Third International Engineering Systems Symposium
CESUN 2012, Delft University of Technology, 18-20 June 2012
Special Session on Sustainable Ports and Waterways

Open water ports -
a sustainable design approach

M.P.C. de Jong[1], O.M. Weiler[1], and J. Schouten[1]

[1]Deltares, Harbour, Coastal and Offshore engineering department,
PO Box 177, 2600 MH, Delft, The Netherlands

martijn.dejong@deltares.nl, otto.weiler@deltares.nl, janjoost.schouten@deltares.nl

Abstract. *In this paper we put forward a port layout design approach based on an exposed terminal. In view of increasingly bigger ships that respond less to environmental conditions this approach departs from traditional ideas on wave sheltering. The paper discusses associated advantages and disadvantages. For the disadvantages we present possible directions in which we foresee that solutions could be found to overcome those (technical) limitations. The concept of an open water port could be used to minimise impacts on coastal and environmental processes. When it becomes more commonly accepted in the shipping industry, and after overcoming remaining technical issues, this alternative design approach is expected to form a more sustainable alternative to traditional port layout design approaches.*

Keywords. *port layout design, wave sheltering, breakwaters, innovative mooring techniques, innovative container cranes, minimising coastal impacts, sustainability*

1 Introduction

Traditionally, ports are designed using large and costly structures, e.g. rubble mound or caisson breakwaters, to provide shelter from ambient wave and current conditions. However, with ships getting bigger and bigger one can ask the question how much protection is still required. Should we invest heavily in protective measures, or can we mitigate the motion response of vessels via new technical means of mooring and cargo transfer, or could we accept higher downtimes?

In this paper we propose an alternative port design approach that departs from the traditional ideas on sheltering and starts off with a (more) open port situation, located close to shore. Similar concepts have been suggested a number of times in the past, e.g. by Bruun (1981, 1990, 1992), Burdall and Williamson (1991), and Tsinker (2004). Bruun (1992) states for example: "*It is obvious that it may sometimes be difficult to justify the cost of… breakwaters and that it therefore may be necessary to find a less expensive alternative to reduce their length to a minimum. This raises the question as to whether in specific cases it will be possible to avoid the use of breakwaters altogether, in favour of an unprotected berth, and thus to construct only a pier.*". However, these suggested concepts were not seen as a standard approach and since then they have mainly been applied for tanker terminals. Furthermore, they were mainly driven by economics and not by sustainability motivations.

Focus of this paper will be on open water ports for container terminals, which is an uncommon concept, since such terminals involve the most stringent criteria on wave and current conditions. For certain other types of cargo the open water port principle is much more common. For decades the oil industry is using open water facilities for liquid cargo. Ongoing developments in that field include the Joint Industry Project HawaII (sHAllow WAter InItiative), which focuses on mooring LNG vessels in relatively exposed conditions in shallow water and the effect of low-frequency (infragravity) waves in particular (De Jong *et al.*, 2009). Bruun (1990, 1992) refers to the classic example of the Port of Hadera in Israel, where coal for a power plant is delivered to shore from an open water mooring location (Fig. 1). Examples of present open port developments and plans, e.g. bulk terminals in Australia, indicate that the concept of an open port has since then remained limited to these specific cargo types.

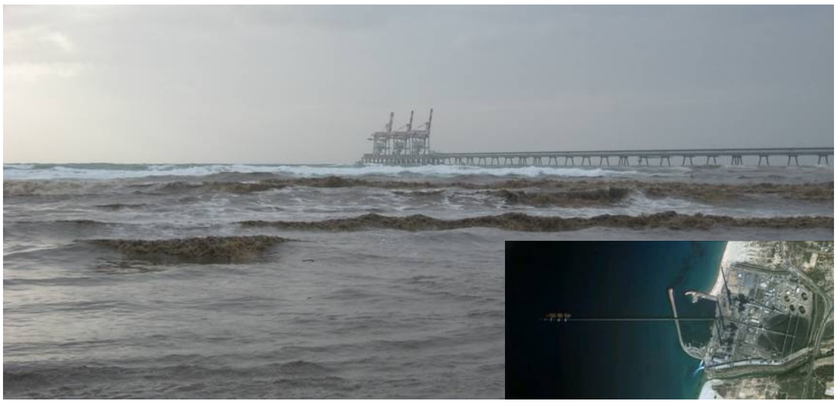

Fig. 1: Open water terminal at Hadera, Israel.

