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Survey of research on the optimal design of sea harbours

Hassan Diab [a,b,*], Rafic Younes [b], Pascal Lafon [a]

[a] *Charles Delaunay Institute, Mechanical System and Concurrent Engineering Laboratory (ICD-LASMIS), UMR CNRS 6281, University of Technologie of Troyes (UTT), France*
[b] *Lebanese University, Faculty of Engineering, Lebanon*

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Abstract

The design of harbours, as with any other system design, must be an optimization process. In this study, a global examination of the different constraints in coastal engineering was performed and an optimization problem was defined. The problem has multiple objectives, and the criteria to be minimized are the structure cost and wave height disturbance inside a harbour. As concluded in this survey, the constraints are predefined parameters, mandatory constraints or optional constraints. All of these constraints are categorized into four categories: environmental, fluid mechanical, structural and manoeuvring.

Keywords: Port management; Harbour; Optimization

1. Introduction

Coastal areas have played a significant role in humanity's progress. Although risks arising from the oceans are sometimes huge, we have found that most of the world's populations live on or near the coast (Creel, 2003; World Resources Institute et al., 1992).

Humans have long tried to benefit from the coast; five thousand years ago (in the 3rd millennium B.C.), the Phoenicians constructed harbours in Tyr and Sidon on the Mediterranean Sea's coast for use in trading (Bosworth, 1915).

A harbour is defined as a place where ships load and unload cargo or shelter from storms (Hornby et al., 1989). At present, there are four major types of harbours according to functionality: fishing, military, pleasure and commercial.

Every type of harbour requires its own design and management considerations. Our interest will be confined to commercial harbours, which constitute the backbone of commercial transport worldwide. As in all commercial sectors, designers and managers always tend to increase the limits of capacity and operating periods of harbours, through optimal forms, design, and management. In addition, protecting a harbour's structures and saving the coastline are two important objectives that demand attention is given to defence structures, including breakwaters.

At present, any system design is an optimization process (Breitkopf and Coelho, 2010). As a consequence, the design of harbours must an optimization problem. In this article, we will outline an optimization problem for defining harbours.

Many researchers have worked on discovering the constraints that menace coastlines, harbours and defence structures to aid ocean and coastal researchers or engineers during the design process.

We will try to summarize what others have done in this field before formulating a breakwater design problem that considers all of the constraints. We will decompose the constraints into four main categories: environmental, fluid mechanical, structural and manoeuvring.

* Corresponding author.
E-mail addresses: hassan.diab.2016@utt.fr (H. Diab), rafic.younes@lsis.org (R. Younes), pascal.lafon@utt.fr (P. Lafon).
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The environmental constraints cover water quality, water level and ecological life as main environment-related issues.

Among the fluid mechanical constraints, we will first observe the effects of waves, which are considered to be a primary if not the most important constraint. We will proceed further into the world of wave modelling and define its bold lines. We will also discuss erosion and flooding phenomena, water depth and ocean currents.

In addition, regarding structural constraints, we will address both economic and mechanical constraints. Economic constraints comprise the cost, materials, and construction process, whereas mechanical constraints include mechanical stresses, position, dimensions, and the effects of the seismic responses of structures. The problems of the floatability and stability of floating breakwaters will also be considered here.

Furthermore, within the manoeuvring constraints, we will mention the influence of harbour architecture on manoeuvrability. The entrance, fairways and manoeuvring area will be discussed to determine the different factors that affect their designs.

2. Environmental constraints

Many problems in the ocean environment could be studied as water levels rise due to global warming, including water pollution, water quality and ecology. These three issues will be addressed in this section.

In addition, many other environmental problems may exist in certain special cases, including noise and the problem of ice. These problems are less studied. The noise in a chipping port was studied and considered to be a type of pollution in the port area (Kamphuis, 2006). The accelerated growth of brash ice is a problem that port operators confront in the very busy harbour basins of cold regions (Tomasicchio et al., 2013).

Air quality in harbour zones is another environmental problem. To date, this problem has not been considered as a functional constraint on harbour design.

2.1. Water quality

Basin water quality is an important aspect that must be considered in harbour design. Water exchanges produce a flushing action (Neelamani and Rajendran, 2002a). Low rates of seawater exchange between the inside and outside of harbours cause environmental problems that include bad smells and ecological disorders (Vidal et al., 2006). The water quality in a harbour will be affected by the existence of structures because of the influence of those structures on the movements of currents and tides. Predicting this influence using mathematical models before constructing the structures is a method that may be utilized to minimize the consequences of problems (Kantardgi et al., 1995). For example, designing coastal structures, such as Current Deflecting Walls, may be an effective solution that will reduce harbour siltation (Bowman and Pranzini, 2003) because harbour layouts are complex geometries that limit water renovation from the open sea in harbour-enclosed zones (Kamphuis, 2006). In addition, seawater exchange breakwaters have been suggested to address the issue of water quality in harbours (Vidal et al., 2006). World harbours that have only one connection to the adjacent ocean experience severe environmental impacts due to systematic and accidental discharges of polluted waters, which is why multi-connection harbours have been recommended (Vidal et al., 2006).

2.2. Water level

At present, water level is receiving increased interest. Climate change is accelerating rising sea levels (Battjes, 2006; Tomasicchio et al., 2013) and should therefore be taken into consideration when designing breakwater with long lifetimes. A safety factor that accounts for sea level rise must be considered (Suh et al., 2013). Higher water levels increase inshore wave heights in shallow waters (Chini et al., 2010).

