# CHAPTER 246

## MOVEMENTS OF MOORED SHIPS IN HARBOURS

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## ABSTRACT

The paper discusses criteria for safe working and safe mooring conditions for various types of seagoing vessels. These criteria are based on acceptable movements for moored ships in harbours and have been established by a working group under the Permanent International Association of Navigation Congresses (PIANC).

## INTRODUCTION

Modern maritime transport requires minimum time for loading and unloading in ports and at maritime terminals, a requirement often restricted by ship movements at quays. If the ship movements experienced are too large, cargo handling operations will slow down or even cease and ultimately damage to the ship and port installations may occur. In recent years changes in cargo handling methods have resulted in changes of both ship and port installations, changes which may have large economic consequences. Requirements for fast cargo handling operations without delays due to ship motions are increasing.

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The Permanent International Association of Navigation Congresses (PIANC) therefore commissioned a special Working Group to study the movements of moored ships in harbours with the aim to establish new criteria for acceptable ship motions in safe working conditions (i.e. when cargo handling operations have to be reduced or even ceased), as well as for safe mooring conditions (i.e. when ships have to leave the berths). Further, it was the aim to assess measures for improving safe working and safe mooring conditions. The main objective in establishing criteria was to provide guidelines for port designers and port operators to minimize downtime for ships in harbours.

The Working Group comprised 14 international members (see Appendix A) and commenced in June 1990. The final report will be published by PIANC in spring 1993. This paper summarises the main findings and conclusions of the Working Group.

## METHODOLOGY

The world fleet of ships is divided into the following categories, each category having its own typical characteristics in view of ship motions and cargo handling operations and safe mooring conditions:

- Small craft and pleasure boats.
- Fishing vessels.
- Freighters and coasters.
- Ferries and RO-RO vessels.
- General cargo vessels.
- Container vessels.
- Bulk carriers.
- Oil tankers.
- Gas tankers

For each category the following aspects have been assessed by the Working Group:

i. Description of the vessels, typical sizes, composition of world fleet, future trends and provisions for mooring outfits on board (positions of winches and fairleads, composition of mooring lines: number, type, diameter).

ii. Description of typical berths and cargo handling equipment (e.g. types of cranes, ramps, loading arms).

iii. Description of governing parameters for ship motions, cargo handling operations, efficiency and safety.

iv. Review and assessment of available literature, including recent test results and prototype measurements.

v. Recommendations for acceptable ship motions, mooring and fender line forces at berths in safe working and safe mooring conditions, taking into account a reduced efficiency in cargo handling in case of worsening weather.

vi. Recommendations for improvement of operation and efficiency with respect to berth location and orientation, application of operational criteria for wind and waves, implementation of dedicated berths and modification of mooring arrangements.

## SHIP MOVEMENTS

Movements of moored ships can be caused by various external influences such as: winds, currents, waves, seiches, tides, passing ships and cargo handling operations. The report of the Working Group addresses the effects of these parameters on the behaviour of a moored ship. One chapter in particular deals with the physics of ships moored in waves and discusses the use of mathematical and physical models in this respect.

The movements of a moored ship at a berth can be either horizontal (surge, sway and yaw) or vertical (roll, pitch and heave). Vertical ship motions are almost independent of the mooring system, but horizontal motions are typically dependent on the loading conditions of a ship, the mooring arrangements, i.e. geometry and stiffness of mooring lines and fenders, and the type of berth.

When ship movements are too large safe working limits and ultimately safe mooring limits are exceeded. This is illustrated in Figure 1 where the cargo handling efficiency is plotted against the ship motions. When ship motions are between A and B the cargo handling efficiency is 100%. Between B and C cargo handling rates are reduced due to increased ship motions. When the motions exceed level C cargo handling operations are stopped: the safe working limits are reached. Between C and D the vessel can still stay at the berth. Once ship motions exceed level D the vessel has to leave the berth in order to prevent damage to ship and/or quay: safe mooring limits are exceeded.

