better absorb dynamic forces. When tugs are equipped with towing winches line can then be paid out as deemed necessary and be shortened when conditions improve or when entering port.

On the other hand, in wave conditions harbour tugs can, instead of towing on a line, operate more effectively and at higher wave heights at the ship's leeside,if circumstances and ship manoeuvres allow. It all depends on the local situation.

In wave conditions the risk of girting for conventional tugs towing on a line is higher than in calm water and passing towlines can be carried out more safely with more highly manoeuvrable tugs. Tractor tugs will in general, therefore, operate more safely and can provide assistance in somewhat larger wave heights. It has been reported that the movements of VS tractor tugs may be more violent in wave conditions. Anyway, waves limit the operating effectiveness of harbour tugs when towing on a line as well as operating at a ship's side when exposed to waves. Performance decreases with increasing wave height. An indication of the upper limits for operations by harbour tugs is:

Maximum significant wave height:
Conventional tug types :1·5 – 1·8 m
Tractor types of tugs (incl. reverse-tractor tugs), ASD tugs : 2·0 m

Visibility:
In several ports a visibility of 0·5 mile is found to be the limit.

4.5 *Design consequences*

What has been discussed with respect to the performance of different types of tug has resulted in an alternative design for some new VS tractor tugs. The reason why is clear. A tractor tug is very effective as a stern tug on a line. It operates with the stern directed towards the ship and the tug captain facing aft. This is also the direction of the assisted ship's movement. When operating at a ship's side a tug captain is also usually facing aft and the same applies during mooring and unmooring operations.

So what can be seen nowadays is a totally new concept VS tractor tug, as for instance in the Norwegian/ Swedish *Bess* and *Boss* – the wheelhouse is turned 180°. The stern is higher to give better protection against incoming waves (see figure 9.16). These tugs will be considered when discussing escorting. Similar changes to VS tug design can be found, amongst others, in the VS tug *Redbridge* of Adsteam Towage, UK, where the tug funnels are placed forward of the wheelhouse, giving an optimum view aft for the captain. The stern in this design is also raised. In addition, alternative towing points can be used, as mentioned in section 4.2.2.

Photo: Bob Donaldson, Southampton, UK

Figure 4.25 VS tug 'Redbridge' of Adsteam Towage, Southampton, UK. (l.o.a. 33m, beam 11·2m, bp 43 tons). A new design, meeting several operational requirements, it has an optimum view of the after deck from the wheelhouse, unobstructed by funnels and a much higher sheer at the stern to keep the aft deck clear of water when running astern at speed, particularly in wave conditions and when escorting

4.6 *Conclusions regarding tug types*

Assuming normal port operations with maximum ship speeds of six to seven knots, it can be concluded – with some reservations – that the suitability of different tug types can broadly be ranked as follows:

As forward tug towing on a line:
- ASD-tugs
- Combi-tugs
- Conventional tugs
- Tractor tugs/Reverse-tractor tugs

As stern tug towing on a line:
- Tractor tugs/ASD-tugs/Reverse- tractor tugs
- Combi-tugs
- Conventional tugs

When operating at a ship's side:
- ASD-tugs/Reverse-tractor tugs/Tractor tugs
- Combi-tugs
- Conventional tugs

The above ranking is, of course, a general one. Differences in design of a particular type can change the ranking, especially tug types with more or less similar characteristics such as tractor, ASD and reverse-tractor tugs. Conventional tugs will never reach the high manoeuvrability of omnidirectional tugs. But conventional tugs also have many differences in design and manoeuvring devices, making one much more manoeuvrable than another. Well chosen deck equipment can improve a tug's performance. For instance, installation of a radial hook in a conventional

tug can make that tug superior to a similar conventional tug without such an arrangement. The same applies to ASD-tugs, when they operate as a conventional tug.

It should be borne in mind, too, that the above broad ranking refers to a tug's effectiveness. When safety of operations is the major requirement, then tractor and reverse-tractor tugs are recommended. Although fire fighting is not discussed in this book it is also an important factor to be considered with respect to a tug's manoeuvrability. Finally, the maximum draft of a tug, e.g. of tractor tugs, can make them unacceptable for certain ports regardless of their high manoeuvrability.

4.7 Some other practical aspects

There are other aspects which are important for safe and efficient shiphandling by tugs.

Cooperation

As stated in section 4.3.1 pilots, ship masters and tug captains should know each others capabilities and limitations regarding ship and tug manoeuvres. This knowledge is the basis of good cooperation and understanding between them. Only then will manoeuvres go smoothly and a ship be handled safely and efficiently. When manoeuvring, the pilot should keep, as far as is possible, a close eye on the assisting tugs. He will then see how the tugs are performing, can take action when they don't act as expected, or when a tug's safety is at risk.

Communications between pilots and tug captains

For good cooperation between pilots and tug captains a good communication system is indispensable. Portable radio-communication sets have been used for years by pilots. When of a good make these sets are very handy and work satisfactorily. Radio sets should be tested prior to a pilot boarding a ship and it is best that every pilot has his own set.

Tug orders should be given clearly and be open to only one interpretation. Tugs should be addressed by name or by operating position. Tug captains should confirm and repeat the orders given, stating their tug's name or position. Any possibility of misunderstanding should be avoided.

Many ports prefer to use a standard system in English, but it will take years before such a system could be introduced worldwide (see also paragraph 9.5.1 Communications and Information).

In nearly all ports the language between pilots and tug captains is a kind of slang and is therefore not always comprehensible to the master of a ship. Although pilots and tug captains understand each other well enough, it is a strange situation because the ship master is still responsible. It would therefore be better if tug orders were given in English, according to an internationally agreed standard vocabulary. Using understandable English is fine in English speaking countries, but it does cause problems in many non-English speaking countries. In particular, tug captains often speak only the local language. An international standard vocabulary is, for that reason, hardly feasible. In addition, a standard vocabulary cannot cover non-standard situations. In critical situations pilots and tug captains should be able immediately to understand what is wanted. A change in communication procedures might result in misunderstandings. This should be avoided.

Nevertheless, tug captains should always be informed by pilots about the intended ship and tug manoeuvres. Furthermore, the use of a basic system for tug orders in a port is necessary, even though only a local system, but should be standard for all local pilots and tug captains.

Tug use

Harbour tugs handling a ship should have a reserve of power, be able to react fast and to handle a ship in such a way that a minimum of space is required for the ship and assisting tugs. The slower tugs react, the longer the towlines and the smaller the tug power, the more manoeuvring space is required for a ship and assisting tugs. However, manoeuvring space is usually very limited in port areas.

Tug size and power should be relative to ship size. Large and powerful tugs should normally not handle small ships. Tug actions in that case could induce too large movements of the attended ship, resulting in inefficient shiphandling and in a worst case damage to the ship. In addition, bollard pull of the separate tugs handling a ship should not mutually differ too much.

Tug configuration should be planned well in advance, taking into account available tugs, the capabilities and limitations of different tugs, manoeuvres to be carried out, the influence of wind, current, and so on. A nice example of tug configuration can be seen in the photo of the bulk carrier at page xiii. Three different tug types are used in an appropriate configuration. The ship has to round a starboard bend. One conventional tug is assisting the ship, positioned starboard forward where it can be effective in applying steering assistance. In addition, this tug can tow with a larger towing angle than a VS tug. One VS tug is therefore positioned at the port bow. At the port quarter aft is a powerful ASD-tug, in the best position for assisting in a turn to starboard. The ASD-tug can assist in the turn in the direct mode without increasing ship's speed and the tug can, if required, control the ship's speed. The second VS tug with less bollard pull than the ASD-tug is therefore positioned on the starboard quarter aft.

Repositioning of tugs may sometimes be considered necessary during a trip, but should be avoided as far as possible, particularly if shifting the tugs involves

releasing and refastening towlines. This takes time, especially with the limited number of crew members on board nowadays. During the time of shifting a tug, the ship has less or no tug assistance and in the worst case towlines may foul ship's or tug's propeller.

Speed

Ship's speed should be carefully controlled in relation to the limitations of the tugs involved. This generally means that speed should be low, taking into account the effect of current and wind. In any case, the lower a ship's speed the more effectively tugs can operate. Also, other factors play a role with regard to ship's speed, factors which can affect the tug assistance required and tug safety, such as interaction and shallow water effects, which are discussed in Chapter 6.

Decreasing effectiveness of tugs when a ship gathers speed

The difference in pulling effectiveness that arises between a forward tug and stern tug when a ship gathers speed has been mentioned earlier. In addition, an effect to keep in mind is the decreasing effectiveness of tugs in general when a ship, initially stopped in the water, gathers speed. This has sometimes resulted in waiting time for ships.

Example: A container ship has to depart from a harbour basin with strong onshore winds. Tugs are ordered. Total bollard pull available seems sufficient to pull the ship off the berth. So far, no problem. However, as soon as the ship's engines are started and she starts moving, the tugs towing on a line take position to be able to keep pace with the ship, so their effectiveness decreases. The ship may drift alongside the berth again and additional or stronger tugs have to be ordered, which takes time. When moored port side to and departing astern out of the harbour basin with an onshore wind the effect is worse due to the transverse effect of the ship's propeller.

Ship pulled or pushed around by a bow tug gathers speed.

A tug pulling at right angles to the bow of a ship stopped in the water will give the ship a lateral velocity and a rate of turn, causing the ship to pivot around a point somewhere near the stern (see for instance figure 4.2B). As a consequence the ship's lateral centre of gravity follows a curved path. A body following a circular path experiences a 'centrifugal force', and such a force also acts on the ship's centre of gravity moving along the curved path. A 'centrifugal force' is always directed outward and perpendicular to the curved path. This 'force' originally acts almost in line with the ship, thus causes the ship to gather headway. The fluid forces also contribute to this effect.

Chapter FIVE

BOLLARD PULL REQUIRED

5.1 Introduction

TUG CONFIGURATION, THE NUMBER OF TUGS and total bollard pull used are normally based on a pilot's experience and may vary depending on port conditions and circumstances. In general this system works well. However, with increasing ship size it is more difficult to determine what exactly is needed to handle a ship safely. Experience alone in such a case is too narrow a basis and may not cover all situations and conditions which might be expected. Information on wind, current and wave forces may be essential. This could be particularly the case when large container ships, car carriers, deep draught tankers or bulk carriers have to be handled in unfavourable environmental conditions and in confined port areas.

Another consideration is that, because of economic pressure, shipping companies often try to minimise tug assistance costs. This can easily lead to a dispute between the pilot, master or shipping agency about the minimum number of tugs to be used. Ships equipped with bow thrusters and/or stern thrusters often use one or two tugs less. Side thrusters, however, have limitations to their maximum power and effectiveness, which decreases very rapidly when a ship gathers headway. The tug assistance required is, therefore, often subject to discussion about acceptable limits of safety. Pilot and master, if well prepared, can avoid these discussions and are in a better position to take the right decision.

Depending on the local situation, tug assistance on arrival or departure generally comprises three phases:

- *The phase whereby a ship has reasonable speed*
  The ship can still use her engines and rudder to compensate for drift forces caused by wind, current and/or waves, by steering a drift angle. Depending on the situation, tugs may assist.

- *The intermediate phase*
  When a ship has to reduce speed, entering a dock, harbour basin, turning circle or approaching a berth. The ship also has to be stopped within a certain distance. When reducing speed, a ship's steering performance also decreases. The propeller has to be stopped, the influence of wind and current increases and tug assistance is needed more frequently and to a larger extent.