Due to rising water levels, the significant wave height, which usually occurs once every 100 years, becomes more frequent, with obvious implications on coastal defence design life (Chini et al., 2010).

2.3. Ecology

The use of coastal structures as breakwaters increases habitat complexity, heterogeneity, and availability by the rapid colonization of sea species in such structures. Breakwaters can be considered as unique and important artificial reef habitats, on which abundant and diverse reef fish communities can develop (Burt et al., 2013). The materials used in constructing those structures significantly influence their role as reef habitats (Burt et al., 2009). To encourage marine life to use them as habitats, the shapes of submerged breakwaters have been studied (Kamphuis, 2006).

The ecological potential of heavily modified water bodies (HMWBs) has been defined to study the influence of the presence of ports on ecological status and to measure physical alterations caused by human activity (Ondiviela et al., 2013).

3. Fluid mechanical constraints

3.1. Waves

Waves have been proven to be the most relevant factor in coastal engineering (Franco et al., 1986), so we have identified a large number of articles that try to model the different types of sea waves or explain their effects.

In addition, most defence structures are built to maintain protection against wave energy (Filianoti, 2000; Hur et al., 2010; Kamphuis, 2006; Tanimoto and Takahashi, 1994; Tomasicchio et al., 2013; Vidal et al., 2006) or to maintain the functionality of harbours by promoting the stability of vessels and ships during accosting and loading/offloading activities (Kamphuis, 2006). Wave-induced ship motion may help cause serious damage to ships, containers and trolleys. It also may increase the duration of the process (Hong and Ngo, 2012). The efficiency of breakwaters decreases when the height of waves transmitted to the harbour area increases (Elchahal et al., 2009a; Hur et al., 2010).

Physically, a sea wave is a disturbance on the water surface that transmits energy from one point to another by the displacement of water particles in circular orbits. There are three types of waves. The first are wind-generated waves that are caused by winds blowing over the vast free surfaces of the oceans. The second are tide waves that are produced by the interference between the gravitational forces due to the moon and the sun and the centrifugal forces caused by the self-rotation of the earth. The last, tsunamis or solitary waves, are usually due to tectonic forces.

Like any other wave, sea waves can be characterized by three main parameters: wavelength and wave height in meters and wave period in seconds. From these parameters, we can calculate the remaining important parameters, such as wave speed in meters per second, which is the wavelength over the period, and the frequency in hertz, which is the inverse of the period. However, a wave in the ocean will never be a monochromatic wave. It is a superposition of several monochromatic waves with different periods and lags. It is characterized by its proper significant height and peak period.

Our interest will be on wind-generated waves, and prior to searching for the effects of these waves, we must introduce the different ways used to represent them. There are two main methods: wave statistics and mathematical models. Wave statistics require huge efforts in collecting data, filtering and analysis to be useful in the design and management process. These data are collected from a fixed station near the shoreline or by ship-based observations around the world. The main disadvantages of the statistical method are the vulnerability of the measurement devices, the random nature of the observations and need for ships to avoid extreme conditions (De Graauw, 1986). In addition, we should note that the main difficulty in the modelling process is the excessive computational effort required to solve the model (Belibassakis and Athanassoulis, 2002), especially 3D models, which require very considerable computational effort (Rakha and Kamphuis, 1997) because of the many antecedent approximations, and to improve the efficiency as calculation hardware and software evolve, many modifications have been made to the initial models.

The state of art of wave modelling was summarized in a review by 26 authors (Cavaleri et al., 2007).

In the wave propagation section, the authors described how it has evolved during the last three centuries (Table 1).

Initially, monochromatic linear and nonlinear wave propagation theory was utilized (Airy, 1845; Stokes, 1847), and nonlinear effects due to shallow water were then added (Boussinesq, 1872), which makes Boussinesq model very useful in coastal engineering as applied in computer models to simulate waves in harbours (Kamphuis, 2006). The irregularity of waves at sea was accounted for by employing a spectral approach for wind-generated waves (Pierson et al., 1955). The interaction with the geometrical forms has been studied; these forms may be breakwaters or natural topography. The combined effects of diffraction and refraction over bathymetry have been described in the mild slope-equation (Berkhoff, 1976). This equation is often used in coastal engineering to compute the wave field in harbours or near the shoreline. The Berkhoff model was later extended to be valid for all bathymetry types (Massel, 1993) and modified to simulate the dissipation of energy due to bed friction and breaking waves (Putnam and Johson, 1949).

Table 1
Wave propagation model.

Date of appearance	Model
1845	Airy model for monochromatic linear waves
1847	Stokes model for monochromatic nonlinear waves
1872	Boussinesq model for shallow water
1955	Pierson model for irregular waves
1972	Berkhoff model for mild-slope, varying depth, seafloor

This model is represented by the following equation:

$$\nabla.\left(CC_g\nabla\varnothing\right)+CC_g\left(k^2.(1+f)+ik\mu\right)\varnothing=0,$$

where C and C_g are the phase and group velocities, respectively, k is the wave number, $\varnothing$ is the velocity potential in the x−y plane, f is the rapidly varying bathymetry coefficient, and μ is the dissipation coefficient.

Waves are considered to be primarily responsible for damage to structures (Neelamani and Rajendran, 2002a; Tomasicchio et al., 2013; Vidal et al., 2006), and their effects have been studied according to the aforementioned multiple parameters that compose their characteristics. Wave height and wavelength play an important role in creating damage to structures and vessels (Tanimoto and Takahashi, 1994). A wave with a height of 0.30 m, for example, might be a threshold value for damage to vessels moored behind a breakwater (de Haan, 1991).

