BERTH SCOUR PROTECTION FOR SINGLE & TWIN PROPELLERS

by

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1. ABSTRACT

Quay structures can be reduced by design using thinner scour protection. The performance of thinner protections as 'Sealed' or 'Open' to flow entry is described.

Established design methods for insitu concrete mattress and rock protections under single propeller action are reviewed. These methods are extended to twin propeller action based upon scale model testing undertaken. Comparison is made to current guidance by PIANC (2015) and PIANC (1997).

Vessels with twin propellers are outlined along with design implications for berths.

2. INTRODUCTION

2.1 Berthing Structures

Common types of berthing structures are shown in Figures 1 to 3. The progressive increase in vessel size has created a need for deeper berthing structures subjected to greater propeller actions.

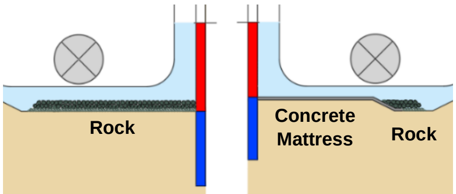

Figure 1. Piled Walls

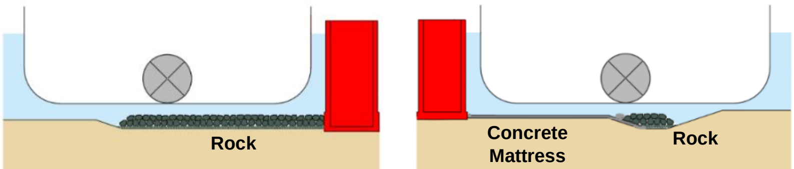

Figure 2. Caisson or Block Walls

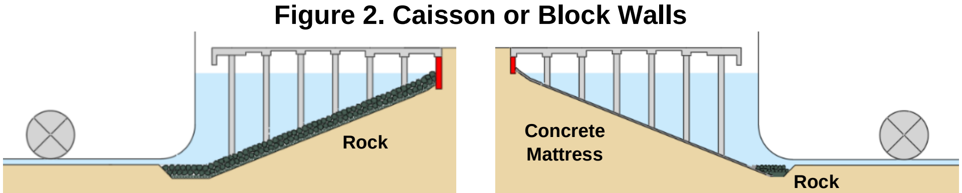

Figure 3. Open Piled Quays

Historically, rock protection has been the most common to berths but larger rock size is now often needed and the rock construction depth can significantly increase the size of piled walls and gravity walls (Figures 1 and 2), HAWKSWOOD, LAFEBER & HAWKSWOOD (2014). Significant savings can be made to these structures using thinner yet reliable mattress construction which is becoming increasingly understood. The use of insitu concrete mattress with rock falling edge aprons is often a beneficial combination. It is also effective for berth deepening projects to existing quay walls.

Open piled quays (Figure 3) can be constructed by the Land Infill method with insitu concrete mattress installed under completed piled platforms, HAWKSWOOD & KING 2016. This gives the prospect of savings in time and cost compared to construction involving marine plant.

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2.2 Vessels with Twin Propeller

Twin propellers are common to ferries, cruise vessels, inland vessels plus many other types of vessel. Some recent large container vessels (Maersk Triple E) also have twin propellers to give better fuel efficiency, redundancy and manoeuvrability. Scale model testing using twin propellers has allowed greater understanding and improved guidance to be developed. Vessels with twin propellers often perform a 'crabbing' movement at berth with one propeller ahead and one astern with rudder deployment to move the stern sideways. Relatively high engine power can be used and high levels of scour can occur particularly where berths are near to turning areas.

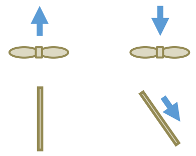

Figure 4. Plan of Crabbing Action

2.3 Protection Types

The performance of mattress protection types largely depends upon whether it is 'Sealed' to flow entry as Figure 5 or with 'Open' joints and edges where higher trapped flow pressures can occur as indicated in Figure 6, HAWKSWOOD, FLIERMAN et al (2016). This aspect significantly affects performance, the protection thickness needed and design methods to be used. The constructability of various mattress types as a 'Sealed' protection are described in Sections 5 and 6, along with grouted rock described in Section 7.

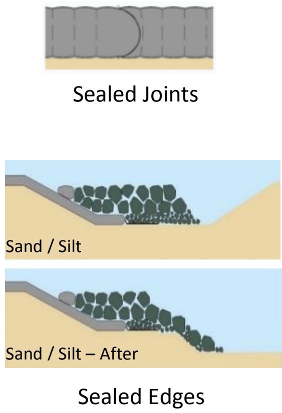

Figure 5. 'Sealed' Protection

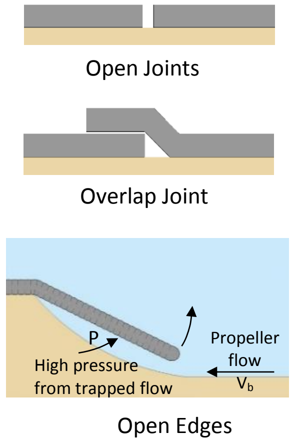

Figure 6. 'Open' Protection

2.4 Insitu Concrete Mattress

Insitu concrete mattress can be reliably installed as a 'Sealed' protection with suitable quality control, which is described in Section 5. Insitu concrete mattress forms a generic and consistent layer of plain concrete for which performance can be reliably predicted and design methods formed. Design methods by HAWKSWOOD, FLIERMAN et al (2016) for insitu concrete mattress under single propellers are presented in a simplified format in Section 5. Design examples for the combination of insitu concrete mattress and rock under both single and twin propellers are shown in Section 10.

2.5 Prefabricated Mattress

Prefabricated mattress types such as concrete block mattresses, asphalt mattresses and gabion mattresses are generally not a generic and consistent layer of material and vary by type, material, joints, manufacture etc. Reliable joints are more difficult to achieve when lowering heavy mattress in marine conditions onto harbour beds. A design method for flexible mattresses as an 'Open' protection by RAES et al (1996) is summarised in Section 6 along with references to some recent testing.

2.6 Rock Protection

The original design method by FÜEHRER & RÖMISCH (1977) was generally supported by previous scale model testing of rock protection by HAWKSWOOD, FLIERMAN et al (2016). This design method for single propellers will be reviewed in Section 8. An improved design method for twin propellers is also proposed in Section 8 following testing of rock subject to twin propeller action presented in Section 9.

2.7 Readership

The paper may assist with design and construction of berth scour protection, aid further testing, and development of design guidance. The paper may be of use to Port Authorities, Design Engineers, Contractors, Operators plus Research and Guidance Authorities.

2.8 Index

3. NOMENCLATURE

V_o	Max. propeller jet velocity	V_b	Bed velocity	L	Jet length
(c)	Propeller type, open/ducted	H_p	Height of propeller axis from bed	S	Propeller axis spacing
f	Ratio of engine power at berth	D_{min}	Design protection thickness	SF	Safety factor
P	Engine power	u	Surface undulation	C_L	Stability Coefficient (Raes *et al,* 1996)
ρ	Density	w	Width between undulations		
D_p	Propeller diameter	I_Q	Surface undulation factor	D_{S50}	Rock size (sphere), 50%
n	No. of propeller revolutions/s	C_S	Stability coefficient for suction	B_S	Stone stability coefficient
K_T	Propeller thrust coefficient	g	Acceleration due to gravity	P_Y	Offset factor for stone size
C	Propeller tip clearance	Δ	Buoyant relative density	Y	Offset distance
R	Propeller radius	C_F	Stability coefficient for flow		

4. PROPELLER ACTION

4.1 Propeller Jet Velocity

Jet flow constricts behind open propellers where the maximum jet flow occurs. In berths the maximum jet velocity normally occurs when the vessel is stationary or slow moving, typically during unberthing and can be calculated from the established formula (1): -

Maximum propeller jet velocity
$$V_o = (c)\left(\frac{f\,P}{\rho\,D_p^{\,2}}\right)^{1/3} \qquad (1)$$

Where:	Coefficient for open propellers	(c) = 1.48
	Coefficient for ducted propellers (with Kort Nozzles)	(c) = 1.17
	Propeller diameter (m)	D_p
	Engine power (kW)	P
	Ratio of engine power at berth	f
	Water density, Sea water 1.03 t/m^3	ρ

This equation is commonly used with guidance for the ratio of engine power at berth taken from PIANC Report 180 (2015) and PIANC WG22 (1997). Alternatively, where the maximum propeller revolutions and propeller thrust coefficient K_T are known, the established formula (2) usually provides more accuracy: -

$$V_o = 1.6\,n\,D_p\,\sqrt{K_T} \qquad (2)$$

Where:	N° of revs. per second (rps)	n
	Propeller thrust coefficient	K_T

A design berthing event is usually the occurrence of low clearance and a design vessel action, as shown in the probabilistic approach outlined in HAWKSWOOD, FLIERMAN et al (2016).