The development of Yangshan, Shanghai’s deep-water container port, can be considered an exceptional situation in which a fairly open container terminal was constructed by connecting several islands in the form of a land reclamation about 30 km off the main coast. However, at that location nearby islands shelter the berths from incoming waves. A recent example of a plan to construct an offshore container terminal in open water is near Venice, Italy (Fig. 2), but this scheme still includes large breakwaters to provide shelter from waves. In all, it can be concluded that so far the open port concept, particularly for container terminals, has not really caught on.

Since the time that more open ports were first suggested (early eighties) the trend of increasing container vessel sizes has continued (from 250-300 m, 4000 TEU, to around 400 m length, 15000 TEU). Furthermore, significant developments have been made in innovative types of mooring equipment. Moreover, a clear trend in the last decades is the increased interest in sustainability and the increasingly common requirement for ports to become more ‘green’. In our view, these elements justify a renewed consideration of the unsheltered port concept, within a broader frame of reference, combining the benefits of an open port as identified earlier in literature with the increased attention to sustainability of port developments.

In this paper we put forward the approach of an open nearshore container port for further discussion and consideration. The approach will be presented including both the associated benefits, mainly focussing on sustainability, as well as the associated disadvantages, including the several technical challenges that still need to be overcome to ensure that an unsheltered port becomes a realistic design alternative on a regular basis. For the disadvantages we present possible directions in which we foresee that solutions could be found to overcome those limitations.

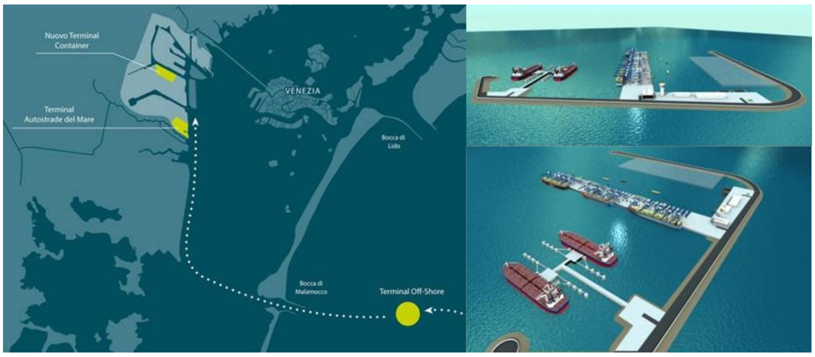

Fig. 2: Terminal plans of the Port of Venice (source: www.port.venice.it).

When the suggested approach proves to be feasible, then that would mean that new (nearshore) port designs will become less invasive, with reduced impacts on the surrounding (coastal) areas. Furthermore, such an open port situation could be designed such that less sedimentation occurs compared to more confined port layouts, which could lead to a reduction in dredging efforts (and associated fuel usage and plume dispersion) and less issues of accumulating pollutants. These types of advantages indicate that the alternative port design considered in this paper could form a more sustainable option compared to traditional port design approaches.

2 Rationale Behind The Open Water Port Concept

Historically, ports started inside naturally sheltered locations along rivers or inside bays and estuaries. With increasing vessel sizes, ports moved towards deeper water along the coast. Often such locations did not provide sufficient shelter from waves and breakwaters were erected to provide calm conditions artificially. Several recent port extensions/developments go a step further and involve large land reclamations that protrude into sea, in which the basins are surrounded by the newly reclaimed land. This ensures that the required depths can be provided at reasonable costs and efforts. Furthermore, the reclaimed land facilitates the quay-side operations very efficiently. Examples are the port developments in Dubai, such as Port Jebel Ali (Padron *et al.*, 2007), and the large Maasvlakte 2 harbour extension of the Port of Rotterdam (see e.g. Clijncke, 2010). In those cases sheltering is provided by breakwaters and/or the (closed) outer contour of the surrounding land area.