Wavelength is an important parameter in wave attenuation (Hardaway and Gunn, 2010) and is also an important parameter in the resonance of harbours or moored vessels and ships (De Girolamo, 1996) caused by wave period and height. Greater damage is expected with longer periods (Franco et al., 1986). Usually, harbour resonances occur when waves of certain periods enter the harbour opening and become trapped and amplified in a semi-enclosed domain (Dong et al., 2013). Consequently, the low-frequency motions of ships can interrupt cargo handling (Kamphuis, 2006; Tomasicchio et al., 2013).

Wave obliquity and multidirectionality are additional parameters that cause waves to behave differently on breakwaters (Bowman and Pranzini, 2003). They also have a great influence on module connector forces applied in the case of floating breakwaters (Tomasicchio et al., 2013).

Another wave effect is the fatigue-breaking of materials and subsequent break-up and removal. Studies of fatigue degradation of a breakwater have introduced the concept of a breakwater's lifetime (Franco et al., 1986). This repetitive load leads to a gradually weakening of foundations that may cause them to fail (Oumeraci, 1994).

The failure of the foundation of a structure and liquefaction seabed scouring due to wave-induced seabed instability can be considered as critical effects of sea waves and constitute a great threat to the stability of coastal structures (Bowman and Pranzini, 2003; Hur et al., 2010; Kim et al., 2011; Neelamani and Rajendran, 2002a; Vidal et al., 2006).

In addition, the phenomena of overspilling and overtopping have been studied because of their inconvenience on the functionality of the area behind breakwaters (Juul Jensen and Sorensen, 1979; Yeganeh-Bakhtiary et al., 2010). Overtopping may produce abnormal forces that are prejudicial to stability (McCabe et al., 2013; Oumeraci, 1994), but it is still a greater source of functional rather than structural damage (Franco, 1994). That is why it has been identified as a potential risk factor that can cause structural damage and operative failure modes (Alises et al., 2014). The different frequencies, volumes and velocities of these overtopping events influence the safety of the structures and of people working or travelling behind them and may reduce visibility on the harbour side, where a sudden loss of visibility may cause significant driving hazards (Bouma et al., 2009). Therefore, breakwaters are built up to the greatest reach of waves to avoid the overtopping phenomena (Silvester, 1978), and moving the breakwater seawards will reduce the effect of overtopping at the working zone within the harbour (Elchahal et al., 2013). Overtopping behaviour is considered to be a major criterion to determine the configuration of rubble mound breakwater armour (Bruce et al., 2009; Isobe, 2013; Yang et al., 2010) and to design seawalls (Schüttrumpf and Oumeraci, 2005). Generally the mean overtopping rate is considered a key parameter for the design of breakwater crests (Shankar and Jayaratne, 2003). Overtopping has also been studied for sediment transport; it alters the current circulation and sediment transport patterns around structures (Du et al., 2010). Numerical models of waves overtopping coastal structures have been developed (Briganti and Dodd, 2009), and an overtopping database has been established (van der Meer et al., 2009).

3.2. Erosion and flooding

Erosion and flooding are major problems in coastal engineering because of their great influence on ecology and environmental issues (Airoldi et al., 2005; Isebe et al., 2008).

Erosion is a phenomenon that occurs on coastlines, which adjust to varying sea levels, energy levels, sediment supplies and existing topography (Cooper and McKenna, 2008), and it may result in the retreat of coastlines, the landward movement of 0 m depth contours or the downward erosion of lower beaches (Cai et al., 2009).

Two approaches are used to prevent erosion: non-structural approaches, which are limited to beach nourishment, and structural approaches, such as revetments, seawalls, and breakwaters (Dean et al., 1997). Multi-segment breakwater systems have been proposed to protect coasts from erosion (Bowman and Pranzini, 2003; Hardaway and Gunn, 2010; Zyserman et al., 2005). The defence structures are also intended to prevent flooding (Airoldi et al., 2005; Castillo et al., 2006).

Coastline flooding occurs due to the combination of large waves and high water levels (McCabe et al., 2013). Climate change, which encourages rising sea levels, increases the risk of flooding, as well as human-induced changes, such as dredging, land reclamation and coastal defence, which impact the natural behaviours of coastal zones and alter the risk of flooding (Bates et al., 2005).

3.3. Water depth

Because the water depth in front of a wall is a major parameter that affects the breaking process of individual waves (Kirkgöz, 1992), it is considered to be highly important. Water depth also affects how to choose the type of breakwaters that must be used in a particular place because it may be a main factor that determines the cost of the structure (Franco, 1994). Construction cost increases with increasing water depth at breakwater sites (Hu et al., 2006).

Water depth is also related to the functionality of harbours or navigable waterways due to the presence of vessels of sizable draft (Galor, 2007; Silvester, 1978). That explains why a good understanding of sediment dynamics in coastal marine ecosystems is a topic of key relevance for coastal management (Jordi et al., 2008) where sediment concentrations may reduce harbour depths (Zuo and Li, 2010).

3.4. Current

An ocean current is a displacement of seawater and is characterized by direction, speed and flow. There are two types of currents: deep and surface.

Imbalances in received solar energy due to solar zenith angle lead to heterogeneities in seawater temperatures, salinities and densities, which create the phenomenon of currents. In addition, the Coriolis force, which is a result of the Earth's self-rotation, influences the characteristics of motion.