- *The phase involving the final part of the arrival manoeuvre.*
  The ship is practically dead in the water, such as in the turning circle and/or when berthing. The ship is very restricted in manoeuvring performance and not able to compensate for wind and current forces. Tugs have to assist fully.

For ships influenced by wind, current and waves this last phase, when a ship is stopped in the water, is most important for assessment of bollard pull required. It is this phase which will mainly be considered, therefore.

In considering bollard pull required, the availability of side thrusters is sometimes taken into account, because a side thruster may replace part of the bollard pull required. Whether this is the case depends on the ship, the local situation, the circumstances and port regulations.

5.2 Factors influencing total bollard pull required

The following main factors influence tug assistance:

- *Port particulars*, including:
  Restrictions in the fairway, port entrance, passage to a berth, turning circle, manoeuvring space at a berth or harbour basin, available stopping distance, locks, bridges, moored vessels, water depths, speed restrictions, and so on.

- *Berth construction*, including:
  Type of berth: open, e.g. jetty, or solid.

- *The ship*, including:
  Type, size, draft and underkeel clearance, trim, windage, and factors such as engine power ahead/astern, propeller type, manoeuvring performance, and availability of side thrusters and specific rudders.

- *Environmental conditions*, including:
  Wind, current, waves, visibility, ice.

- *Method of tug assistance*, including:
  Towing on a line, operating at a ship's side or a combination of methods.

The port is more or less a constant factor. Particulars of port layout, such as fairway, port entrance, passage to the berth, turning circle and berth location, determine a basic number, type and total tug bollard pull for a particular class of ship. This is based on local experience and sometimes, for more difficult situations, on simulator research. An indication of bollard pull required for tankers, bulk carriers and container vessels is given below. Berth construction has to do with the transverse approach speed towards a berth, which is also dealt with in this chapter.

In addition to tug assistance requirements following from port layout and berth construction, the varying factors influencing the required total bollard pull for a particular ship are:

- Wind.
- Current.
- Waves.

These factors have to be considered in relation to ship details such as size, draft, underkeel clearance, etc. The manoeuvring performance of a ship may influence required tug assistance in a positive or negative way. The towing method should also be taken into account. Reduced visibility is also considered a factor of importance regarding tug assistance. This is true, but it mainly concerns specific safety procedures for tug assistance during fog. Reduced visibility, therefore, is not discussed further in this chapter. Tug assistance in ice conditions was dealt with in Chapter 3.

The total force acting on a ship could, in theory, be compensated for by tugs when bollard pull equals the total forces of wind, current and waves. However, there are some important factors to be taken into account:

- Tugs must have sufficient reserve power to push or pull a ship up against wind and current or to stop a drifting ship quickly enough.
- Tugs are not always pulling or pushing at right angles to a ship. For instance, during arrival or departure manoeuvres, a ship may have some forward or astern movement. Tugs try to keep pace with a ship, and thus use engine power in the direction of ship's movement at the expense of pull or push forces. The same happens in situations where there is a current and a ship has relative speed through the water.
- Bollard pull actually available may, due to wear and fouling, no longer be a full 100% compared to the original bollard pull tests.
- Forward and after tugs often cannot pull or push at full power simultaneously, even when the required bollard pull forward and aft is carefully considered, taking into account possible yaw moments caused by wind and/or current or trim. A ship may start to swing. At one end of the ship the tug then has to reduce power in order to stop the swing.
- The propeller wash of tugs towing on a line may hit a ship's hull and decrease pulling effectiveness. This can be influenced to a certain extent by correct towline length and towing angle, as explained later.

So, when calculating the forces of wind, current and waves on a ship, a specified safety factor should be taken into account for bollard pull required. In the graphs showing bollard pull required to keep a ship up against a beam wind, cross current and beam waves, a safety factor of 20% is included. For tugs pulling at a ship's side this safety factor is not sufficient due to the large loss of pulling efficiency, which is separately considered.

5.2.1 Wind forces

The forces on a ship caused by wind can be calculated by the formulae:

Lateral force:
$F_{Yw} = 0{\cdot}5\ C_{Yw}\ \rho\ V^2\ A_L$ Newton

Longitudinal force:
$F_{Xw} = 0{\cdot}5\ C_{Xw}\ \rho\ V^2\ A_T$ Newton

Yaw moment:
$M_{XYw} = 0{\cdot}5\ C_{XYw}\ \rho\ V^2\ A_L\ L_{BP}$ Newtonmetres

C_{Yw} = Lateral wind force coefficient.
C_{Xw} = Longitudinal wind force coefficient.
C_{XYw} = Wind yaw moment coefficient.
ρ = Density of air in kg/m^3.
V = Wind velocity in m/sec.
A_L = Longitudinal (broadside) wind area in m^2.
A_T = Transverse (head-on) wind area in m^2.
L_{BP} = Length between perpendiculars in m.

The lateral force, longitudinal force and yaw moment coefficients depend on a ship's form, draft and trim, superstructure such as bridge, deckhouses, masts and ramp, and angle of attack of the wind. It should also be noted that deck cargo, as on container vessels, should be included in calculating wind areas. The coefficients C_{Yw}, C_{Xw} and C_{XYw} differ by ship and can be determined by means of model tests in wind tunnels.

For several ship types the wind coefficients are known for all angles of attack and certain loading conditions. For tankers they can be found in 'Prediction of Wind and Current loads on VLCCs'. Lateral forces are largest and most important for calculating bollard pull required. C_{Yw} varies between approximately 0·8 and 1·0 for beam winds, depending on ship's type and loading condition, but lies mostly between 0.9 and 1.0. With value 1·0 for C_{Yw}, 1·28 kg/m^3 for density of air and calculating the outcome in kilograms instead of Newtons, the formula for beam wind forces can be simplified to: $F_{Yw} = 0{\cdot}065V^2A_L$ kgf.

To allow a safety margin of 20%, 25% should be added to the previous formula, resulting in the following handy formula for estimating bollard pull required for beam winds:

$$\mathbf{F_W = 0{\cdot}08\ V^2\ A_L\ kgf}$$

The graph in figure 5.1 is based on this formula, whereby 1 m/sec = 2 knots* The calculated required bollard pull in the wind graph of figure 5.1 is approximately 5% higher when, for wind speed in knots, a more accurate equivalence in m/sec is taken. The safety factor of 20% included is in some cases even higher, because for a lateral wind force coefficient the value 1·0 is allowed, which is sometimes only 0.8 or 0.85, although difficult to assess in daily practice. The

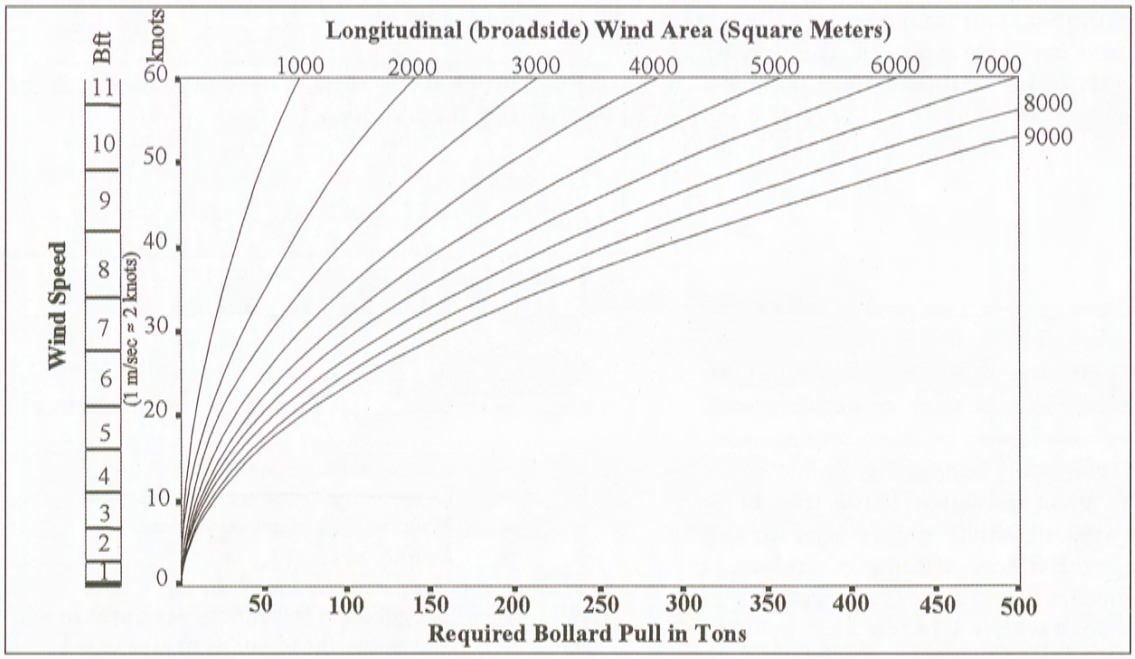

Figure 5.1 Bollard pull required to compensate for beam winds

Note 1: Ton is equal to 1000kg force (= 9·8 kN)

Note 2: For large gas carriers see note in text original data from UK National Ports Council 1977

graph is only valid for tugs towing on a line or pulling at a ship's side on a rather long towline.

Note:

For loaded tankers the outcome is too high, because the lateral wind coefficient of fully loaded tankers is approximately 0·7. For fully loaded tankers, however, it is generally more the mass that counts. Care should be taken when calculating the required bollard pull for large liquefied gas carriers. The lateral wind coefficient for these ships varies between 1·05 for gas carriers with prismatic tanks and 1·2 for gas carriers with spherical tanks (see References for 'Prediction of Wind Loads on Large Liquefied Gas Carriers'). Therefore, for gas carriers with prismatic tanks 5% and for gas carriers with spherical tanks, 20% should be added to the outcome calculated by the formula or indicated by the graph in figure 5.1.

For winds not coming from abeam the total bollard pull required can roughly be derived from the bollard pull required for beam winds. It can then be seen that when the angle of attack of the wind is between abeam and up to approximately 30 degrees each side of abeam, the bollard pull required is nearly the same as for beam winds. In general, yaw moment is maximum for quartering winds but depends, amongst other things, on type of ship, loaded condition, trim and deck cargo.

Wind does not blow constantly with the same force – wind velocity fluctuates continuously. Therefore not just mean wind velocity should be accounted for, but wind that may be experienced in gusts and squalls. A wind meter, properly installed with a recording device at a pilot station, gives the best information. If considered necessary gust factors, e.g. from PIANC, can be applied tentatively to find the relationship between mean wind speed and associated maximum speeds for shorter periods.

Wind velocity also varies by height, as shown in the graph in figure 5.2. The graph is based on the following formula:

$$V_w = v_w (10/h)^{1/7}$$

V_w = wind velocity at 10 metres height (m/s).
v_w = the wind velocity at elevation h (m/s).
h = elevation above ground/water surface (metres).

