

# BERTH SCOUR PROTECTION FOR MODERN VESSELS

By

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## 1. ABSTRACT

The increase in vessel size and vessel types along with new propulsion systems has created an increase in the scour action to berth beds. Traditionally, rock rip rap or armour has been predominately used for berth protection, but the required rock size now often makes it impractical and other scour protection types with a higher performance are required. To date scour protection design has generally been based upon bed flow velocity, however failure is generally due to the loads or forces acting upon it.

Recent research of the hydrodynamic load distribution upon berth beds will be presented. This provides greater understanding and supports a more appropriate basis of design for relatively impermeable insitu concrete scour protection types which will be presented. The use of a beneficial combination of scour protection types will also be shown in greater detail. The paper will highlight the effect that joints and edge protection have upon performance along with the importance of marine constructability and experienced supervision.

The paper may be of interest to Port Authorities, Design Engineers, Contractors, Operators, Vessel Manufacturers and Research and Guidance Authorities.

## 2. INTRODUCTION

The size of conventional vessels is continually increasing creating a reduction in bottom clearances and a demand for deeper berths. The combination of larger propellers with greater power and a reduction in bed clearance has created higher levels of bed scour action affecting berthing structures.

New types of vessels are now also in operation with a wider range of propulsion types as summarised below:-

### Conventional Propulsion Systems

- Propellers
- Transverse thrusters

### New Propulsion Systems

- Podded propulsors
- Azimuthing thrusters
- Water jets

These new propulsion types can also create increasing scour actions. In many cases the new actions have not been well understood and failures to quay walls and scour protection have occurred. Little authoritative guidance is currently available for some of these new vessels and actions.

The different failure modes and design methods available for various types of scour protection will be presented or outlined along with their relative merits:

### Scour Protection Types

- Rock
- Insitu concrete
- Prefabricated mattress

### Limiting Failure Mode

- Flow displacement
- Suction uplift
- Various

For relative impermeable protection types, a design method for the hydrodynamic loading from propellers by WELLICOME (1981) will be shown along with supportive model tests recently undertaken at MARIN (2014). This research has provided the magnitude of the bed loadings and the effects of

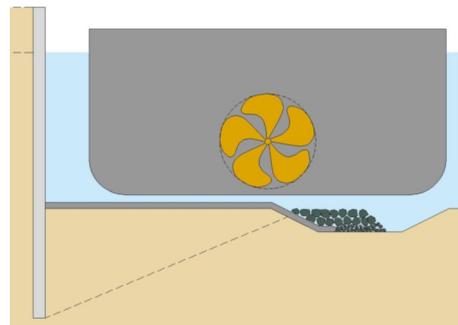


Figure 2.1. Propeller

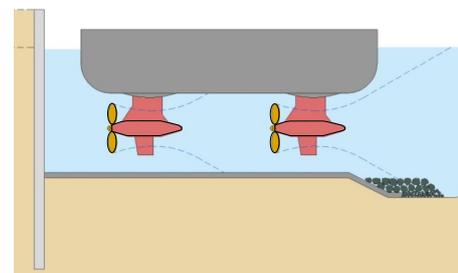


Figure 2.2 Podded Propellers

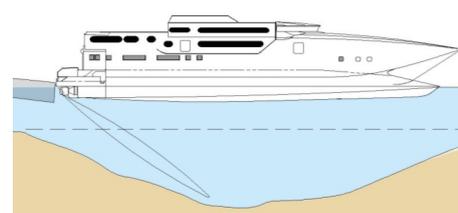


Figure 2.3 Water Jets

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the highly turbulent flow generated by the propeller blades, effects of the presence of the rudder and its deployment, plus propeller reversal effects. The model tests were supported by a matching computational fluid dynamics (CFD) study.

Specifically, the beneficial combination of insitu concrete mattress with a rock falling apron edge has been found to be a good combination for high and reliable performance. Details of the combination will be given along with a design example and reference to case histories.

For water jet propulsion, the hydrodynamic bed loading for inclined water jets from RoRo Fast Ferries will also be presented based upon CFD modelling undertaken at the Wolfson Unit, HAWKSWOOD, EVANS, & HAWKSWOOD, (2013). Case histories show that insitu concrete mattress has given reliable performance against water jet flow to 12.5 m/s and a design method will be presented based upon modelled bed loadings and upon case history performance.

The PIANC guidance in general use dates from 1997 (Working Group 22) and presently only covers conventional propulsion systems and rock scour protection, however this guidance is presently being updated by PIANC Working Group 48 (expected publication 2014).

### 3. BERTH SCOUR ACTIONS

Berth scour actions may comprise a combination of the following:-

#### Berth Scour Actions

- Propeller
- Transverse thruster
- Podded propulsors
- Azimuthing thrusters
- Water jets
- Current flows and Waves



Figure 3.1 Container Vessel

For the consideration of scour and scour protection, an understanding is needed of the vessel movements and associated scour action whilst berthing and unberthing for the proposed design life of a berth. Captains and Pilots are likely to use any reasonable vessel propulsion action available to them to ensure the safety of their vessel. This is generally influenced by windage of the vessel which has rapidly increased for container and cruise vessels. Actions that might be uncommon, with only a very low percentage of usage, should still be allowed for as they need to be protected against to avoid the risk of operational loss of the berth and relatively expensive repairs. Scour protection costs are low compared to overall berth costs.

The design actions for berths can be for a range of present day design vessels or with allowance for future trends for a berth of a particular draft. Vessel sizes are continually increasing and the increasing windage of vessel generally affects the maximum engine powers used during berthing (figure 3.1). Published advice by PIANC WG 22 (1997) shows a wide disagreement in the level of design engine power to be used upon a berth compared with EAU (1996) and BAW (2005) which is well presented in a paper by RÖMISCH & HERING (2002), in PIANC Bulletin 109. The PIANC WG 48 (expected 2014) update will provide further guidance.

When berthing in high winds (or currents), containers and other vessels may use berthing powers much higher than PIANC WG 22 (1997) guidance, with peak levels likely to approach EAU 1996 advice. It is presently common to use berthing powers of 40-70% for ferries, 100% for tugs and 50-100% for inland vessels. A large increase in engine berthing power produces only a relatively small increase in propeller jet velocity (1), however better agreement and understanding is needed. Where possible designers should consult and agree the key parameters with Port Owners and Operators based upon the present maximum likely use and future requirements. A probabilistic approach for the consideration of berth scour actions and protection design can be considered and applied to the following:-

- High power (high wind and direction)
- Low tide level/tidal range
- Vessel movement frequency
- Design life
- Ease and cost of maintenance

It is suggested the design water level can be taken as mean low water (MLW) for a high tidal range and low movement frequency and as lowest astronomical tide (LAT) for a low tidal range and high movement frequency such as ferries. For management of berths, design parameters for manoeuvring should be incorporated into operational berthing guidance and into inspection and maintenance plans.

## 4. PROPELLER ACTION

### 4.1 Introduction



Figure 4.1. Berthing with a Tug

Modern container vessels have developed to draughts of 16m with propellers up to some 9m in diameter and further increase is planned. Tankers, bulk carriers and other vessel sizes are also increasing. This is creating an increased level of scour actions to berths from larger propellers with greater power and lower propeller clearance ratios C/R (propeller tip clearance to bed/propeller radius).

The berthing and unberthing actions for larger vessels will often be tug assisted. When twin tugs are used, the vessel propeller and transverse thrusters are usually not used, giving a low level of scour action upon a berth as tugs have a relatively large clearance. However, a single tug maybe used for reduced cost or when twin tugs are not available. For this case, a tug can pull astern of the vessel with the vessel position balanced by propeller power ahead, and deployment of the rudder then allows sideways ‘crabbing’ movement for berthing and unberthing along with any available transverse thrusters (figure 4.1). This is a common berthing method using full rudder deployment for larger vessels. For this case, the vessel engine power could approach that required to match the bollard pull of the tug and would often be much greater than PIANC WG 22 (1997) advice and expected further advice by PIANC WG 48.

When unberthing, vessels usually seek to move sideways approximately one beam width from solid quay walls so that the vessel does not get sucked onto the quay with ahead movement and also to clear other moored vessels.

### 4.2 Propeller Jet Velocities

An understanding of propeller jet velocities and factors affecting their dispersion are needed to allow consideration of bed scour velocities. PIANC WG22 (1997) guidance on propeller jet and bed velocities is now in need of updating and more extensive and recent guidance by BAW (2005) should also be considered by Designers.

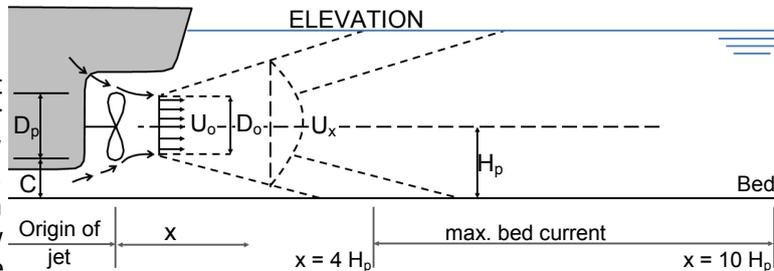


Figure 4.2 Idealised propeller jet, redrawn from PIANC WG 22 figure 4.4

The jet flow constricts only behind open propellers where the maximum jet velocity occurs (figure 4.2). For berthing vessels using propellers, maximum jet velocity generally occurs when the vessel is stationary or slow moving. For this case and situations with and without a rudder, the maximum jet velocity ( $U_o$ ) is given by (1):-

Maximum jet velocity  $U_o$

$$U_o = (c) \left( \frac{f P_b}{\rho D_p^2} \right)^{1/3} \quad (1)$$

- Open propeller coefficient (c) = 1.48
- (jet constriction diameter  $D_o = 0.71D_p$ )
- Ducted propellers (with Kort nozzles) (c) = 1.17
- Transverse thrusters (c) = 1.1



Figure 4.3 Kort Nozzles

### Propeller and Rudder Design Parameters

- Propeller type: Open/Ducted (Kort nozzle)/Transverse thruster
- Propeller diameter (m)  $D_p$ , (radius R)
- Engine power (kW) P
- Ratio of Engine power at berth f
- Propeller tip clearance to bed (m) C
- Water density seawater  $1.03 \text{ t/m}^3$   $\rho$
- Rudder type and deflection

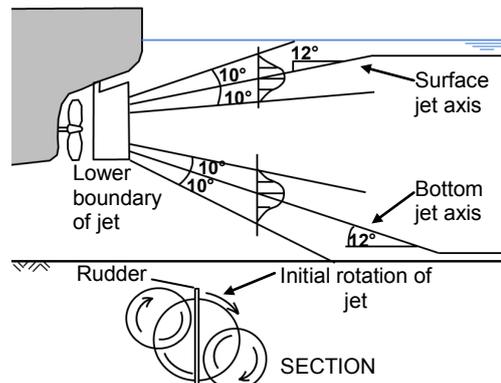


Figure 4.4 Effect of rudder on propeller jet PIANC WG22 (1997) (BAW Condition 2)

The x axis in figure 4.2 is taken from the propeller as clarified in PIANC BULLETIN 107 (2002).