Researchers have been interested in understanding this phenomenon and its influences on harbours and coastal zones.

Deep currents may lead to sea bed deformation due to sediment transport (Zuo et al., 2009). The motion of currents around the entrance of harbours and the influence of entrance layouts on current motion have been studied (Xie and Zhang, 2010). The effects of existing structures or those caused by the introduction of new structures on water quality inside harbours, due to their influence on the current-induced upflushing of harbour water, have also been numerically simulated (Kantardgi et al., 1995).

4. Structural constraints

Regarding structural constraints, economic and mechanical perspectives will be considered.

4.1. Economic constraints

Economic constraints are usually the main issue in all engineering structure modelling. The methods used to calculate cost, material selection and construction process are the main economic factors.

4.1.1. Cost

Some authors have considered construction cost or total cost (construction, maintenance and repairs) as the design criteria. They have also tried to minimize cost under different constraints, including geometric constraints (Castillo et al., 2006), working on the topology to minimize structure weights to reduce costs (Chaves and Cunha, 2014; Elchahal et al., 2009a, 2008a, 2006), and even by choosing alternative materials (Elchahal et al., 2006).

4.1.2. Material selection

Defence structures require huge quantities of construction materials (Latham et al., 2006). Material cost is a key factor of the overall cost of structures.

In addition, when choosing materials, it is very important to consider the aggressive chemical environment, which will lead to large amounts of damage due to material degradation (Franco et al., 1986). The chosen materials must be sound and resist extreme weathering conditions, including ice exposure (Bruun and Kjelstrup, 1981).

4.1.3. Construction process

The construction process has been discussed to show the importance of using correct installation methods. The speed of the installation process has a great influence on decision making when designing a breakwater to protect a harbour. An incomplete structure may be more exposed to danger of failure if extreme conditions occur during construction.

The flexibility in building, modifying and even removing a breakwater may also advantage one type of breakwater over others and must be taken into consideration by coastal engineers (Franco, 1994). These are strong advantages of floating breakwaters. They may be adopted to the different shapes and sizes of harbours and constructed relatively more quickly and cheaply (Gesraha, 2006; Michailides and Angelides, 2012; Patil et al., 2012).

4.2. Mechanical constraints

The mechanical constraints are the physical considerations related to the structure. Those constraints will be discussed in this section.

4.2.1. Mechanical stresses

Mechanical stresses on a body's structure, which are the result of the different forces acting on it, especially the wave force, which is a hydrodynamic pressure and a hydrostatic pressure due to the weight and height of water acting on the different sides of the structure, impose an important limitation on the structure's design (Akoz et al., 2011; Elchahal et al., 2009a, 2008a, 2006).

The highest impact pressure occurs at the striking point of a wave crest tip in the vicinity of the still water level (Elchahal et al., 2009a, 2008a, 2006; Silvester, 1978). In addition, negative pressure may occur because of the expansion of the compressed air that could be imprisoned between the wave and structure at the moment of the impact (Hattori et al., 1994).

The fatigue phenomenon represents another mechanical stress that may act on the structure due to the cyclic nature of wave loading (Franco et al., 1986; Oumeraci, 1994); to address this type of stress, more complicated models are required.

4.2.2. Position

Breakwater position is discussed from two perspectives. First, regarding the tourist value of a site, it should not exceed +2.5 m above water level (Spǎtaru, 1990).

The other perspective is functionality, so that a breakwater is lengthened relative to its distance offshore (Hardaway and Gunn, 2010). In harbours, that distance is called the sidewall clearance and is considered to be the main factor that affects the amount of energy accumulation in an enclosed domain that produces resonance. Varying the clearance can dominate the problem of resonance (Elchahal et al., 2009b, 2008b). In addition, as mentioned before, breakwater position can affect the degree of functional damage produced by the phenomenon of overtopping on a harbour (Elchahal et al., 2013).

In addition, the gap between two adjacent breakwaters must be chosen carefully; it may be determined according to the incident wave length, where if the gap between two adjacent breakwaters is twice the incident wave length or more, the shoreline behind each breakwater responds independently, as if there was no interaction among the breakwaters (Hardaway and Gunn, 2010).

4.2.3. Geometry and dimensions

Many authors have tried to find a way to optimally determine the different dimensions of defence structures.

The length of the structure under consideration must be larger than the wavelength for the scattering to significantly impact the shoreline (Isebe et al., 2008) and must simultaneously respect the breakwater length to breakwater gap ratio in multi-breakwater systems (Hardaway and Gunn, 2010).

In floating breakwaters, the width must be once or twice the wavelength to be effective (Silvester, 1978); it is a key design parameter (Peña et al., 2011). The height can be limited to where the dynamic pressure is effective; at a considered depth from the free surface, the pressure becomes approximately constant at a low value (Elchahal et al., 2008a, 2006). The cross section shape is also considered when dimensioning the breakwater; it influences weight, cost, mechanical resistance, floatability and stability (Elchahal et al., 2008a, 2006; Peña et al., 2011).

The type of breakwater and its geometry and configuration have been tested, and the influence of wall slope has been examined (Elsharnouby et al., 2012; Günaydın and Kabdaşlı, 2004, 2007; Liu and Li, 2011; Martinelli et al., 2008; Morgan Young and Testik, 2011; Neelamani and Rajendran, 2002a, 2002b; Kirca and Kabdaşli, 2009).