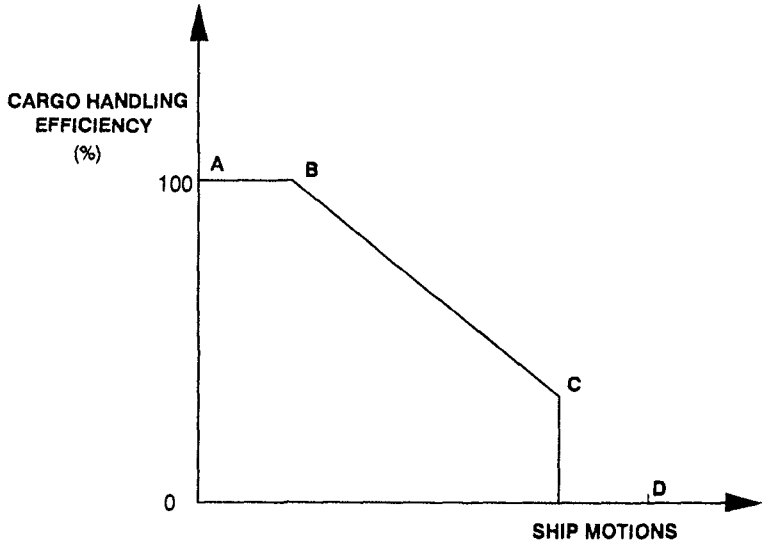


Figure 1. Relation Cargo Handling Efficiency and Ship Motions.

It should be noted that ship motion is one parameter affecting the efficiency of cargo handling operations. Other parameters are, amongst others, cargo handling equipment, skill of crane operators, and operational conditions such as wind, rain, ice, day- and nighttime (light conditions).

## MOORING ARRANGEMENTS

The mooring arrangements for ships moored at berths may comprise the following elements:

- Mooring lines connecting ships to berths
- Bollards and storm bitts on shore.
- Mooring hooks or quick release mooring hooks on mooring and breasting dolphins.
- Fenders between ship and berth.
- Mooring winches and bollards on board the ships.

The report of the Working Group contains a brief description of type and characteristics of mooring lines and fenders, mooring arrangement principles and operational considerations for mooring lines. Further, the report discusses the guidelines as issued by various classification societies concerning the number and type of mooring lines to be carried on board. It was felt that an update of these guidelines would be useful. Such new guidelines should reflect that a moored ship is a dynamic system having special requirements with respect to safe working as well as safe mooring conditions.

## SMALL CRAFT AND PLEASURE BOATS

Small craft and pleasure boats may be defined as boats with lengths up to 20m. Moored boats are particularly sensitive to short period waves coming from abeam or quartering directions. Their berths require a sheltered location to prevent damage to ships and quays as well as to increase the comfort of passengers on board. In designing harbours for pleasure boats and small craft due attention should be given to the effect of locally generated wind waves having short fetch lengths.

The Working Group has defined acceptable ship motion criteria in terms of wave height and period, because it was felt that these parameters would reflect sufficiently the comfortability criteria for these boats. The criteria are reported in Table 1 and correspond to an acceptable exceedance frequency of once to a few times per year.

## FISHING VESSELS

Fishing vessels range from small ships of 10-100 GRT up to large trawlers liners and net boats of 3,000 GRT. These vessels are mainly berthing in their home ports and the berths and mooring arrangements should meet the criteria for safe working as well as safe mooring conditions.

Fishing vessels are typically moored with polypropylene lines against truck tire fenders or rubber fenders. Cranes, elevators and suction pumps are used for unloading the fish. Acceptable ship motion criteria for safe working conditions are determined by sizes of hatches and the dimensions of boxes and tubs handled.