Ship simulation is increasingly used to model vessel movements in berths and harbours. This can help determine the engine power or propeller revolutions for design conditions in particular harbours.

4.2 Bed Velocity

The maximum bed velocity V_b is dependent upon the maximum propeller jet velocity V_o, propeller type, the propeller clearance ratio C/R and whether a central rudder is present behind the propeller, as is most common. A central rudder splits the rotational flow into two jets and creates higher bed velocity as indicated in Figures 7 and 8 from CFD modelling by Marin, HAWKSWOOD, LAFEBER & HAWKSWOOD (2014).

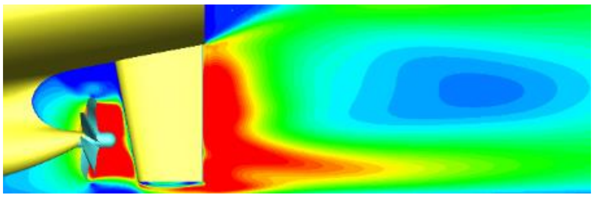

Figure 7. Velocity – *With Straight Rudder*

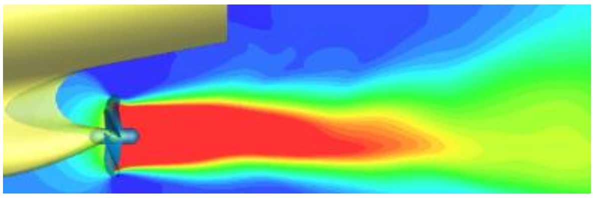

Figure 8. Velocity - *No Rudder*

For single propellers, bed velocities can be taken from Figure 9 based upon graphs from the original work by FÜHRER & RÖMISCH (1977) and PIANC BULLETIN 109 (2002). This method adequately takes into account the significant effect of a central rudder HAWKSWOOD, FLIERMAN et al (2016).

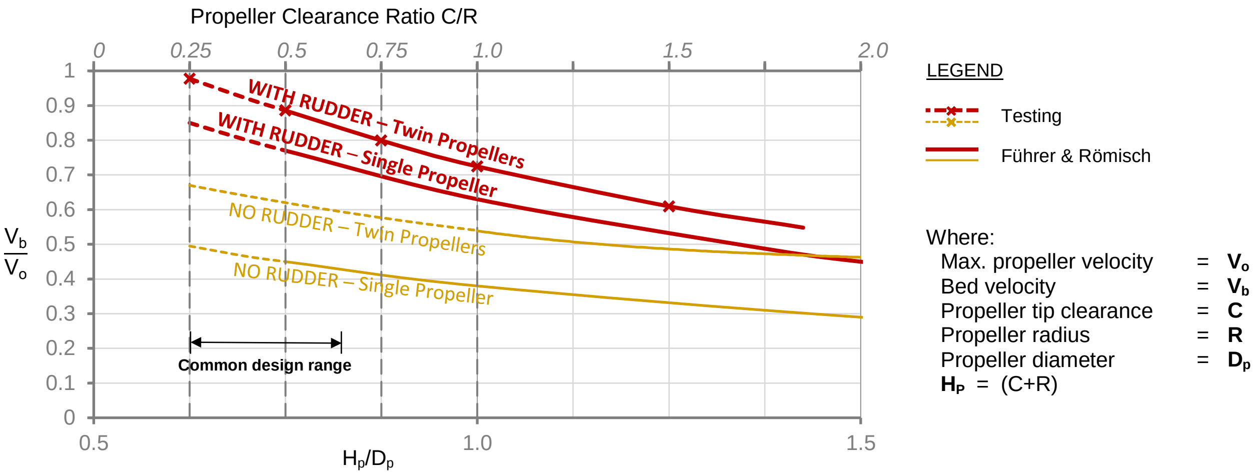

Figure 9. Bed Velocity, V_b Graph

Twin propeller jets combine and this creates higher bed velocities than for a single propeller. Figure 9 also shows recommended bed velocity established from testing, as Section 8.2. It also incorporates guidance from Führer & Römisch given in PIANC Report 180 (2015) Equation 8-34 for twin propellers with no central rudders and C/R > 1. This is supported by recent testing, MUJAL-COLLILES et al (2017). Bed velocities determined by Figure 9 are the basis of design methods for insitu concrete mattress and rock scour protection in the following sections.

The bed velocity for ducted propellers (with Kort nozzles) can be estimated from PIANC Report 180 (2015). Established guidance is not known to be readily available for ducted propellers with central rudders. It is suggested that Azimuthal thrusters (pushers) can be taken as open or ducted propellers as the case may be, without a rudder. Azipods (pullers) can conservatively be taken as open propellers with a central rudder as suggested by HAWKSWOOD, LAFEBER & HAWKSWOOD (2014) until testing guidance becomes available.

4.3 Hydrodynamic Bed Loads

Examples of hydrodynamic loads upon a bed are shown in Figures 10 and 11 from scale model testing conducted at Marin, HAWKSWOOD, LAFABRE & HAWKSWOOD (2014). A large area of bed suction occurs in front of propellers and impermeable protections need to be designed for this effect.

Behind the propeller, hydrodynamic loads upon the bed are higher but more variable. Areas of standing suction and pressure combine with fluctuating waves of suction and pressure in the propeller jet.

For a single propeller with a rudder, the flow is split by the rudder and has relatively low turbulence initially which then increases as the jet velocity decays.

For a single propeller with no rudder, the velocities reaching the bed are much lower but with higher turbulence and rotation.

The hydrodynamic distribution upon the bed is not symmetrical and is dependent upon the direction of rotation of the propeller. For twin propellers, inward and outward propeller rotation combines these different effects.

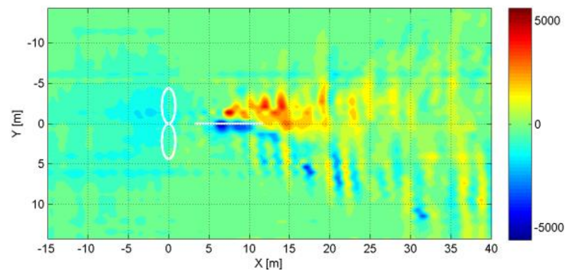

Figure 10. With Rudder

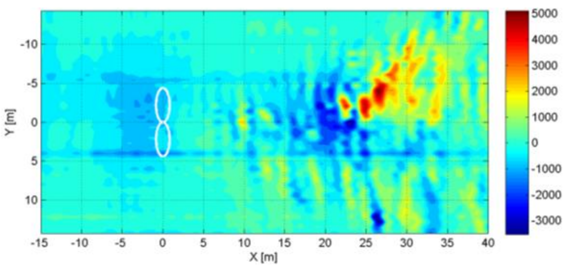

Figure 11. Without Rudder

5. INSITU CONCRETE MATTRESS

5.1 Introduction

Insitu concrete mattress aprons resist vessel actions to harbour beds and slopes. A rock falling edge apron is often used in erodible strata to provide a ‘Sealed’ edge detail as Figure 12. Constant Thickness Mattress types (CT) as Figure 13 are normally used to beds and permanently submerged slopes. Porous mattress types are needed to wave zones, HAWKSWOOD & ASSINDER (2013).

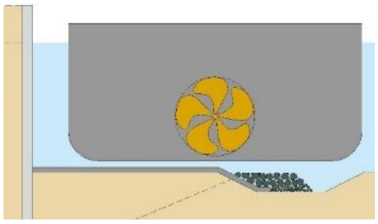

Figure 12. Typical Section

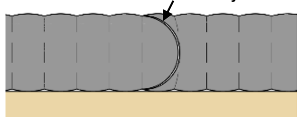

Figure 13. Constant Thickness Mattress (CT)

Insitu concrete mattress aprons are formed by divers rolling out mattress fabric underwater (Figure 14) which is zipped together and pump filled with highly fluid small aggregate concrete. The fluid concrete is protected from wash out by the mattress fabric. The system typically comprises two layers of woven fabric interconnected with thickness ties as shown in Figure 13. The fabric mattress is essentially a temporary works system. Joints between mattress panels are formed using zipped or sewn ‘ball and socket’ concrete shear joints, Figure 13. CT mattresses are typically pump filled with a sand: cement micro concrete mix of 35 N/mm² strength. This produces an apron of interlocked plain concrete slabs underwater. Seals to walls are achieved by using a concrete bolster detail as Figure 15. For sheet piled and combi walls, any inpans are infilled with tremie concrete.