For ducted propellers also known as Kort nozzles (figure 4.3), the jet constriction effect and thus the coefficient (c) reduces with increasing duct/nozzle length.

### 4.3 Bed Scour Velocity

With no rudder splitting the flow, the idealised jet flow is dispersed onto the bed as shown in figure 4.2 (BAW Condition 1).

A central rudder is usually located behind the propeller and this splits the flow with deflection upwards and downwards due to propeller rotational effects. This has a very significant effect creating much greater bed velocities than propellers without a rudder. This is described and shown in figure 4.4 taken from PIANC WG 22 (1997)(BAW Condition 2).

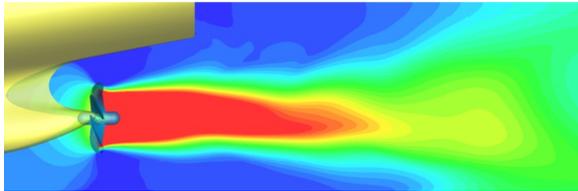


Figure 4.5. Velocity distribution no rudder

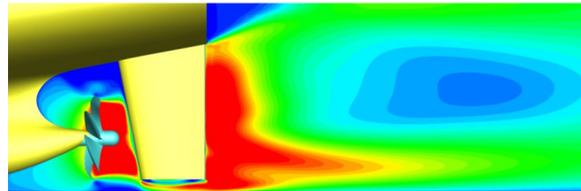


Figure 4.6. Velocity Distribution with Rudder

This idealised presentation is better shown in figures 4.5 & 4.6 from CFD modelling by MARIN (2014) of a propeller with no rudder and with a central rudder. These show the top and bottom jets split by the rudder, separation and how the bottom jet spreads upon impact with the bed.

Bed velocities have been determined from tests by FUEHRER & RÖMISCH (1977) as shown in figure 4.7. These graphs were expressed by the following equations and coefficients, RÖMISCH (1993) and EAU (1996):-

$$U_b = U_o E \left[ \frac{D_p}{H_p} \right] \quad (2)$$

Where from figure 4.2

$$H_p = C + (D_p / 2) \quad (3)$$

- E = 0.71 for slender stern with a rudder central to the propeller.
- E = 0.42 for slender sterns with no rudder behind the propeller.
- E = 0.25 for modern inland navigation craft with a tunnel stern with twin side rudders, (figure 4.8).

These proposed relationships are also represented in figure 4.7 and show significant error and over estimation of bed velocity in the region of present day design clearance ratios mostly being used, commonly  $H_p/D_p = 0.65$  to  $0.8$  ( $C/R = 0.3$  to  $0.6$ ). It is proposed that the original test results should be used.

These test results were also incorrectly represented in PIANC WG 22 (1997) figure 7.1 as outlined by RÖMISCH & HERING (2002) in PIANC Bulletin 109 figure 1 and also shown in figure 4.7.

Updated guidance for bed velocity is now needed for modern vessel arrangements with lower clearance ratios ( $C/R$ ) and rudder deployment included. Bed velocities are reported to reduce by a factor of 0.85 with propeller deployment of  $15^\circ$  or greater BAW p66 (2005) and this is supported by HAMILL, RYAN, & JOHNSTON, (2009) for  $C/R = 1$ , however, this is considered unlikely to be the case for lower clearances approaching  $C/R$  values of 0.25. See section 4.5, figure 4.23.

Design guidance by CIRIA ROCK MANUAL (2007) omits to mention the importance of the rudder effect and this has misled some designers.

The design power at berth may be used when the vessel is stationary and initially when unberthing, to gain steerage. Power is often reduced as the vessel unberths, particularly when a relatively high berthing power relative to 1/2 ahead is being used. Also with increasing vessel velocity, bed velocities are reduced (BAW (2005) equation 5-75).

Traditional single rudder types commonly deploy up to  $35^\circ$  presently. For oil tankers, it is common for rudder deployment to be up to

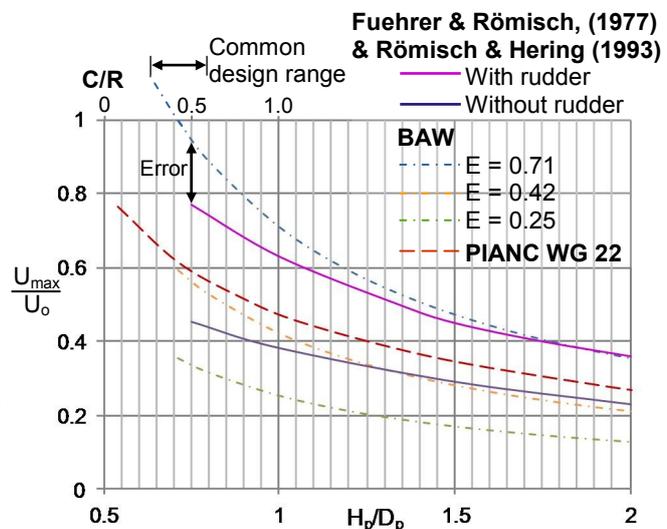


Figure 4.7. Maximum bottom velocities; BAW (2005); PIANC WG 22 (1997); RÖMISCH & HERING (2002); FUEHRER & RÖMISCH (1977)

45°. These rudders may start to be used on other vessel types. A Becker type two-stage rotation rudder causes a much greater degree of rudder and flow deflection and gives vessels much tighter turning circles. The maximum rudder angle should now be seen as one of the vessel parameters for design of vessel berthing actions.



Figure 4.8. Twin Rudders

Rudder deflection of propeller jets is often important to affected slopes such as slopes to piled jetties where deflected propeller velocities are often greater than transverse thrusters. BAW provides calculation methods to estimate velocities at distance to the propeller for many cases. The reported jet deflection efficiency of simple solid rudders is variable ranging from approximately 90% for high rudder deployment MARIN, (2014); HAMILL, RYAN & JOHNSTON, (2009) to 50%, for low deployment angles, PIANC WG22, (1997).

Some vessel types have twin propellers which are common to ferries, inland waterway barges and some other vessels. These vessels will often have central rudders behind each propeller which affords greater sideways manoeuvrability in harbours by 'crabbing'. Balanced forward and reverse propeller action can be created with rudder deployment used for sideways movement. No modelling of this action is known and it is suspected to cause greater erosion depths than is common for single propellers.

Ducted propellers such as Kort nozzle types are common on inland waterway barges which may have rudders central to propellers as figure 4.4 or twin fin rudders as or similar to figure 4.8 which practically do not split the flow. Ducted propellers are also common on tugs.

4.4 Hydrodynamic Bed Loadings from Propeller Action

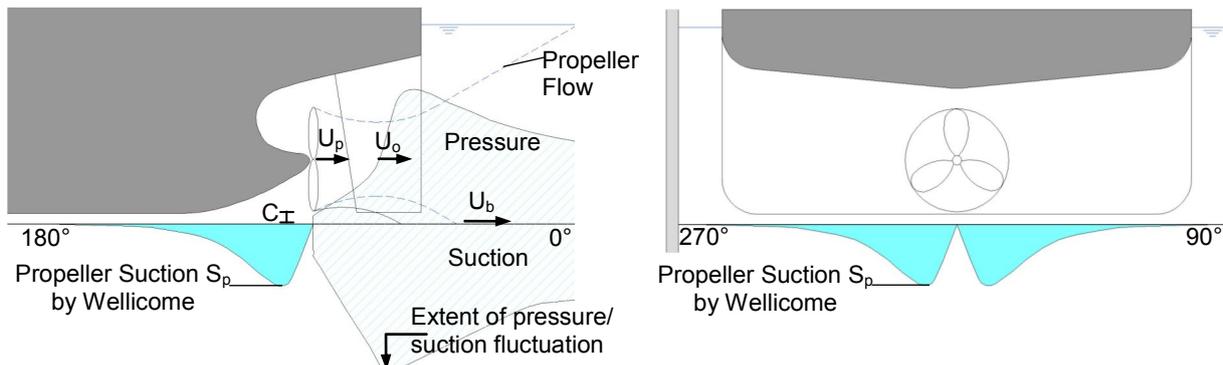


Figure 4.9. Propeller Flow and Bed Hydrodynamic Loadings (C/R = 0.25)

Hydraulic loadings from propeller action (figure 4.9) are needed for the consideration and design of insitu concrete protection types and any other relatively impermeable types. Propeller suction loads were first analysed by WELLICOME in 1981 using the following method, which relates the propeller thrust pressure  $t$  (propeller thrust/area) to the general peak suction under the propeller  $S_p$  for various clearance ratios  $C/R$ , as shown in figure 4.10. This figure clearly demonstrates the relationship between reducing clearance and increasing bed suction. This method can be safely applied to cases with a rudder and without a rudder.

The propeller thrust per propeller area  $t$  is based upon the induced velocity at the propeller  $U_p$ .

Propeller thrust per propeller area  $t$  (kN/ m<sup>2</sup>) MARIN (2014)

$$t = 2 \tau \rho U_p^2 \tag{4}$$

$\tau$  is the ratio between thrust from the propeller and the total thrust of the system where:-

- Open Propellers  $\tau = 1$  and  $U_p = 0.5 U_o$
- Ducted Propellers (Kort nozzle)  $\tau = 1/2$  and  $U_p = U_o$
- Transverse Thrusters  $\tau = 1/3$  and  $U_p = U_o$

Where  $U_o$  is taken from (1)

Peak suction under the propeller  $S_p$  (kN/m<sup>2</sup>) is taken from figure 4.10, which is derived from Wellicome for a flat bed. To take into account the effect of local surface undulation, Wellicome provides the factor  $I_Q$  which is applied to give:

Max. Suction  $S_d$  (kN/m<sup>2</sup>).

$$S_d = S_p \times I_Q \tag{5}$$

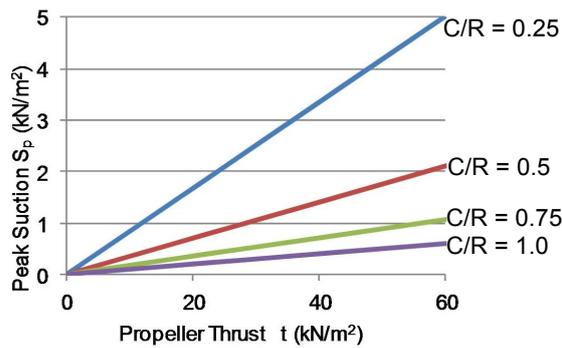


Figure 4.10. Peak Suction  $S_p$  vs. Propeller Thrust Pressure,  $t$

The local undulation or quilting ratio is measured by undulation height/undulation length, with typical values for  $I_Q$  shown in table 4.1.  $I_Q$  varies widely for different mattress manufactures and for other protection types and should be checked or specified as it has a significant effect. For propeller suction, other bed undulation effects are usually offset by an increase in the design propeller clearance  $C$ .

