving the increased volume of cargo through the land-based transportation network.

In this respect, to avoid a waterfront conflict, many countries have developed a master plan for its major ports. For example, in

Canada, both the Canada Ports Corporation (a Canadian Crown Corporation) and individual ports have developed land use plans and economic impact assessment in cooperation with the cities and local special-interest groups which interface with port activities (Gaudreault, 1989).

In the view of many experts, modernization of existing ports will continue and many new ports will be developed in the 1990s and beyond due to major expansion of the world economy. The latter is result of dramatic growth of the world population, general industrial growth, and growth of petroleum and mineral material industries.

The real value of world trade will continue to grow. The new North American Free Trade Agreement (NAFTA) between the United States, Canada, and Mexico and new improved GATT treaty arrangements are expected to encourage similar agreements elsewhere in the world that will eventually result in the total world market free from protectionism and immune to destabilizing political upheaval in some regions. As pointed out by Barker (1990/1991) in future trade,

> ...the exporters will seek to increase the added value of their trade, which will tend to reduce tonnages of raw commodities and increase those in partially or fully processed materials. Thus increasingly refined petroleum products, chemicals, alumina or aluminum ingots or aluminum products, steel products, vehicles, sawn and processed timber products, processed agricultural commodities and such-like will be the cargoes rather than the basic raw commodities. These are more valuable and readily damaged cargoes which require more careful handling and storage. The trend to more specialized vessels such as reefer, parcel tanker, car carriers and roll-on/roll-off will continue and many of the processed cargoes will end up being handled in containers.

This trend is already quite visible in Asia. For example, today, Thailand's exports consist of 75% manufactured goods as opposed to export of raw materials and this trend is characteristic of most countries in South East Asia. Wider, nonstandard container are already the reality, and the trend for use of larger containers will continue. New container sizes will inevitably have great impact on the design of new containerships and the container handling technologies.

The most radical and far-reaching changes in container terminal technology will be their continuing automation which will lower manpower requirements and operating costs, increase control, and speed the flow of goods through the ports. Future terminals will be more flexible and easily adaptable to changes in the world's economy resulting in cyclic changes in demands.

Alternatives to dredging and construction of deep water ports will be design of wider vessels with lesser drafts. The important new development in port operations that occur about three decades ago was the virtual disappearance of the true passenger liners; the cruise industry has emerged to replace it. Today, the passenger trade exists basically on local lines on inland waterways and between coastal ports.

Cruise vessels, to date, have continued to look like liner vessels, notwithstanding that speed is no longer of paramount importance. Cushing (1989) predicts that cruise vessels will change; they will become larger, slower moving floating resorts.

The new ideas in port operations will bring new engineering and construction ideas in their wake. As pointed out by Hochstein (1992), the nontechnical aspects of port performance, such as commercialization, liberalization, and privatization, along with improvements of port administration will continue to contribute to the institutional restructuring and drastic improvements in port operations.

Commercialization gives to the port authorities freedom similar to the private sector where decision making is decentralized and management is held accountable for port performance.

Liberalization lessens the port authorities' monopoly on power by allowing the private sector to provide similar services and is complementary to commercialization.

Privatization transfers functions previously performed by the port authority (government) to private sector. It may involve transfer of full or partial ownership of port facilities, or it may be limited to private sector management practices for the provision of port services via lease and operating contracts. Privatization usually associates with eliminated subsidies and reduced costs of port operation.

The privatization of ports brings greatly enhanced commercial freedom to port managers and is recognized as one way to react more positively to market opportunities and use human incentives, based on personal gains and improvements, to increase efficiency of the port operations. This trend is natural and will continue both in developed and developing countries.

