criteria for the mooring forces of ocean-going ships in locks

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CRITERIA FOR THE MOORING FORCES OF OCEAN-GOING SHIPS IN LOCKS
(Subject C.c)

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Summary

For the quantitative analysis of model investigations concerning the mooring forces of ships, criteria have to be defined.

The criterium applied in this paper is that the ratio of the hydrodynamic force and the ship's displacement should not exceed a distinct value.

From investigations concerning the representative mooring outfit of ships, their normal behaviour in the lock and the influence of external hydrodynamic forces acting on the ship when berthed, criteria for the mooring forces have been determined for ships up to 150,000 DWT.

The origin of the external hydrodynamic forces have been left out of consideration. It appears that the criteria for the mooring forces of ocean-going ships are low, in addition they are to a great extent dependent on the pre-tension in the mooring lines and they are decreasing accordingly as the size of the ships increases.

Sommaire

Pour pouvoir arriver à une analyse quantitative des résultats d'expériences dans des modèles réduits, destinées à établir les efforts d'amarrage, il faut définir certains critères. Le critère appliqué dans le présent exposé est comme suit: le rapport entre les forces hydrodynamiques d'une part et le déplacement d'eau du navire d'autre part ne doit pas dépasser une valeur bien déterminée.

Il a été établi des critères concernant les efforts d'amarrage pour des navires jusqu'à 150 000 t de tonnage réel, sur la base d'études de l'outillage d'amarrage type des navires, de leur comportement normal dans une écluse, et des forces hydrodynamiques extérieures sur des navires amarrés.

Les origines des forces hydrodynamiques extérieures ne sont pas traitées. L'analyse quantitative démontre que les critères des efforts d'amarrage des navires de haute mer sont bas; en outre, ils sont dans une large mesure fonction des forces de précontrainte dans les aussières, et ils décroissent à mesure que le tonnage des navires est plus important.
1. Introduction

The forces acting on a moored ship while the lock chamber is being filled or emptied can be determined from model investigations. The results of the investigations are only valid in a quantitative sense in case the measured forces can be compared to a certain criterion.

For inland navigation often a criterium of 1 0/oo is used, meaning that in the case of a rigidly moored ship (of less than 2000 tons load carrying capacity) the hydrodynamic forces in a longitudinal direction should not exceed a value equal to 1 0/oo of the ship's displacement.

For the sea-going navigation a similar criterium has not yet been determined. By order of the Netherlands Department of Transport and Public Works, this matter has been the subject of investigation. The results of the investigations, referring to ships up to 150,000 DWT, are presented here with in [1]. For each range of ship's size, an reasonable selection has been made in order to arrive at a representative outfit of mooring lines and winches. A kind of standard mooring procedure has been considered. With the help of this information an attempt has been made to determine by way of calculation the criteria for the mooring forces which can be applied to the majority of the filling and emptying processes.

No attention has been paid to the origin of the hydrodynamic forces and the influence of the wind.

2. Mooring lines and winches on board ships

2.1 Mooring lines [2]

To moor ocean-going ships either steel wire-ropes or synthetic ropes are used. For the calculation of criteria for the mooring forces, it has been attempted to make a reasonable selection from the great variety of mooring lines on board of ships, in order to arrive at a representative mooring line as far as it concerns elasticity and break load.

Steel wire-ropes are composed of six strands plus a core, each strand consisting of a number of wires. At present the wires of successive layers have varying diameters, resulting in a line contact between the wires. Strands and wires have been twisted in opposite direction, preventing the line to unwind. Most mooring lines are from 22 mm to 48 mm in diameter. The elastic relation between stress and stretch is non-linear. The determinations have been based on a representative steel mooring line having:

\[ \sigma = 0.68 \times 10^{12} \Sigma^{3/2} \quad (\sigma = \text{stress in N/m}^2) \]

Failure of the wire-rope occurs at an elastic stretch of \( \Sigma_u = 1.44 \% \).