The propeller suction distribution is conservatively taken as a radial distribution to three sides from  $45^\circ$  to  $315^\circ$  as shown in figure 4.11 as suction is not generally present under the initial propeller jet HAWKSWOOD & ASSINDER, (2013). The radial suction profile can be interpolated from Wellicome’s dimensionless suction distributions (figure 4.12) for the relevant  $C/R$  with the peak of the curve given the value of the max suction  $S_d$ . An example is shown in section 11.5. For ducted propellers, no separate modelling is available and Wellicome’s method can be conservatively applied using (1) and (4).

Table 4.1. Surface Undulation Factor

	Undulation ratio	$I_Q$
CT mattress	0.16	1.15
“	0.21	1.20
FP mattress	0.33	1.30
Tremie concrete	0.21-	1.20-
	0.33	1.30

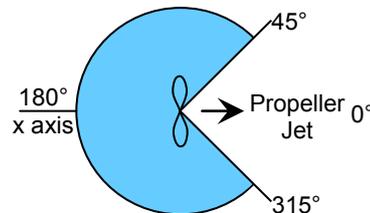


Figure 4.11. Design Suction Zone

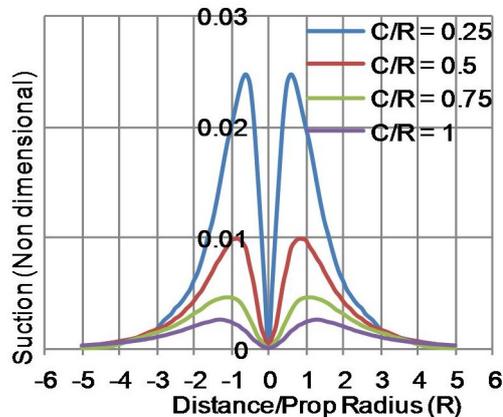


Figure 4.12. Wellicome’s Suction Distribution

#### 4.5 Hydrodynamic Loading Research at MARIN

A series of model tests have been carried out in MARIN’s Shallow Water Basin using a ship model of a typical container vessel with the corresponding propeller model and rudder model. The propeller was driven by an electric motor inside the ship. The propeller rotation rate, thrust and torque were also measured to determine the delivered power for each test. The water level in the basin was varied to obtain the various bottom clearances.

By very slowly towing the ship model with the propeller rotating at a given rotation rate over bed pressure sensors, the pressure distribution on the bed was measured; MARIN (2014)<sup>1</sup>.

A series of CFD computations has been performed using the geometry of the same typical container vessel as used in the model tests. This vessel, including its rudder was modelled with  $C/R = 0.25$  (figure 4.13) and  $C/R = 1.0$ , using a large domain; MARIN (2014).

Example hydraulic loads from the model testing are shown in figure 4.14 to 4.17 for various  $C/R$  ratios. Pressure and suction fluctuation behind the propeller is demonstrated relating to the effect of the individual propeller blades. Corresponding CFD modelling at MARIN modelled the axial velocity and flow rotation effects of the propeller but not the pulsing effect of the individual propeller blades, due to computational limitations. Example results shown in figure 4.13 displays only the general hydraulic trends due to jet velocity and rotation as can be seen by comparison to the equivalent test results in figure 4.14.

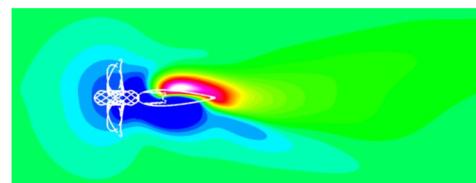


Figure 4.13. CFD modelling MARIN,  $C/R = 0.25$

<sup>1</sup> see <http://www.marin.nl/web/Facilities-Tools/Basins/Shallow-Water-Basin.htm>

Model Testing Results, 0.3m Diameter Propeller, MARIN (2014)

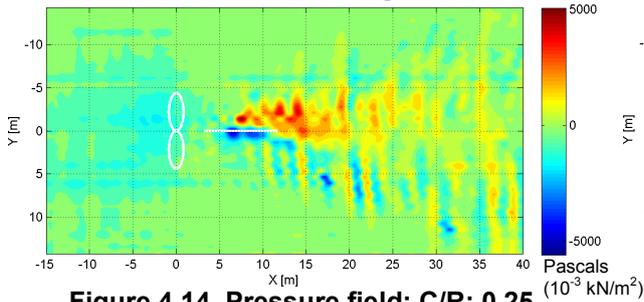


Figure 4.14. Pressure field; C/R: 0.25, Power: 10262 kW, Rudder: Straight

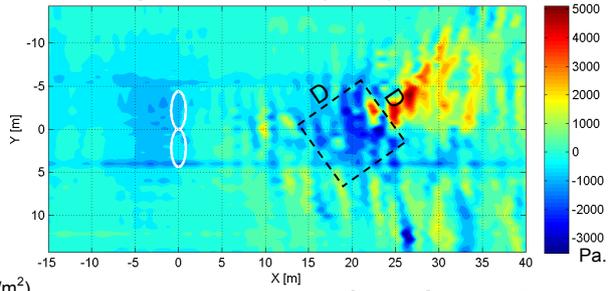


Figure 4.18. Pressure field; C/R: 0.25, Power: 10084 kW, Rudder: None

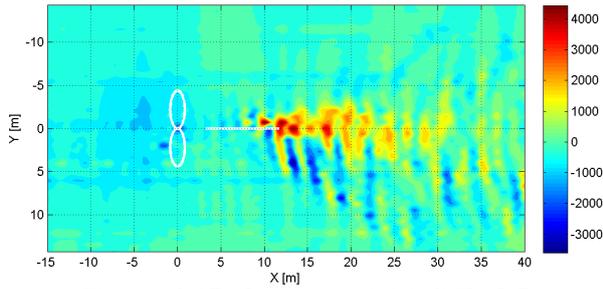


Figure 4.15. Pressure field; C/R: 0.5, Power: 11633 kW, Rudder: Straight

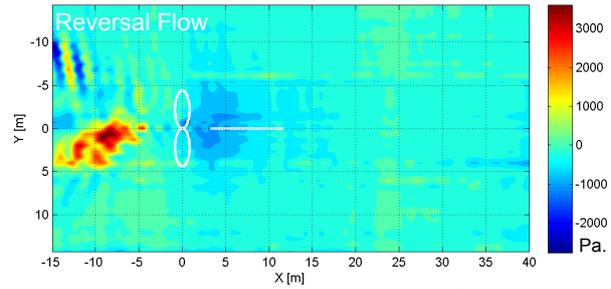


Figure 4.19. Pressure field; C/R: 0.25, Power: -6201 kW, Rudder: Straight

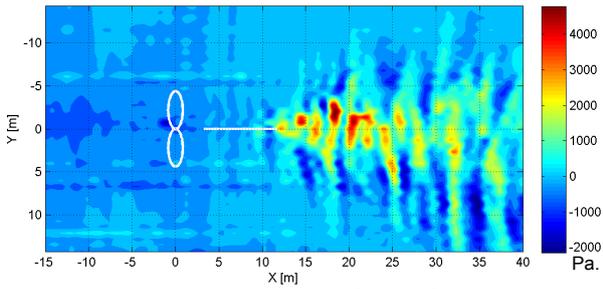


Figure 4.16. Pressure field; C/R: 0.75, Power: 17667 kW, Rudder: Straight

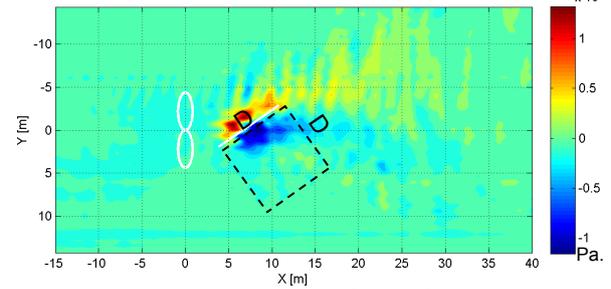


Figure 4.20. Pressure field; C/R: 0.25, Power: 10090 kW, Rudder: 35° Starboard

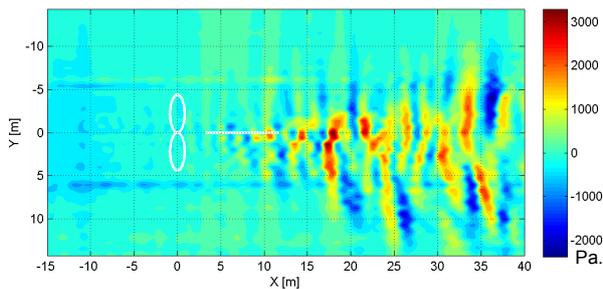


Figure 4.17. Pressure field; C/R: 1.0, Power: 18412 kW, Rudder: Straight

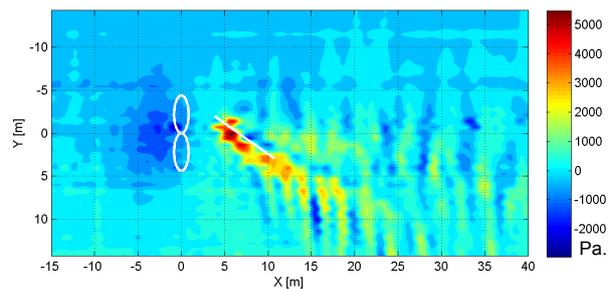


Figure 4.21. Pressure field; C/R: 0.25, Power: 10411 kW, Rudder: 35° portside

The physical model test results are considered to be more representative distributions than the CFD modelling. Figures 4.14 to 4.21 show typical test examples of the standing suction and pressure trends behind the propeller with the fluctuating effects of the propeller blades which are moving over the bed at the jet bed velocity. Figure 4.22 shows a comparison of the model testing and CFD modelling to Wellicome's suction curves along the x axis for various C/R ratios.

The test results and these comparisons confirm that Wellicome's method is a safe basis of design. The tests and CFD results are both much lower than Wellicome at C/R = 0.25 considered to be due to the low clearance restricting bed flow under the hull. Independent initial testing by HAMILL (2013) for C/R = 0.25 without hull or rudder effects found results closely matching Wellicome. The test results at MARIN for higher clearances are closer to Wellicome but lower in magnitude and distribution.

Estimated envelopes of the overall fluctuation extent from all similar clearance tests are shown in

dotted in figure 4.22 relative to Wellicome's characteristic value of propeller suction  $S_p$ . The standing and fluctuating local suction can be much higher than Wellicome's radial prediction near the propeller to some  $2.3 \times S_p$  at  $C/R = 0.25$  and  $7.2 S_p$  at  $C/R = 1.0$ . However these areas are much less than the area of Wellicome's propeller suction and have neighbouring areas of positive pressure which will stabilize typical cast insitu concrete panels.

The testing and CFD modelling both show occasional suction spikes forming under the propeller (figure 4.15). These are always over a very small area and less in magnitude than the range of suction fluctuation shown in figure 4.22. Figure 4.18 shows test results with no rudder for  $C/R = 0.25$ . A significant area of suction occurs in front of the flow impact area at  $x = 20m$  ( $4.5R$ ) with a peak suction of  $1.5 \times S_p$ . For design panel sizes greater than  $D$ , which are common to insitu concrete protection types, the effective panel suction is below  $0.7 \times S_p$  and this location is not critical compared to Wellicome as noted above.