At other locations in the world developments on such a large scale might not be feasible because of technical, ecological, and/or economical reasons. In search of even larger depths for increasingly larger (container) vessels, with lengths in the order of 400 m, a logical next step would be to move out to open sea and develop berthing facilities there.

An open nearshore container terminal could be a basic detached reclamation behind which vessels are moored. Because of their large dimensions, it will be possible to (off)load container vessels in quite severe wave conditions, also without providing sheltering via additional large (breakwater) structures. The less confined geometry compared to traditional designs of port basins might even help reducing the seiching response of basins, particularly when low-frequency (infragravity) waves are present, which are well known for causing excessive motions of moored vessels (see e.g. Van der Molen *et al.* 2004, De Bont *et al.*, 2010).

The reclamation can be aligned with the dominant physical coastal processes as much as possible, including tidal currents and sediment transports. This will ensure that alongshore morphological processes are impacted as little as possible. Furthermore, the open port layout could be designed such that sedimentation can be kept to a minimum, possibly even up to the point where the tidal conditions ensure that settling sediments during slack tide are flushed out of the manoeuvring areas during other tidal stages. Also the influence on ecology could be minimised in this way, because the natural migration paths of sea animals are hindered as little as possible.

An open water port could require less building efforts than a traditional port design, although it will involve constructing a connection to shore. Such a connection could be a train bridge connection, or a road deck on piles. Although of high relevance for the general feasibility of port planning, the potential economic benefit of an open water port is not the main topic of the present paper. Here we mainly discuss technical aspects of the open nearshore port design, limitations and benefits, the latter with a focus on sustainability aspects.

In order to have a sustainable development of a port, a port design should include a direction of growth which is aimed at meeting the present requirements while at the same time preserving the environment so that these needs can be met not only in the present, but also for future generations. This implies that future developments, although difficult to foresee, should also be considered in the initial port master plan as much as possible. An additional benefit of the nearshore open port design is that fewer complications are foreseen in terms of future port extension compared to the traditional port located inland. Although marine spatial planning is an issue, more directions of freedom for port expansion are available offshore, automatically resulting in less conflicting functions. This makes the open port design more ‘future proof’, allowing flexible adaptations to future developments.

3 Limitations and Mitigation

3.1 Identification of Most Critical Limitations

It is realistic to note that a number of technical challenges still needs to be overcome in order for the open nearshore port to become a common and equivalent alternative to the traditional way of port designing. The main challenge for a design approach based on an open water port will be to keep the downtime of a container terminal at an acceptable level, i.e. comparable to terminals in traditional, sheltered ports. This can be achieved via different means, either by limiting the response of the vessel to waves or by adapting container cranes to deal with increased motions of the vessel.

3.2 Mitigation via Reduction of Vessel Motion Response

Recently, PIANC Working Group 52 finished their work on updating guidelines for maximum allowable motions of moored container vessels for efficient (off)loading (PIANC, publication expected in the course of 2012). They conclude that for large container vessels the requirements for surge motions are critical because present-day container cranes cannot follow that motion efficiently. The working group report states that when surge motions are kept within prescribed limits, movements in other degrees of freedom are expected to be within acceptable limits as well.