Table 1: Recommended wave criteria small craft and pleasure boats.

| Ship Length (m) | Beam/Quartering Seas | | Head Seas | |
|---|---|---|---|---|
| | Period (s) | Height $H_s$ (m) | Period (s) | Height $H_s$ (m) |
| 4 - 10 | < 2 | 0.20 | < 2.5 | 0.20 |
| | 2 - 4 | 0.10 | 2.5 - 4 | 0.15 |
| | > 4 | 0.15 | > 4 | 0.20 |
| 10 - 16 | < 3 | 0.25 | < 3.5 | 0.30 |
| | 3 - 5 | 0.15 | 3.5 - 5.5 | 0.20 |
| | > 5 | 0.20 | > 5.5 | 0.30 |
| 20 m | < 4 | 0.30 | < 4.5 | 0.30 |
| | 4 - 6 | 0.15 | 4.5 - 7.0 | 0.25 |
| | > 6 | 0.25 | > 7.0 | 0.30 |

An extensive research program was carried out by the Nordic countries to establish acceptable criteria of moored fishing vessels. Motions of moored ships were measured at a number of ports for various ships being unloaded by different gear. Acceptable motions were determined based on interviews with ship crews and port operators ( Jensen et al, 1990) and are shown in Table 2.

Requirements for safe mooring conditions for these home port fleets are rather high. In many cases there is no other alternative than to stay in the port once a storm has reached the site. The recommended criteria comprise ship motions as well as velocities and are presented in Table 3 for various ship sizes. Velocities and ship sizes represent the dynamic impact of a moored ship on a berth and are considered adequate parameters regarding safe mooring conditions.

Table 2. Recommended motion criteria[1] for safe working conditions.

| Ship Type | Cargo Handling Equipment | Surge (m) | Sway (m) | Heave (m) | Yaw (°) | Pitch (°) | Roll (°) |
|---|---|---|---|---|---|---|---|
| Fishing vessels | Elevator crane | 0.15 | 0.15 | | | | |
| | Lift-on-Lift-off | 1.0 | 1.0 | 0.4 | 3 | 3 | 3 |
| | Suction pump | 2.0 | 1.0 | | | | |
| Freighters, | Ship's gear | 1.0 | 1.2 | 0.6 | 1 | 1 | 2 |
| coasters | Quay Cranes | 1.0 | 1.2 | 0.8 | 2 | 1 | 3 |
| Ferries, RO-RO | Side ramp[2] | 0.6 | 0.6 | 0.6 | 1 | 1 | 2 |
| | Bow/stern ramp | 0.8 | 0.6 | 0.8 | 1 | 1 | 4 |
| | Linkspan | 0.4 | 0.6 | 0.8 | 3 | 2 | 4 |
| | Rail ramp | 0.1 | 0.1 | 0.4 | - | 1 | 1 |
| General cargo | -- | 2.0 | 1.5 | 1.0 | 3 | 2 | 5 |
| Container | 100% efficiency | 1.0 | 0.6 | 0.8 | 1 | 1 | 3 |
| vessels | 50% efficiency | 2.0 | 1.2 | 1.2 | 1.5 | 2 | 6 |
| Bulk carriers | Cranes | 2.0 | 1.0 | 1.0 | 2 | 2 | 6 |
| | Elevator/bucket-wheel | 1.0 | 0.5 | 1.0 | 2 | 2 | 2 |
| | Conveyor belt | 5.0 | 2.5 | | 3 | | |
| Oil tankers | Loading arms | 3.0[3] | 3.0 | | | | |
| Gas tankers | Loading arms | 2.0 | 2.0 | | 2 | 2 | 2 |

Remarks:
[1] Motions refer to peak-peak values (except for sway: zero - peak ).
[2] Ramps equipped with rollers.
[3] For exposed locations 5.0 m (regular loading arms allow large movements).

Table 3. Recommended velocity criteria[1] for safe mooring conditions.

| Ship size (DWT) | Surge (m/s) | Sway (m/s) | Heave (m/s) | Yaw (°/s) | Pitch (°/s) | Roll (°/s) |
|---|---|---|---|---|---|---|
| 1,000 | 0.6 | 0.6 | - | 2.0 | - | 2.0 |
| 2,000 | 0.4 | 0.4 | - | 1.5 | - | 1.5 |
| 8,000 | 0.3 | 0.3 | - | 1.0 | - | 1.0 |

[1] These criteria are applicable for fishing vessels, coasters, freighters, ferries and RO-RO vessels.

A unique system of berth and port classifications has been developed in Iceland, which is based on various exceedance frequencies for critical ship motions as presented in Table 2.

## COASTERS AND FREIGHTERS

Coasters and freighters are ships of less than 10,000 DWT sailing on short sea and domestic routes. These vessels are generally moored with polypropylene lines against rubber fenders.