4.2.4. Floatability and stability

Floatability and stability are two constraints that we could find only in the design of floating structures. The floatability condition is simply represented as an application of Archimedes principle. The goal is to be certain that the structure will not sink, whatever the forces acting on it. The difference between the buoyancy force and weight must be compensated by the tension in the mooring lines that fix the structure.

Stability is defined as the ability of a structure to return to its initial position after any perturbation. This equilibrium state could be obtained by studying the moments of forces acting on the structures (Elchahal et al., 2009a, 2008a, 2006).

4.2.5. Seismic response

Breakwaters are subjected not only to water related effects but also to other types of environmental loading, such as earthquakes. The design of coastal structures should take into account the most relevant factors in each case, including seismic loading. Earthquakes may impose destructive loadings on coastal structures (Cihan et al., 2012; Ling, 2001).

The seismic responses of port structures have been studied to resist cyclic loads attacking the structures during perturbations (Cihan and Yuksel, 2011). A seismic safety factor is introduced into the structural design characteristics to insure a structure's capability to resist earthquakes (Ling, 2001).

5. Maneouvering constraints

The fundamental criteria to consider when defining and dimensioning navigation channels or harbour basins are manoeuvring and operational safety. In general, marine casualties most frequently occur near ports (Hsu, 2012). The increasing number of ship collisions, resultant ship groundings and immense costs of cleaning oil spills have led to significant efforts toward improving ship manoeuvrability performance (Yavin et al., 1995).

Therefore, to correctly define the different harbour structures, many elements must be studied, including the geometric configuration of the structures and seabed and vessel dependent parameters, such as type, size, age and operational conditions (Chin and Debnath, 2009; Hsu, 2012; Schelfn and Östergaard, 1995). In addition, the influence of maritime and atmospheric limit conditions or environmental conditions on a structure's architecture and vessel manoeuvring must be determine to define what is known under normal operating conditions (Puertos del Estado (España), 2007). Although ships usually sail in waves, the manoeuvring performance in that environment may be significantly different from that in calm conditions (Seo and Kim, 2011). Maneouvering in the face of wind disturbances is quite complicated (Ohtsu et al., 1996).

5.1. Architecture constraints

The harbour basin is where a vessel needs to manoeuvre for the purpose of performing its job (navigation, staying and loading/unloading), and as a result, an adequate architecture of the maritime area is quite essential to ensure safe vessel manoeuvring. The entrance of a harbour is where vessels enter and exit the harbour, the fairway is the navigation channel in the harbour domain used by vessels, and finally the manoeuvring area is the area necessary to stop and turn vessels.

5.1.1. Entrance

Harbour entrances must be designed in a manner to maintain good wave conditions at the entrance site (Rusu and Guedes Soares, 2011), and the following factors must be taken into account:

1- The integration of harbour entrances into their infrastructure and floatation areas,
2- The traffic densities for navigation and the largest design vessels envisaged operating in the harbour,
3- Limiting as possible wave energy from entering the harbour, which will disturb the flotation area,
4- The influence of marine environment conditions, such as breaking waves and heavy cross currents, and
5- The littoral dynamics at the entrance and around the harbour infrastructures.

In addition, the harbour entrance approach fairways should be as straight as possible so that vessels do not need to alter course in such a critical zone (Puertos del Estado (España), 2007). It has also been found that the reflection of obliquely incident waves from a breakwater can increase wave agitation at the harbour entrance (Kim et al., 2011).

The position of the breakwater and its dimension should not have any negative impact on navigation in the harbour, a sufficient entrance width must be maintained (Elchahal et al., 2013; Xie and Zhang, 2010), and this width could be defined according to the type of harbour and the sizes of the vessels that generally pass through it under varying environmental conditions. To maintain safe navigation conditions, the spaces occupied by the vessel must have sufficient room within the physical spaces available at the site. An additional width must also be added to correct for the effect of any uncertainty factors (Lee et al., 2009; Puertos del Estado (España), 2007). An approach channel with double guard breakwaters is considered to be a common form of sea harbour entrance and is used to maintain safety during ship navigation (Xie and Zhang, 2010). Seabed type may impose additional constraints on the design of harbour navigation entrances. On sandy coastlines, jetties and breakwaters stabilize navigation channels and protect vessels from adverse wave action, and periodic dredging maintains channels at safe navigable depths (Hughes and Schwichtenberg, 1998).

5.1.2. Fairway and manoeuvring area

Designing a fairway is not remarkably dissimilar from designing an entrance to a harbour, and all of the aforementioned factors must be considered. The wave distribution along the channel depends on the orientation, side slope, width and depth of the fairway (Yu et al., 2000).

In addition, other parameters may require attention:

1- The number of fairways needed for safe navigation in the harbour,
2- The fairway's depth and cross geometric characteristics,
3- The fairway's slope stability,
4- To avoid S alignments, a fairway must be as straight as possible, and
5- To minimize the effects of crosscurrents, the fairway must be designed so that it follows the direction of the main currents.

The manoeuvring area also demands taking into account almost the same factors that depend on the vessels and traffic, without forgetting the space needed by the vessels to make turns and the influence of the bathymetry of the area (Puertos del Estado (España), 2007). The problem of swell reflections on sea walls must also be taken into account to insure safe shipping near seawalls and inside harbours (Lebey and Rivoalen, 2002; Liu and Li, 2011; Weng et al., 1996).