For calculating wind force in the equations, its velocity at 10 metres height should be used. For wind velocities obtained at a different elevation, adjustments to the equivalent 10 metre velocity can be made with this formula. On the other hand, wind indications given

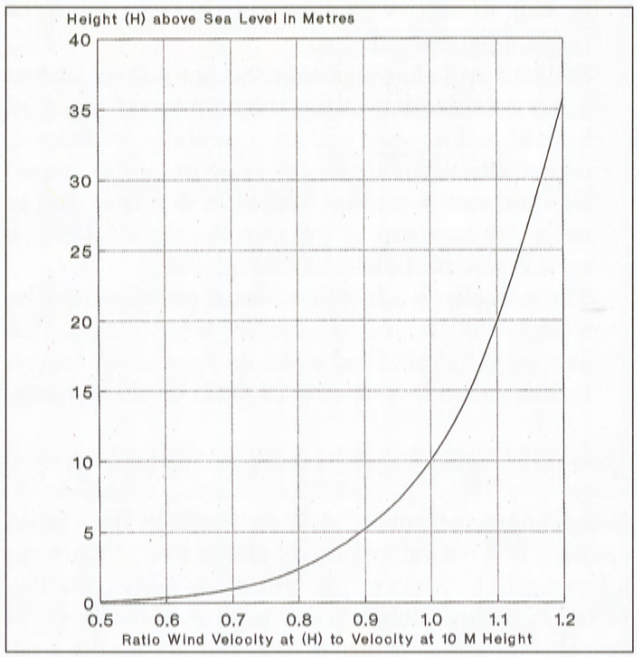

Figure 5.2 Wind height velocity ratio

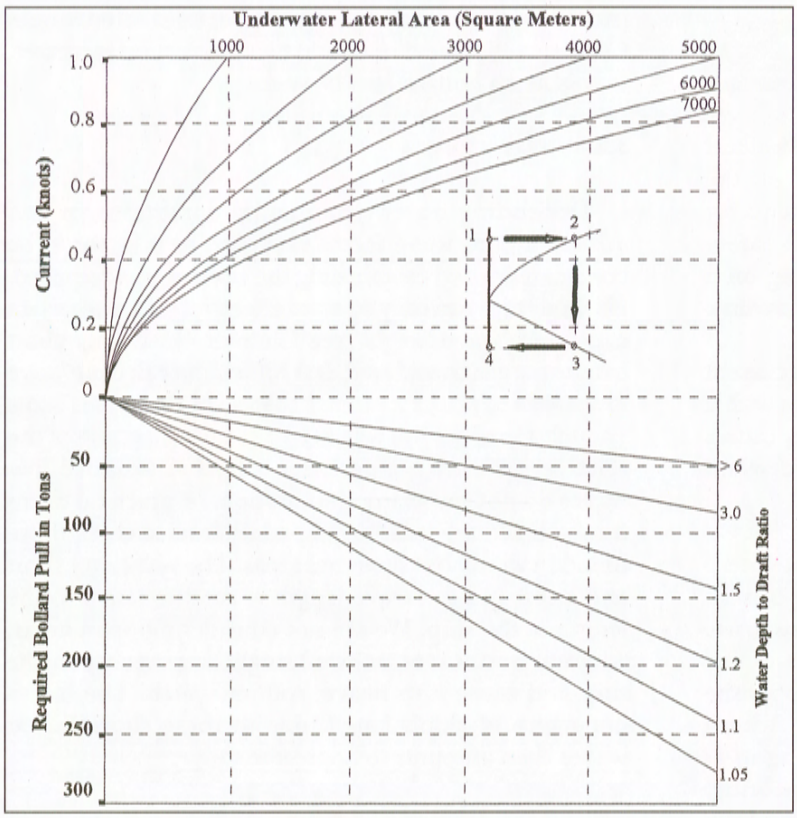

Figure 5.3 Bollard pull required in a cross-current
Note: Ton is equal to 1000kg force (= 9·8 kN)

Original data from UK National Ports Council 1977

by a wind meter on top of a ship's mast give safe approximations for evaluation of the lateral wind force and bollard pull required.

A ship drifts under the influence of wind when the wind forces acting on her are not compensated for by tugs. A factor influencing drift velocity is underkeel clearance. A drifting ship has a relative speed through the water, as with current. The drift speed of a ship decreases with underkeel clearance, because the forces created by the opposing water increase when underkeel clearance gets smaller. This is considered later when discussing current forces.

Of course, a smaller drift speed does not imply that less bollard pull is needed. A drifting vessel has to be stopped and pulled back through the water. Stopping a ship from drifting and pulling back also needs more power in shallow water than in deep water. The amount of water moving with a ship when drifting, the added mass, also increases with decreasing underkeel clearance, requiring additional bollard pull to stop and pull back a drifting vessel in shallow water.

5.2.2 Current forces

The current forces acting on a ship can be calculated in the same way as wind forces. For the sake of completeness, the formulae used in OCIMF publications are given:

Lateral force:

$$F_{Yc} = 0{\cdot}5\ C_{Yc}\ \rho\ V^2\ L_{BP}\ T \text{ Newton}$$

Longitudinal force:

$$F_{Xc} = 0{\cdot}5\ C_{Xc}\ \rho\ V^2\ L_{BP}\ T \text{ Newton}$$

Yaw moment:

$$M_{XYc} = 0{\cdot}5\ C_{XYc}\ \rho\ V^2\ L_{BP}^2\ T \text{ Newtonmetres}$$

C_{Yc} = Lateral current force coefficient.
C_{Xc} = Longitudinal current force coefficient.
C_{XYc} = Current yaw moment coefficient.
ρ = Density of water kg/m³.
V = Current velocity in m/sec.
L_{BP} = Length between perpendiculars in m.
T = Draft.

The current coefficients, C_{Yc}, C_{Xc} and C_{XYc}, differ by a ship's underwater shape, draft, trim and angle of attack, and are also affected by underkeel clearance which has a very strong effect on the coefficients. These are determined by using ship models in test tank studies.

For the bollard pull required the maximum transverse forces exerted by a crosswise current are important. The transverse force is calculated using the formula: $F_{Yc} = 0{\cdot}5\ C_{Yc}\ \rho\ V^2\ L_{BP}\ T$.

The lateral force coefficient for cross currents in deep water is around 0·6. This is, amongst others, the OCIMF-coefficient for loaded tankers. When C_{Yc} equals 0·6, density of salt water is 1025 kg/m³, adding 25% for loss of tug's effectiveness and giving the outcome in kilograms instead of Newtons, the following simplified formula for calculating the approximate bollard pull required for cross currents in deep water can be used:

$$\mathbf{F_C = 40\ V^2\ L_{BP}\ T\ \ kgf}$$

Current velocity is taken in metres/second, the outcome in kilograms. This formula is only valid for deep water, i.e. more than six times ship's draft.

Since underkeel clearance in port areas can be small, the current forces in these conditions are at least as important as they are in deep water. With underkeel clearance decreased to 1·5 x ship's draft, bollard pull required increases considerably to approximately:

$$\mathbf{F_C = 110\ V^2\ L_{BP}\ T\ \ kgf}$$

With an underkeel clearance of 20% of ship's draft, the bollard pull required is roughly:

$$\mathbf{F_C = 150\ V^2\ L_{BP}\ T\ \ kgf}$$

When underkeel clearance is further reduced to 10%, the bollard pull required is nearly five times as high as in deep water, approximately:

$$F_C = 185\ V^2\ L_{BP}\ T\ \text{kgf}$$

25% has in all cases been included for safety reasons.

The graph in figure 5.3 gives an indication of bollard pull required for cross currents and is based on the aforementioned formulae and OCIMF coefficients for loaded tankers. The outcome includes a 20% safety margin. The graph is only valid for tugs towing on a line or pulling at a ship's side on a not too short towline.

The effect of reduced underkeel clearance on current force is also clearly shown in figure 5.4. Starting with a current force of 10 tons, the same current velocity causes a strongly increasing force on the same ship when underkeel clearance decreases.

With a small underkeel clearance, current forces decrease quickly when the angle of attack of the current becomes less than 90° to a ship's centre line. Longitudinal forces then increase. The effect of the current forces on a ship may then even be in the opposite direction to that expected, in particular when with a small underkeel clearance the current is coming in at about 20-30° on the bow. When, e.g. after unmooring, turning with the assistance of tugs a deep loaded bulk carrier with a small underkeel clearance in a river with current, the ship may gather headway and move against the current direction coming in from the port or starboard bow. Pilots have experienced such effects and while turning have constantly to apply astern power to check the ship's headway.

Not only do current forces increase considerably with decreasing underkeel clearance. Small underkeel clearance also results in a larger turning diameter, a decrease in rudder effectiveness and an increase in stopping distance. To compensate for these effects, the assistance of tugs might be welcome for safe shiphandling. Underkeel clearance also considerably affects the duration of swinging round a ship. The transverse forces to be overcome fore and aft of midships increase with decreasing underkeel clearance. Consequently, the duration of swinging round increases, unless more bollard pull is used.

5.2.3 Wave forces

Depending on environmental conditions in and around a port, wave forces may also be a factor to be considered when establishing the bollard pull required. Harbour tugs can only operate effectively up to a certain maximum wave height (see Chapter 4), so only short beam seas are considered. It is difficult to calculate wave forces exactly. It is assumed that a ship's draft is large enough to reflect the waves completely. Because of the relatively short wave period it is further assumed that waves do not cause any ship motion. In practical terms it means we are considering conditions such as those found in windy but sheltered areas. The waves are short and steep and the wave length is small relative to the length of the ship. We are not considering open areas, where ocean waves or swell might impinge upon the ship and cause it to heave, roll and pitch. The forces per metre of ship's length due to these short period waves then amounts to approximately:

$$F_{wave} = 0{\cdot}5\ \rho\ g\ \zeta_a^{\,2}\ \text{Newton}$$

Because a ship's hull is not flat over its whole length and draft, the total force on a ship caused by short period waves is roughly:

$$F_{wave} = 0{\cdot}35\ \rho\ g\ L\ \zeta_a^{\,2}\ \text{Newton}$$

ρ = Density of seawater in kg/m^3.
L = Length of waterline; assume length between perpendiculars.
ζ_a = Wave amplitude, equal to 0·5 x wave height (H_S).
H_S = Significant wave height from trough to crest, as indicated by an experienced observer when estimating visually.

A 25% safety margin is again added, and converting to kilograms instead of Newton and wave amplitude in