Cargoes can be handled by quay cranes or ship's own gear. Safe working conditions are determined by hatch openings and cargo parcel sizes. The criteria recommended by the Working Group are based on the studies carried out by the Nordic countries as discussed earlier and are shown in Table 2.

## FERRIES AND RO-RO VESSELS

Vessel types considered comprise car and rail ferries, and RO-RO vessels. These vessels are characterised by loading and unloading operations taking place horizontally via ramps and walkways. Ramps may be shore ramps, bridge ramps (including link-spans) and ship ramps.

The main function of the mooring arrangements for these ships is to reduce the horizontal ship motions as much as possible, in particular at the position of the ramps or walkways. This can be achieved by tensioning the mooring lines, sometimes up to 40 tonnes.

Recommended criteria for allowable ship motions for safe working conditions are presented in Table 2. In addition, for movable rail ramps and for walkways, the vertical velocity is recommended not to exceed 0.2 m/s and the vertical accelerations should be less than 0.5 $m/s^2$.

The governing parameter for safe mooring conditions, defined as the limiting conditions for damage to ship and/or quay, is the kinetic energy, which is characterised by the ship size and velocities. The recommended velocity criteria are presented in Table 3.

## GENERAL CARGO VESSELS

General cargo vessels range typically from 5,000 to 10,000 DWT and may carry a wide variety of cargo. Ships are most often moored with polypropylene lines, while large vessels are equipped with nylon ropes and/or steel wires. Generally these vessels are moored with 8 to 10 lines.

The cargo is handled by ship's gear or quay cranes. Acceptable ship motions in safe working conditions are determined by the sizes of the hatches, sizes of boxes and units handled, and by the type of unloading gear. The criteria recommended by the Working Group are based on an extensive Japanese research program (Ueda, 1987; Ueda and Shiraishi, 1988). These criteria have been established based on interviews with port and ship operators in various ports along the Japanese coast. Numerical simulations were applied to correlate identified critical wind speeds and wave heights with acceptable ship motion limits. Provisional limits were then discussed with various operators and authorities to arrive at the final criteria for safe working conditions as presented in Table 2.

In situations where large general cargo ships are exposed to long period waves, it is recommended to use soft mooring systems, i.e. synthetic lines or steel wires with nylon tails and soft fenders. Smaller vessels should preferably be moored in protected port basins (inner harbour) to reduce wave influences on moored ships.

## CONTAINER VESSELS

The world fleet of container vessels has increased considerably during the last decades and comprises nowadays small feeders, second and third generation container vessels as well as Post Panamax vessels, which came into operation recently.

Container vessels are generally moored with steel spring lines, to reduce surge motions, and polypropylene mooring lines. All lines are connected to bollards positioned at the front side of the quay wall. Rails for container cranes extend along the whole quay and prevent the use of typical breasting lines.

Containers are handled by shore based gantry cranes and ship motions should be kept to a minimum to provide uninterrupted container handling conditions. Positioning and picking-up of containers for example are hampered and containers can become stuck in their guides in the case of strong roll motions. Maximum container handling rates are an essential requirement for these ships sailing on tight time schedules.

Two levels of safe-working criteria are established by the Working Group for this special category of ships. One level is representing an uninterrupted container handling at an efficiency rate of 90 to 100%, whereas the second level reflects a 50% handling efficiency rate (see Table 2). It should be noted that besides ship motions the skill of the container crane drivers plays an important role for the overall efficiency of handling containers in a port.

## DRY BULK CARRIERS

Dry bulk carriers have been developed to transport cargoes such as ore, coal, grain and fertilizer in bulk and mostly in large quantities. Some typical sizes for bulk carriers are the Handy size (30,000-40,000 DWT), Panamax size (70,000-80,000 DWT) and CAPE size (120,000-150,000 DWT).

Bulk carriers are mainly moored with 8 to 10 synthetic lines and 4 steel spring lines. Mooring lines are attached to bollards located at the front side of the quay walls for the same reasons as for the container vessels. Loading operations are generally carried out using conveyors and hoses (grains). For unloading operations cranes, bucket-wheel unloaders, elevators and suction devices are used. A special category of bulk carriers is nowadays the so-called self-unloading bulk carrier. Horizontal ship motions are mainly induced by low frequency waves (and winds). Vertical ship motions are mainly caused by first order wave effects.