Results for propeller reversal are shown in figure 4.19 for  $C/R = 0.25$ . No increase in suction effects were found, as would be expected with reduced propeller efficiency.

The effect of rudder deflection was tested as examples shown in figure 4.20 and 4.21 for a worst case  $C/R = 0.25$ . For starboard deployment, a local suction of  $0.5 \times S_p$  developed under the sheltered side of the propeller. Highest suction occurred under a straight rudder as figure 4.14 which shows local suction spikes to  $2.3 \times S_p$  over relatively small areas. Importantly, the greatest local pressure was found for starboard propeller deployment at  $6.4 \times S_p$  for  $C/R = 0.25$  figure 4.20.

Use of Wellicome's suction loading is considered appropriate for cast insitu concrete panels with reliable joints and load distribution capacity over panel sizes greater than the propeller diameter. This safely applies to the effects tested. It is also supported by performance experience to date, figure 11.12.

Flexible and relatively impermeable mattress types with reliable joints could be designed using the fluctuating suction values. More commonly where joints are not reliable, design could be based upon fluctuating suction or positive pressures values summarised in figure 4.23, or pressure caused by trapped flow that can occur under protection layers.

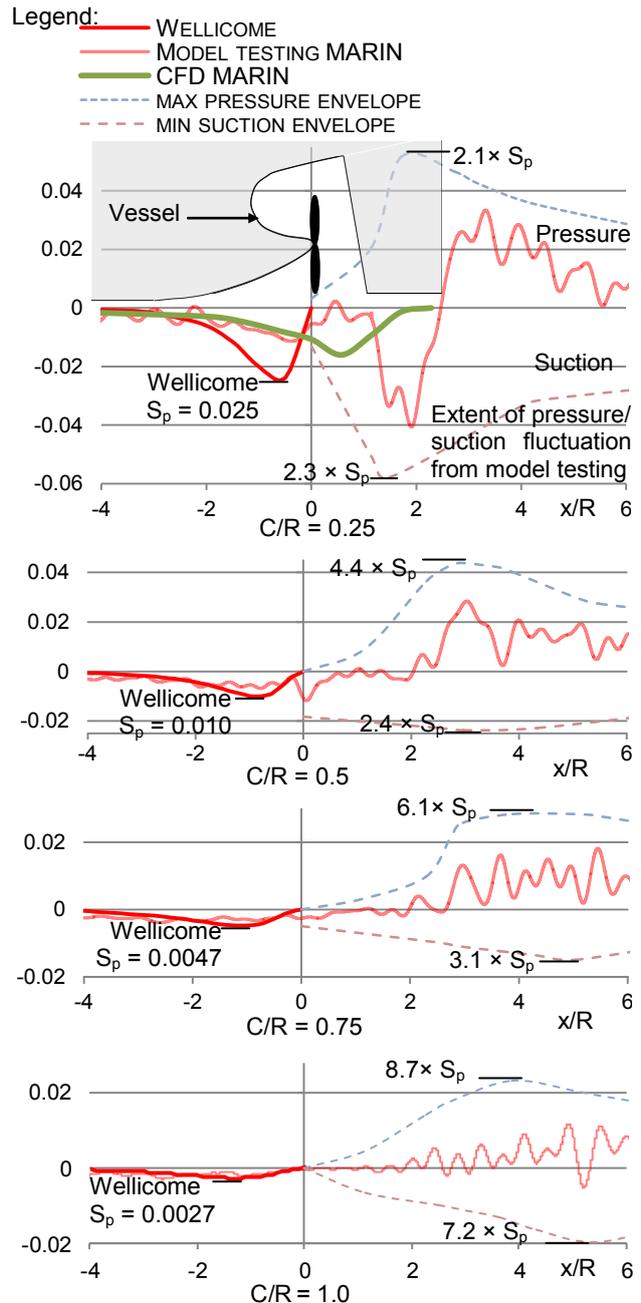


Figure 4.22 Hydraulic Distributions from Tests Straight Propeller (dimensionless)

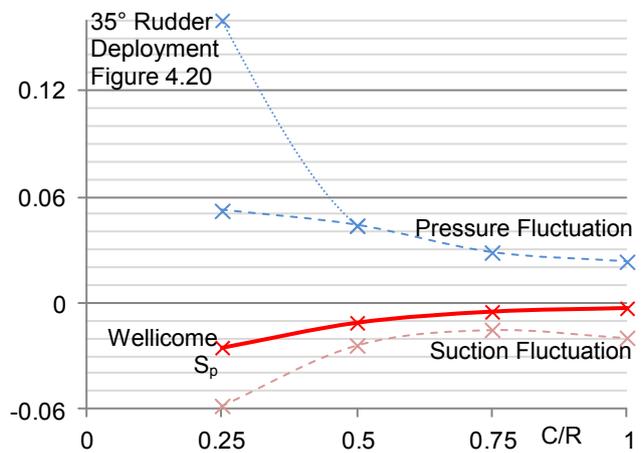


Figure 4.23 Summary of Dimensionless Pressure/Suction Vs C/R

## 5. TRANSVERSE THRUSTERS

Transverse thrusters are also known commonly as bow and stern thrusters which are used to aid berthing and unberthing. Bow thruster power is typically 350 - 3500kW, max 5500kW presently. The exit velocity of transverse thrusters can be found from (1) using the propeller/tunnel diameter and commonly using the full thruster power for berthing manoeuvres.

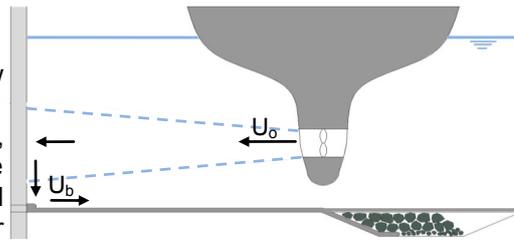


Figure 5.1. Side Thruster Action

Transverse thruster action onto quay walls (figure 5.1) can cause significant erosion from deflected downwash. Methods to estimate wall and bed velocities are given in BAW (2005) guidance. Bow or stern thruster velocities onto slopes (figure 5.2) can also be calculated from BAW (2005). Transverse thrusters are typically fully ducted propellers in long tunnels and as such the Wellicome type suction underneath them is not likely to develop or be significant.

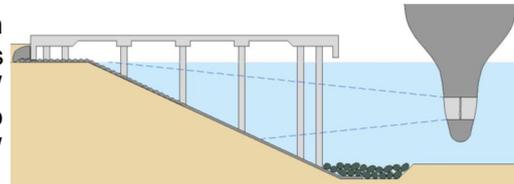


Figure 5.2. Slope

## 6. PODS – PODDED PROPULSERS

Podded propulsors generally have an open propeller which is directly driven by an electric motor contained in a pod behind it. The propulsors are able to rotate on plan giving good manoeuvrability capability with multiple propulsors often being used. The propeller is generally located in front of the pod, the arrangement being termed a pulling propulsor. Typical applications are for cruise ships, Ro Ro ferries, naval vessels and ice going vessels.



Figure 6.1. Podded Propulsors, courtesy of the ABB Group

Propeller diameters range from some 3.7 m to 6 m with bollard pull engine powers typically some 4 to 21 MW presently.

For berthing and unberthing by crabbing action, the engine powers of the pods at the vessels stern are likely to be similar to the thrust of the bow thrusters to avoid rotation, and for larger vessels this would presently be in the region of 50-60% engine power.

For unberthing, some pods are likely to be jetting directly onto side quay walls with a dispersal of flow down onto the bed protection. Until appropriate research and authoritative advice is available for flow and hydrodynamic action, design advice is best safely related to present advice for propellers. The pod and mounting will split the flow behind the propeller but probably not as effectively as a simple central rudder and design bed velocities can conservatively be taken as a propeller with a central rudder. Use of Wellicome's suction loading for open propellers is expected to be safe for pods. Where multiple pods are being used, Designers should consider the possibility of potentially higher scour velocities and bed loadings being created from the combined flow of inline rotated pods, figure 2.2 and make conservative allowances.

## 7. AZIMUTHING THRUSTERS

Azimuthing thrusters are similar to podded propulsors, but the propeller is driven by a mechanical Z-drive with the engine installed inside the ship. The thruster can rotate around a vertical axis to deliver thrust in all directions. Thrusters are generally in a pushing configuration and fitted with ducted propellers. Typically these units range from 1m to 3.5m diameter with power output of some 1 to 3.2MW. They are usually used on smaller vessels than podded Propulsors, such as tugs, offshore supply/service vessels and some cargo vessels.



Figure 7.1. Azimuth Thruster, courtesy of Wärtsilä

For design velocities, it is suggested to use appropriate methods for partially ducted propellers or open propellers as the case may be. For pushing thrusters and the dispersed jet flow onto the bed,  $E=0.25$  can be considered as the vessel arrangement is likely to be equivalent to a tunnel stern arrangement defined in BAW (2005). Use of Wellicome's propeller suction loading will be conservative for ducted propeller types.

## 8. WATER JETS

The water jets of vehicle carrying Fast Ferries have often caused significant erosion and damage to berths since their introduction in 1990. During berthing, the high speed propulsion water jets are deflected under the vessel and cause direct scour of the bed with scour holes up to 9m deep. This water jet action is summarised from HAWKSWOOD, EVANS & HAWKSWOOD, (2013).



Figure 8.1. Ro Ro Fast Ferry

### 8.1 Fast Ferry Vessels, Jets & Deflection Buckets

Larger vehicle carrying Fast Ferries are usually catamaran vessels built in aluminium [INCAT (2014) & AUSTAL(2014)]. Vessels above some 60 m long usually have twin water jets in each hull similar to figures 8.1. To berth, the vessels usually reverse onto floating roll on, roll off (Ro Ro) linkspan structures for stern mooring.

These ducted propulsion jets usually have exit diameters up to 1.0 m and typically have mooring jet exit velocities  $U_0$  from 15 m/s to 23 m/s. The ducted impellers are not reversed but deflection buckets divert the jet under the hull for reversal and mooring (figures 8.2).

The main manufacturers of Ro Ro Fast Ferries are Incat and Austal. Incat vessels are mostly equipped with Wärtsilä [WÄRTSILÄ (2014)] jets & buckets and Austal with Kamewa [ROLLS-ROYCE (2014)] jets and buckets. Plan rotation of the buckets is common up to some  $30^\circ$  which aids manoeuvring control of the vessel and can certainly be applied during mooring jetting for the Wärtsilä bucket system.