It must be recognized, however, that ports and harbors are built and operate within a certain societal framework that includes an array of political, financial, environmental, and other considerations. Therefore, the port planner must have a clear understanding of local technical and nontechnical issues. For example, in some developing countries, existing or new ports are not solely an industrial development but also enterprises aimed at solving some regional, social, or demographical problems. Therefore, a careful approach to port privatization is needed in developing countries. The latter assumes that although commercial spirit there must not be discouraged, the commercial approach to port operations in some developing countries should not pursue a short-term financial gain.

In Europe, port privatization has been successfully introduced in the 1980s in the United Kingdom where it is likely to accelerate in the 1990s. Also, today it is most apparent in Asia.

Improvement of port administration encompasses actions that improve the performance of the organization. It may include corporate planning and carrier development, as well as installation and constant modernization of a computerized management information systems that enhances management without changing the port's institutional structure.

Recent experience in ports worldwide suggest that commercialization and privatization are the most far-reaching and effective strategies to achieve the objective of port effectiveness.

In conclusion to this section it should be noted that the future is not possible without thorough familiarity with the past which is a true foundation for new ideas. As Tooth (1989) rightfully said, "The past is not just something out of date, it is a record of human experience—an experience is certainly something which should be used to help shape the future."

For more information on port developments the reader is referred to Dally (1981), Cushing (1989), Clearwater (1992), Thomson (1992), and PIANC (1987, 1989, 1990).

Engineering Advancement in Port Design and Construction

The primary construction materials that were used for construction of older marine facilities were wood and stone. They were worked by hand and used for construction of sheet-pile bulkheads, piled piers, quay walls, breakwaters, and other structures. Wooden sheet piles and regular piles were driven by using primitive power equipment, and stone was placed from crude construction platforms.

More than five centuries ago the Phoenicians extensively used wooden sheet piles and piles for construction of their marine facilities. For sheet-piling they used long planks made from Lebanon cedar. Various types of timber sheet-piling techniques (e.g., tongue and groove, laminated, and others) were used. These piles were driven successively edge to edge to form a vertical wall for the purpose of preventing the retained materials from spreading and from being undermined by the action of waves and current. This type of construction was also known to ancient Egyptians and Romans. The Phoenicians also used heavy blocks locked together with copper dowels for construction of the open-sea port at Tyre. This type of construction was also used by the Romans. In the 1800s, both materials still played a major role in port construction.

A great variety of gravity-type walls constructed from rubble masonry or heavy granite or limestone blocks have been built during the 1880s. The history of heavy blockwork construction is traced back to ports in Mediterranean, at Marseilles and Algiers, with much of this pioneering work being carried out at the Port-of-Bonqie, Algeria where a quay wall composed of limestone blocks had been built as far back as 1840. During the same period of time, wood was extensively used for the construction of piled wharves and piers, as well as for gravity-type quays comprised of floated-in timber cribs with or without a masonry superstructure.

It should be noted that improved and economically sound blockwork quay walls are still in use. Details are provided in Chapter 5. Today, timber cribs are used where wood is in abundance, and timber sheet-pile bulkheads made from treated wood have been constructed elsewhere, particularly in coastal regions as a secondary line of shore defense in ocean-exposed locations and for construction of low-height marine structures in small-craft harbors. Well-treated timber sheeting is also employed in permanent structures where it is always hidden under water, thus preserved from rot, and at locations where there is no marine organisms (e.g., borers) which can destroy wood. The same is true for wooden piles.

Cast-iron piles became complementary to timber piling in the early 1800s (Borthwick, 1936). The earliest reported use of iron sheet piles was construction of the North Pier of Bridlington harbor, the United Kingdom, in the early 1820s (Mackley, 1977). Various types of iron sheet-pile sections were available at that time, and a considerable amount of exploratory work was carried out in order to develop the most economical profile. Cast iron, however, as a material had limitations primarily because of its vulnerability to brittle fracture during driving in hard soils. Typically, wrought-iron piles were used in a composite riveted form and were based primarily on the fitting of plates between suitable guides or against supports.