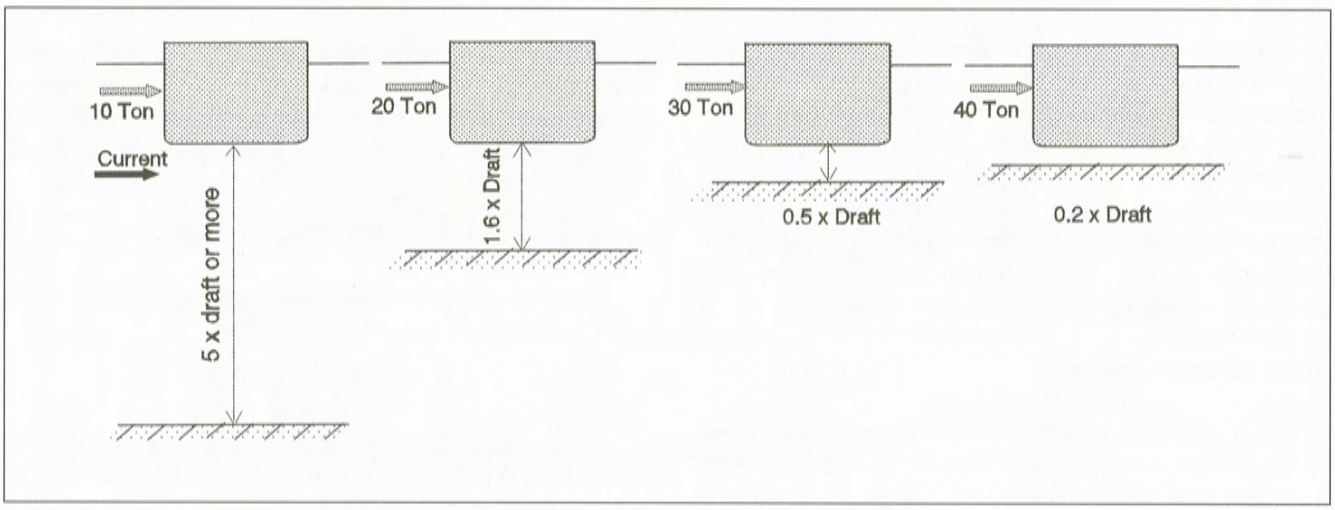

Figure 5.4 Effect of underkeel clearance on current force

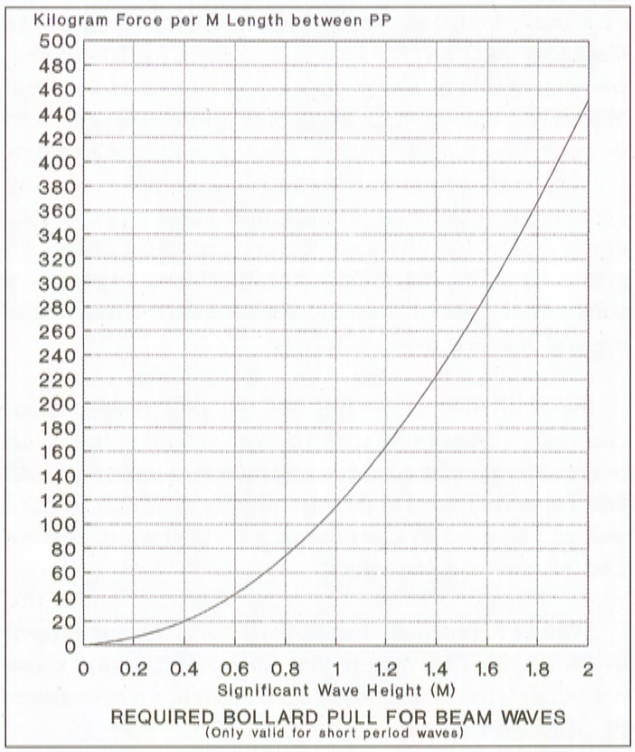

Figure 5.5 Bollard pull required for beam waves

significant wave height, the simplified formula for roughly calculating the bollard pull required to hold a ship up against short period beam waves reads:

$$F_{wave} = 112\ LH_S^2\ \text{kgf}$$

On the basis of this formula the bollard pull required is represented in the graph in figure 5.5. An example: A ship has a length between perpendiculars of 200m, and estimated wave height is 1m. The force of the beam waves on the ship is then (see formula):

$$112 \times 200 \times 1 \times 1 = 22400\ \text{kgf} = 22\ \text{tons}$$

5.2.4 The effect of ship's mass and berth construction

As mentioned earlier, tugs should have sufficient reserve power to stop a drifting ship. A comparable situation exists during berthing. An arriving ship is stopped parallel to a berth or jetty and is then pushed, pulled or heaved alongside. Wind, current and even waves may also push a ship towards a berth. Due to these forces a ship gains transverse speed which should be slowed down by tugs to 'dead in the water' or to a safe berthing speed at the moment a ship touches the fenders. So, tugs have to oppose the forces of wind, current and waves, and in addition have to reduce the transverse approach speed of a ship towards a berth, which requires additional bollard pull. Of course, the wind may blow offshore and tugs may need full power to push or pull a ship alongside. But even when there is no wind, current or waves, bollard pull is needed to control a ship's transverse speed.

The larger a ship's displacement the more bollard pull is needed to stop sideways movement. Not only the displacement but also the water mass moving with a ship influences bollard pull required. This is called 'added' or 'hydrodynamic' mass. Virtual mass is the sum of displacement and added mass. The exact amount of added mass is difficult to determine. The added mass increases with decreasing underkeel clearance. Furthermore, it depends on a ship's underwater shape and is very large with a sideways motion. It then normally varies between 25% to 100% of a ship's displacement. Many formulae used for calculating virtual mass of a berthing ship, especially for fender design, indicate values ranging from 1·3 up to more than 2·0 times the displacement.

Photo: Port of Gladstone, Australia

Figure 5.6 Open berth construction for bulk carriers

Berth construction also affects approach speed. Solid berths reduce a ship's approach speed because a water cushion builds up between ship and berth. Open berths or jetties do not reduce approach speed as the water can flow away in any direction.

For fender calculations it is generally recommended to apply for a water depth of 1·5 times ship's draft as virtual mass 1·5 times the displacement and for a water depth of 1·1 times ship's draft as virtual mass 1·8 times the displacement.

As virtual mass 1·8 times displacement is taken and berth construction is then accounted for. A rough indication can thus be made of tug forces required to stop sideways movement:

For open berths: $$\frac{0{\cdot}09\ D \times V_i^2}{S} \text{ tons}$$

For solid berths: $$\frac{0{\cdot}07\ D \times V_i^2}{S} \text{ tons}$$

V_i = Initial speed in metres/sec
D = Displacement
S = Stopping distance in metres

This formula is based on zero final speed and the calculated force is in tons. Final safe approach speeds for VLCCs are generally a maximum of 6-8 cm/sec.

In the following three examples an initial speed of 0·5 knots (0·25 m/sec) is assumed and tugs start pulling when a ship is 30m away from a berth. Transverse speed should be zero when a ship touches a jetty or berth.

- *A 250,000 dwt ballasted tanker*
  Length overall 340m, beam 38m, draft 9m (29·5ft) and displacement 124,000 tons. She has to be berthed alongside an open jetty. According to the formula the total tug power required to stop the ship in 30 metres is approximately 23 tons.
- *A 250,000 dwt loaded tanker*
  Draft 20·4m (67ft) and displacement nearly 300,000 tons – much more power, almost 60 tons, is needed.
- *A container ship*
  Length overall 294m, beam 32·2m and draft 12·2m (40ft), displacement 80,000 tons. She has to be berthed at a solid berth. Based on the assumptions above the bollard pull required to stop her in approximately a ship's width is 12 tons.

These calculations give an indication of the forces required. In line with experience they show that large displacement ships require large stopping forces. Furthermore, berth construction is a factor influencing approach speed.

Loaded tankers and bulk carriers with large displacement need the largest tug power for controlling transverse speed. These ships are less affected by wind. When there is any current, berth construction should be such that the current runs in line with the berth or jetty, though unfortunately this is not always so. In any case, tugs should have sufficient reserve power to compensate for any current and/or wind effect. In general, when handling heavy ships, tugs use a substantial part of their power to control transverse approach speed towards a berth.

As draft decreases the bollard pull required for controlling transverse speed becomes less, as indicated in the examples for a loaded and ballasted tanker. Lateral wind area increases and consequently available bollard pull can be used to keep the ship up into wind, current and/or waves, if necessary.

Newer tugs are able to operate for a limited time at 110% MCR. This means that for a short period these tugs can deliver additional bollard pull, an advantage in critical situations.

For ships affected by wind, current and/or waves a safety margin is included in the graphs, also for the purpose of controlling transverse speed. For loaded vessels, tankers and bulk carriers, bollard pull required for controlling transverse speed is included in the formula in section 5.3.1.

5.2.5 Tug wash effects

In certain pulling situations, a tug's propeller wash impinges on a ship's side, bow or stern, reducing pulling effectiveness. The smaller a ship's underkeel clearance

Photo: Author

Figure 5.7 A tug's propeller wash hitting a ship's hull, reducing towing effectiveness

the larger the negative effect of propeller wash hitting the hull. Increasing propeller revolutions or thrust worsens the situation because counter effect also increases, caused by a larger, more concentrated propeller wash. Proper towline length and towing angle

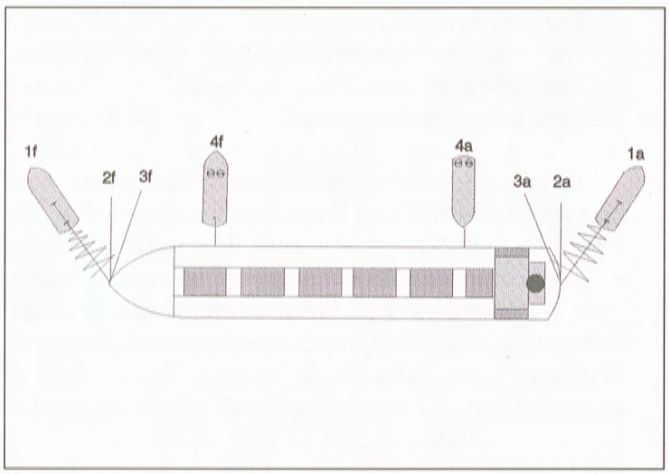

Figure 5.8 Different towing positions

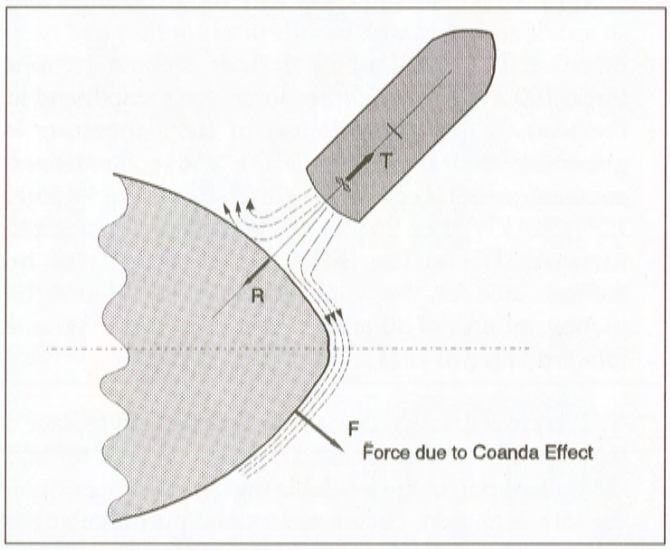

Figure 5.9 'Coanda' effect

reduce this adverse effect. The less the underkeel clearance and the more power needed, the longer a towline should be.

In figure 5.8, several towing positions are given for a ship stopped in the water. In positions 1f (f=forward) and 1a (a=aft) there is a fair possibility that the pulling tugs experience loss of pulling effectiveness due to propeller wash hitting the bow and stern almost at right angles. A ship's hull form, shape of bow and stern and whether she has a large bulbous bow, influence loss of effectiveness. For the pulling tugs, e.g. tug 1f, it might even be possible that the tug's wash effect causes a turning moment on the ship in an opposite direction to that expected from the orientation of the tug. Such an effect is shown in figure 5.9. The ship is loaded, has a bluff bow and a small underkeel clearance. A conventional tug is pulling at right angles to the ship's hull on a short towline. The consequence is an almost total loss of towing effectiveness by the reaction force R of the propeller wash hitting the ship's hull. In addition, the bulk of the accelerated water flow goes around the bow of the ship and remains attached around the curved surface. This is called the 'Coanda Effect'. The flow creates a low pressure resulting in a force F. This has to do with the Bernoulli effect, which is explained in the next chapter. The result is that the pulling force T is opposed by the reaction force R and the only force left is force F, giving the ship a forward and starboard instead of port turning movement.

Compared to positions 1f and 1a of figure 5.8, positions 2f and 2a may show less loss of effectiveness. Regarding loss in effectiveness due to propeller wash towing positions and towing directions 3f and 3a are considered the most effective. Tugs operating at a ship's side, in positions 4f and 4a, have a large loss of effectiveness when pulling. When operating in the push-pull mode towline lengths are short and pulling effectiveness can even be less than 50%, depending on how close the tug's propellers are to a ship's hull.