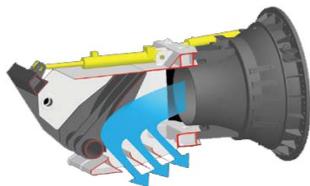


Figure 8.2 Deflection Bucket - Reversal

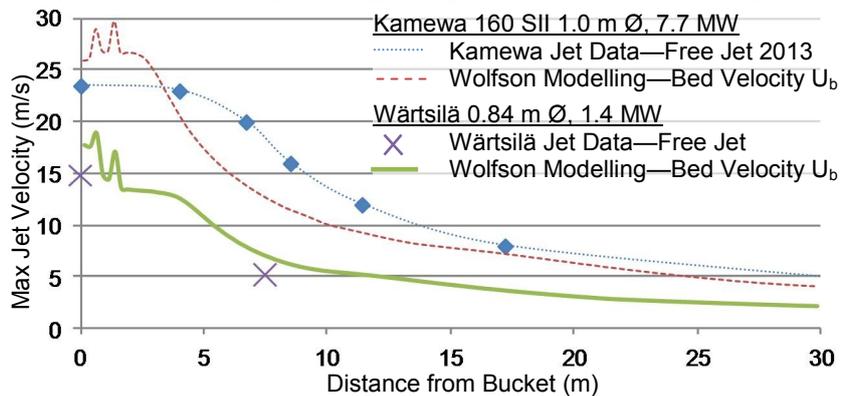


Figure 8.3 Max Jet Velocity vs. Jet Length

### 8.2 Mooring Jetting

Ro Ro Fast Ferries reverse slowly onto their linkspan moorings under a modest fairly constant power with control from deflection bucket operation. Passenger only Fast Ferries normally side berth without creating the mooring jetting action.

For Ro Ro Fast Ferries, peak mooring jetting scour action typically occurs when the vessel makes contact with the linkspan berthing face as shown in figure 2.3. Vessels usually 'push on' with significant power with the deflection buckets in full reversal mode as figure 8.2, for some 30 to 45 seconds. This 'mooring jetting' is to temporarily maintain the vessels position whilst mechanical mooring linkages or similar are secured. Figure 8.3 shows mooring jetting velocity profiles provided by manufactures for two jet types along with improved CFD estimates of the flow taking account of losses from the forward bucket openings, flow suppression from bucket back pressure and the presence of the bed.

Figure 8.4 shows the modelled jet flow through the deflection bucket and impact onto the bed. The CFD modelling also produced estimates of bed suction and pressure distributions which are useful for the design and consideration of bed protection.

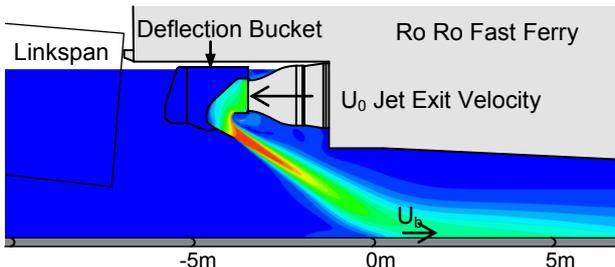


Figure 8.4 Modelled Mooring Jetting

The modelling gave reasonably common local suction/pressure coefficients for the two jet examples as shown in figure 8.5. The local pressure coefficients  $C_{pb}$  relate to the following equation derived from Bernoulli's Law:

$$\text{Pressure (or Suction)} = C_{pb} \frac{\rho}{2} U_b^2 \quad (6)$$

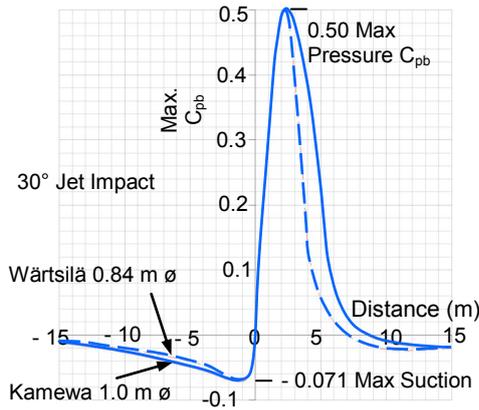


Figure 8.5 Suction/Pressure Coefficient

Where:  $C_{pb}$  = Local Pressure or Suction Coefficient  
 $U_b$  = Max Jet Impact Bed Velocity  
 $\rho$  = Relative Density of Water ( $t/m^3$ )

The modelled coefficients show that for jet impact at 30°, maximum pressure levels are some 7 times greater than suction levels. Calculated examples of peak bed suction and pressures are  $-5.7 \text{ kN/m}^2$  and  $40 \text{ kN/m}^2$  for  $U_b = 12.5 \text{ m/s}$  (Stranraer).

9. BERTH SCOUR PROTECTION

Berth scour protection is often required to protect quay structures from the effects of berth scour actions. For embedded pile and gravity wall types, it is usually much more cost effective to provide scour protection than to design walls for increased heights due to scour. Slopes to piled jetties also need to be protected. Scour protection also helps to reduce scour mounding and maintenance to maintain clearance. Advice on hull clearance and maintenance siltation depths are given in PIANC WG 22 (1997) and Designers should consider the erodibility of the bed soil type, likely siltation and wave effects.

A range of bed velocities presently commonly occurring are shown in figure 9.1 with velocities shown as high largely developing over the last 20 years.

The extent of scour aprons needs careful consideration. For embedded walls, sufficient length of the passive wedge should be protected for structural stability (figure 10.1). Where harbour siltation is significant and hull clearance is low, consideration should be given to widening aprons to reduce siltation and maintenance. The most significant scour velocities for conventional vessels are produced when the vessel is near stationary and typically when unberthing. PIANC WG 22 (1997) considered the cost effectiveness of the width of protection and provided general advice of a minimum of 5m beyond the propeller axis with scope for the Designer to consider relevant issues. In some situations, protection widths lower or greater than PIANC WG 22 (1997) guidance would have merit, with consideration of inspection and possible maintenance compared to increased capital costs.

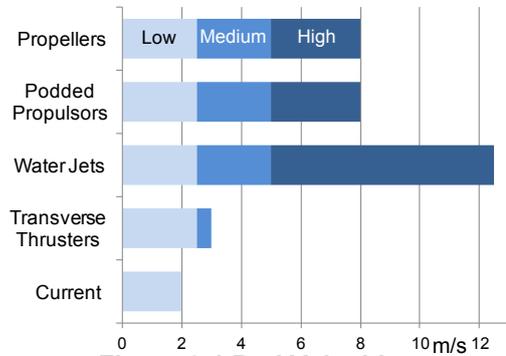


Figure 9.1 Bed Velocities

Berth scour protection underwater cannot be readily visually observed or inspected and construction should be supervised by suitably experienced professional engineer(s) using a proven marine quality control system.

9.1 Scour Protection Types and Failure Modes

Rock protection general fails in rolling/sliding particle displacement from the turbulent hydrodynamic action upon it outlined in figures 4.14 to 4.21. Insitu concrete protection generally fails due to propeller suction uplift or from edge underscour failure with trapped flow pressure as figure 9.2. Prefabricated mattress of various manufactures and types are generally not continuous or generic materials, are more complex and potentially have multiple modes of failure.

Scour Protection types can be characterised by their nature and failure modes as listed below:-

Type	Principle Failure Mode
<ul style="list-style-type: none"> <li>ROCK</li> </ul>	Particle displacement (1)
<ul style="list-style-type: none"> <li>INSITU CONCRETE                             <ul style="list-style-type: none"> <li>- Concrete mattress</li> <li>- Tremie concrete</li> <li>- Grouted rock</li> </ul> </li> </ul>	Uplift panel failure (2) Edge underscour (3)
<ul style="list-style-type: none"> <li>PREFABRICATED MATTRESS                             <ul style="list-style-type: none"> <li>- Concrete block mattress</li> <li>- Asphalt mattress</li> <li>- Gabion/reno mattress</li> </ul> </li> </ul>	Joint failures Unit movement Component failure Edge underscour Others

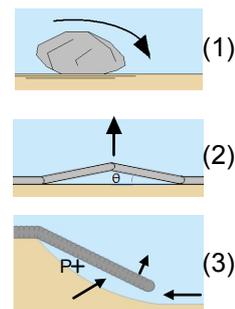


Figure 9.2 Principle Failure Modes

## 10. ROCK PROTECTION

Historically, rock protection has been the main type of scour protection used for propeller action with many case history examples outlined in PIANC WG 22 (1997) guidelines. Rock protection generally comprises two layers of rip rap or armour stone upon a bedding/filter layer and often a geotextile filter membrane figure 10.1. The design, specification of construction of the rock protection is well developed and generally understood using authoritative guidance.

Rip rap stone with a wider grading than armour is generally preferred as it can be mass placed by excavator bucket etc rather than individual placement of armour stone PIANC WG 22, (1997). Rock protection often needs to be grouted at walls and structures to prevent wash out from flow down or along walls etc. (Figure 10.1)

Rock protection has many good qualities, being porous and flexible, it performs very well as falling edge aprons, and is relatively easy to repair unless the bedding layer is lost.

For propeller actions, established design methods are available to take into account velocity, turbulence, slopes and edge effects BAW, (2005); PIANC WG 22 (1997) and WG 48 (expected 2014). For propeller flow, BAW (2005) advice is presently considered the most comprehensive used, which is based upon the testing work of FUEHRER & RÖMISCH, (1977). This recognises the higher turbulence for bed flow without a rudder which was not included in PIANC WG 22 guidance as shown in figure 10.2. (Note that the  $D_{s50}$  sieve analysis value obtained from BAW has been converted to  $D_{s50}$  for comparison to PIANC.) This significant increase due to turbulence is offset by the relatively slower bed velocities shown in figure 4.7 for a propeller without a rudder. An updated study of actual rock performance for lower clearances, higher velocities and rudder deployment is now needed.

As vessel size and power have increased and design methods updated, Engineers have increasingly become aware of stone sizes and construction thickness becoming impractical, figure 10.3. Principally, as the rock construction depth increases, the span and embedment heights of walls also increase and this has a major cost effect. For bed flow above 2-3 m/s, insitu concrete mattress or grouted rock systems are likely to be more cost effective as outlined in figure 10.4. (Example based upon: Rock £60/m<sup>3</sup>, Geotextile £8/m<sup>2</sup>, Dredging £24/m<sup>3</sup>, 0.45m maintenance dredging depth)

The edge performance of rock construction as a falling apron against edge scour is widely acknowledged, as example case histories shown in PIANC WG 22 (1997), commonly using a standard 3 layer construction at edges BAW, (2005) PILARCZYK, (2000). This edge performance can also be used in conjunction with other scour protection types.

For the inclined and high bed velocities from water jets of Ro Ro Fast Ferries, rock protection failure has occurred HAWKSWOOD, EVANS & HAWKSWOOD (2013). No suitable design method for rock protection against water jets is presently known and it's use should be safety limited to low exposure conditions or conditions where it has proven performance.