In 1897 a Danish engineer, Larssen, revolutionized the use of iron sheet piles by introducing a new pile section which was developed from a rolled trough section plus a riveted "z" section, to form an interlock; this shape is very familiar in modern construction.

In 1914 Larssen also introduced the first deep-arch section in which interlocks were situated in the neutral axis of the complete section; thus, their material bulk did not influence the bending moment to be taken up.

Larssen's inventions and modifications helped to greatly increase the capacity and effectiveness of sheet piles in their ability to resist earth and water pressures. Increased pile stiffness enabled it to be driven without buckling or springing under the blows of the driving hammer, increased water-tightness of the sheeting prevented seepage through the wall, and, most importantly, efficient use of rolling mills produced an economical section with interlocks.

At the beginning of this century, both wood and iron have been replaced by steel and reinforced concrete. The first sheet pile ever made from a rolled section was used in Chicago in 1901; it was called the Jackson pile. This was followed by the rather fast development of numerous straight or trough sections of steel piles that were produced around the world, either with integral locking arrangements or with a separate interlocking member.

The first steel "z"-shaped sheet piling known as the Hoesch system was introduced in Belgium in 1913. In comparison with other sections, this type of piling was stiffer and had a higher section modulus at equal weight with other piling systems. Since this time, various combinations of different piling systems and various types of box piles (H-section) have been introduced in North America and Europe. At present, a variety of high-strength sheet-pile sections are available from different pile manufacturers.

In addition to the above-mentioned piles, relatively low sectional modulus straight web steel sheet piles are often used in marine application for construction of cellular-type bulkheads. These piles were first manufactured and used in the United States in 1908/1909.

It should be noted that steel pipe-type sheet piles are now coming into widespread use for deep water construction where a sheeting of greater strength is required.

Reinforced concrete sheet piles have been used in harbor construction since the beginning of this century. They are usually considered relatively maintenance-free components of a sheet-pile wall. Although many different design types have been developed and used in the past 50 or so years, the straight web piling bar provided with a tongue and groove, similar to that used on timber piles, is the most commonly used. Since the 1950s, prestressed concrete sheet piles have replaced almost completely the ones made from regular reinforced concrete.

Prestressing of concrete sheet-pile reinforcement has an advantage, especially in seawater environment, as cracking of concrete in the tension zone is thereby largely eliminated and the danger of corrosion of reinforcement is decreased.

The same applies to regular concrete piles that are extensively used in marine application. The advantage of piled structures is that they enable practically free passage of waves, which makes them particularly attractive for construction of the deep water offshore terminals.

A great variety of concrete and steel piles have been developed and used from the beginning of this century. The wide variety of these piles is discussed in Chapter 7.

The most significant development in this area is the use of large-diameter (up to 3.0 m and more), very long (60 m and longer) prestressed concrete and steel cylindrical piles. Depending on geotechnical site conditions, these piles can be installed by different methods (e.g., driven by hammer, vibrator, hydraulically, or a combination of some of these). It should be pointed out that the vibratory hammers introduced in the fifties and sixties changed the basic way piles had been driven since the late 1800s. New hydraulically operated hammers enable the constructors to drive piles under water. Similarly, very large floating and jack-up pile-driving equipment was developed and used for pile installation at exposed offshore locations. An array of piles with enhanced bearing capacities have been developed; for example, screw piles of different designs, prefabricated piles with enlargements on their shafts, belled piles, and other have been successfully used in port and offshore construction.

High-strength steel and prestressed concrete allow the port designers and constructors the flexibility to design for greater depth, longer spans and higher capacity. For example, general cargo wharves are now routinely designed for 5.0 tonnes/m^2, up from 2.0 tonnes/m^2 60–70 years ago.

Galvanization and the use of protective coatings, such as epoxy, which came into use in the 1950s increased the longevity of marine structures. Epoxies are also used by constructors for splicing concrete structural elements in the field.