Operational criteria for cargo handling are determined by the risk of cargo handling equipment hitting the hatches or ship's bottom. This is of particular importance for unloading operations. The safe working criteria for bulk carriers recommended by the Working Group are based on practical experiences of port and ship operators (Bruun 1987, Moes 1992), supported by numerical simulations (Ueda and Shiraishi 1988). These criteria are presented in Table 2. Safe mooring conditions are determined by acceptable mooring line and fender forces (BSRA 1969 and OCIMF 1978).

Cargo handling operations may be improved by the application of softer springs and by the use of shore based mooring equipment, particularly when moored ships are exposed to long period wave actions. Further, pretensioning of mooring lines will result in an increase of fender friction and will contribute in reducing surge motions. Particular attention should be paid to the resonance of long waves in harbours (seiches) when designing basins for dry bulk vessels.

## OIL TANKERS

Oil tankers are used to transport oil and oil products. Oil products are generally transported in tankers under 70,000 DWT, while crude oil is transported in high capacity tankers up to 420,000 DWT. Tankers are loaded and unloaded through the manifold located in the middle and close to the side of the ships. The manifold is connected to the pipelines onshore by loading arms and sometimes by flexible hoses.

A typical berth lay-out for an oil tanker is shown in Figure 2 and comprises breasting and mooring dolphins, and a loading platform. Tankers are moored with spring lines, breast lines and (optionally) head and stern lines. The mooring lines for large tankers are in general steel wires and steel wires with nylon tails. The OCIMF (OCIMF, 1978) has issued guidelines for jetties and mooring arrangements of oil tankers, as well as for the design and operation of loading arms (OCIMF, 1980).

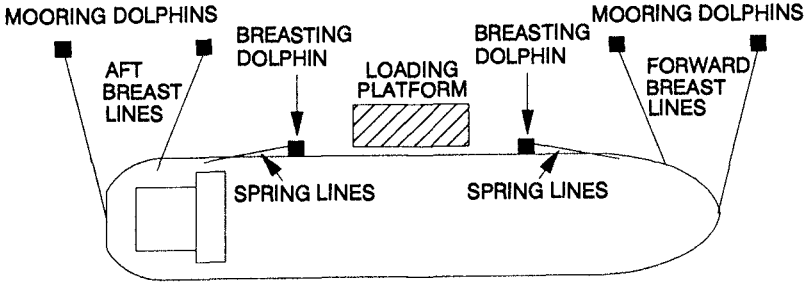


FIGURE 2. TYPICAL BERTH LAY-OUT FOR TANKERS

The motions of moored tankers are characterised by low frequency horizontal motions (with typical periods of 1 to 2 minutes) caused by long period wave effects, and relative high frequency vertical motions with periods ranging from 5 to 20 s.

Operational cargo handling criteria are determined by the allowable reach of the loading arms in the surge (longitudinal) and sway (transversal) direction. Other tanker motions are generally well within the design motion envelopes of the loading arms. The criteria recommended for safe working conditions are shown in Table 2.

Berths for large tankers are generally located in deep water and at more exposed locations. Due attention should be given to align a berth with predominant wave and current conditions. Tanker motions may be reduced by pretensioning the breast lines in order to maintain sufficient friction between the ship's hull and fenders.

## GAS TANKERS

Gas tankers may range from refrigerated ships of over 100,000 $m^3$ for the transportation of LNG and LPG to small tankers of up to 5,000 $m^3$ for the shipment of propane, butane and chemical gases in pressure tankers. The number of gastankers in the world fleet is relatively small; some 780 in 1991.

Berths for LNG and LPG tankers are generally designed for dedicated ships and trades, whereas berths of small gas tankers are multi- functional. The berths and mooring arrangements for gastankers are similar to the ones for oil tankers (Figure 2). Comprehensive guidelines for berths and gas tanker moorings are issued by OCIMF/SIGTTO (1985).