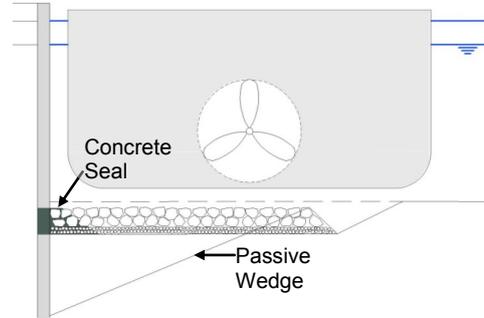


Figure 10.1 Rock Protection

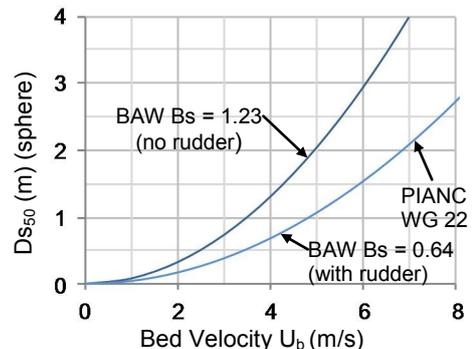


Figure 10.2. Stone Size for Vessel Actions

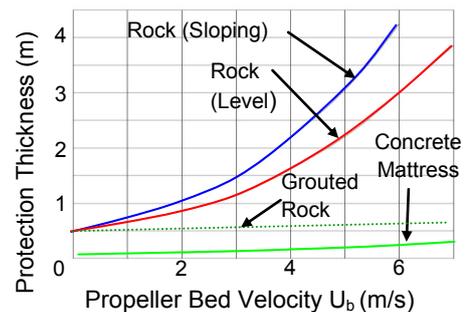


Figure 10.3. Thickness

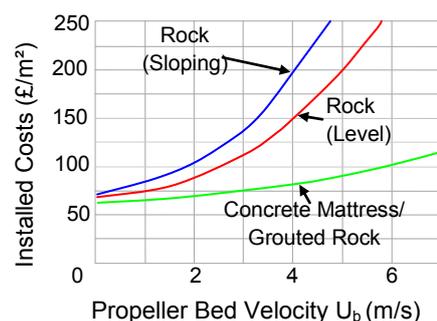


Figure 10.4. Relative Cost

## 11. INSITU CONCRETE MATTRESS

Concrete or grout mattress aprons are formed by divers rolling out mattress fabric underwater which is zipped together and pump filled with highly fluid small aggregate concrete. The fluid concrete is protected from wash out from currents and limited wave action by the mattress fabric. The system typically comprises two layers of interconnected woven fabric as shown in figures 11.2 and 11.3 which allows use on level beds or slopes. CT mattresses are typically pump filled with a sand:cement micro concrete mix of 35 N/mm<sup>2</sup> strength which has proven durable since its use started in the 1960's.

Joints between mattress panels are formed using zipped or sewn 'ball and socket' shear joints (figure 11.2). This produces an apron of interlocked concrete slabs underwater, which gives a high resilience against currents, propeller and jet flows to 12.5m/s (figure 11.14.)

Constant Thickness Mattress types (CT) are normally used to resist vessel actions on harbour beds and permanently submerged slopes. Mattress aprons readily cope with high propeller and jet velocities with relatively low thickness when compared with rock protection. CT Mattress is specified by its thickness and surface undulation, smoother mattress types are more hydraulically efficient, table 4.1 and flexurally stronger. Thicknesses of 100mm to 600mm are commonly available. A 200mm minimum thickness is recommended to berth beds where controlled maintenance dredging by dredging vessels is likely.

Filter Point Mattress (FP). The porosity of the woven in filters allows use on slopes in tidal ranges and for wave heights (Hs) typically below 1 to 1.5m. Filter Point (FP) mattresses commonly have an overall thickness of 150mm to 250mm, with an average thickness of 100mm and 166mm respectively. A geotextile fabric is required under the mattress to protect against filter loss. These mattresses are not generally used in lower zones of direct jetting action where filter point and geotextile may be lost by abrasion from suspended particles, figure 11.13.

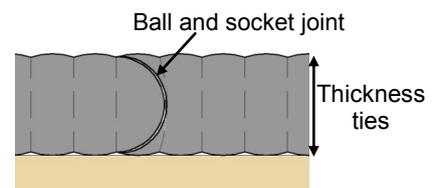
Concrete mattress has a high durability and abrasion resistance created from the 'free' water bleed of the fluid mix through the fabric. Mattress panel widths are typically some 3m to 5m from the weaving process. Residual ground water movement may occur under quay structures, piling or slopes created by tidal movement etc figure 11.9. Weep holes can be provided in CT mattress (figure 11.4) to provide low porosity to cater for these effects. For soils, a geotextile should be provided to the bottom of the weep holes to retain fines, with the weep hole size and spacing designed to suit.

Most berths are dredged into natural ground strata where bed soils will have been previously over consolidated and are therefore not generally prone to settlement. In these cases, no precautions for mattress flexibility have been required, with mattress panels extending the width of the apron. In filled ground, or other cases where settlement is an issue, the mattress panel size can be reduced to increase flexibility as shown in table 11.5 (Relative settlement is based across the apron width). For example a 1m panel size was used at the port of Belawan over hydraulically placed sand fills, using crack failure lines LOEWY, BURDALL, PRENTICE, (1984).

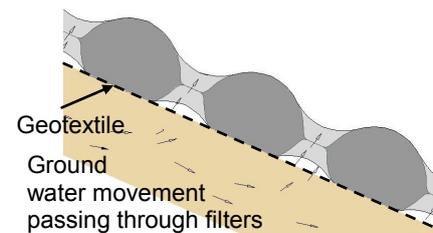
The fabric mattress is essentially a temporary works system and typically needs a filling strength of 50kN/m<sup>2</sup> for effective installation on beds and slopes. Insitu concrete mattress should be reliably installed using a proven marine quality control system overseen by engineers with experience in the system. For further details on technology, construction, installation, supervision, maintenance and design methods for wave and current action refer to HAWKSWOOD & ASSINDER, (2013) and KING & HAWKSWOOD, (2014) for specification guidance. The engineered use and reliability of fabric formwork systems is also shown for other applications, such as foundations to precast marine



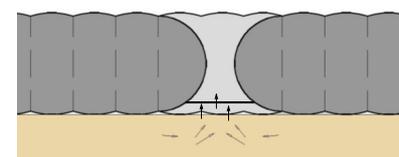
**Figure 11.1 Lowering mattress to be rolled out by divers.**



**Figure 11.2 Constant Thickness Mattress (CT)**



**Figure 11.3 Filter Point Mattress (FP)**



**Figure 11.4 Weep Holes to CT Mattress**

Relative Settlement	Mattress Panel Size
0-70mm	Apron width
75mm	10m
125mm	3m
500mm	1m

**Table 11.5 Settlement and Panel Size**

structures HAWKSWOOD & ALLSOP, (2009).

### 11.1 Edge Details

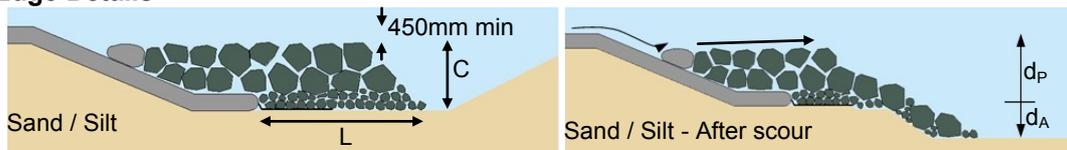


Figure 11.5. Edge Detail with Falling RipRap



Figure 11.6. Bolster Edge Protection to Clay

The concrete mattress system requires robust edge details to prevent under-scour failure. This is best achieved with in-filled edge toe trench details. Falling riprap edge details are generally preferred (figure 11.5) although in stiff clays a concrete trench infill bolster can also be considered (figure 11.6). Falling apron edge details consisting of 3 layers of stone are acknowledged solutions that can be designed to overcome the estimated local edge scour PILARCZYK, (2000). Importantly, riprap stone edges have a higher scour protection depth comprising the embedment depth  $d_P$  and the active falling apron depth  $d_A$ .  $d_A$  is dependent upon the falling apron length  $L$  and table 11.2 shows an estimated relationship. To match the edge protection performance of continuous stone aprons which have been widely used,  $L = 3C$  is suggested. Any rock protection should be below the maintenance dredging level by a minimum of 0.45m suggested by PIANC WG 22 to avoid damage to the rock. Where the top of the rock is below initial bed level, length  $L$  can be reduced relative to table 11.2. This edge detail can be readily monitored and maintained to overcome any unexpected vessel action or bed strata, etc, and effectively helps manage edge protection risk.

[L] Length of falling apron	[d <sub>A</sub> ] Active Depth of falling apron
1 C	1/3 C
2 C	2/3 C
3 C	C

Where C is the Construction depth of the falling apron

Table 11.2

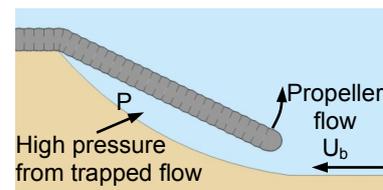


Figure 11.7 Underscour Edge Failure

Edge trenches must be securely infilled to prevent flow travelling down the toe slope and promoting scour at the edge. If scour protection edges become underscoured progressive failure can ensue caused by higher positive pressure from trapped propeller flow, figure 11.7. This type of failure is commonly reported by Divers and Engineers with uplift cracking to rigid slabs and roll up of flexible protection types.

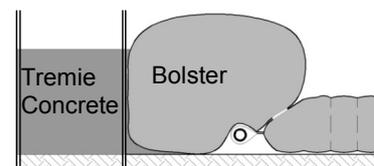


Figure 11.8. Wall Seal

To seal against piled profiles, a concrete edge thickening bolster is commonly used allowing a deeper tremie concrete infill seal to in pans (figure 11.8). An edge thickening bolster can also be used to unprofiled walls with inspection and a tremie concrete infill seal to any gaps.

### 11.2 Design of Concrete Mattress Bed Protection for Propeller Action

For concrete mattress aprons with reliable joints and interlocked panels some 3 to 5m wide, the failure mode due to suction uplift is generally taken as a square panel with a size of 45 times the panel thickness (BS 5628, 36:3(b)(2)). The worst case loading for these panels is the relatively large area of suction under the propeller described by Wellicome's method in section 4.4, which has been confirmed by testing in section 4.5. The fluctuating suction and pressures behind the propeller are readily distributed by relatively large and interlocked concrete panels. The mattress surface is relatively smooth with low hydraulic roughness coefficients as table 4.1 which creates much lower design thickness than protection with greater roughness. Concrete mattress thickness should be designed using robust safety factors (to limit the likelihood of repairs), using a realistic worst case combination of water level/clearance and applied engine power. This is particularly important to berths in continual use and under jetty slope protection.

For a simple dead weight design analysis, the dead weight thickness  $D_{min}$  can be solely used to resist the average panel suction  $S_A$  with a dead weight load factor  $\gamma_D = 0.9$  and a minimum safety factor S.F. of 1.5 proposed.

Dead Weight Design Method: Mattress Thickness

$$D_{min} = \frac{S.F. \cdot A \times S_p \times I_Q}{\gamma_D \Delta g} \quad (7)$$

Average suction factor A is typically taken as 0.8.

Buoyant relative density for micro concrete Δ is typically taken as 1.3.

More rigorous panel analysis can be used where the dead weight and panel flexural strengths are used to resist the average suction  $S_A$  over the panel. For unreinforced concrete panels, this analysis can be based upon the allowable low flexural cracking strength allowed in the concrete code (EUROCODE 2, 2004) and a yield line method of panel analysis, or equivalent. This method is similar to unreinforced masonry panel design. For this analysis a S.F. > 2 is proposed along with a dead weight load factor  $\gamma_D = 0.9$ . Using this method concrete flexural stresses at working loads, can be designed to be zero.