Maneouvering in offshore harbours has also been studied, where the safety of ships is considered in entering and departing the harbour and while anchoring in an offshore harbour during a storm (Sasa and Incecik, 2012).

5.2. Vessel dependent constraints

Typically, harbours are used by vessels of different types with very different dimensions and manoeuvrability characteristics. Harbours must be designed according to the vessels with the most demanding navigation and operational requirements.

The parameters primarily used to define a vessel are the Dead Weight Tones (DWT), which is the weight in metric tons for the maximum load that can be carried by the vessel, the vessel's Gross Tonnage (GT), which is the overall internal volume in metric units and the Gross Registered Tons (GRT), which is also the overall internal volume but is measured in Moorsom tons, which is equivalent to 100 cubic feet.

The means of propulsion, steering system, shape of the underwater hull, draught, trim, loading condition, shallow waters or restrictions of the mass of water in which a vessel moves could be considered to be the main factors that determine how a vessel behaves.

In addition, wind, current and wave effects must be considered. Wind must be considered in manoeuvres because a wind is almost always blowing. A heavy wind has a marked influence on the action of the rudder and the propellers when the vessel is going ahead and alters the turning laws when going astern.

The currents increase the resistance of vessels to advance or move. The effect of wind on the upper works and the effect of current on the underwater body are very similar, but the resulting force of the latter is much greater because the density of water is higher than that of air.

It is necessary to consider the effect of waves when a vessel manoeuvres. Swinging motions caused by the vessel's longitudinal and transverse axes due to waves must be considered. The most significant effect of those motions is increasing the additional draughts of the vessel and water depths necessary to safely navigate. According to the type, dimensions and loading conditions of a vessel, natural periods of pitching and rolling could be defined independently of the amplitudes. If either of those natural periods coincides with wave apparent period, resonance may occur. In that case, the swinging motion of the vessel will increase dramatically. It should be noted that the apparent period of the waves is different from the real one in the case of a vessel in motion; it is the time interval between two successive crests passing the same point of the vessel.

Moreover, the influence of the water flow created by vessel motion must be considered. If navigation occurs close to a shore or bank, the water flow around the hull loses its symmetry, and a disturbance in the distribution of the pressure will occur. This will lead to one of two phenomena; the vessel will drift in the direction of the shore or bank if a transverse suction occurs, or a yawing motion will separate the vessel's bow from the shore or bank if a moment on the vessel's vertical axis passes through its centre of gravity. Both effects will be greater for a vertical wall than an inclined slope.

Finally, a vessel may interact with other vessels. As they approach, the water pressure between them will try to separate their bows. They will tend to stay parallel when they are passing abeam (Puertos del Estado (España), 2007).

6. Discussion

Optimization is a combination of decision-making mathematics, statistics and computer science. This scientific method aims to maximize or minimize one or more objectives. In practice, optimization is often used to increase the profitability or reduce the cost in cases of mono-objective problems or to find a compromise between them in multiple objective cases.

It seeks an optimal solution or set of optimal compromises, known as Pareto optimal solutions, taking into account a set of constraints and variables inherent to the problem. In fact, optimal solutions based on mathematical models do not necessarily reflect reality, depending on the precision of those models. Therefore, good solutions based on good models that need to be reliable and robust must be identified to aid decision makers in their tasks.

The objective function represents one or several engineering demands. The constraints represent either an operational limitation, such as navigation zones, or a natural limitation, such as floatability. Violating the operational limitations is applicable but undesired; however, solutions that violate natural limitations are physically inapplicable.

The optimization problem is represented as

$$F(\boldsymbol{x}_\mathrm{i}) = Min\{f_1(\boldsymbol{x}_\mathrm{i}), f_2(\boldsymbol{x}_\mathrm{i}), \ldots, f_p(\boldsymbol{x}_\mathrm{i})\}$$
$$\text{s.t} \quad \begin{cases} C_j(\boldsymbol{x}_\mathrm{i}) = 0 \\ C_k(\boldsymbol{x}_\mathrm{i}) \leq 0, \end{cases}$$

where $\boldsymbol{x_i}$ is the vector of variables, the f_i are the objective functions to be minimized, and the C_j and the C_k are respectively the constraint equations and inequalities.

To obtain an optimal design of the port, the problem must be subjected to all aforementioned restrictions. Those considered as system design criteria must be taken as objective functions. However, functional restrictions must be treated as optimization problem constraints. Sometimes, we can eliminate one or more of those constraints according to case considerations. When more than one constraint becomes linearly dependent, as for the structure cost and length for a constant depth harbour, we can retain a single constraint and eliminate the others. In some cases, constraints might not have any influence; an example is the problem of sea surface icing, which does not exist in most harbours around the world. Many other constraints can be eliminated if their influences are considered negligible or lack importance for the designers.

A global problem must be suggested in the beginning of any new study, and an elimination process must be applied to determine the essential constraints to formulate the optimization problem. The final problem could be treated as a multilevel problem, when some sub-groups of constraints are taken together to find the optimal solution for them, before others, and are considered to be fixed parameters for the later ones. These groups must be independent or weakly dependent. Otherwise, the optimal solution of the global problem may be questioned.

These constraints may represent physical phenomena that demand physical models to simulate their influences. These models could be hydrodynamic. Non-hydrodynamic models may be complicated; for example, combined physical and biological models are sometimes used for simulating ecological influences. The other constraints must either have a continuous or discrete mathematical model or a predefined and limited number of values.

Some complex phenomena do not yet have physical models to simulate them. Those phenomena cannot be considered in optimization problems until appropriate models are developed for them.