Figure 14. Lowering mattress to be rolled out by divers

Concrete mattress is generally installed without the need for marine plant by divers working from the quay. Installation is not practical in currents above 0.5 m/s. Concrete mattress has a high durability and abrasion resistance created from the ’free’ water bleed of the fluid mix through the fabric resulting in a low water: cement ratio at the surface. Mattress panel widths are typically some 3m to 5m due to the weaving process. A 200mm minimum thickness is recommended to berth beds to cater for controlled maintenance dredging. For protection in more critical locations such as at gravity wall foundation levels as shown in Figure 2, thickness is often increased to 300mm for increased robustness.

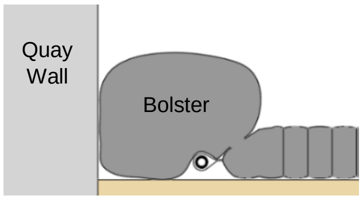

Figure 15. Wall Bolster Seal

Residual ground water movement may occur under quay structures, piling or slopes created by tidal movement etc. Weep holes can be provided 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 or heave is an issue, the mattress panel size can be reduced to increase flexibility HAWKSWOOD, LAFEBER & HAWKSWOOD (2014).

5.2 Marine Quality Control System

Work in the marine environment benefits from good skills, experience and procedures. Insitu concrete mattress can be reliably installed as a ‘Sealed’ protection using a proven marine quality control system, overseen by professional engineers with experience in the system. This should be specified and typically includes: -

- assessment of working conditions
- risk analysis
- concrete mix development
- mattress layouts, fabrication drawings
- temporary works design
- method statement
- installation training, demonstration trials
- bed preparation control
- quality control record system
- supervision (possible check diving)

This specialist engineering is normally provided by manufacturers who should have professional engineering capability and proven performance, which should be specified.

This insitu concrete mattress system is described in PIANC Report 180 (2015) along with the need for a suitable marine quality control. Insitu concrete mattress, reliably installed, can be used for high velocities. It has been used as berth protection to HSS vessels resisting inclined jet action upon the bed up to some 12 m/s, HAWKSWOOD, EVANS & HAWKSWOOD (2013).

5.3 Design Introduction

Insitu concrete mattress under propellers should be designed for:

- propeller suction
- propeller flow

Design methods for both propeller suction and propeller flow are taken from HAWKSWOOD, LAFEBER & HAWKSWOOD (2014) and relate to ‘Sealed’ protection with the following parameters: -

- sealed joints and edges (protected from underscour)
- concrete panels 3 to 5m wide between interlocked joints
- concrete strength 35 N/mm^2 (MPa)

Design for propeller suction is based upon work by Wellicome originally provided in HAWKSWOOD & ASSINDER (2013) as referred to in PIANC Report 180 (2015). At lower clearance ratios C/R, suction is usually the design condition for vessel actions. Where protection is offset from propeller locations, it should be designed for rudder deflected flow which is usually greater than bow thruster effects for larger seagoing vessels. Concrete mattress should be designed and constructed with suitable safety factors and robustness.

5.4 Surface Undulation Ratio

The spacing of mattress thickness ties *w* controls the surface undulation u as shown in Figures 16 and 17. The surface undulation ratio is given by u/w. Higher surface undulation increases hydrodynamic loading and reduces load distribution ability due to stress concentrations, HAWKSWOOD, LAFEBER & HAWKSWOOD (2014). Figure 18 shows an example of low surface undulation ratio with spacing of thickness ties at 100 mm centres.

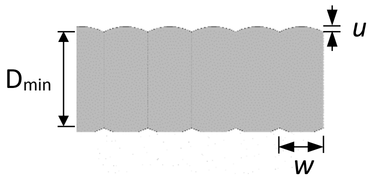

Figure 16. Low Surface Undulation

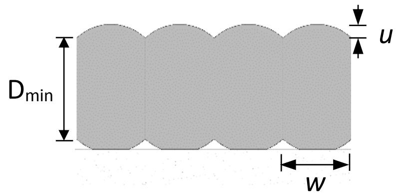

Figure 17. High Surface Undulation

Figure 18. Low Surface Undulation

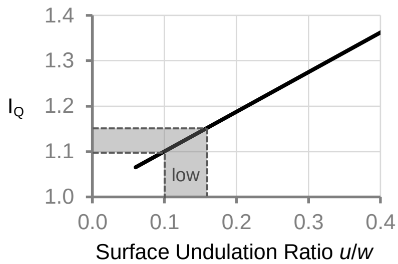

Figure 19. Surface Undulation Factor I_Q

The surface undulation factor I_Q for design is taken from Figure 19 and is related to the undulation ratio *u/w*. Mattress with low surface undulation ratio of 0.1 to 0.16 as Figure 16 are preferred and should be specified as they are subject to lower suction loads and distribute loading better. Mattress types with higher undulation ratios as Figure 17 are less effective and need a greater thickness.

Insitu concrete mattress is specified by:-

- Design thickness D_{min}
- Tie spacing w and I_Q value

Both of these should be verified during initial trial sample filling on site.

5.4 Design for Propeller Suction – Single Propellers

Insitu concrete mattress has good load distribution properties and is designed for the large area of bed suction which occurs to the intake side of a propeller as outlined in Figure 20 and shown in Figures 10 and 11.

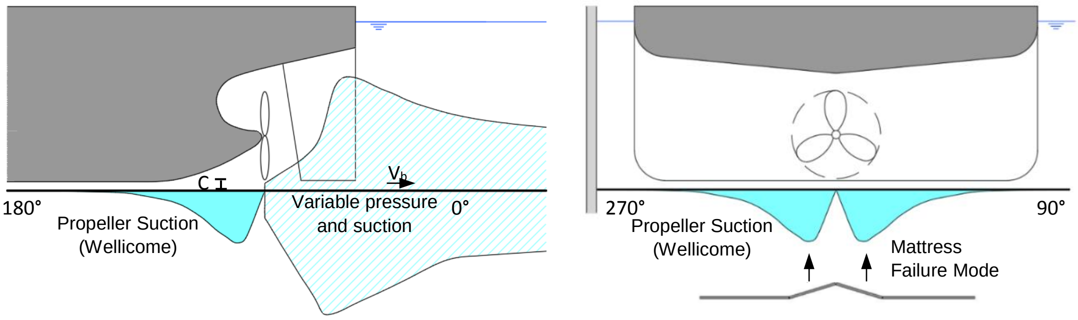

Figure 20. Propeller Suction

The dead-weight design method by HAWKSWOOD, LAFEBER & HAWKSWOOD (2014) is used for 'Sealed' protection, based upon the propeller exit velocity V_o, and is presented in a simplified format below: -

Simplified dead-weight design method

$$D_{min} = C_S \frac{V_o^{\,2}}{2\,g\,\Delta} \times \frac{I_Q}{1.15} \qquad (3)$$

Where: Stability coefficient for insitu concrete mattress propeller suction C_s
Mattress surface undulation factor (Figure 19.) I_Q

The stability coefficient for propeller suction C_S is taken from Figure 21. Propeller suction upon the bed reduces as the bed clearance ratio increases.

This method applies to open propellers with or without a rudder. For ducted propellers (with Kort nozzles), the original design method in HAWKSWOOD, LAFEBER & HAWKSWOOD (2014) should be followed.