Motions of moored gastankers are in particular induced by currents and low frequency wind and wave effects. Wind effects on gastankers are more important compared to oil tankers because of higher freeboard and the presence of spherical tanks. Acceptable motions are determined by restrictions in the cargo handling systems (i.e. loading arms) and mooring line and fender forces (hull pressure). Recommended values for tanker motions are presented in Table 2.

Particularly for gas and oil tanker berths it is important to establish Operational Manuals including, amongst others, guidelines for mooring arrangements and safety operations as well as checklists to improve the safety of cargo handling operations.

## ACKNOWLEDGEMENTS

The authors are very grateful for the permission of the members of the Working Group "Movements of Moored Ships at Berths" as listed in Appendix A to prepare this paper. Without their work and enthusiasm the Working Group would not have completed its task and the data necessary for this paper would not have been collected.

## APPENDIX A. MEMBERS PIANC WORKING GROUP 24

## MOVEMENTS OF MOORED SHIPS AT BERTH

| Country | Name | Company |
|---|---|---|
| Belgium | H. Smits | Dienst Ontwikkeling Linker Scheldeoever, Antwerp |
| Denmark | O. J. Jensen (Chairman) | Danish Hydraulic Institute[1],Hørsholm |
| | J. M. Thompson | Comar Engineers A/S, Virum |
| Faroe Islands | S. Heinesen | Landsverkfrødingurin, Torshavn |
| France | P. Hébert | Port Autonome du Havre, Le Havre |
| Iceland | G. Viggósson | Icelandic Harbour Authority, Reykjavik |
| Italy | L. Bolatti Guzzo | Estramed S.P.A., Rome |
| Japan | S. Ueda | Port and Harbour Research Institute, Min. of Transport |
| The Netherlands | Th. Elzinga | Frederic R. Harris B.V., The Hague |
| | S.Th. Schuurmans | Delft Hydraulics, Delft |
| Norway | S. Bjørdal | Norsk Hydroteknisk Laboratorium, Trondheim |
| South Africa | H. Moes | Counsel for Scientific and Indus- trial Research (CSIR), Stellenbosch |
| Spain | J.R. Iribarren | Centro de Estudios y Experimentación de Obras Públicas (CEDEX), Madrid |
| United Kingdom | E. Bowers | Hydraulics Research, Wallingford |

[1] Danish Hydraulic Institute also provided the secretary Mr. M. Hebsgaard

## APPENDIX B. REFERENCES

Bruun P. (1987) Marine Terminal Technology, Winch Berthing and Mooring Methods, Recent Developments. Proceedings NATO Advanced Study Institute on Advances in Berthing and Mooring of Ships and Offshore Structures, Trondheim, pp 31 - 61.

BSRA (1969) Research Investigation for the Improvement of Ship Mooring Methods; Second Report, Tankers and Bulk Carriers, Existing Tonnage and New Construction. BSRA Report NS 256.

Jensen O.J. Viggósson G., Thomson J., Bjørdal S., Lundgren J. (1990). Criteria for Ship Movements in Harbours. Proceedings of the International Conference on Coastal Engineering, Venice.

Moes H. (1992) Acceptable Ship Motions for Loading Bulk Carriers In South Africa. Written Contribution to the Working Group 24, Madrid.

OCIMF: Oil Companies International Marine Forum (1978). Guidelines and Recommendations for the safe Mooring of Large Ships at Piers and Sea Islands, London. ISBN 0 900866 33 1.

OCIMF: Oil Companies International Marine Forum (1980). Design and construction Specification for Marine Loading Arms, London.

SIGTTO: Society of Gas Tankers and Terminal Operators (1986). Liquified Gas Handling Principles on ships and in Terminals, London. ISBN 0 900886 93 5.

Ueda S. (1987). Motions of Moored Ships and their Effect on Wharf Operation Efficiency. Report of the Port and Harbour Research Institute. Vol. 26, No. 5, pp 319-373.

Ueda S. and S. Shiraishi (1988). Allowable Ship Motions for Cargo Handling at Wharves. Report of the Port and Harbour Research Institute. Vol. 27, No. 4, pp 3-61