Synthetic ropes are often made of nylon. They are composed of three strands. Current mooring ropes are from 40 mm to 80 mm in diameter. The elastic relation between stress and stretch is non-linear. The calculations have been based on a representative nylon mooring rope having:

\[ \sigma = 2.5 \times 10^{10} \Sigma^3 \quad (\sigma = \text{stress in N/m}^2) \]

Failure of this rope occurs at an elastic stretch of \( \Sigma_u = 21.8 \% \).

When subjected to a load for the first time, steel wire-ropes as well as synthetic ropes take an elastic plus a permanent stretch. For further calculations it has been assumed that a representative mooring line only takes an elastic stretch whereas no more permanent stretch appears.

From a comparison of the elastic behaviour of steel wire-ropes and of nylon ropes it clearly appears that the stretch of nylon ropes is considerably higher than that of steel wire-ropes when subjected to equal stresses (see Figure 1).


2.2 Winches [3], [4]

To tension the mooring lines, winches are used of which two types can be distinguished.

With common winches the line is wound a few times around the warping head. As soon as the line has been tensioned it is temporarily held by a stopper and then belayed on the bollards.

In the case of tension winches the mooring line remains permanently on the drum. The drum also serves as a line storage. This type of winches can be equipped with tension control, caring for the line tension to remain fairly constant.

For winches the following forces can be distinguished:
- hauling force: the line can maximally be tensioned by the winch up to the hauling force. The line will hardly move.
- rendering force: the line can maximally be held by the winch up to the rendering force. The winch is just not moving by the line pull.
- braking force: the braking force is attained when the winch does not start to slip by the line pull through the tightened band brake.

In the case of a two cylinder steam powered winch without any additional provisions the ratio of rendering force and hauling force amounts to 2-3; in the case of electric or hydraulic winches this ratio does not exceed a value of 1.25.

Usually the mooring line is matched to the winch in such a way that the braking force is 0.6 to 0.7 times the break strength of the line.

As an average the hauling force of the mooring line is 0.2 times its break strength.

In the further calculations the following forces have been applied to the representative winch: \( T_u \) being the break strength of the mooring line
- hauling force: \( 0.2 T_u \)
- rendering force: \( 0.3 T_u \)
- braking force: \( 0.55 T_u \)

2.3 Size and numbers of mooring lines and winches

In general the deck outfit is selected in such a way that the ship will withstand a 60 knots wind and a one knot current from any direction using its complete mooring equipment consisting of head and stern lines, breast lines and springs. From prototype data it appears that the mooring equipment of ships shows a considerable variety in size and numbers of mooring lines and winches.

In the following table the representative characteristics have been collected of the mooring lines and winches pertaining to various sizes of ships. These characteristics have been used in the calculations. In addition, representative displacements and lengths of ships have been indicated.

Table 1: Hauling forces and break strengths of mooring lines, displacements and lengths of ships.

<table>
<thead>
<tr>
<th>Ship's size tons D.W.</th>
<th>hauling force ( [\text{kN}] )</th>
<th>break strength of line ( T_u ) ( [\text{kN}] )</th>
<th>displacement ( \text{[kN]} )</th>
<th>length of ship ( l_{oa} ) ( [\text{m}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000</td>
<td>70</td>
<td>350</td>
<td>280,000</td>
<td>170</td>
</tr>
<tr>
<td>40,000</td>
<td>100</td>
<td>500</td>
<td>560,000</td>
<td>200</td>
</tr>
<tr>
<td>80,000</td>
<td>160</td>
<td>800</td>
<td>1,040,000</td>
<td>250</td>
</tr>
<tr>
<td>120,000</td>
<td>220</td>
<td>1100</td>
<td>1,560,000</td>
<td>285</td>
</tr>
</tbody>
</table>

In general an increase of the displacement attends with a relatively smaller increase of the hauling force.


With modern tankers and bulk carriers usually steel wire-ropes and steam powered winches are applied whereas automatic tension winches and synthetic ropes are mostly used with freighters.

3. Procedure in the lock

In Dutch and Belgian sea locks, accessible to ships up to 150,000 DWT, the procedure is such that during the filling and emptying process four mooring lines are used viz. head and stern line plus fore and aft spring. Only these four lines are used in order to pass the lock in the shortest possible time. An additional breast line can be applied in the case of heavy side wind whereas an additional head line is used in the case of increased salt-fresh influences or when the lock chamber has been blocked to a high extent. Also the location of the bollards in the lock area is important in view of the most favourable arrangement of the mooring lines.