Designers can consider increasing concrete thickness for longer design life periods and robustness to cover more unlikely events such as engine testing, uplift pressures from underscour, dredging, grounding or miscellaneous impact.

**11.3 Example: Concrete Mattress Bed Protection with Stone Edge Detail for the Propeller Action from a Container Vessel**

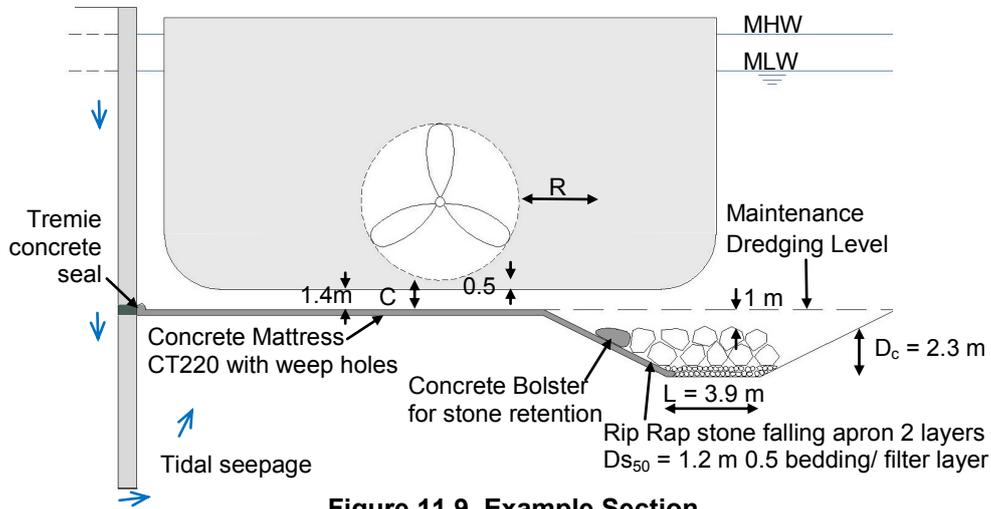


Figure 11.9. Example Section

Propeller and Rudder Design Parameters

Propeller type	Single open propeller	
Propeller diameter (m)	$D_p = 8.75$ m	(R = 4.375 m)
Engine power (kW)	P = 40,000 kW	
Propeller tip above keel	0.5 m	
Rudder type and max. deflection	Standard rudder, 35° deploy range	
Ratio of Engine power at berth	f = 0.35	
Propeller Tip Clearance to Bed	C = 1.9 m at MLW	

Max. jet velocity:  $U_o = 1.48 \left( \frac{0.35 \times 40,000}{1.03 \times 8.75^2} \right)^{1/2} = 8.3$  m/s (1)

Velocity at propeller:  $U_p = \frac{8.3}{2} = 4.15$  m/s

Propeller thrust:  $t = 2 \times 1 \times 1.03 \times 4.15^2 = 35.5$  kN/m<sup>2</sup> (4)

$\frac{C}{R} = \frac{1.9}{4.37} = 0.43$

Peak suction pressure:  $S_p = 1.7$  kN/m<sup>2</sup> (figure 4.10)

CT mattress (Proserve) surface undulation is 16mm, take undulation/quilting factor  $I_Q = 1.15$  (table 4.1)

Design peak suction:

$S_d = 1.7 \times 1.15 = 2.0$  kN/m<sup>2</sup> (5)

Dead Weight Design: Mattress Thickness:

$$D_{\min} = \frac{1.5 \times 0.8 \times 1.7 \times 1.15}{0.9 \times 1.3 \times 9.8} = 205\text{mm} \quad (7)$$

USE 220 mm THICK CONCRETE MATTRESS (CT220)  
Check Panel Size and Suction Distribution

The suction distribution for C/R = 0.43 with a peak suction  $S_d = 2.0 \text{ kN/m}^2$  is interpolated as figure 11.10, using Wellicome's suction distribution profiles shown in figure 4.12. Take load factor for dead weight/thickness  $\gamma_D = 0.9$ .

Take the allowable and worst case panel size = 45 × slab thickness: 45 × 0.9 × 0.22 m = 9.0 m (BS5628 cl 36.3 b2) figure 11.10 shows  $S_A = 1.6 \text{ kN/m}^2$  is reasonable for a 9m square panel.

Minimum thickness for maintenance 200mm, 220mm thickness. OK

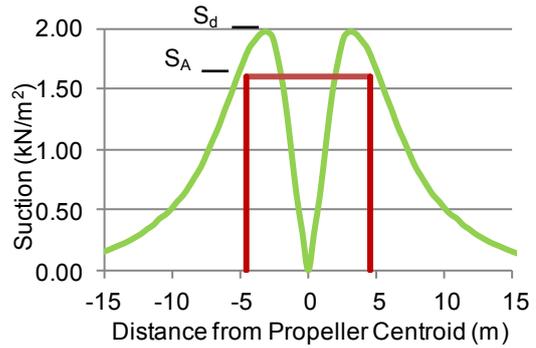


Figure 11.10. Design Suction Distribution and Design Panel Action

**Toe Stone Design—Rip Rap Falling Apron**

Provide 3 layer stone falling edge apron following typical historical performance case histories PIANC WG 22, (1997) and PILARCZYK, (2000)/BAW, (2005). The top of stone is 1.0 m below maintenance dredging level, 0.5 minimum PIANC WG 22, (1997).

Locate rip rap one propeller radius clear of the berthed propeller position, and reduce bed velocity by 0.85 allowing for a reduction in bed velocity by a combination of vessel speed/propeller deployment C/R = 0.46. (See 4.5 and BAW (2005)equation 5-75)

$$\frac{H_p}{D_p} = \frac{1.0 + 1.9 + 4.37}{8.75} = 0.83$$

From figure 4.7 RÖMISCH & HERING (2002)PIANC Bulletin 109, FUEHRER & RÖMISCH (1977)

$$U_b = 8.3 \times 0.7 \times 0.85 = 4.9 \text{ m/s} \quad (2)$$

Stone size is selected from figure 10.1 (BAW 2005,  $B_s = 0.64$ )  $D_{s50} = 1.0 \text{ m}$  (for level bed)  
Construction thickness take  $C = 2 \times 1.1 \times 0.8 + 0.5 = 2.3\text{m}$

As apron is submerged by 1.0 m, provide reduced apron length  $L = 3 \times C \times \frac{1.3}{2.3} = 3.9 \text{ m}$  (Table 11.2)

USE 2 LAYERS OF RIP RAP STONE  $D_{s50} = 1.1 \text{ m}$ , WITH 0.5 M THICK BEDDING STONE LAYER

(To reduce stone size the edge apron can be increasingly submerged below the general bed level.)

**11.4 Comparison of Design Methods**

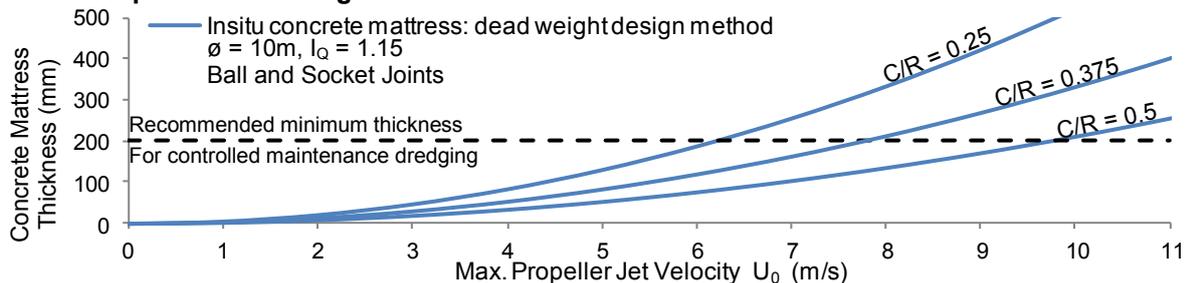


Figure 11.11 Insitu Concrete Mattress Thickness Design

Figure 11.11 shows the relationship between concrete mattress thickness and max propeller jet velocities  $U_0$ , using the Wellicome suction and simple dead weight design method. The mattress thickness  $D$  is proportional to the velocity squared in common with other stability formulas, for any given C/R ratio. As the propeller clearance ratio C/R increases, insitu concrete mattress thickness decreases. It is generally recommended to limit C/R values used to a maximum of 0.5 for mattress thickness robustness.

Figure 11.12 shows insitu concrete mattress thickness plotted relative to bed velocity  $U_b$ , which is based upon Fuehrer & Römisch's test relationship for  $U_b$  and  $U_0$  with a central rudder as shown in the earlier figure 4.7. The curves in figure 11.12 should not be used for design in case other relationships between  $U_0$  and  $U_b$  are established, however they allow useful comparison with other design methods.

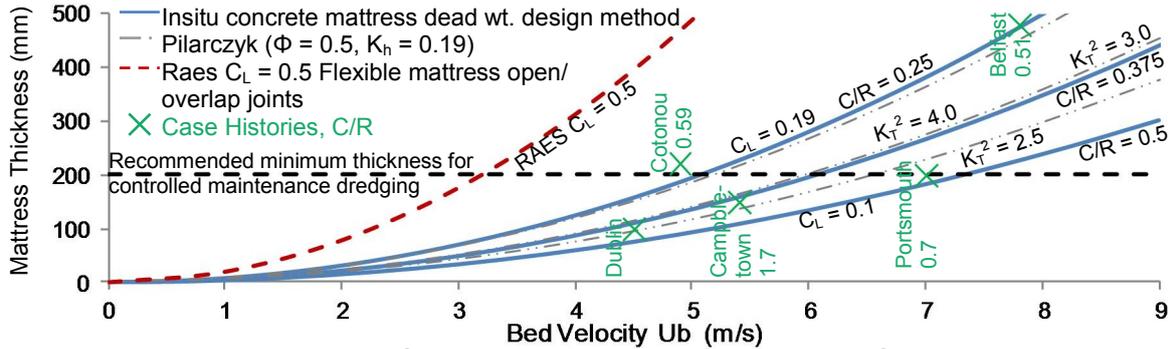


Figure 11.12 Insitu Concrete Mattress Thickness Design Comparison

C/R	$K_T^2$	$C_L$
0.250	4.1	0.19
0.375	2.9	0.14
0.500	2.0	0.10

Table 11.3

Pilarczyk developed a complicated stability formula for rock and many other protection types using many coefficients, PILARCZYK (2000). For propeller action and mattress protection, Pilarczyk advises that many of his coefficients are estimates that require validation PILARCZYK (2011). Curves from Pilarczyk’s formula are plotted for various  $K_T^2$  values using,  $\Phi = 0.5$ ,  $K_h = 0.19$  ( $h = H_p$ ,  $r = 0.05m$ ) and provides the following provisional relationship shown in table 11.3, pending confirmation of the relationship between  $U_o$  and  $U_b$ . Although Pilarczyk’s equation does not relate to clearance and the design method for propeller suction failure, the tabulated relationship provides useful reference between the methods. As the bed clearance ratio reduces the  $K_T^2$  factor increases.