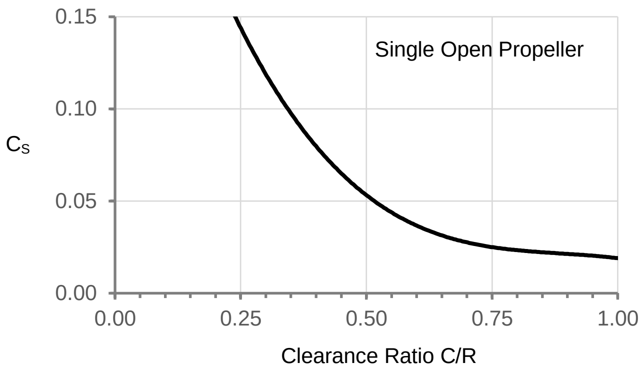

Figure 21. Propeller Suction Coefficient Cs

5.5 Design for Flow – Single Propellers

The design method for 'Sealed' insitu concrete mattress under propeller flow as Figure 22 is based upon the maximum bed velocity V_b as below:-

$$D_{min} = C_F \frac{V_b^{\,2}}{2\,g\,\Delta} \times \frac{I_Q}{1.15} \qquad (4)$$

Where: Stability coefficient for insitu concrete mattress under propeller flow C_F
Mattress surface undulation factor (Figure 19.) I_Q

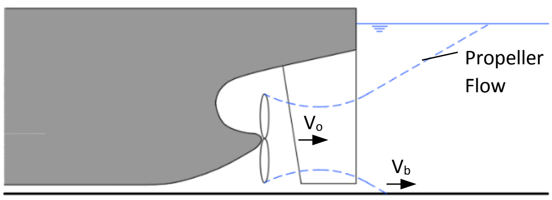

Figure 22. Propeller Flow

Design Condition	C_F
With rudder, Level beds	0.12
With rudder, Slopes + variable bottom	0.16
No rudder, Level beds	0.19
No rudder, Slopes + variable bottom	0.23

Table 1. Mattress Flow Coefficient C_F

The coefficient for propeller flow C_F can be taken from Table 1. This is based upon performance examples by PILARCZYK (2000), HAWKSWOOD & KING (2016) plus recent testing shown in Section 5.9. A variable bottom is assumed when bed undulations/ construction tolerances exceed 600mm. Where bed forms cause large areas of accelerated flow and suction, uplift can be estimated using Bernoulli's equation and mattress thickness designed accordingly.

5.6 Rudder Deflected Flow

Where protection is offset from the propeller, as with open piled quays (Figure 23), the protection should be designed for flow from deflected rudders, PIANC WG22 (1997).

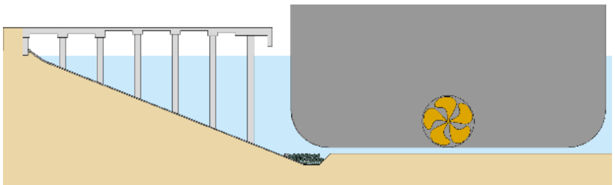

Figure 23. Open Piled Quay

Standard rudder types to container and seagoing vessels typically rotate to 35° with oil tankers often to 45°. Greater rotation is obtained from 2 stage (Becker) type rudders. Flow deflection is taken as 0.9 x the rudder rotation as shown in Figure 24, HAMILL et al (2009).

The propeller jet velocity is slowed by maximum rudder rotation by an approximate factor of 0.85, BAW (2010). To estimate bed velocity V_b at offset locations, this factor can be used along with the established propeller jet decay formula, from PIANC Report 180 (2015) Eq (1) for single propellers as shown in (5): -

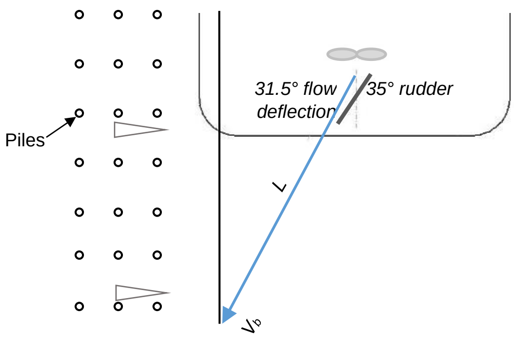

Figure 24. Rudder Deflected Flow

Bed velocity at offset locations
$$V_b = 0.85 \times V_o \times \frac{2.6\ D_p}{L} \qquad (5)$$

Where: Jet length (to offset location) L (For $L > 2.6\ D_p$)

To design insitu concrete mattress around piles, the increased velocity due to blockage of the piles should be used in (4) and the thickness further increased by ratio of the blockage velocity to approach velocity, HAWKSWOOD & ASSINDER (2013). Concrete mattress should be installed on stable slopes as it does not increase slope stability. Further guidance on construction is given in HAWKSWOOD & KING (2016).

5.7 Design for Propeller Suction – Twin Propellers

The suction distribution for twin propellers can be taken by combining the suction distributions for single propellers as shown in Figure 25. Analysis for various clearance ratios C/R and propeller shaft separations enables the stability coefficient Cs for insitu concrete mattress and twin propeller suction to be taken from Figure 26. This allows mattress thickness to be calculated from (4). This method is confirmed by recent testing. Section 5.9.

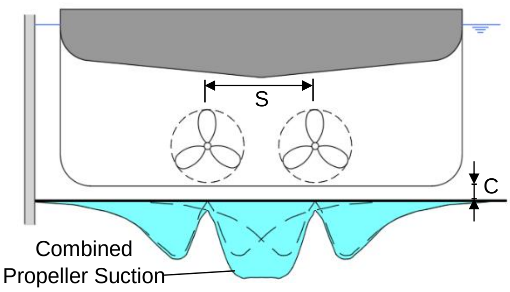

Figure 25. Suction Distribution
- Twin Propellers

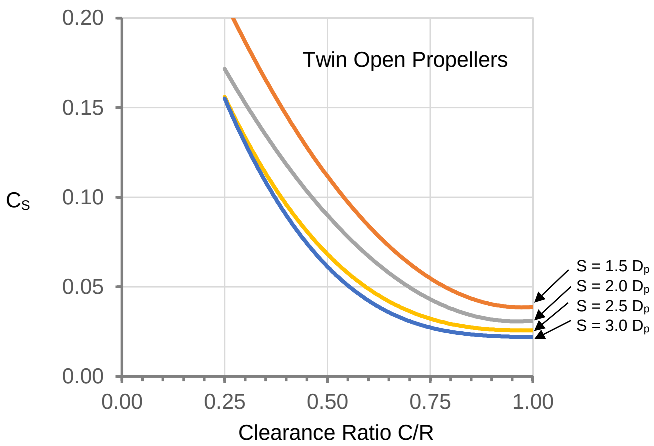

Figure 26. Suction Coefficient Cs
- Twin Propeller

5.8 Design for Propeller Flow – Twin Propellers

For insitu concrete mattress under twin propellers, the maximum bed velocity V_b can be taken from Figure 9 and stability coefficients for flow C_F as Table 1 for single propellers. The design mattress thickness can then be obtained from (4). This basis has been confirmed by recent testing presented in Section 5.9. If bed tolerances are greater than 0.6m, coefficients for variable bottom should be taken.

5.9 Scale Model Testing of Insitu Concrete Mattress – Twin Propellers

The test mattress had a strength and Young's Modulus replicated approximately to scale with interlocking joints. Scale model testing of insitu concrete mattress was undertaken as described in HAWKSWOOD, FLIERMAN et al (2016) for previous testing under single propeller action. Previous testing under single propeller action did not create failure but established a safety factor SF > 2.8 for propeller suction and a SF > 2.1 for propeller flow when compared to the design methods proposed. The simplified deadweight design method (3) for propeller suction has a nominal safety factor of 1.5 included but this excludes flexural capacity of the concrete apron and other stabilizing effects.

Figure 27. Test Arrangement

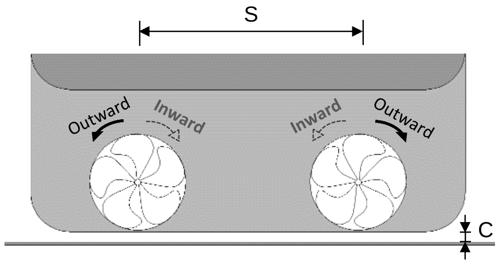

Figure 28. Test Arrangement, Rear View

The test arrangement for twin propellers is shown in Figures 27 and 28. For propeller suction, safety factors of greater than 2.8 and 5.3 were obtained without failure being reached as shown in Figure 29 for the worst case propeller separation S=1.5 D_P. The comparison is based upon the design method given in Section 5.8. Both inward and outward propeller rotations were tested, although this is not considered to be a significant influence.

For propeller flow, safety factors SF greater than, 5.0 and 6.4 were obtained for the various conditions shown in Figure 30. The tests included the conditions with and without a rudder. The test conditions were for a worst case propeller separation S=1.5 D_P and comparison based upon the method given in Section 5.8.