With tension winches the mooring line is continually kept on the drum and during the filling or emptying process it should be possible to haul or veer the lines at any moment. In addition it should be possible to adjust the winch at any time without the use of a band brake or an automatic tension control. In the case of common winches the mooring line is usually kept on the warping drum as long as the lock is being filled or emptied, although occasionally the line is slung over bollards when the lock is being filled. In the calculation a representative situation in the lock has been assumed using head and stern line plus fore and aft spring.

4. Mooring line forces during the filling or emptying process

4.1 Starting points

During the filling or emptying process the ship is subjected to various hydraulic forces. When the lock chamber is being filled the water level in the lock chamber will rise as a consequence of which surges, a negative slope in water level, the lowering of the water level near openings etc. will create hydraulic forces. The origins of these forces have been left out of consideration.

The following calculations refer to the maximum forces which can be absorbed by the ship, assumed mooring equipment and situation in the lock are representative for most locking processes.

The calculations have been based on the following starting points:

a) The ship's dimensions are as shown in Figure 2. The ship is moored symmetrical-ly using a head and stern line under an angle of 45° plus a fore and an aft spring under an angle of 1:10 with the lock chamber wall. The angle between the lines and a horizontal plane is small. The mooring lines are of equal length and have equal diameters. Before the filling or emptying process the mooring lines have an equal pre-tension Tpr, during the process they have an equal non-linear elasticity in accordance to paragraph 2.1. The ship is equipped with tension winches in accordance to paragraph 2.2.

b) Under all circumstances the mooring lines should be kept in pre-tension, in order to absorb the forces and movements in the elastic range. A force, which is suddenly acting on the ship might cause a dynamical movement of the ship and any slack mooring line which is tightened by this action will surely snap. The minimum mooring line force has been put at 0.15 Tpr.

c) During the filling or emptying process the ship should only move parallel to the lock chamber wall. Under no circumstances it should move away from the wall or rotate around bow or stern: the ship should remain close to the wall.

d) Any friction between ship and lock chamber wall can be disregarded. During rising or lowering of the water level the friction remains low.

4.2 Vertical movement of the ship

While the lock chamber is being filled or emptied, moving of the ship in vertical sense will proceed relatively slow. The mooring lines will stretch or shorten. In the case of steel wire-ropes the mooring line forces will change considerably, which makes it necessary to continuously adjust the lines: heaving or veering. In the case of synthetic mooring ropes the load changes are considerably less due to
the small modulus of elasticity, allowing the winch to be kept by band brake if possible.

4.3 The horizontal forces acting on the ship

When the lock is being filled or emptied the horizontal forces and moments acting on the ship may show rapid changes. It is therefore necessary that these forces and moments are absorbed without heaving or veering.

Before the filling or emptying process is started, the mooring lines should be tightened to a pre-tension $T_{pr}$. This pre-tension produces a normal force between the lock chamber wall and the ship of $N = 1.6 T_{pr}$, see the diagram of forces in Figure 3. ($T_{pr}$ = pre-tension of mooring line, $N$ = normal force).

Any longitudinal force acting on the ship will be absorbed by the mooring lines. The ship shifts over a distance $w$ along the side wall of the lock. The longitudinal force will produce a change in the distribution of the normal forces. When the acting mooring line forces amount to $0.15 T_u$ at minimum, then the maximum longitudinal force $L$ to be taken up amounts to $2.5 T_u$. See the line stretch and force diagrams in Figure 4. ($L$ = horizontal longitudinal force).

Any transverse force acting on the ship will only change the magnitude of the normal force. The ship should not move away from the lock chamber wall. In this case $D = 1.6 T_{pr}$. See the force diagram in Figure 5. ($D$ = horizontal transverse force).

Any moment $P_{r'a'}$ acting on the ship will only change the location of the normal force. The ship is not allowed to rotate around bow or stern. In this case $M = 0.8 T_{pr}$. See the force diagram in Figure 6. ($M$ = horizontal moment).