Tug propellers should be as far as possible away from a ship's hull. Conventional tugs, towing on a line, have their propellers closer to a ship's hull compared with tractor, reverse-tractor and ASD-tugs. The latter two types, when towing or pulling over the bow, have their propellers furthest away from the ship's hull. This is of special importance for tugs operating at a ship's side or in narrow harbour basins where they often have to work on short towlines due to limited manoeuvring space. VS tugs have less pronounced propeller wash compared with conventional tugs and tugs with azimuth thrusters, in particular those with propellers in nozzles. Consequently, the negative effect of VS propeller wash hitting a ship's side is less. Tugs with azimuth thrusters can set their thrusters at a small angle, at least with independently controlled thrusters, thus deflecting the wash.

So, loss of pulling effectiveness of forward and aft tugs towing on a line can be minimised by appropriate towline length, towline angle and/or thruster setting. A towing winch is very useful for adjusting towline length in accordance with circumstances. For tugs operating at a ship's side, when pulling, the larger the distance between propellers and ship's hull the better.

For tugs operating at a ship's side and holding her up into the wind, current or waves on short towlines, the required pull in the graphs in figures 5.1, 5.3 and 5.5 should be increased by, say, at least 20%, resulting in a total safety margin of 50%.

5.3 Bollard pull required

5.3.1 Bollard pull required based on environmental conditions and displacement

In the following assessments of required bollard pull it is assumed that equal tug power is required forward and aft, which is not always the case. Yaw moments can be caused by wind and depend on the wind force, angle

of attack and on the ship's profile above the water, which varies with draft, trim and deck cargo. In addition,

current may cause a yaw moment, depending on the current velocity, angle of attack and ship's underwater profile which varies with draft and trim. Although with beam winds or currents a ship may experience a yaw moment, they are generally largest with quartering winds and currents. Yaw moments caused by currents even increase with decreasing underkeel clearance. Yaw moments caused by wind and/or current may result in a higher bollard pull requirement forward or aft.

There is another aspect to be taken into account. When for example pulling a ship off the berth, the lateral underwater resistance becomes effective. On a ship having a large stern trim, the centre of pressure of the lateral resistance lies aft of midships. When forward and aft the same amount of bollard pull is used, the after tug(s) have to use more power than the forward tug(s) to pull the ship parallel off the berth. A ship down by the head may require more bollard pull forward than aft.

It is because these turning moments vary so much, only the required total bollard pull is considered. How much bollard pull or how many tugs forward and aft are required should be carefully considered each time, based on an assessment of the actual situation and circumstances.

Therefore, experience is an indispensable factor. As mentioned earlier, master and pilot are in a better position to assess requirements for tug assistance and unwanted effects to be avoided if they have a good understanding of the forces and other factors influencing a ship and of tug performance.

Ships affected by current, wind and/or waves

The graphs in figures 5.1, 5.3 and 5.5 give an indication of the bollard pull required by ships affected by wind, current and/or waves. As an example for using the graphs:

Container ship: length overall 294m, length between perpendiculars 281m, beam 32m, draught 12·5m, water depth 13·8m. Top of containers to waterline approximately 22m. Onshore wind at right angles to the berth. Wind speed 30 knots (7 Bft). The location of the container berth is not too good, with a cross current of 0·5 knots. Short period waves of 0·5m height are also coming from a direction perpendicular to the berth.

Ratio draft/water depth 13·8: 12·5	= 1·1
Area above water, approx. 294 x 22	= ±6500 m^2
Underwater area, approx. 281 x 12·5	= ±3500 m^2
Displacement	= 75,000 t

When towing on a line or pulling at a ship's side on not too short a towline, the following compensatory total bollard pull is required:

The onshore wind (figure 5.1)	=	117 tons
The crosswise current (figure 5.3)	=	42 tons
The waves 281 m x 30 kg (figure 5.5)	=	8 tons
Total bollard pull required	=	167 tons

To compensate for wind, current and waves, four tugs with at least 40 tons bollard pull are needed. In the total bollard pull required for wind, current and waves a safety factor of at least 20% = 33 tons is included. This reserve power is also, amongst other things, sufficient to control approach speed towards the berth. Without any current or waves, four tugs of approximately 30 tons bollard pull would be needed or, when available, two of 60 tons, to compensate for wind forces.

Most container ships, car carriers, ro-ro ships and so on are equipped with bow thrusters or bow and stern thrusters. 100 HP of a bow thruster is about 1·1 tons force, 100 kW about 1·5 tons force, for a ship 'dead in the water'. The effectiveness of stern thrusters is generally somewhat less. If the above mentioned container vessel is equipped with a bow thruster of 2500 HP (1840 kW) then 28 tons less bollard pull is required forward. If just the influence of wind is to be compensated for, this would lead to a reduction in the number of tugs of 30 tons from four to three, i.e. one forward and two aft.

It is clear that whether a bow thruster can replace a tug depends on the forces to be compensated for and the bollard pull of the available tugs. It also depends on the local situation, circumstances and port regulations as to whether side thrusters can replace one or more tugs. For certain situations, for example when passing narrow bridges where tug assistance is required, it is preferable to have a forward tug on a line. Regardless of the fact that a ship is equipped with a bow thruster, its effectiveness decreases very quickly as a ship gathers forward speed. At a speed of two knots through the water, effectiveness is usually reduced by 50% compared to zero speed. At four knots the effectiveness of a bow thruster is reduced almost to nothing. At such speeds a bow thruster cannot replace a forward tug.

It should also be noted that the effect of a bow thruster on a ship becomes less with decreasing underkeel clearance, due to the higher forces needed to turn a ship, to move a ship sideways or to stop a sideways movement and to compensate for the influence of currents. Therefore a ship equipped with a bow thruster, which normally uses no tugs, may require tug assistance in shallow water conditions.

When tugs operate in push-pull mode and have to hold a ship on short towlines up into wind, current and/or waves, the required pull in the graphs in figures 5.1, 5.3 and 5.5 should be increased by at least 20%. In the case of the container ship with a bow thruster and an

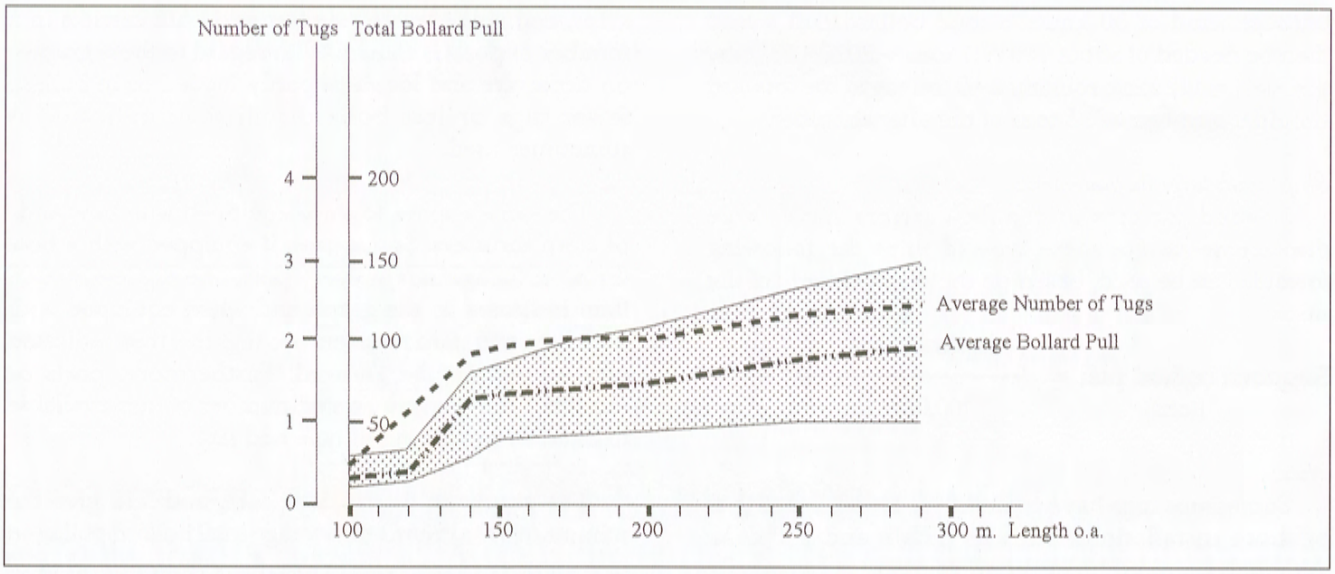

Figure 5.10 Total bollard pull in tons and average number of tugs for container and general cargo vessels as used in a number of ports around the world. Depending on the port and local circumstances less tugs may be used when ships are equipped with side thrusters

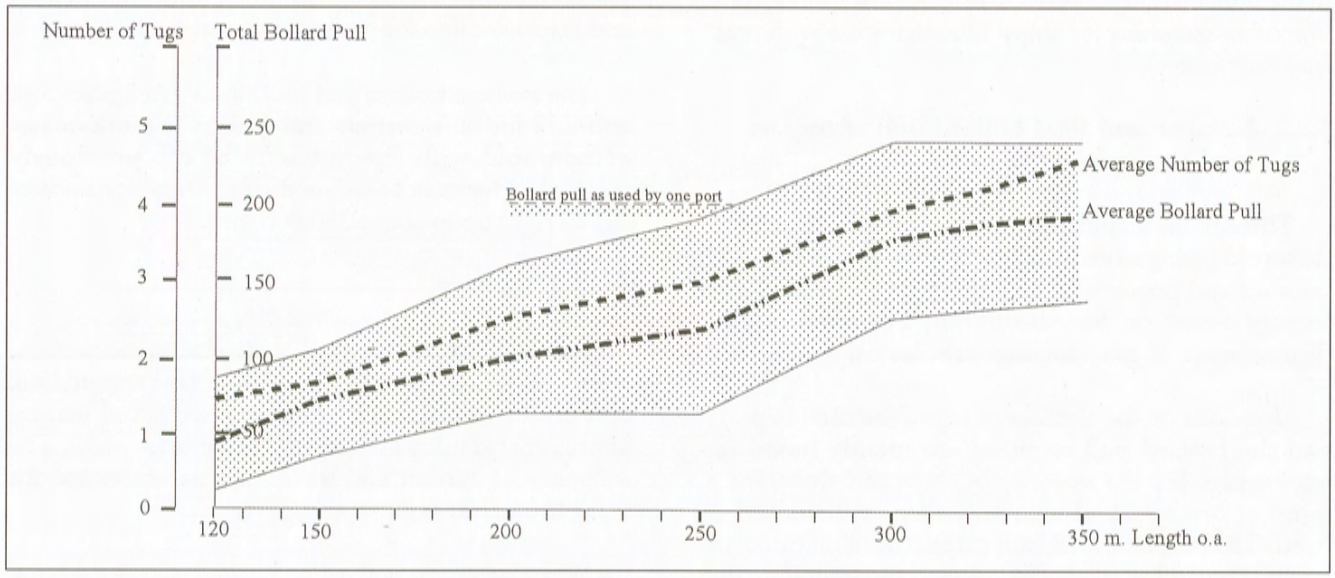

Figure 5.11 Total bollard pull in tons and average number of tugs for tankers and bulk carriers as used in a number of ports around the world (based on length overall)