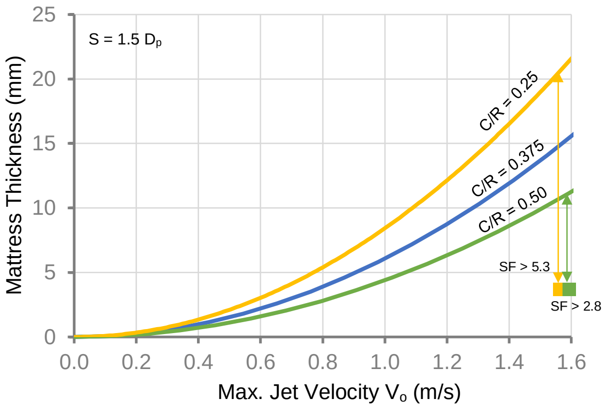

Figure 29. Suction – Twin Propeller

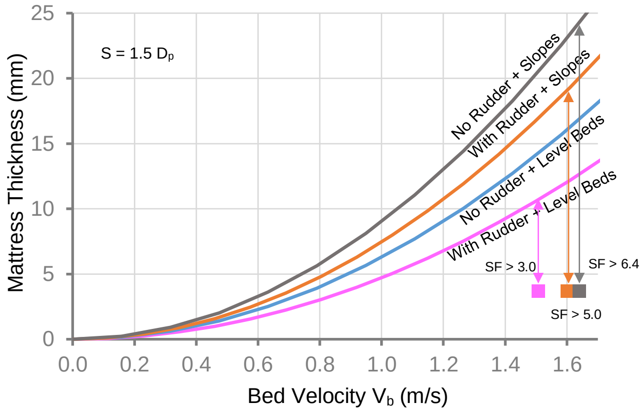

Figure 30. Flow – Twin Propeller

The testing indicates the design methods for both suction and flow have safety factors well above 2 for 'Sealed' protection.

6. PREFABRICATED MATTRESS

Precast concrete block and asphalt mattresses can be prefabricated with good quality control and offer the prospect of rapid installation, however installation often requires heavy marine plant and lowering presents an entrapment risk to divers during placement. Also, joints with reliable performance are more difficult to form working on the seabed. Prefabricated mattress performance is normally dependent upon the following: -

- Joints and edges
- Material
- Reinforcement / Ties
- Manufacturers mattress arrangement

RAES, ELSKENS, RÖMISCH & SAS (1996) provided a formula (6) for the stability of thin flexible bottom protections determined by experiment for overlapping or open joints and underscoured edges:-

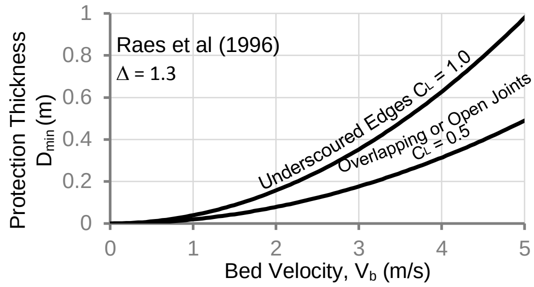

Figure 31. Open Mattress Stability

$$\textit{Thickness, } D_{min} = \frac{C_L V_b^2}{2\,\Delta\,g} \times I_Q \qquad (6)$$

Where C_L = 0.5 for overlapped or open joints and C_L = 1.0 for underscoured edges. The resulting thickness design curves are shown in Figure 31. This method can be compared to Bernoulli's equation applied to trapped flow pressure. Previous scale model testing of an example concrete block mattress by HAWKSWOOD, FLIERMAN et al (2016) indicated a safety factor SF of the order of 1.5 for both joints and edges, Figures 32 and 33.

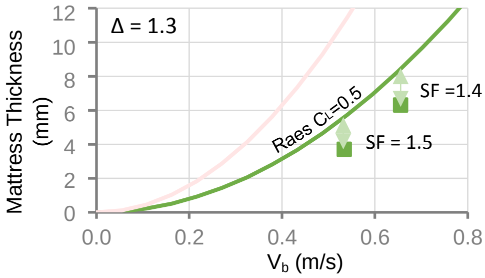

Figure 32. Testing of Block Matt – *Joints* Single Propeller

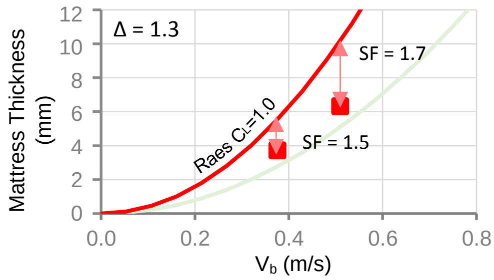

Figure 33. Testing of Block Matt – *Edges* Single Propeller

It has been common past practice for prefabricated mattress to have unprotected edges and failure by rolling up of edges has been reported. For propeller flow and scour depths now commonly occurring, suitable edge protection details are needed. Recent testing at Deltares by VAN VELZEN, DE JONG et al (2016) replicated likely bed tolerances and reported lower performance than estimated by Pilarczyk's formula, (PIANC Report 180 (2015). Pilarczyk's formula does not adequately take into account 'Sealed' and 'Open' conditions and the parameters were estimated and not validated for propeller flow, PILARCZYK (2011).

Design methods could be developed for particular types and manufacture of prefabricated mattress from scale model tests taking into account the worst condition of joints and edges likely to be achieved in projects, supported by case history performance.

7. GROUTED ROCK

Typically a rock layer is placed over a geotextile which is then pump in-filled typically with grout or tremie concrete. However, it is difficult to use on sloping areas and toe trench slopes to form important embedded edge details. Grouted rock is common in northern Europe where specialist skills in its reliable use are more available. There are some construction and environmental aspects to overcome for reliable berth protection, HAWKSWOOD, LAFEBER & HAWKSWOOD (2014).

For propeller action, if the protection is reliably constructed as a 'Sealed' protection, then the thickness design method for insitu concrete mattress can be used taking into account appropriate surface roughness and allowance for construction thickness tolerances.

8. ROCK DESIGN

8.1. Introduction

Rock protection generally comprises two layers of rip rap or armour stone upon a bedding/filter stone layer and often a geotextile filter membrane (Figure 34). The design, specification and construction of the rock protection can follow authoritative guidance by FÜHRER & RÖMISCH (1997), PIANC Report 180 (2015) and PIANC WG22 (1997) as outlined in earlier sections. The Rock Manual (2007) and PIANC WG22 (1997) give useful construction guidance. Rock protection has many good qualities, being porous and flexible; it performs well as falling edge aprons and is relatively easy to repair unless the bedding layer is lost. Rock protection often needs to be grouted at walls and structures to prevent wash out from flow down or along walls. (Figure 34). Rip rap stone with a wider grading than armour is generally preferred for lower flows as it can be mass placed by excavator bucket etc. rather than individual placement of armour stone PIANC WG22, (1997). Rock protection can be installed in modest currents. The rock construction depth can have a significant effect on structures, increasing the effective span height to piled walls, Figure 1, and increasing the depth of gravity walls, Figure 2.

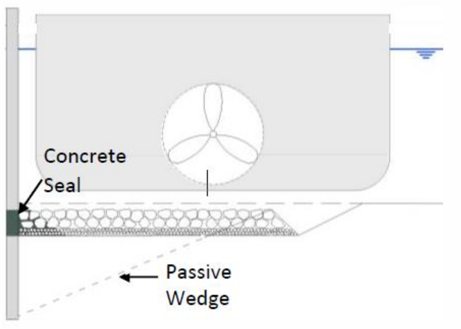

Figure 34. Rock Protection

Design of rock for no movement is particularly important where rock movement would cause grounding or loss of berthing clearance.

8.2. Level Bed Protection under Single Propellers

Design methods for rock stability have generally been based upon the 'threshold of motion' for no movement or scour. The most common design method emanates from the original testing work of FÜHRER & RÖMISCH (1977) who produced curves for bed velocity V_b as partly reproduced in Figure 9. They also provided a formula for rock protection size with no movement BAW (2005) as (7) below: -

Rock size, with no movement
$$D_{s50} = B_s \frac{V_b^{\,2}}{g\,\Delta} \tag{7}$$

Following recent testing, the following stability coefficients B_S are proposed: -

With Rudder	$B_S = 0.64$	FÜHRER & RÖMISCH (1977), BAW (2005)
No Rudder	$B_S = 1.55$	HAWKSWOOD, FLIERMAN et al (2016)

The above method and stability coefficients were generally well supported by recent testing by HAWKSWOOD, FLIERMAN et al (2016). The stability coefficient for no rudder of $B_S = 1.23$ by FÜHRER & RÖMISCH (1977) was found to be too low.