In recent years innovative mooring systems have been developed that show potential to be very efficient at keeping vessels constrained at the berth, particularly for surge motions. A method where magnets are used to hold the ship at the quay has been developed at Delft University of Technology by Fiktorie (Fiktorie, 2002). Another new mooring technique is the Moormaster$^{\mathrm{TM}}$ unit, which uses vacuum pads to keep the vessel at the berth. Evaluations of the performance of such units showed that ship (surge) motions for a given sea state can be reduced significantly using such techniques (see e.g. De Bont *et al*., 2010). A third system has recently been developed by the Boatmen Association in the Port of Rotterdam. This technique is called Shoretension (see http://www.shoretension.com/). It consists of units positioned on the quay (Fig. 3) that ensure that the proper line tensions are maintained, leading to reduced motions of the vessel moored along a quay.

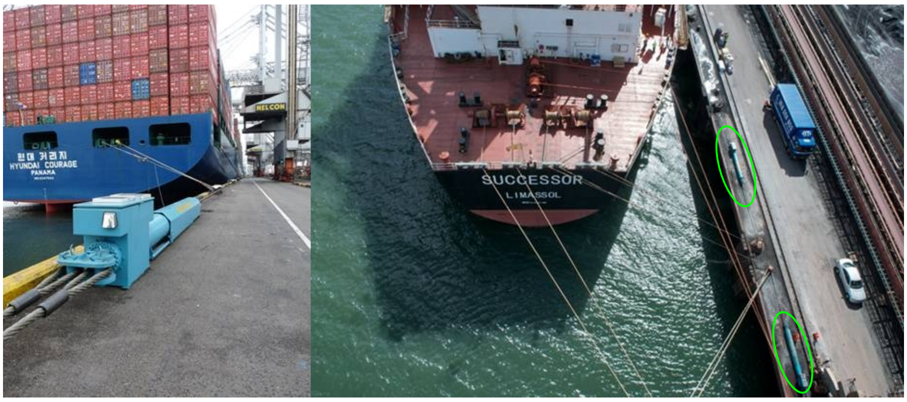

Fig. 3: Example of a recent development in mooring techniques: the Shoretension system (source: www.shoretension.com).

Although each of these systems has its own benefits and limitations, these ongoing developments indicate that on the response side of the vessel there is much to gain in efficiency compared to traditional mooring techniques, even more so than was the case when Bruun (1981) first suggested the option of an open, exposed port. The increased capability of reducing the vessel response is expected to be exchangeable for a lower level of sheltering provided by an open port, even for container vessels.

3.3 Mitigation via Increased Container Crane Capabilities

The criteria reported by PIANC (2012) have been developed based on the present state of technical developments. Nowadays, gantry crane spreaders may have the capability to compensate for vessel surge motions to some level, but in practice these are not always used to their full extent. This can be related to either the level of experience of a crane operator, to the complexity of the methods, or to the time it takes to apply these methods compared to just wait for the next window of opportunity to place the container on the ship. On the other hand, ongoing innovations by container crane designers and builders are expected to lead to smarter cranes with practical surge compensation capabilities in the future. A very interesting innovation in this field is the recent development by the Office of Naval Research (ONR) of the Large Vessel Interface Lift On/Lift Off (LVI Lo/Lo) Crane (Fig. 4) for ship-to-ship container transfer at sea (Quadvlieg *et al.*, 2011). This development shows that using information on vessel motions, and enabling the crane to compensate for those motions, will greatly enhance container crane capabilities.

Fig. 4: The Large Vessel Interface Lift On/Lift Off (LVI Lo/Lo) Crane for ship-to-ship container transfer at sea (source: ONR, USA).

The LVI Lo/Lo system has been developed for ship-to-ship cargo transfer operations in up to Bft 4 sea states. Vessel motions inside a port will be much smaller. Therefore port container cranes will probably not require the same level of complexity (and costs). Nevertheless, the operational reliability of such a system in a high throughput situation inside a port will require ample attention. Overall, it is expected that even when only specific elements of elaborate crane innovations are adopted for container gantry cranes that the capabilities of those cranes will already be greatly enhanced, further contributing to the feasibility of an open nearshore port design.