RAES, ELSKENS, RÖMISCH & SAS (1996) provided a simple equation for the stability of thin flexible revetments and their stability at overlapping or open joints and underscoured edges.

$$D_{min} = \frac{C_L U_b^2}{2\Delta g} \quad (8)$$

The equivalent stability coefficient values for  $C_L$  for insitu concrete mattress are shown in table 11.3. As expected, these are much lower than the value of  $C_L = 0.5$  &  $1.0$  proposed by RAES, ELSKENS, RÖMISCH & SAS (1996) respectively for open/overlapped joints and underscoured edges of flexible mattress types, which relates to exposure to positive pressure and flow getting under joints. For water jet impact flow at  $30^\circ$  to the bed, figure 8.6 similarly shows a pressure coefficient  $C_{PB} = 0.5$  This shows the need for protection types to have good reliable joints, safely sealed with embedded edges and distribution ability or thickness needs to be increased significantly.

Historically from 1960’s to 1990’s, berth beds where generally protected by FP mattress with an average thickness of 100mm. Lately, thicker CT mattress types have been used for increased vessel actions as case histories, Cotonou, Benin, HAWKSWOOD & ASSINDER (2013), Belfast VT4/II, Campbeltown and Portsmouth, UK etc, as shown in figure 11.12

### 11.5 Propeller Flow onto Slopes

For propeller jet impact onto slopes as figure 11.13, the jet impact generally creates a stabilizing positive pressure onto the concrete mattress. Lower thickness than 200mm have been used to slopes where dredging is unlikely. Mattress stability for flow beyond the jet impact area can be undertaken using Pilarczyk’s formula with coefficients correlated form above with the reduced bed velocity at that location. Porous FP mattress is used in the tidal range, with CT mattress needed to protect lower slopes against particle abrasion for flows above 2-3m/s. Slopes need to be geotechnically stable.

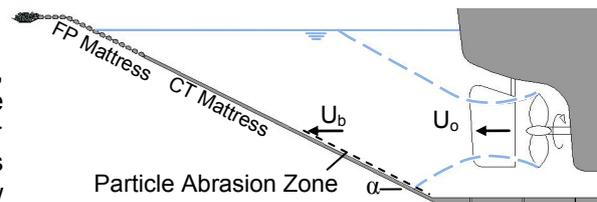


Figure 11.13. Propeller Action

Revetments and slopes to piled jetties have been protected by insitu concrete mattress since the 1970’s with well referenced examples at Belawan, Indonesia LOEWY, BURDALL, & PRENTICE (1984), PIANC WG 22 (1977), Teesside UK, Oslo Harbour, Portbury Dock & Shell Jetty at London Gateway.

### 11.6 Concrete Mattress Protection to Fast Ferry Jets

Insitu concrete mattress has been the main type of scour protection used against Ro Ro Fast Ferry jets in the UK with bed velocities ( $U_b$ ) up to 12.5 m/s (Stranraer). The Stranraer performance history along with 5 other case histories are shown in HAWKSWOOD, EVANS & HAWKSWOOD, (2013) which demonstrates the high and reliable performance that has been achieved.

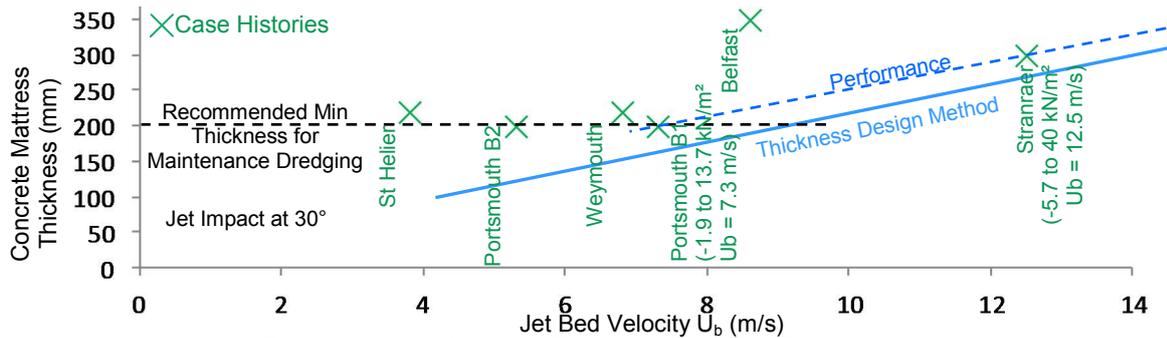


Figure 11.14: Mattress Thickness vs. Jet Bed Velocity  $U_b$

Thickness design has been based upon CFD modelling of suction uplift WOLFSON UNIT (2003 & 2013) with yield line panel analysis used to account for the distribution capability of concrete slabs. Mattress thickness from the design method is shown in figure 11.14 relative to bed velocities and suctions based upon the 2013 Wolfson modelling. The design method is now supported by the short term performance of the 6 case histories shown in figure 11.14. Where a longer design life is required in comparison to the case history performance, a suitable factor for increased exposure could be applied. Due allowance should also be made for possible different vessel behaviour in different ports.

Edge details should be located away from the direct action of the mooring jets to protect against uplift from jetting pressures getting underneath any mattress slabs. Edge protection depths should be designed to safely exceed the scour potential in that area. These are the major design issues as the scour potential is large.

## 12. TREMIE CONCRETE

Tremie concrete has the performance potential to create good protection against propeller and water jet action. However, it cannot effectively be used to sloping areas and toe trench slopes to form important embedded edge details. Practically, tremie slabs often need to be a minimum of at least 0.5 - 0.6 m thick to cope with tight bed and tremie surface laying tolerances. There are also some construction and environmental difficulties to overcome:-

- Panel joints
- Toe trench slopes for edge details
- Weep holes
- Siltation/Fluid bed mud
- Quality control
- Unconfined concrete into marine habitats
- Flexibility
- Wash out

Where these difficulties can be overcome, the thickness design methods for concrete mattress can be used for panel sizes greater than  $45 \times D_{min}$  or the propeller diameter. Where panel edges are not fully interconnected, it is recommended to use the peak suction  $S_D$  for the dead weight design method with a surface undulation factor from table 4.1. The design thickness  $D_{min}$ , should be increased by appropriate bed and concrete surface tolerances. Interlocked joints should be provided where there is likely to be ground settlement. A method of providing edge protection greater than the expected erosion must be found for a secure design.

## 13. GROUTED ROCK

Typically a rock layer is placed over a geotextile which is then pumped in filled with grout, tremie concrete or liquid asphalt. As for tremie concrete the minimum thickness is typically 0.5 to 0.6m if relatively tight bed and tremie concrete surface tolerances are used. This system is increasingly being used for berth scour protection. For reliable protection in medium and high propeller velocities, the problems noted for tremie concrete must be overcome, principally the formation of embedded edge details and control to achieve sufficient grouting of voids to prevent wash out failure.

The grouting is dependent upon marine working conditions, siltation plus diver grouting and inspection reliability which depends upon visibility. In poor visibility, Engineers should consider limiting its use to low propeller flow. For propeller action, the thickness design method for tremie concrete is suggested taking into account appropriate surface roughness. A system with greater construction reliability should be preferred for the inclined high speed water jets of Ro Ro fast ferries.

## 14. PREFORMED MATTRESS

Prefomed mattresses generally offer the prospect of efficiency and a reduction in marine construction time. However the formation of joints between elements underwater is a serious weakness as this

generally defines the effectiveness and performance of a system to withstand turbulent propeller flow and fluctuations in pressure and suction. Large plant is also often needed to transport and place them. Diver entrapment whilst positioning heavy units on the bed is also an additional risk. Although preformed mattresses are generally flexible, secure edge details are still needed to prevent underscour and progressive uplift failure. Flexible mattresses tend to span partially over underscour holes in catenary action (figure 11.7) with divers often reporting the roll up or displacement of edges trapped from flow under the mattress. Generally these mattresses are less appropriate for higher propeller flows and not generally suitable for water jet flows common to Ro Ro Fast Ferries.

#### 14.1 Asphalt Mattress

These normally comprise a preformed mat of porous stone asphalt with a layer of mesh reinforcement and bottom geotextile. They are normally barged to site and craned in with diver positioning. The system requires a high degree of bed preparation to limit steps at joints. The open butt joints between panels are generally filled insitu with either hot mastic asphalt or concrete grout. The joints are highly dependent upon the marine working conditions, bed silt and siltation which may obstruct the joint, joint steps from bed undulation, plus Diver installation and subsequent inspection which are largely dependent upon water visibility. Problems have occurred with asphalt joints. For design of thickness, Pilarczyk's method has often been used. However if the joints or edges are not constructed reliably, Raes (8) with  $C_L = 0.5$  for overlapped or open joints or  $C_L = 1.0$  for unprotected edges should be considered along with proven performance.

#### 14.2 Precast Block Mattress

Precast Block Mattresses are cast in many forms, often comprising concrete blocks cast with interlinkage by nylon rope, steel cables, nylon mesh or bottom fabric. The connection type, panel size and shape are usually particular to individual manufacturers. As such, there are various general failure modes as listed in section 9.1. As for asphalt mattresses, the joint construction is important for reliability. Any open joints between blocks would allow flow entry and high positive under pressures. Areas which are not porous would be subject to high local suctions as described earlier, figure 4.23. Design of these mattresses and their thickness would be best based upon recorded performance.

#### 14.3 Gabion Mattress

Gabion or Reno mattresses are generally preformed from coated wire or mesh baskets containing stone. These are generally prefilled and lifting into place for berth beds guided by divers and placed onto a filter fabric. For medium and high propeller flows, coated wire types are prone to wire failure from stone movement in the gabion or above it. Steel bar mesh baskets can be more resilient to stone movement and the bars sized to give a suitable corrosion allowance, with attention to tied and closed joints plus appropriate embedded edge detail. Design guidance can be based upon performance of a particular system and its joints. The difference between open and closed joints/edges is outlined by

### 15. CONCLUSION

Present case histories show bed scour velocities from propellers, podded propulsors and azimuthing thrusters have increased typically to some 5-8 m/s. Bed velocities from the inclined water jets of Ro Ro Fast Ferries typical reach 8 – 12.5 m/s.

Traditional rock armour and many other scour protection types are impractical for these higher scour flows and hydrodynamic actions. The characterisation of scour protection types by their nature and failure mode has been introduced and related design methods presented or outlined. Insitu slab types have the potential for high effective performance with a design failure mode commonly due to hydrodynamic suction uplift (or edge underscour). Research test modelling has provided engineers with an understanding of the hydrodynamic bed load conditions and this has supported Dr Wellicome's method for design suction loads under propellers.

The importance of effective joints and edges has been highlighted for effective scour protection particularly under water jets. Insitu concrete mattress has proven to have high performance and versatility to be widely applied when used in conjunction with a stone falling edge detail.

The need for updated research on bed velocities, hydrodynamic effects and scour protection performance has been shown which would lead to advances in efficiency being made.

The marine constructability of scour protection types should be appraised relative to working conditions. Supervision for all scour protection types should be specified, including use of proven Marine Quality Control Systems by experienced engineers to achieve reliable work in the marine environment.

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