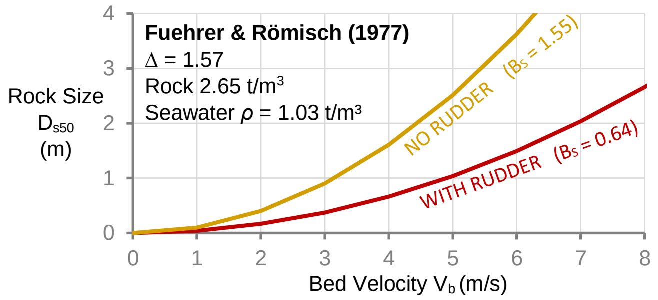

Figure 35. Stone Size for Vessel Actions

The relationships of rock size D_{s50} to bed velocity V_b are shown in Figure 35 for the general case with a central rudder behind the propeller, and with no rudder. The higher stability coefficient B_S for no rudder is created by the increased rotation and turbulence within the critical area of the flow acting upon the bed

The recent testing also showed that propeller tip clearance C can be taken from the centre of the top layer of rocks as Figure 36, HAWKSWOOD, FLIERMAN et al (2016). This takes into account the increasing stability effect for larger rock sizes which has been demonstrated in testing. This effect can make a useful saving to larger rock sizes.

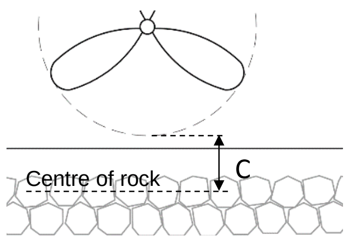

Figure 36. Propeller Tip Clearance, C

The method following Führer & Römisch's original work is termed the German method in PIANC Report 180 (2015) but with D_{85} used for stone size and a more conservative formula used for calculation of bed velocity. The design method termed the Dutch method has been found to underestimate bed velocity and rock sizes, particularly the effect of rudders, HAWKSWOOD, FLIERMAN et al (2016).

8.3. Rudder Deflected Flow

Where rock protection is offset from the propeller, such as open piled quays as Figure 37, the stone size should be designed for rudder deflected flow PIANC WG22 (1997). This is usually greater than bow thruster flow for seagoing vessels. A design method for rock size can be used by HAWKSWOOD, FLIERMAN et al (2016) for a single propeller with a level bed, and a standard rudder rotation of 35°, as shown in Figure 38 and the relationship given in (8) below:-

Offset rock size D_{s50} = Rock size directly under the propeller $D_{s50} \times P_Y$ (8)

Where: Offset factor P_Y
Offset distance Y
Offset ratio Y/D_P

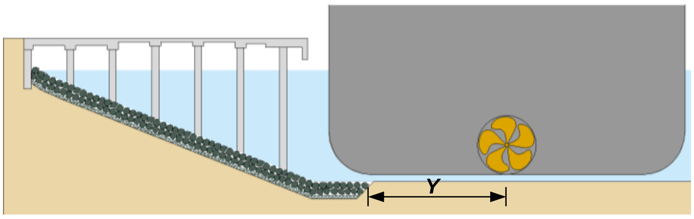

Figure 37. Open Piled Quay, Section

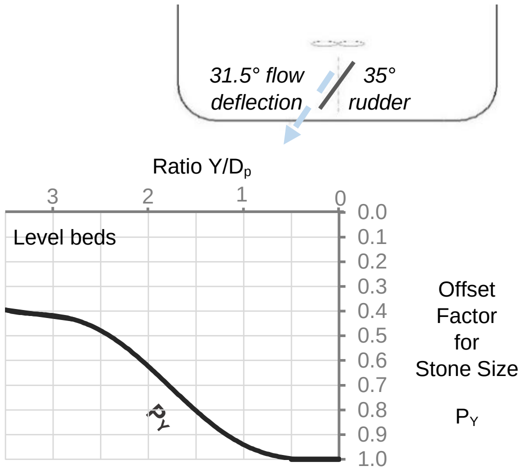

Figure 38. Offset Factor for Stone Size, P_Y, for Rudder Deflected Flow

This method was determined by testing and takes into account the increase in turbulence as the jet velocity decays. The flow deflection angle is taken as 0.9 x the rudder rotation, HAMILL et al (2009). This method can be applied to the crabbing action of a single deflected jet for twin propeller vessels, Figure 4.

This method should only be used for rudder rotation angles of 35° or below. For rudder rotation angles above 35°, the rock size needed can be interpolated from Figure 38 by using an equivalent jet length.

8.4. Slopes and Piles

The increase in rock size needed for slopes can be obtained using a slope factor by Pilarczyk, PIANC Report 180 (2015). The increased flow and turbulence around piles can cause rock stability failure. A pile effect factor estimated by Van Doorn, interpreted from PIANC Report 180 (2015) can be used.

Slope protection under piled quays is also described in HAWKSWOOD & KING (2016).

8.5. Rock Falling Edge Aprons

For propeller flow, the quantity of armour rock needed in a falling edge apron should give at least 1 layer of armour on a 3:1 slope down to the required scour protection level, HAWKSWOOD, FLIERMAN et al (2016). A fully deployed apron is likely to function only in the short term due to the risk of potential suffusion between the layer of dispersed armour and bedding stones. Where longer performance is required, some additional 50% of rock is suggested as Figure 39, shown as Deployed. This also provides for greater robustness as edge scour depths are often difficult to estimate along with the use of future vessels.

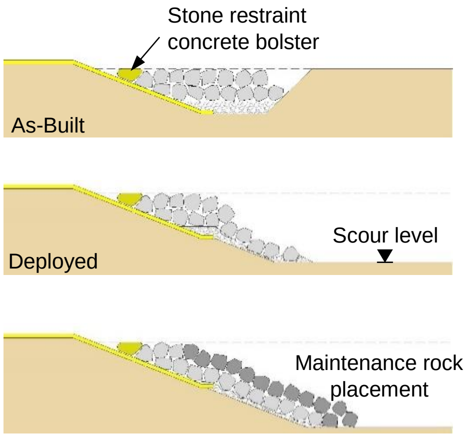

Figure 39. Falling Edge Apron Maintenance

Rock falling aprons provide an effective way to manage this risk. They are particularly useful when used in conjunction with insitu concrete or mattress protection types where 'Sealed' edges are required. Falling edge aprons can achieve a relatively high protective depth (VAN VELZEN et al 2014) and importantly can be monitored and maintained. In harbours, it is common to monitor performance of berth beds on an annual basis.

Rock aprons start to deploy when the edge scour exceeds the trench embedment depth as shown in Figure 39. Before aprons fully deploy and possibly fail, additional rock can be placed to any local scour areas.

The rock size is designed as for level beds with the support of testing, HAWKSWOOD, FLIERMAN et al (2016). A stone restraint concrete bolster is cast insitu to restrain edge rocks from movement, as shown in Figure 39. A rock falling edge apron design example is sown in Section 10.4.

8.6. Rock Design for Twin Propellers

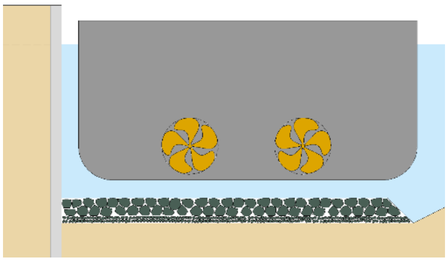

Figure 40. Rock Protection for Twin Propellers

Rock design for twin propeller action to level beds, as Figure 40, can be based upon the estimated bed velocity provided in Figure 9 for twin propellers, and used in (7) with the same rock stability coefficients B_S proposed for single propellers.

This method is supported by the stability testing shown in Section 9.

9. ROCK STABILITY TESTING FOR TWIN PROPELLERS

9.1 Test Arrangements

Scale model testing of rock was undertaken using two 150 mm diameter open propellers, as Figures 41, 42 and 43. The propeller rotation to initiate movement of various rock sizes was determined. To replicate actions in berths, the following effects were tested: -

- with rudders and without rudders
- varying propeller clearance C
- varying propeller separation S
- inward and outward propeller rotation (Figure 43)

Figure 41. Test Arrangement

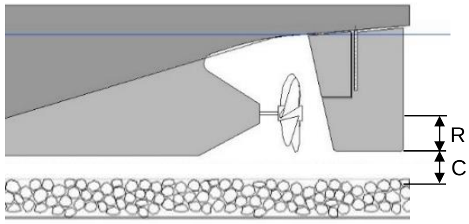

Figure 42. Test Arrangement, Elevation

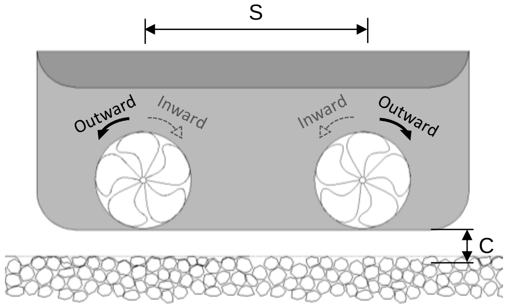

Figure 43. Test Arrangement, Section

The testing was carried out with a range of model rock sizes with W_{85}/W_{15} ratios from 1.8 to 2.6. This testing was an extension of a previous testing programme for single propellers with similar arrangements, HAWKSWOOD, FLIERMAN et al (2016). It has allowed the effect of twin propellers to be demonstrated and appropriate design guidance suggested. The testing covered a common range of low clearance ratios and a pair of handed twin propellers were used with 5 blades. The propellers were produced by MARIN with a K_T value of 0.587 which is now common.