4 Benefits, with Focus on Sustainability

4.1 Coastal (Morphology) Processes in a Traditional Port Design

The main sustainability benefit of an open port design will be the smaller impact on coastal (morphology) processes. In this section first those processes are considered for a traditional port design including breakwaters, before discussing the advantages that the open port design could provide (Section 4.2).

No severe erosion or sedimentation will occur as long as a coastal system is stable. In case of sandy coastlines, wave and current conditions generate longshore sediment transport along the coast. The magnitude of this transport spatially differs in cross-shore direction, which is determined by the local hydrodynamic conditions. In general these hydrodynamic conditions are dominated by the nearshore wave climate. The magnitude of the longshore transport has its maximum in the surf zone, i.e. the area between the breaker line and the coastline, and reduces further offshore (Fig. 5). The sediment transport will be proportional to the current velocity.

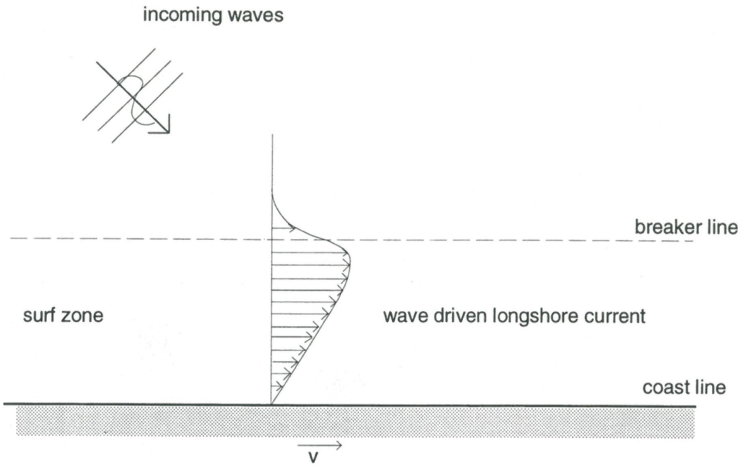

Fig. 5: Wave driven longshore current, most dominant in the surf zone.

The longshore sediment transport will be blocked when reclamations and/or breakwaters are constructed and therefore this can significantly affect the coastal stability. This will result in accretion at the updrift side of the port and in erosion at the lee side of those structures.

The process of accretion will move the coastline, actually the whole cross-shore profile, in offshore direction until sediment is no longer completely trapped by the updrift breakwater. From that moment on a part of the longshore sediment will move around the tip of the breakwater and enter the navigation channel and port basins. Depending on the local hydrodynamics and bearing capacity of the port basins and navigation channel, the sediment can become trapped inside the port. The examples of these types of coastal problems are numerous. A classical example is the Port of IJmuiden, The Netherlands, see Fig. 6. When reaching this point in coastal development, the nautical depth of the navigational channel can no longer be guaranteed as well as the depth of the port basins. Maintenance dredging costs may increase significantly. Not only maintaining the nautical depth is a problem, in terms of costs, energy or hindrance to navigation activities, also the dredged material itself can form an issue. The dredged material could be contaminated and require special storage or specific cleaning methods.

Fig. 6: Port of IJmuiden, sediment transport is directed in northern direction (i.e. towards the top left of the image). Accretion occurs at the south side of the breakwaters (source: RWS).

Erosion will occur at the downdrift side. An example is the coastal impact of the Port of Carrara, Italy, which is shown in Fig. 7. In response to the construction of the port, the coastal area southeast of the port started to show erosion. A series of coastal protection schemes were constructed in order to maintain the initial coastline position. Most often, hard coastal structures, here a combination of groins and detached breakwaters, are designed to maintain the position of the coastline. However, this automatically results in a shift of erosion further downdrift. The extent of this shift is limited only by locations where the natural local longshore sediment transport is reduced to zero or alters its direction. This example shows that the extent of the coastal impacts of a traditional port design can easily be a number of times larger than the horizontal dimensions of the port itself, as is visible in Fig. 7.