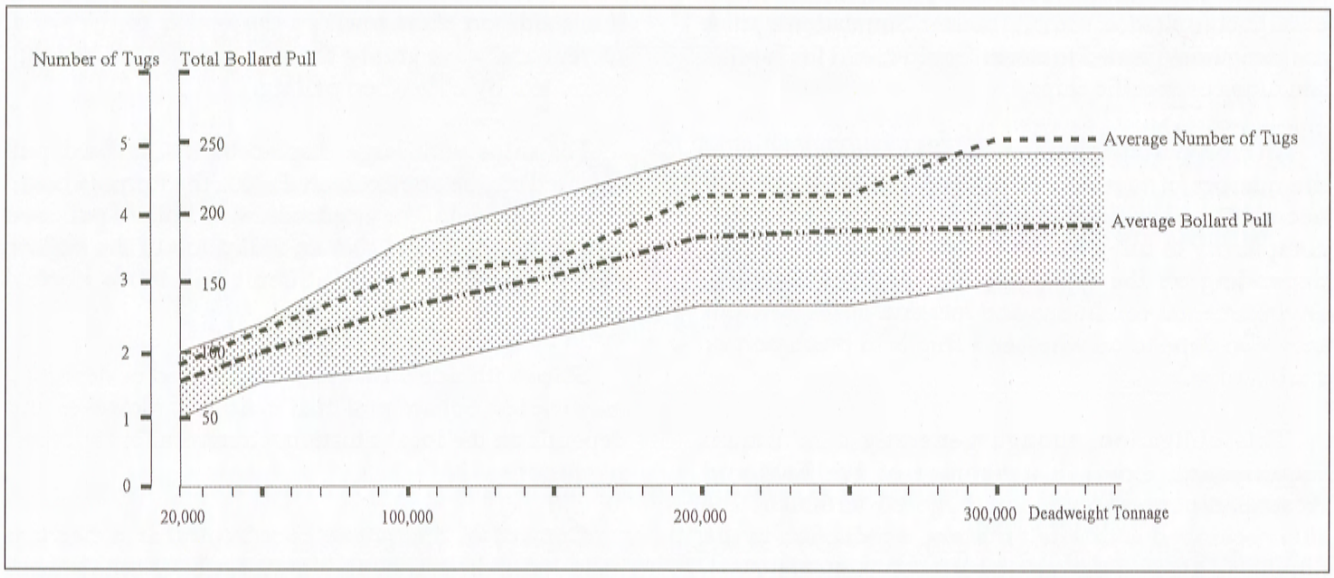

Figure 5.12 Total bollard pull in tons and average number of tugs for tankers and bulk carriers as used in a number of ports around the world (based on deadweight)

onshore wind of 30 knots, a total bollard pull would then be needed of about 140 (117 tons + 20%) - 28 (bow thruster) = 112 tons: roughly a 40 ton tug at the forward shoulder and two of 35 tons at the after shoulder.

Ships with large displacements

Loaded tankers and bulk carriers have large displacements. For these type of ships the following formula can be used, based on the displacement of the ships:

$$\text{Required bollard pull (tons)} = \left(\frac{\text{displacement}}{100{,}000} \times 60\right) + 40$$

Note:

Sometimes tugs have to assist in station keeping at offshore installations, such as SPMs and F(P)SOs. Although required bollard pull as discussed generally also applies to these tugs, the reader is further referred to the information included in the OCIMF publication 'Recommendations for ships' fittings for use with tugs' (see References).

5.3.2 Number and total bollard pull of tugs as used in a number of ports

There is no uniform system in use in ports around the world giving a relationship between size of ship and number and power of tugs required. Calculations are mostly based on length overall, but deadweight, displacement or gross tonnage are also used as factors.

Decisions on the number of tugs to be used in ports and the bollard pull required are mainly based on experience. For the majority of ships and situations a more or less standard number and/or bollard pull is used. Large ships and more specific situations or circumstances are generally assessed separately by the pilot and/or port authorities to determine the tug assistance required and if necessary and possible this is done in consultation with the master. Simulation studies are sometimes needed to assess requirements for specific situations or specific ships.

In most ports shipmasters or pilots are free to order the number of tugs and/or bollard pull they consider necessary to handle a ship safely. In some ports it is compulsory to use a fixed number and power of tugs, depending on the type, size and draft of the ship, environmental conditions and location of the berth. It may also depend on whether a ship is to berth port or starboard side to.

This obligation, though generally a minimum requirement, exists in a number of Far East and Australian ports and at some large oil terminals. For ships equipped with side thrusters, a reduction in the number of tugs or required power is sometimes allowed.

In figures 5.10, 5.11 and 5.12 tug use for general cargo ships, container vessels, tankers and bulk carriers in a number of ports is shown. With regard to these graphs, on departure and for ships partly loaded or in ballast, fewer tugs or less bollard pull than indicated is sometimes used.

The same applies to ships equipped with bow and/or stern thrusters. Sometimes, if equipped with a bow thruster, though not in every port, one tug less is used than indicated in the graph and when equipped with both bow and stern thrusters two tugs less than indicated may sometimes be allowed. Furthermore, ports or terminals may have a limited number of tugs available to assist ships varying in type and size.

The graphs in figures 5.10, 5.11, and 5.12 give the minimum, maximum and average total bollard pull used in a number of ports, including the average number of tugs. For bollard pull used the upper line of the graph is assumed as the requirement for more difficult situations and the lower line for normal and easier situations.

The average bollard pull used shown in figures 5.11 and 5.12 for bulk carriers and tankers is more or less comparable with the outcome of the previously mentioned formula based on displacement for ships of deadweight up to about 230,000 tons.

5.3.3 Summary

For ships affected by wind, such as container vessels, ro-ro vessels, car carriers, gas carriers, tankers and bulk carriers in ballast, the bollard pull required can be approximated using the wind graph for cross winds. The influence of current and waves can be accounted for using the current and wave graphs.

When assessing bollard pull required, the assisting mode – whether on a line or operating at a ship's side – should be taken into account. For tugs operating at a ship's side on short towlines the results of the wind, current and wave graphs should be increased, roughly estimated, by 20% when pulling.

For ships with large displacements, bollard pull required can be approximated using the formula based on displacement. The graphs showing bollard pull used in a number of ports give an indication of the bollard pull required for more difficult and more normal situations.

Ships with side thrusters, partly loaded or departing may use less bollard pull than indicated. However, this depends on the local situation, circumstances and port regulations.

Control of transverse speed towards a berth is included in the graphs and formulas. For a rough check the formula as shown in section 5.2.4 can be used.

5.3.4 Influence of tariffs on availability and number of tugs used

Shipping companies have to pay for the use of tugs, though in some ports tug tariffs are included in port dues. Tug tariffs are usually based on the size of ship and number of tugs or total bollard pull used. In many ports ships are charged extra for tug assistance during adverse weather conditions such as strong winds, ice or fog. The same applies to tug services during night hours, at weekends and when tug assistance takes longer than a specific basic time period.

Tug tariffs often affect the number or bollard pull of tugs used. That is why some attention is paid to this subject, bearing in mind that circumstances and tariffs differ by port.

Ship arrivals and departures have an irregular pattern and may be influenced, amongst other things, by the working hours of dock labour and tidal restrictions. This means that ships may arrive during peak hours, for example during hours of slack or high tide. The number of tugs in a port is to some extent determined by shipping traffic during these peak hours. A number of tugs rendering assistance during busy hours will be unemployed outside those hours, so peaks in shipping traffic affect efficient employment of a tug fleet in a negative way.

To run a fleet more efficiently and to reduce costs a tug company could consider reducing the number of tugs. However, this automatically affects the availability of tugs during peak hours, causing waiting time or resulting in fewer tugs being used for a particular ship movement, thus affecting safety.

A category of ship with an irregular pattern of tug use is those with side thrusters, twin screws and high lift rudders, such as large container vessels, cruise vessels, ferries, car carriers and ro-ro vessels having a large windage. These ships often don't use tugs, or only a minimum number, except when the wind is increasing. This can happen after weeks of calm weather. These ships affect the availability of tugs, especially during adverse weather conditions, resulting in a further decrease in tug fleet efficiency.

In addition, ships are getting larger and consequently tug power has increased considerably in recent years. Port dimensions have often not expanded proportionately to the increase in ship sizes so large ships in restricted manoeuvring areas place a heavier demand on towing assistance. More powerful tugs also mean higher costs for towing companies.

Due to the high costs of tugs and their crews the inefficiency of tug fleet use may result in the availability of tugs coming under pressure, which is the case in a number of ports. However, the availability of a sufficient number and bollard pull of tugs, especially during peak hours, is an essential factor in good service to the shipping industry and to running a port efficiently. But considering the position of towing companies, availability alone does not pay. Neither does increased tug power, unless tug tariffs are also based on total bollard pull used.

Depending on shipping traffic in a port, a more efficient tug fleet – without affecting the availability of tug assistance – can be achieved by the use of less units but of higher power. Less tugs can thus be used per ship, for example, for large tankers or bulk carriers. These types of ship normally use a standard number of tugs of certain bollard pull. Beyond peak hours less tugs will then be unused.

In ports where problems emerge regarding the availability of tugs and tug power a review of the existing tug fleet may be necessary including a review of tug tariffs. This may result in less units of higher power, as mentioned above.

Regular meetings between port authorities, towing companies, shipping companies and pilot organisations is necessary, in order to keep port services at an acceptable level without raising tug tariffs too much. It might be worth considering whether a basic tug tariff could be included in a port tariff to ensure minimum availability of tugs.

As indicated, in certain ports tug tariffs may influence the availability of tugs and consequently a pilot's work. Pilots should be permitted to assess the minimum tug requirement to handle a ship safely. On the other hand, it is quite reasonable that the cost of tug assistance is a factor taken into account by a shipping company when ordering tugs, although economy should never have priority above safety. The cost of tugs is frequently the background of discussions between masters and pilots, when the number required is discussed, except for ports where the use of tugs is compulsory or strictly regulated.

A good contract between shipping companies and tug owners, stating the number and bollard pull of tugs to be used, and covering circumstances when additional tug power might be needed, e.g. adverse weather conditions, is strongly recommended. When tug assistance is necessary it can then be expected that the required number and bollard pull of tugs will be available without additional cost.

Chapter SIX

INTERACTION AND TUG SAFETY

6.1 Introduction

PREVIOUS CHAPTERS DEALT WITH THE CHARACTERISTICS and effectiveness of various types of harbour tug. Another very important aspect, sometimes mentioned in those chapters, is the risks harbour tugs may encounter when rendering assistance. It is an essential point when engaged in shiphandling operations. Essential, because it is not only the safety of a tug and her crew that could be at risk but also the safety of a vessel. When rendering assistance tug captains and pilots should be fully aware of the risks involved. Since a number of unsafe situations can be traced back to interaction effects, attention is first paid to this subject and also the influence of shallow water on several interaction effects and the tug assistance required.

6.2 Interaction and shallow water effects

6.2.1 Interaction effects influencing tug performance

There are different kinds of interaction. Some influence tug performance, others affect tug safety, some both. Interactions influencing tug performance are:

- *Tug propeller – tug hull interaction*
  For example, the astern thrust of a reverse-tractor tug/ASD-tug is 5-10% less than ahead thrust, as a result of propeller wash hitting the afterbody of the tug and so reducing bollard pull when astern thrust is applied.
- *Interaction of tug propellers*
  This is especially the case with azimuth thrusters and VS propellers. Depending on thrust direction, the two propellers of tractor and ASD/reverse-tractor tugs interact to a certain extent and affect a tug's performance.
- *Tug – ship interaction due to tug fendering*
  Fender characteristics such as energy absorption capabilities and friction coefficients influence the interaction of forces between tug and ship and also tug performance.
- *Tug – towline interaction*
  Tug reactions such as tug list and consequently tug performance are influenced by towline characteristics, especially by its dynamic load absorption capabilities.
- *Tug propeller – ship hull interaction*
  The reduction in pulling performance due to tug propeller wash hitting a ship's hull has been dealt with in a previous chapter. In the case of small underkeel clearance this effect is more pronounced. Pushing tugs are also affected by this type of interaction when propellers are close to a ship's hull, due to interrupted water flow towards the propellers.
- *Tug hull – ship hull interaction*
  The influence of this effect on tug performance is particularly marked when a tug operates at a ship's side. This kind of interaction is also influenced by shallow and narrow waters and in particular by ship's speed, affecting tug safety as well.
- *Ship propeller/ship hull – tug interaction*
  These interactions affect performance when operating as stern tug in the propeller slipstream or ship's wake. The effect of ship's wake increases in shallow and narrow waters.