9.2 Test Results and Findings

The bed velocities assumed in testing are based upon Figure 9. The test results for twin propellers with rudders are shown in Section 9.3. For twin propellers with no rudders, results are shown in Section 9.4. Both Figures 44 and 48 show that rock movement is predominately within the zones of single propeller jet flow rather than in zones where the jets are considered to merge, BAW (2010). This suggests the stability coefficients B_S for single propellers can also be used for twin propellers.

Rock stability testing results with a rudder are shown in Figures 45 to 47 for varying propeller separation S. These tests support the use of bed velocity as Figure 9, stability coefficient B_S = 0.64 and also taking the propeller clearance C from the centre of the top layer of rocks, Figure 36, as is suggested for single propellers, HAWKSWOOD, FLIERMAN et al (2016). Increase in the propeller separations made little difference, as the lower jets were still observed to combine.

Test results for rock stability without a rudder are shown in Figures 49 to 51 for varying propeller separation S. The results support the use of bed velocity as Figure 9, stability coefficient B_S = 1.55 and propeller clearance C to centre of top rocks, Figure 36. The increased rotation and turbulence in this action caused a wide spread of results with outward rotation being the worst case for larger stone sizes. Increase in propeller separation S made only a slight increase in stability, Figure 51, as the jet were still observed to combine upon the bed.

PIANC Report 180 (2015) advises bed velocities for twin propellers should be based upon those for single propellers x $\sqrt{2}$. For twin propellers with rudders this overestimates the rock size by a factor of some 1.5. For twin propellers with no rudders, the rock size is similar.

Rock movement in the tests was usually smaller stones below the D_{s50} size. Rock with lower W_{85} / W_{15} ratios were slightly more stable and indicate ratios below 2.0 are preferable for design.

Testing was conducted for ‘crabbing’ with one propeller ahead with rudder deployment and the other propeller astern as Figure 4. No change in rock stability was found, but the size of the scour zone appeared to be increased and this may contribute to significant scour often observed to turning areas next to berths by vessels crabbing, often with high power. This appears to be more common with ferry vessels.

Further comparison to rock performance in harbours would be useful along with testing to cover other propulsion types such as ducted propellers (Kurt nozzles), podded propulsors and azimuthal thrusters.