Usually a combination of longitudinal forces, transverse forces and moments is acting in the lock. When at all times the following conditions are met, a minimum mooring line force of $0.15 T_u$, a maximum mooring line force equal to the rendering force and finally the ship should not move away from the lock chamber wall, then a combination of longitudinal force, transverse force and moment (all related to the pre-tension $T_{pr}$) is possible as indicated in Figure 7. Within and underneath the frame of this diagram any combination is allowed whereas any combination outside this diagram does not meet the conditions.

5. Criteria for the mooring forces

5.1 Introduction

The criterium for the mooring forces can be defined as the ratio (in per mil) of the maximum force to be absorbed and the ship's displacement. The calculations have been based on the assumption of favourable conditions in the lock as far as it concerns mooring lines and winches. In order to allow for non-ideal conditions such as a non-ideal course of the lines (usually as a result of the location of the bollards in the lock area), the limited capacity of winches and mooring lines, friction, poor handling of lines etc., a reduction coefficient of 2/3 has been introduced. Usually some of these conditions will be present, therefore this reduction coefficient should not be regarded as a safety coefficient.

Table 1 shows the ship's displacement and lengths which can be regarded as representative values.

5.2 Criteria for the longitudinal forces

In the case of end-filling of the lock chamber mainly longitudinal forces will develop. In the absence of transverse forces and moments a criterium for the longitudinal forces is applicable, defined as:

$$\text{maximum longitudinal force} \quad \text{displacement} = 1000 \quad \frac{0}{\text{oo}}$$

A reduction coefficient of 2/3 has been included.

From Paragraph 4.3 it appears that the maximum longitudinal force depends on the pre-tension in the mooring lines. Owing to the vertical movement of the ship, steel wire-ropes should be continually adjusted in order to keep the maximum mooring line forces down to $0.3 T_u$. In the case of nylon ropes it is possible to brake
the winch to a maximum line pull of 0.55 \( T_u \).
The following table shows the criteria for the longitudinal forces as a function of
various pre-tensions and ship’s sizes.

Table 2: Criteria for longitudinal forces

<table>
<thead>
<tr>
<th>ship’s sizes tons DW</th>
<th>break strength of rope ( T_u )</th>
<th>criterium longitudinal force in ( \circ/\text{o} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>steel wire-ropes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( T_{pr}/T_u = 0.15 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( T_{pr}/T_u = 0.10 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( T_{pr}/T_u = 0.20 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( T_{pr}/T_u = 0.10 )</td>
</tr>
<tr>
<td>20,000</td>
<td>350</td>
<td>0.34</td>
</tr>
<tr>
<td>40,000</td>
<td>500</td>
<td>0.24</td>
</tr>
<tr>
<td>80,000</td>
<td>800</td>
<td>0.21</td>
</tr>
<tr>
<td>120,000</td>
<td>1100</td>
<td>0.15</td>
</tr>
</tbody>
</table>

5.3 Combination criterium

In general the horizontal forces acting on the ship during the filling or emptying
process are not restricted to longitudinal forces only, but in addition also transverse forces and moments will be present. In consequence of this, a combination criterium should be applied, defined by:

\[
\frac{\text{max. longitudinal force}}{\text{displacement}} \times 1000 \, \circ/\text{o}
\]

\[
\frac{\text{max. transverse force}}{\text{displacement}} \times 1000 \, \circ/\text{o}
\]

\[
\frac{\text{max. moment}}{\text{displacement} \times \text{length over all}} \times 1000 \, \circ/\text{o}
\]

A reduction coefficient of 2/3 has been included.

Figure 8 shows the coordinates of the combination criteria, \( x \) referring to the longitudinal force, \( y \) to the transverse force and \( z \) to the moment.

The table shows the coordinates for various sizes of ships, types of mooring lines and pre-tensions.