The constraints taken into consideration in defining any optimization problem to determine harbour layout and the type of those constraints will affect the computational effort needed to find the optimal solution in a reasonable time. Computational limitations sometimes guide us to simplify the model, although some eliminated constraints are representative.

In this discussion, we will try to define an optimization problem that accounts for our capabilities regarding the mentioned limitations.

6.1. Objective function

Harbour design performance is measured by two means: structure costs and profits. By minimizing costs and maximizing profits, the optimal solution can be obtained.

6.1.1. Cost

Many studies have exclusively focused on minimizing the cost objective in harbour design problems (Castillo et al., 2006; Elchahal et al., 2009a, 2008a, 2006). This cost is a function of many parameters, including materials, construction process, dimensions of the structure, distance from the construction site to the shore and the depth of water there. It may also include the anticipated damage and economic loss due to failure of the structure (Piccoli, 2014). This function has been reduced to the volume of the structure when all of the other parameters are considered to be constants or do not affect the study (Elchahal et al., 2009a). The volume of the structure has been repeatedly reduced to the cross section when the width was held constant for all of the solutions (Diab et al., 2014). It may be represented by the length only when the water depth is constant.

However, the relation between these different parameters and the cost may sometimes be strongly nonlinear, which is why employing the structure cost as an optimization criterion will accommodate all of the others.

6.1.2. Wave disturbance

On the other hand, maximizing the economic revenues of the harbour demands that the attenuation of waves be maximized to extend the operational period. This in turn is interpreted by minimizing the transmission of wave height into the harbour:

$$C_t = \frac{max(H(x,y))}{H_i},$$

where C_t is the transmission coefficient, and H_i is the incident wave height.

The harbour disturbance is considered to be a constraint in a mono-objective optimization problem that minimizes the cost only, where a wave propagation model must be introduced. It has been expressed by the inequality that the wave height inside the harbour is limited by a predefined allowable wave height for a given incident wave (Elchahal et al., 2009a):

$$C(x_i) = max(H(x,y)) \leq a,$$

where H is the wave height at each point (x,y), and a is the predefined allowable wave height.

The choice of hydrodynamic model depends on the type of structure. For a fixed breakwater, a Berkhoff model could be used (Elchahal et al., 2013), whereas for a floating breakwater, a dynamic model of fluid–structure interactions is needed (Elchahal et al., 2009a).

A probabilistic approach may be used here to choose some extreme sea states that may occur during a period. The duration of a storm (Teisson, 1990) and frequency of appearance during the expected life time of the structure (Burcharth and Sørensen, 2006) could affect the selected wave height.

Other studies, as presented in Fig. 1, considered both the cost of the structure and the attenuation degree by emphasizing how they are correlated (Piccoli, 2014).

Based on the two mentioned objectives, the problem must be defined as a multi-objective problem, where the cost of the structure and the height of wave in the harbour will be minimized simultaneously. It is more convenient to define the

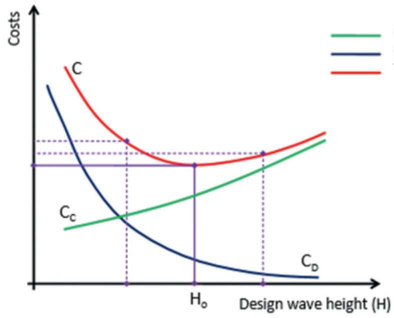

Fig. 1. The relation between different types of cost and design wave heights, as presented by Piccoli.

problem having multiple objectives because the obtained Pareto front includes the set of all solutions of the mono-objective problem when the wave height inside the harbour is predefined.

The cost and wave height inside the harbour depend on the positions and dimensions of the defence structures. Hence, the optimization variables are the coordinates of the breakwater nodes and its cross-sectional parameters.

6.2. Predefined parameters

Some criteria do not need to be involved in the optimization process; they could be determined before starting, according to many appropriate considerations.

6.2.1. Type of breakwater

The choice of breakwater type is based on many variables. The water depth at the construction site and the project budget are the main considerations. The power of the wave chosen to be resisted is also important when selecting a breakwater's type. The influences of the structure on the water quality inside the harbour and ecology play a role in preferring one type or another.

The breakwater may be a rubble mound breakwater, a vertical wall breakwater, a combination of the two, or a floating breakwater.

Vertical wall breakwaters, where the width is considered to be constant along the depth (Elchahal et al., 2013), are the simplest forms that have been studied. Taking the material resistance into account will allow a rubble mound breakwater that supports extreme wave power situations to be found.

Furthermore, because of the pollution problem and the high water depths at offshore sites and the need for flexible structures for non-fixed offshore harbours or structures push us to begin employing floating breakwaters. The use of floating breakwaters may be limited to their capacity for attenuating wave power. It is useless when the incident wave that should be absorbed is very high. This implies an asymptote that limits the benefits of using floating breakwaters.

6.2.2. Navigation safety

Navigational safety must be maintained at all times in harbours, regardless of the best breakwater solution. According to ship types, sizes, drafts, types of cargo transferred and manoeuvring capabilities, the domain of possible solutions will be fixed to respect all of the navigational constraints.

6.3. Optimization constraints

The constraints of the optimization problem may be defined as inequalities. They may also be defined before starting the optimization when determining the domain. We can distinguish two categories of constraints: mandatory and optional. Any harbour design problem must take into account the mandatory constraints, whereas a consideration of optional constraints depends on the nature of the problem.