The points above show that there are several kinds of interaction affecting tug performance. Tug hull – ship hull interaction affects tug safety as well. This effect and ship propeller/ship hull – tug interactions are dealt with in this chapter. The others have been discussed in previous chapters. Small underkeel clearance affects some of the interaction effects, as indicated. It is worth considering some other effects of shallow water.

6.2.2 Shallow water effects with respect to tug assistance

Some effects of shallow water have already been dealt with when discussing the bollard pull required in relation to current forces and a ship's displacement. The relationship between decreasing underkeel clearance and increasing bollard pull required to hold a ship up into a current or to stop a sideways moving ship has been mentioned previously.

There are other shallow water effects necessitating tug assistance and requiring the full attention of pilots and tug captains. There are situations where these effects occur and tug assistance is then very welcome. Shallow water, meaning small underkeel clearance, has the following effects amongst others:

- *Increase of bank suction and bow cushion effects*
  A ship proceeding to one side of a river or channel and close to a bank experiences suction forces towards the bank. These forces are not uniformly distributed over a ship's length. Their resultant acts somewhere abaft of midships. The overall effect is a bodily attraction towards the bank – bank suction – and a yawing effect away – bow cushion. A ship can proceed in a stable situation parallel to the bank by applying rudder towards the bank. But as soon as this stable situation is disturbed e.g. by an irregular profile of the bank, even a submerged bank, or by careless steering, a ship may sheer away from the bank. If this happens it is difficult to control the ship and she may even sheer to the other side of the river or channel.

The smaller the underkeel clearance the more pronounced bank suction and bow cushion effects are. They can be kept under control by keeping away from banks as far as possible and by adjusting ship's speed. Bank suction and bow cushion effects increase proportionately with ship's speed, viz. by the square of the speed. At a speed of four knots attraction towards a bank and yawing moment away from it are four times as high as at two knots. Also, the lower a ship's speed the more reserve power is available to give a 'kick ahead' with rudder hard over to counteract a sheer. In shallow waters and when close to banks tugs should be on the alert to counteract an unexpected sheer. Bank suction and bow cushion effects have all to do with a Mr. Bernoulli, which is explained in the next section.

- *Decrease of rudder effect*
- *Possible increment of transverse effect of the propeller*
- *Increase of turning circle radius*
  The turning circle radius in shallow water is much larger than in deep water. The initial rate of turn is much smaller. Manoeuvring a bend in really shallow water is therefore more difficult than in deep water. Tug assistance may be required to take a bend properly. The lower a ship's speed, the more reserve power is available to control movement and the more effectively tugs can operate.

- *Increase of stopping distance due to larger virtual mass*
  In shallow water a ship drags a large amount of water along with her, increasing to as much as 40% of her displacement when keel clearance reduces to 20% of the draft. When underkeel clearance is small, more astern power and consequently more tug power are needed to stop a ship than in deep water.

When passing through a channel with little underkeel clearance the large amount of water following a ship occasionally leads to another interesting effect. When a ship comes to an abrupt stop in a basin at the end of a channel the following mass of water needs time to slow down and overtakes the ship. It may push her ahead, may increase the rate of turn, or push her sideways when she is turning. One has explained that this effect is caused by the so-called 'added mass'. However, it is more likely to be the water flow in the channel following the ship and filling the gap behind which causes the delayed effect when a ship comes to an abrupt stop. This effect has been experienced, for example, with large tankers in a Caribbean port (see figure 6.1). The extent of the effect is directly related to ship's speed.

It is clear that low ship's speed is very important when proceeding in shallow waters. Shallow water effects also enlarge interaction effects between ships. From the point of view of safety during tug operations one should always be aware of the possible occurrence of these effects.

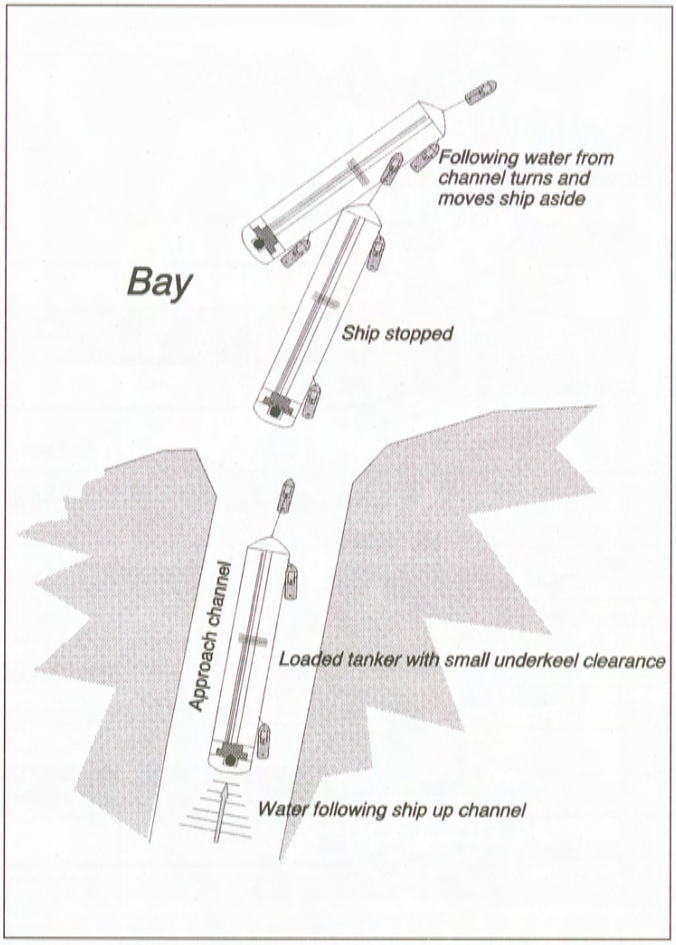

Figure 6.1 Effect of following water when passing through a channel with a deep loaded ship and coming to a stop at the end of the channel

6.2.3 Interaction effects influencing tug safety

Flow pattern around a ship

The interactions which most endanger tug safety are those happening when ships are sailing or manoeuvring close to one other. It is the water flow around a ship which produces interaction effects. Whether a ship is moving through the water or water is moving along a ship does not make any difference; water speed relative to the ship is the same.

For further explanation see figure 6.2, where the actual flow pattern that could be experienced, for instance, by a tug stopped in the water is shown. In figure 6.3 the water flow relative to the ship's speed is given.

If a ship underway through the water had no beam or draft, the water round the ship would have constant speed relative to the ship – the relative speed of the water would be the same as the ship's speed. Naturally, however, a ship does have beam and draft, so water is pushed sideways and downwards by the ship and still has to pass along the ship from bow to stern in the same time but on a path that is longer than the length of the ship. Hence most of the time during its passage along the ship the relative velocity of the water flow is increased.

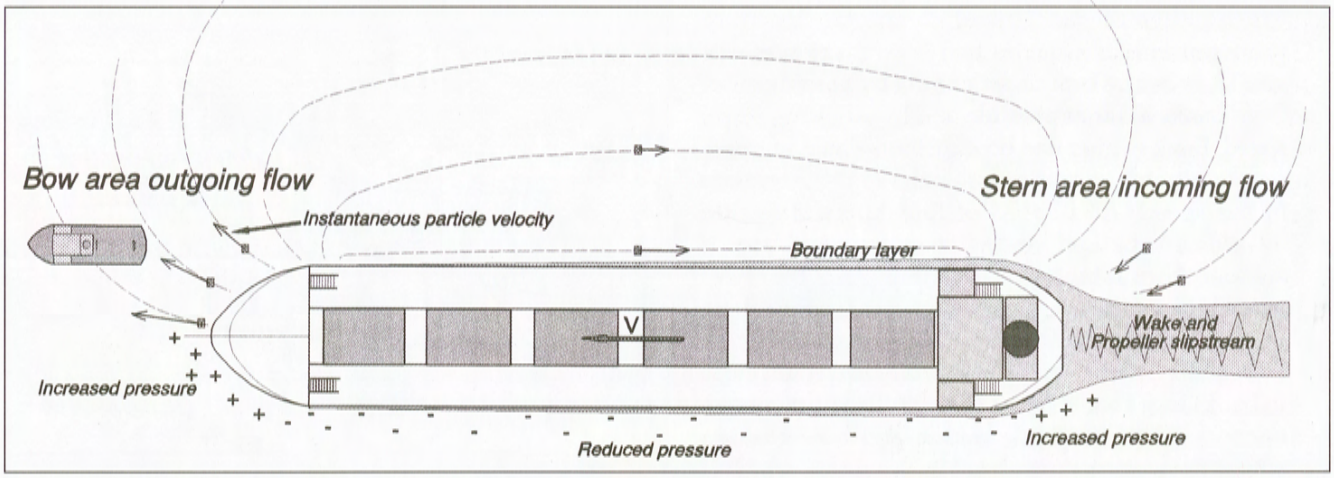

Figure 6.2 Schematic flow – unsteady flowfield as felt by an observer in a stationary tug seeing a ship approaching

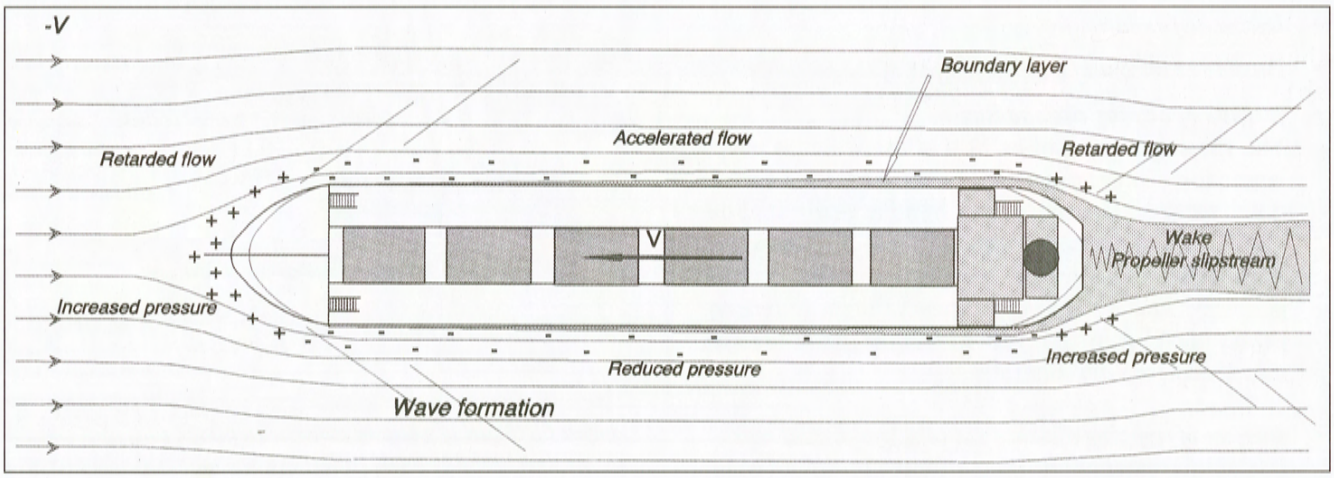

Figure 6.3 Pressure pattern and relative flow field around a bulk carrier

This is where Mr. Daniel Bernoulli comes into the picture. An 18th century Swiss philosopher, he established the relationship between water speed and water pressure. He showed that an increase in water speed results in a decrease in water pressure and vice versa, whereby the change in pressure is proportional to the square of the speed change. So, when water speed is doubled pressure reduces to a quarter.