A possible solution to overcome the negative effect of blocking longshore sediment transport due to a port is to apply a sand bypass system. Such a system involves the installation of pumping stations at the updrift side of the port breakwaters, where the accretion occurs. The pumped sand is placed at the downdrift side of the port. Such a system aims at preventing sediment from being transported towards the entrance channel and the port basins and additionally, erosion is prevented at the downdrift side of the port. In order to be efficient, the pumps will have to be operational on a daily basis, like at the Nerang River entrance in Queensland, Australia, where the sand bypassing system is operational since 1986. Operating such a system will have a number of drawbacks. The first issue is the environmental impact of bringing sediment into suspension at the disposal area. Secondly, a large amount of energy is required for the pump systems on a daily basis.

Fig. 7: Port of Carrara, Italy (source: Google Earth). Sediment transport is directed in south-eastern direction. Sand accumulation occurs at the north-western side of the port. The groins on the eastern, downdrift side of the port indicate the area with erosion problems.

Another option is to regularly apply coastal sand nourishments in eroding areas. A drawback of such an approach is that it can have an adverse effect on the marine environment and particularly on the benthic communities (bottom-dwelling sea life). Dredging is widely considered as an activity that is stressful to the environment and many studies have described its impacts (see e.g. Van Dalfsen and Essink, 2001). In some countries this has resulted in policies that restrict dredging operations. As there is a strong relation between the local sea bed characteristics and the associated faunal community, changes in the geomorphological structure and hydrodynamic conditions due to dredging and nourishment activities are expected to result over time and in space in adaptations in the faunal composition. A result could be the alteration of the marine species diversity and productivity of an area, also of commercial fish species.

It is obvious that none of the presented mitigating measures for coastal stability result in a truly sustainable strategy and this speaks for considering alternative port designs.

4.2 Coastal (Morphology) Processes in an Open Port Approach

Following the understanding that the longshore sediment transport is most significant in the nearshore zone, the location of the open port design further offshore in open and deeper waters avoids blocking the longshore sediment transport and therefore reduces accretion and erosion issues. This is if the open port is connected to the mainland with an ‘open’ structure, like a jetty. In this way the longshore currents and the related longshore sediment transport remain largely undisturbed. To achieve such a situation, the distance from the shore would typically need to be at least several hundreds of meters, depending on the average wave and tidal conditions.

The construction of port infrastructure will to some extent influence the local wave conditions. This means that also in an open port design approach the coastline will be influenced. This might result in e.g. the initial stages of salient formation. Nevertheless, the coastal impact of an open port design is expected to be minor compared to the accretion and erosion that could be caused by port breakwaters.

In addition to coastal impacts, sedimentation of the harbour basins can be a major concern when considering maintenance costs as well as environmental impacts. The dredged material will have to be disposed at an appropriate dump location. This is either offshore, or in case of contaminated sediment, it will have to be deposited in special confined disposal facility. The advantage of the proposed open port design is that the use of relative large water depths offshore and the local current conditions could result in much less or possibly no dredging activities of the port basins. This not only limits the dredging during the construction phase but also for the following operational (maintenance) phase of the port basins.

5 Discussion and Outlook

Most of the separate elements and viewpoints presented in this paper are not new on their own. However, social developments like increased focus on sustainability combined with technical innovations in the last decade, e.g. on advanced mooring techniques, mean that the combination of these elements merits renewed consideration within a larger framework. Therefore the open-water port concept is presented here as a starting point for further discussion. Particularly the benefits on sustainability and minimisation of (coastal) impacts should form important incentives to elaborate on the option of open port layouts for future port developments.

We suggest to alter the design approach that is most commonly applied nowadays. Instead of a-priori assuming that a fully tranquil basin is required and designing a port to match that criterion, we propose to start with reviewing the level of shelter that is required and continue from there. This requires that all parties involved should come together early in the design, including future terminal managers/users, to set up an overall port layout plan that is a balance between providing wave sheltering and measures to limit or mitigate the response of a vessel. Only in that way the benefits of an open nearshore port design can be used to its fullest potential.