6.3.1. Mandatory constraints

Mandatory constraints are ubiquitous constraints in every harbour structure design optimization problem. They are the responsible for maintaining the minimum acceptable degree of functionality under safe conditions.

6.3.1.1. Geometrical constraint. The results of the navigational constraints determine the domain of possible solutions, in which an optimization algorithm will be used to find the best breakwater definition. This constraint does not form a constraint equation; it is completely within the definition of the domain. Fig. 2 shows how safe navigational channels are maintained by defining the solution domain (Elchahal et al., 2013).

6.3.1.2. Mechanical resistance. The mechanical resistance of the structure will aid in determining the dimensions of the required structure; it will be responsible for specifying the breakwater shape and width to resist wave static and dynamic pressures. It is an inequality that links the material strength to the stress applied on the structure. It is also responsible for material selection (Elchahal et al., 2006):

$$C(x) = (\sigma_1 - \sigma_2)^2 - (\sigma_t + \sigma_c)(\sigma_1 + \sigma_2) - \sigma_t \sigma_c \leq 0,$$

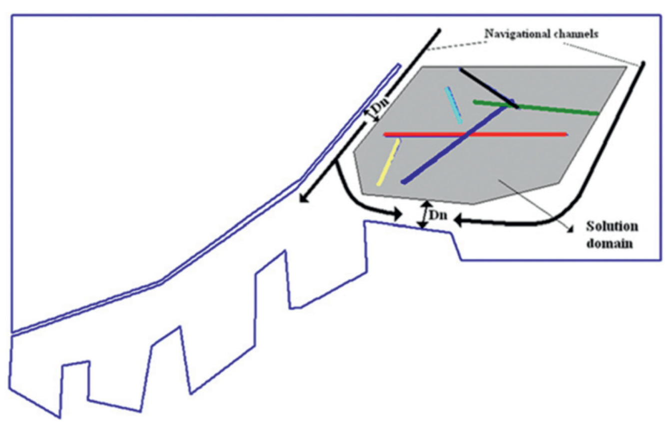

Fig. 2. The geometrical constraint.

where σ are the mechanical stresses.

6.3.1.3. Floatability. For the floating breakwater type, floatability is considered to be a mandatory constraint. As a natural limitation, any design that does not have proper dimensions that are verifiable under this constraint is physically inapplicable. This constraint could be presented as inequalities by applying the Archimedes principle (Elchahal et al., 2009a):

$$C(x) = -\rho_m V_m + \rho V_T \leq 0,$$

where ρ and ρ_m are the densities of sea water and the construction material, respectively, and V_m and V_T are the volumes of the material and displaced water, respectively.

6.3.2. Optional constraints

The optional constraints are all of the other mentioned constraints. The overtopping problem may be studied but requires a new numerical model to be solved. It helps determines the portion of a breakwater above sea water level. Sedimentation is an important phenomenon that occurs in harbours and near shorelines in general and therefore also could be added. The sedimentation problem may threaten navigational safety because of the accumulation of sediments in ship fairways, which require excavation. The sedimentation constraint involves the use of transport models.

Water quality inside harbours is another constraint that could be introduced with a corresponding proper numerical model. The presence of new structures disturbs the motions of currents, which prevents harbour water from being sufficiently cycled to prevent the concentration of pollution inside harbours.

The ecology and its vulnerability due to new structures may also be studied, but here a more complex numerical model is needed that combines hydrodynamics with organisms. The problem becomes a multidisciplinary one.

Finally it is good to observe that are no ultimate solutions, the result of the optimization process must be tested, and it is possible that the study must be repeated after some predefined criteria are changed, including breakwater type, number of pieces, functional period and attenuating ratio, until a satisfied solution is obtained.

7. Conclusions

Coastal areas have played a significant role in human progress, and humans have long tried to benefit from coasts by constructing harbours for different uses. Harbours are defined as places where ships load and unload cargo or shelter from storms. At present, any system design is an optimization process. As a consequence, the design of harbours must be an optimization problem.

The constraints used in coastal engineering problems have been summarized into four main categories. The first is environmental constraints, and the water quality, water level and biota are considered to be the main issues. The second is fluid mechanical constraints; waves are considered to be the main if not the most important constraint. They have many different consequences, as wave pressure, overtopping, and sediment transport, as well as modelling the propagation of sea waves, are major considerations in coastal engineering. The flooding, erosion water depth and current are also cited in this category. Within the third category are structural constraints, of which cost, materials and construction process were presented under the economic section and mechanical stresses, locations, dimensions and the effect of the seismic response of the structures were studied as mechanical constraints. The final category is manoeuvring constraints, of which the architecture of the harbour and the vessel dependant constraints were presented.

For the optimization problem, which is a multi-objective problem, the objective functions that represent engineering demands are the cost of the structure and the wave disturbance inside the harbour. There are predefined parameters, including the type of breakwater and navigation safety considerations.

The constraints represent either operational or natural limitations.

There are two categories of optimization constraints in harbour design: mandatory and optional. The mandatory constraints are geometrical constraints, mechanical stress, and the floatability of the structure in the case of floating breakwaters. The optional constraints may be from the modelled ocean phenomena. They usually demand the use of additional numerical models that must be solved, which results in computational issues.

Finally, ultimate solutions cannot be obtained, the results of the optimization process must be tested, and it is possible that a study will be repeated after some predefined criteria, such as the breakwater type or number of pieces, are changed, until a satisfactory solution is obtained.

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