Following Bernoulli's theory there are reduced pressure areas round a ship where the relative velocity of water flow is increased. If stream lines were parallel around a ship the reduction in pressure would be uniform. Well ahead of a ship the stream lines are equally spaced, but at a certain point they are wedged apart and as they go round the body of the ship they are compressed. At the stern the stream lines tend to spread again in an effort to fill the gap astern of the ship.

When stream lines diverge the speed of the water reduces and, according to Bernoulli, pressure increases. When stream lines converge, water speed increases and water pressure reduces. This boils down to conservation of energy in fluid flow. At low speeds a ship's wave making resistance is minimal. The wave pattern generated by a ship travelling at higher speeds causes wave making and wave braking (at the bow) resistance. The wave length found in such a wave pattern is a function of the speed of the ship. Pressure fields caused by the Bernoulli effect are the main cause of the wave pattern around a ship at low speeds.

It means that at the bow there is a high pressure area, a bow wave, followed by a low pressure field around the midsection while at the stern there is again a high pressure area, although lower than that at the bow.

Due to viscous resistance or skin friction water is dragged along with a ship, a little at the bow but more and more towards the stern. It forms a fairly dead layer of water, called the boundary layer, increasing in thickness from bow to stern. Abaft the stern the boundary layer forms the frictional wake. This boundary layer and wake astern of a ship result in a less marked spreading of stream lines, resulting in a smaller high pressure field near the stern than at the bow. Particularly in the case of wide bodied ships, water speeds up round the forward but less round the aft shoulders, causing a local wave trough.

In shallow water the flow underneath a ship is restricted and more water has to pass along the ship

sides than in deep water. Consequently along the ship sides the water has a higher speed and the reduction in pressure is larger, while high pressure near bow and stern increase, assuming the same ship's speed as in deep and open waters. When in shallow and in narrow waters, the water flow between a ship and the banks is much more confined, causing an even higher water speed and a much larger reduction in pressure along a ship side and a further increased pressure near bow and stern, with the highest pressure near the bow.

This also explains bank suction and bow cushion effect. A ship proceeding on one side of a channel has a more confined water flow at the side nearest the bank, causing higher water speed and lower pressure at that side. The ship is forced towards the low pressure side. Due to the boundary layer, also formed along the bank, the space between bank and ship narrows towards the ship's stern, causing the resultant force to act somewhat abaft of midships, giving the ship a yaw moment away from the bank. In addition, the high pressure near the bow close to the bank increases and forms a pressure cushion, causing the bow cushion effect. The effect of a steep bank is bigger than that of a sloping bank, because with a sloping bank some sideways inflow of water is possible causing a smaller reduction in pressure.

The most relevant pressure fields around a ship have now been explained. The important role that the ship's speed plays is clear. Besides the importance of an appropriately low speed, it is also important to keep in mind that interaction effects will increase when underkeel clearance is small and when close to banks.

Interaction effects between ships or between a ship and a tug are generated in the same way as between a ship and a bank. It is again the distance off and the relative speed of the water between the ship and the tug which causes the degree of interaction.

Tug – ship interaction with respect to tug safety

In figure 6.4, a tug is slowly overtaking a bulk carrier and travelling past the ship. The most relevant interaction effects on the tug are now considered. The approximate stream lines around the ship are shown.

When the tug approaches the stern from a position behind tug no. 1, it experiences an increase of speed due to the relatively low water speed. The tug may be pushed sideways to starboard as well by the incoming waterflow (see also figure 6.2).

When coming nearly abeam of the stern (position 1) the tug is sucked towards the ship because the speed of water increases between tug and ship's hull causing a low pressure field and consequently a suction force towards the ship. Since the tug's forepart is closer to the ship than the stern the tug experiences a starboard turning moment. A lift force caused by a cross flow on the tug also pushes the tug towards the ship.

As it proceeds the tug's bow reaches the trough near the aft shoulder of the ship, causing an increased turning effect to starboard and the tug needs more power in order to maintain speed due to the higher water speed encountered.

When abeam of the aft shoulder the tug is sucked more towards the ship, due to the local wave trough. In addition, there may still be some lift force experienced due to cross flow. As soon as the tug moves further forward and parallel with the ship's hull it experiences a sudden outward turning moment, caused by the tug's bow cushion. In addition, the tug's stern is near the wave trough at the aft shoulder (position 2) where the water speed between the tug's stern and ship's hull is high. As a consequence the stern is sucked towards the ship. The tug is also sucked bodily towards the ship.

Near the ship's midship section the tug is still sucked towards the ship with an outward turning moment (position 3), all caused by effects identical to bank suction and bow cushion effects. Near the bow the situation changes quickly. When the tug reaches the forward shoulder, due to the higher water speed and the local wave trough the tug needs more power to proceed at the same speed. When passing the forward shoulder suction forces increase rapidly due to increased local flow velocities. As soon as the after end of the tug reaches the wave trough the outward turning moment increases again (position 4).

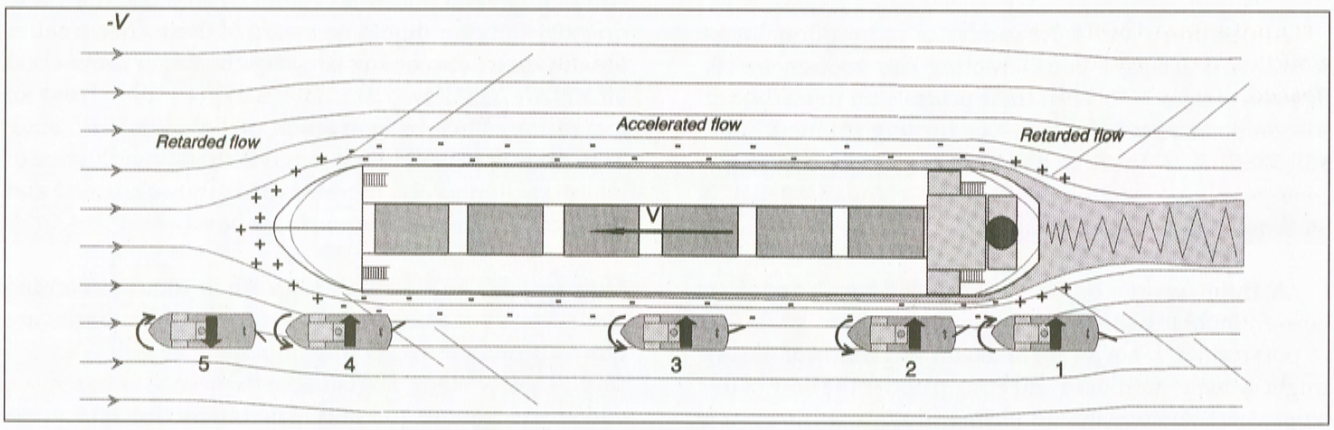

Figure 6.4 Interaction effects on a tug when proceeding along a ship

When moving a little further forward (between positions 4 and 5) the outward turning moment suddenly changes into an inward turning moment. This is due to the cross flow near the bow of the ship acting on the tug's rudder or skeg as a steering force. Due to the lift force caused by the cross flow the tug drifts sideways away from the ship.

Manoeuvres to pass safely past a ship, including the positions where towlines are passed, are now considered for two main types of tug. Conventional tugs with propulsion and steering aft and ASD/reverse-tractor tugs with steerable propulsion aft are all considered conventional tugs. Tractor tugs with steerable propulsion forward are the other main type. The steerable bow thruster of combi-tugs tends to give a similar effect to the propulsion of tractor tugs, but the power of the bow thruster is low compared to the propulsion of tractor tugs.

Tugs approaching the stern to pass or pick up a towline should be well aware of the increased speed and possibly sideways movement to avoid a collision with the ship's stern.

A conventional tug when in position 1 should apply port rudder to counteract the turning moment. However, port rudder also creates a sideways force in the same direction as the suction forces. Therefore when near this position conventional tugs should keep well away from the ship. Tractor tugs can direct their propulsion away from the ship, thus counteracting the starboard turn and the suction force, which is safer. Position 1 is also a position where towlines are passed. Conventional tugs should be particularly careful because of the turning moments and suction forces in this position.

Between position 1 and 2 the situation changes. A conventional tug should, within a short space of time, change from port to starboard rudder. In doing so, the sideways steering force created now points away from the ship. Tractor tugs have to set their propulsion in the direction of the ship's hull to counteract the turning moment but at the same time a sideways force is introduced in the direction of the suction force, which is not safe.

At position 3 and 4 the rudder of conventional tugs is still to starboard counteracting the suction force. Tractor tugs have to keep their propulsion to starboard to compensate for the bow-out turning moment, and still in the same direction as the suction forces. Especially near position 4, suction forces and turning moments to starboard may be marked.

A little further on, between positions 4 and 5, a conventional tug should abruptly change from starboard to port rudder. If not aware of the turning moment the tug might swing to starboard and end up under the bow of the ship. A tractor tug should change the propulsion from starboard to port to avoid coming under the ship's bow.

Between positions 4 and 5 tug power can be reduced to keep the same speed since the relative water speed reduces. Tugs not aware of the change in turning moment and maintaining their power setting run with increasing speed to starboard and possibly dramatic consequences. Attention should also be given to the fact that the cross flow acting on the underwater body of the tug causes a decrease in effective stability.

Positions 4 and 5 are also positions where towlines are passed. A conventional tug can keep a steadier position, because the application of rudder to counteract turning moment also involves counteraction of the suction and lift forces. A tractor tug when counteracting turning moments sets the propulsion in the same direction as the suction and lift forces and at the positions where suction forces occur the tug may come too close to the ship's bow. For a tractor tug it is more difficult to keep a steady position close to the ship's bow to pass a towline. Nevertheless, a tractor tug is safer because when coming too close to the ship's hull the steering forces with a tractor tug are directed away from the ship.

From position 4 a tug generally steers somewhat inwards to come closer to the bow to pick up or pass the towline. It is evident that this should be done with utmost care, due to the changing influences on the tug near the bow.

The interaction effects described here only give an indication of the influences on a tug. The effects differ by ship type and loading condition. For instance, the diversion of stream lines ahead of a ship is less with a fine formed ship, resulting in lower high pressure near the bow and consequently a smaller bow wave. The change in turning moment experienced on a tug near the ship's bow occurs further aft at slender ships. These ships also have less pronounced shoulders, so effects in these regions are less pronounced. There is also a shorter, flat area around the midsection, so changes in interaction effects quickly follow each other when passing along a slender ship, e.g. a container vessel.

A tug's underwater body and appendages have their influences as well, especially on the turning moments. Although interaction effects differ by ship and tug, these do exist and one should be aware of them. The smaller the distance between tug and ship the larger interaction effects are. Shallow water and narrow waters have an increasing effect on interaction between tug and ship. Most important to keep in mind is that the influence of all interaction effects increases sharply with speed and are most dangerous near a ship's bow.

Ship speeds can be rather high when tugs are coming alongside or making fast. Speeds up to five knots are quite normal for tugs taking or passing a towline near a ship's bow or stern. Higher speeds are not uncommon, even up to nine or 10 knots. The interaction effects are then large, especially for tugs taking a line at the bow.