Remarkable progress has been achieved in concrete technology. Today's structural concrete is indeed a mixture of admixtures. Products such as superplasticizers, retarders, accelerators, air entrainers, and others allow concrete pours in cold temperature or hot weather. A denser and higher quality product is obtained by use of silica fume in a slurry or powdered form. Silica fume can substantially increase strength and density of concrete and make it virtually impervious to chloride penetration in the harsh marine environment. Furthermore, use of corrosion inhibitors may slow down the potential onset of corrosion in steel reinforcing bars.

Development of huge floating heavy lift equipment revolutionized the construction of gravity-type quay walls and breakwaters. These structures, generally built in water depths of 6–9 m in the late 1800s, are now constructed at depths of 25 m and below.

Finally, it should be pointed out that in the past 30–40 years primitive fenders used for protection of marine structures from ship impact have been replaced by very efficient high-energy-absorbing and low-reaction-force rubber fender systems. At the present time, fender units are manufactured from solid and laminated rubber in different shapes and sizes. They are also manufactured in the form of a low-pressure inflated balloon (pneumatic fenders), or as a closed-cell foam filled unit. The pneumatic fender units have been manufactured up to 4.0 m in diameter and 12.0 m long.

In modern marine engineering practice, a number of innovative and economical gravity-type quay walls have been employed. Among them are concrete large-diameter floated-in caissons, bottomless concrete cylinders, and prefabricated L-shaped retaining walls of miscellaneous designs.

An economical solution to gravity wall construction in the wet was also achieved by use of the traditional structures such as a large-diameter steel sheet-pile cell, a conventional boxlike floated-in concrete caisson, and blockwork walls of enhanced designs.

The economy of gravity wall construction was significantly improved by using innovative methods of bed preparation and placement and densification of backfill materials. Detailed information on this subject is given in Chapter 5.

Waterfront construction was accelerated by the use of prefabricated structural components. Prefabrication dramatically reduced the time required for overwater construction and enhanced quality and therefore longevity of marine structures.

The design of any project is a continuous process, which begins with the perception of a need or opportunity, followed by a feasibility study that usually includes a conceptual design, and embedded by the detail design. The latter is followed by the construction of the project with subsequent commissioning. Furthermore, where required to support the basic concept of the project (e.g., harbor layout) or permit innovative structural designs to be used with confidence, research is undertaken.

In the past, port and its related marine structures have been designed with a high degree of redundancy, largely because of the relatively rapid deterioration rate of structural materials in the marine environment, but also due to a lack of proper understanding of wave mechanics, mechanisms of ship–structure and/or soil–structure interaction. The latter was particularly true in designing a "flexible" structure such as sheet-pile bulkheads.

In the past 50 years, substantial progress has been achieved in such areas as the development of new, much stronger and more durable structural materials, the introduction of better construction technology, and a better understanding of the process of soil–structure interaction. Thus, research and development directly or indirectly became the integral part of the design process.

The design of port layout with its related structures such as breakwaters, piers, and quay walls normally involves a great number of parameters that are generally considered to be far beyond the ability of purely analytical methods to achieve the reliable solution. This has been overcome by use of large-scale physical models, which appear to be a viable tool in solving a complex multiparameter problem.

Today's engineers have abundant analytical capability supported by computers. The mathematical modeling of a complex phenomenon such as the interaction between nature and engineering developments has become commonplace in the design process. It enables the engineer to closely predict the behavior of the complex structure in practice.

For complex projects, both mathematical and physical models are best used in combination. However, despite the prediction of model studies, the designer should exercise the proper level of conservative engineering judgment which is dictated by the complexity of marine foundations, marine environment, ship maneuvers, and so forth.