The same applies for the coastal impacts of a scheme, which are often studied when the port design is almost fully completed and the resulting coastal impacts are seen as given, almost unavoidable, side effects. By first studying the local coastal system, including morphological processes, the port design can be made such that it takes those processes into account from the start and could even make use of them.

Although not the focus of the present paper, it is relevant to mention that developing the open port concept for container terminals is expected to also involve adapting the business cases for such terminals. This will include the (re)distribution of costs, e.g. will the port bear the investment costs of the advanced mooring facilities and/or can the lower construction costs of the port geometry result in lower lease fees for terminal operators? Only in that way ports based on an alternative design approach can compete with ports with traditional mooring facilities.

In the end we expect that full acceptance of an open port approach will take a number of successful pilot projects by port developers that see the long term benefits of this alternative design approach and are willing and able to take up this challenge.

References

Bruun, P. (1981), Breakwater or mooring system?, *The Dock and Harbour Authority*, Vol XLII, No. 730, September 1981, pp. 126-129.

Bruun, P. (1990), *Port engineering*, 4th ed. Gulf Publishing Company, Houston.

Bruun, P. (1992), Marine terminal technology, in *Handbook of coastal and ocean engineering, Volume 3 – Harbors, navigational channels, estuaries, environmental effects*, J.B. Herbich Edt., Gulf Publishing Company, Houston.

Burdall A.C. and H.J. Williamson (1991), A green port: an engineer's view, *Ports into the next century*, proceedings of the conference UK ports 2000, Hull, 17-18 October 1990.

Clijncke, A., Maasvlakte 2: development of the masterplan, paper no. 107, *PIANC MMX Congress*, Liverpool UK, May 2010.

De Bont, J., W. van der Molen, J. van der Lem, H. Ligteringen, D. Mühlestein and M. Howie (2010), Calculations of the motions of a ship moored with Moormaster™ units, paper no. 82, *PIANC MMX Congress*, Liverpool UK, May 2010.

De Jong, M.P.C., M.J.A. Borsboom, and J. Dekker (2009), Calculation of low-frequency waves in shallow water and comparison to common practice in diffraction methods, *ASME 28th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE2009-79401, 31 May – 05 June, 2009, Honolulu, Hawaii, USA.

Fiktorie, E.H.G. (2002), *(off)loading without mooring lines* (in Dutch, originally: Laden & lossen zonder trossen), MSc. Thesis, Delft University and Ingenieursbureau Gemeentewerken Rotterdam.

Padron, D.V., J. Itriago, and A. Al Abbar (2007), Master Plan for Expansion of Jebel Ali Port, *Ports 2007: 30 Years of Sharing Ideas…1977–2007*, Proceedings of the Eleventh Triennial International Conference, ASCE Conf. Proc. doi:10.1061/40834(238)6.

PIANC (2012), *Criteria for the (Un)loading of Container Vessels*, report of MarCom Working Group 52, submitted for publication, expected in the course of 2012.

Quadvlieg, F.H.H.A., R. Hallmann, G. Hughes, D.H. Harris (2011), Using dynamic positioning for side-by-side cargo transfer operations, *2nd International Conference on Ship Manoeuvring in Shallow and Confined Water: Ship to Ship Interaction*, Trontheim, 2011

Tsinker, G.P. (2004), *Port engineering: planning, construction, maintenance, and security*, John Wiley & Sons, Hoboken, New Jersey, United States.

Van der Molen, W., P. Monárdez Santander, and A.R. van Dongeren (2004), Modeling of infragravity waves and moored ship motions in Tomakomai Port, *Harbor Long Wave Conference 2004*, Yokosuka, Japan.

Van Dalfsen, J.A., and K. Essink (2001). Benthic Community Response to Sand Dredging and Shoreface Nourishment in Dutch Coastal Waters. *Senckenbergiana maritime* 31 (2), pp. 329-332.