Table 3: Combination criteria

<table>
<thead>
<tr>
<th>ship’s size tons DW</th>
<th>rope’s type</th>
<th>rope ( T_{pr}/T_u )</th>
<th>long. force ( x )</th>
<th>transv. force ( y )</th>
<th>moment ( z_1 )</th>
<th>( z_2 )</th>
<th>( z_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>40,000</td>
<td>steel</td>
<td>0.15</td>
<td>0.24</td>
<td>0.14</td>
<td>0.075</td>
<td>0.050</td>
<td>0.025</td>
</tr>
<tr>
<td>40,000</td>
<td>steel</td>
<td>0.10</td>
<td>0.15</td>
<td>0.10</td>
<td>0.051</td>
<td>0.034</td>
<td>0.017</td>
</tr>
<tr>
<td>40,000</td>
<td>nylon</td>
<td>0.20</td>
<td>0.26</td>
<td>0.20</td>
<td>0.102</td>
<td>0.068</td>
<td>0.034</td>
</tr>
<tr>
<td>40,000</td>
<td>nylon</td>
<td>0.10</td>
<td>0.14</td>
<td>0.10</td>
<td>0.102</td>
<td>0.068</td>
<td>0.034</td>
</tr>
<tr>
<td>80,000</td>
<td>steel</td>
<td>0.15</td>
<td>0.21</td>
<td>0.12</td>
<td>0.066</td>
<td>0.044</td>
<td>0.022</td>
</tr>
<tr>
<td>82,000</td>
<td>steel</td>
<td>0.10</td>
<td>0.13</td>
<td>0.085</td>
<td>0.044</td>
<td>0.029</td>
<td>0.015</td>
</tr>
<tr>
<td>80,000</td>
<td>nylon</td>
<td>0.20</td>
<td>0.22</td>
<td>0.16</td>
<td>0.087</td>
<td>0.058</td>
<td>0.029</td>
</tr>
<tr>
<td>80,000</td>
<td>nylon</td>
<td>0.10</td>
<td>0.115</td>
<td>0.08</td>
<td>0.043</td>
<td>0.029</td>
<td>0.015</td>
</tr>
<tr>
<td>120,000</td>
<td>steel</td>
<td>0.15</td>
<td>0.19</td>
<td>0.11</td>
<td>0.060</td>
<td>0.040</td>
<td>0.020</td>
</tr>
<tr>
<td>120,000</td>
<td>steel</td>
<td>0.10</td>
<td>0.12</td>
<td>0.08</td>
<td>0.041</td>
<td>0.027</td>
<td>0.014</td>
</tr>
<tr>
<td>120,000</td>
<td>nylon</td>
<td>0.20</td>
<td>0.205</td>
<td>0.16</td>
<td>0.081</td>
<td>0.054</td>
<td>0.027</td>
</tr>
<tr>
<td>120,000</td>
<td>nylon</td>
<td>0.10</td>
<td>0.105</td>
<td>0.08</td>
<td>0.040</td>
<td>0.027</td>
<td>0.013</td>
</tr>
</tbody>
</table>

6. Conclusions

The criteria for the mooring forces are highly dependent on:

a. the size of the ship. With an increase of the dead weight the capacity of the
mooring lines and winches does not increase in the same proportion but less. Consequentlly, the mooring force criteria of large ships are lower, because the same number of mooring lines are used.

b. the pre-tension in the mooring lines. The maximum longitudinal forces, transverse forces and moments which can be absorbed are directly determined by the pre-tension in the mooring lines.

c. steel wire-ropes or synthetic ropes. In the case of large lifts, steel wire-ropes have to be continually heaved or veered, the winch should be continually adjusted. Synthetic ropes can take a larger stretch without a considerable change of the mooring force, consequently the winch can be kept on band brake. Therefore steel wire-ropes have lower mooring force criteria.
FIG. 1 STRESS-ELASTIC STRAIN RELATIONSHIP FOR STEEL WIRE AND NYLON MOORING ROPES

FIG. 2 STANDARDISED SITUATION AND DIMENSIONS MOORED SHIP

FIG. 3 PRE-TENSION

FIG. 4 LONGITUDINAL FORCE
FIG. 5 TRANSVERSE FORCE

FIG. 6 MOMENT

FIG. 7 MAXIMUM COMBINATION OF LONGITUDINAL FORCE, TRANSVERSE FORCE AND MOMENT

FIG. 8 COMBINATION CRITERIUM