Today, port and harbor engineering has entered the electronic age. The computer vastly enhances an engineer's productivity and his or her opportunities for innovative design. In addition to reducing the opportunities for making errors, the use of computers drastically enhances engineering judgment. By taking advantage of the speed of computer analysis, the engineer can explore a number of design alternatives in a short period of time. Today, computer hardware and software allow the engineer to see his project from all perspectives, investigate each detail, make changes by shaping as a sculptor might, then, when all is finished, have the calculations and drawings produced. Computer-aided design and drafting (CAD) open opportunities for transition from traditional two-dimensional (2-D) design to three-dimensional (3-D) design. This has been made feasible by the rapid advances in computer-graphics hardware which now permits full 3-D CAD models to be displayed quickly and effectively, with hidden lines removed or with shading; 3-D computer models can be viewed from any angle and viewpoint, in orthographic, isometric, perspective, or cutaway views. This helps to make the project aesthetically more acceptable to the community and overcome the public resistance to some projects regarded as a "visual pollution" to the area. The importance of aesthetic aspects of any project now is fully recognized by the designers and developers, and the 3-D approach to structural and civil design helps to bridge the gap between art and science.

Unfortunately, computerization of the design process has its own drawbacks; it provides not only the leading edge of technology but have been also a major source of concern. The popularity of computers has resulted in a flood of software, and on today's software market, there are nearly as many computer programs as there are researchers. Unfortunately, the quality of some software presently available on the market is questionable, and it would be of great interest and perhaps shock to some when results of analyses of a certain structures are compared with the same input data using different programs.

The difference in the software output happens because some developers of computer software blindly rely solely on the mathematical approach to solving the problem and are ignorant about current state-of-the-art knowledge.

Sometimes problems with software (e.g., incorrect sign convention) may cause a computer to subtract stresses when it must be added can be difficult to detect.

Growing reliance on computer-aided analysis and design without adequate controls on misuse can lead to structural failures and, subsequently, to "computer-aided liabilities," the term used by Backman (1993) in her interesting paper on a subject matter.

Recognizing this as a potential problem, the Committee on Practices to Reduce Failures, under the American Society of Civil Engineers Technical Council on Forensic Engineering, is currently preparing a monograph titled "Avoiding Failures Caused by Misuse of Civil Engineering Software." The monograph, scheduled for publication in 1996, will examine all computer-related issues where misuse could result in catastrophic failures, poor performance of facilities, and poor solutions to problems in civil engineering.

Due to a worsening legal climate for practicing engineers, the designers are often not willing to accept potential risk associated with a more economical or innovative design. The conservative approach, which limits innovations in design and construction practices, causing economical problems, has been especially visible in foundation engineering. This has been explained by the uncertainties in soil–structure interaction and usually limited information on foundation soils available to the designer. In the past 35–40 years, this has been improved by the extensive research into statistics and risk analysis, as applied to the field of geotechnical engineering.

Also, the observational (monitored decisions) method, which provides the designer with flexibility in the decision-making process, has been introduced.

Statistics provide procedures for obtaining information from given quantitative measurements, which, in turn, permits analysis of how the aforementioned listed uncertainties of soil and other parameters involved in soil–structure interaction may affect the design of the structure; risk analysis is a set of decision-making procedures dealing with difficult design circumstances, where many components interact such that there is more than one mode of failure; and the observation method is a departure from the traditional design process in geotechnical/foundation engineering, because it allows one to make a final decision on foundation design in the future, both during construction when uncertainty in foundation soils became understood and during facility operation. The latter is particularly important where long-term changes in soil–structure interaction are expected.

Several advancements in port engineering have been pointed out in this section and the reader will find much more elsewhere in this book.

Finally, it should be noted that in the past in order to reduce the cost of a design, attempts to standardize construction of marine structures have been made. It has been proved, however, that standard designs to meet various site conditions, in general, and marine facilities, in particular, are not economical. In general, it is because the cost of the waterfront structure is so high that it would be false economy to attempt to reduce design costs by limiting the scope of design studies.

In conclusion, it must be said that producing a good, sound, and effective design is, of course, science; however, it is also an art. Just as an artist does, the designer must be imaginative in developing the concept of his or her project and, as a scientist, careful and meticulous in paying attention to all details.

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