9.3. Rock Stability for Twin Propellers with Central Rudders

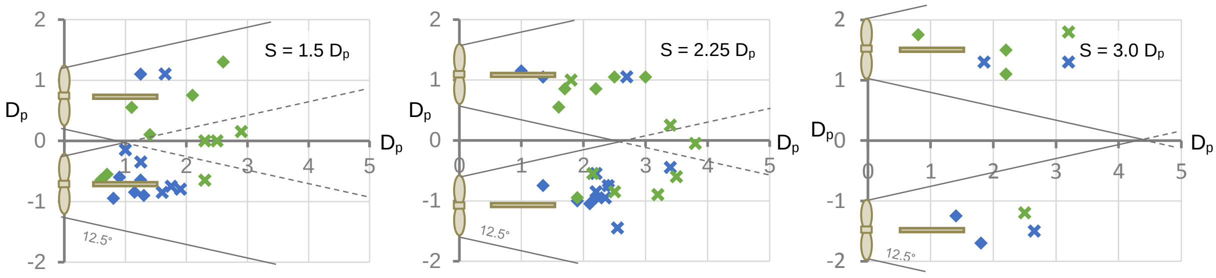

Figure 44. Plan of Rock Movement – With Rudder

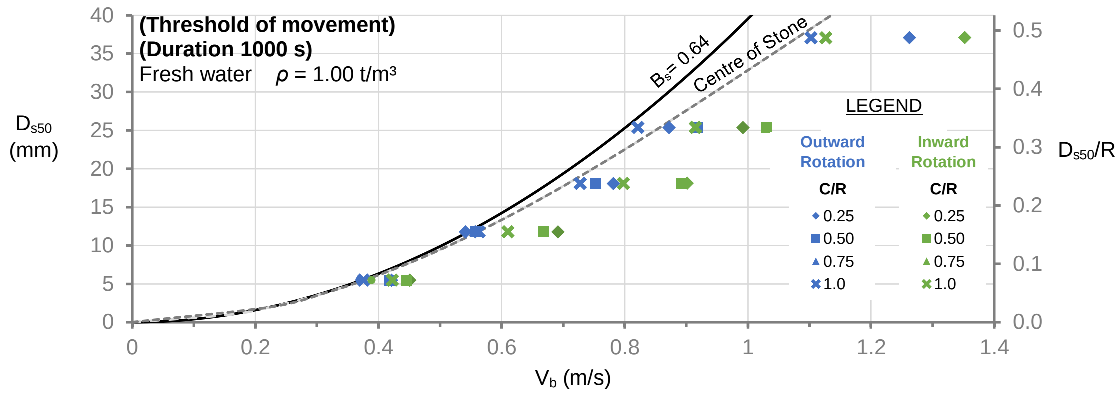

Figure 45. Rock Stability Testing – S = 1.5 D_p

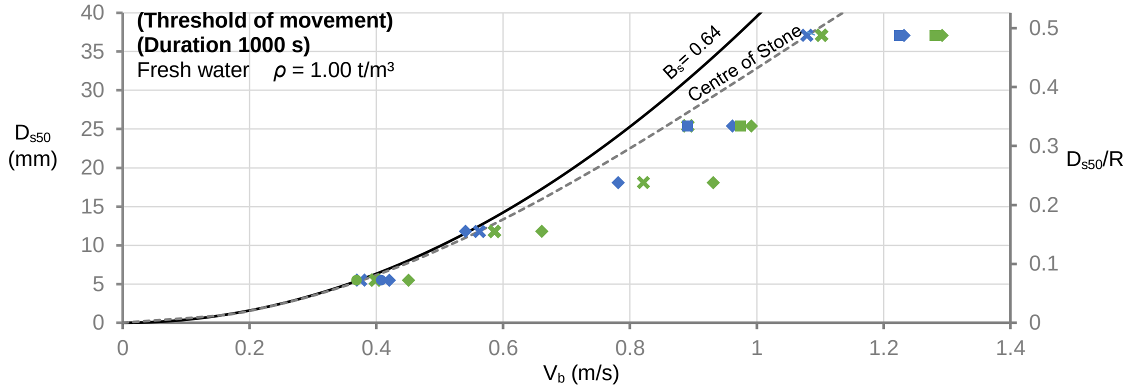

Figure 46. Rock Stability Testing – S = 2.25 D_p

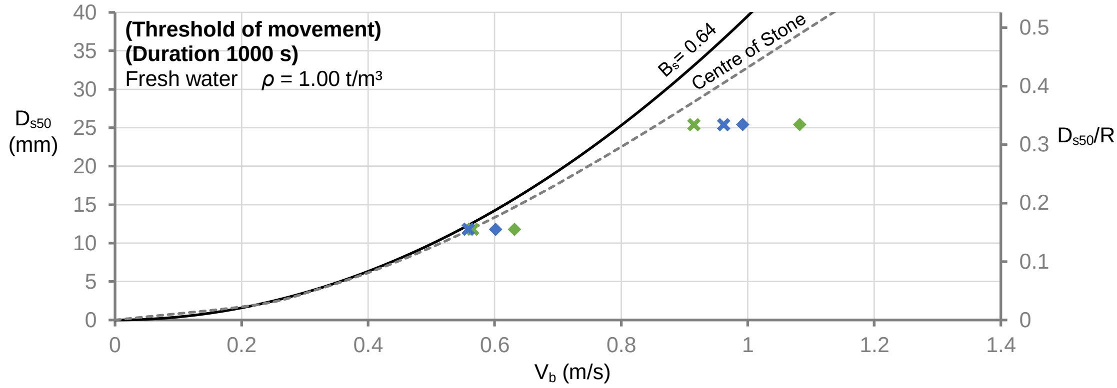

Figure 47. Rock Stability Testing – S = 3.0 D_p

9.4. Rock Stability for Twin Propellers with No Rudders

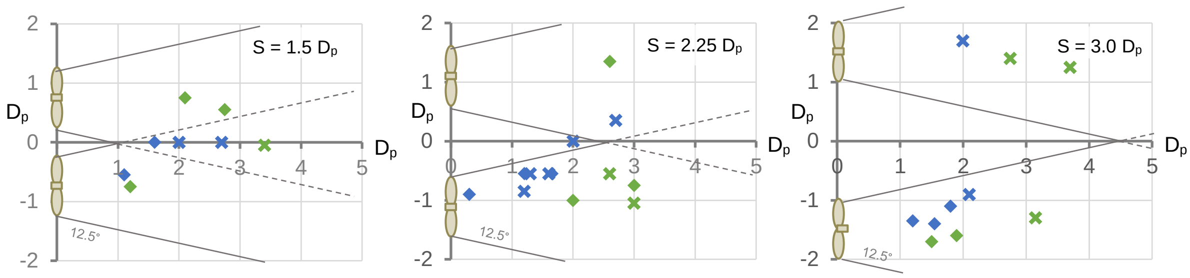

Figure 48. Plan of Rock Movement – Without Rudder

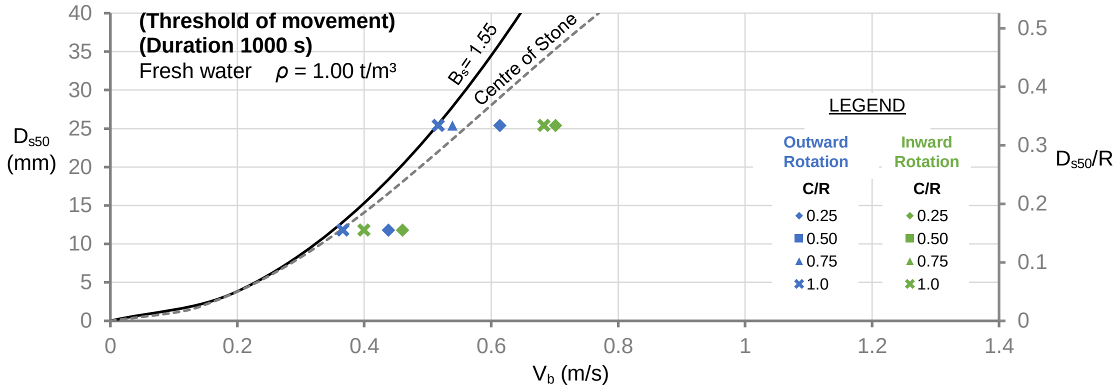

Figure 49. Rock Stability Testing – S = 1.5 D_p

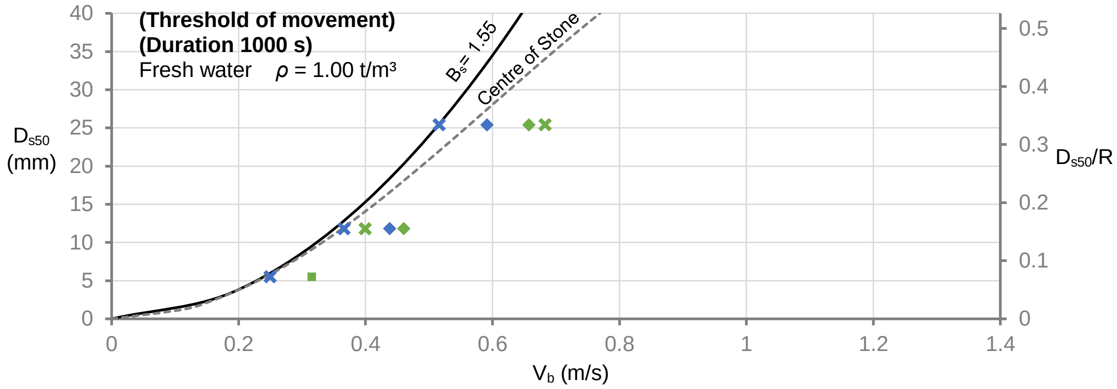

Figure 50. Rock Stability Testing – S = 2.25 D_p

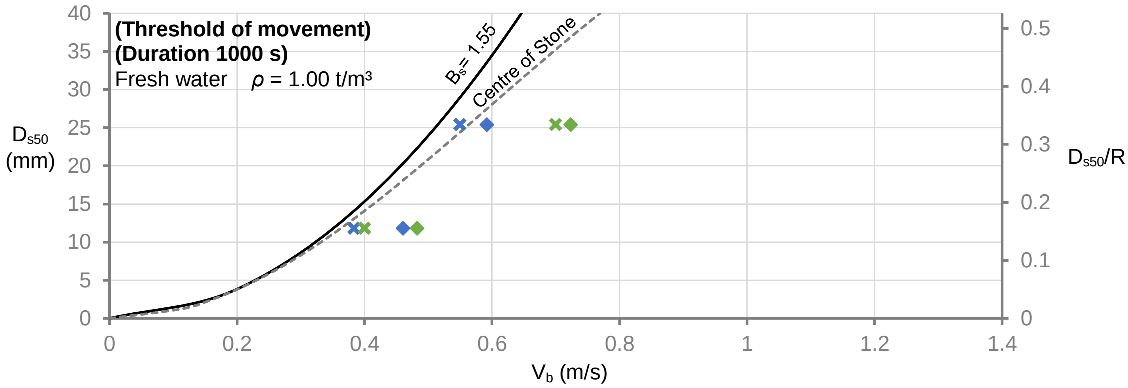

Figure 51. Rock Stability Testing – S = 3.0 D_p

10. DESIGN EXAMPLE

10.1. Single Propeller Vessel

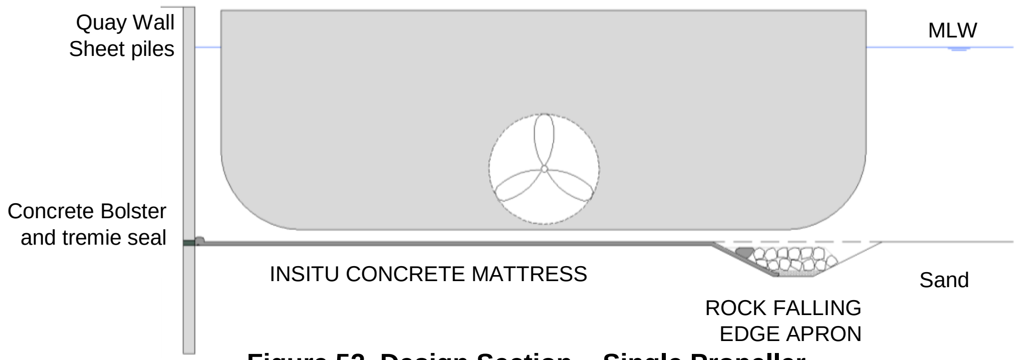

Figure 52. Design Section – Single Propeller

Design Parameters: Container Vessel

Propeller type	Single open propeller	
Propeller diameter (m)	D_P= 9.6 m	(R = 4.8 m)
Engine power (kW)	P = 80,080 kW	
Rudder type and max. deflection	Standard rudder, 35º deploy range	
Ratio of Engine power at berth	f = 0.1	PIANC Report 180 (2015)
Propeller Tip Clearance to Bed	C = 1.3 m	at MLW

Max. jet velocity: $$V_0 = 1.48\sqrt[3]{\frac{0.1\times 80{,}080}{1.03\times 9.6^2}} = 6.5\text{ m/s}$$ PIANC Report 180 (1)

Use 250 mm Thick Insitu Concrete Mattress (CT250) Tie spacing w = 100 mm, I_Q = 1.15 *(Fig. 19)*

Prop. tip clearance ratio to matt: $\frac{C}{R} = \frac{1.3}{4.8} = 0.27$ $\left[\frac{H_P}{D_P} = 0.64\right]$

Design for Suction: C_S=0.13 *(Fig. 21)*

$$D_{min} = C_S\,\frac{V_o^2}{2\,g\,\Delta}\times\frac{I_Q}{1.15} = 0.13\,\frac{6.5^2}{2\,g\,1.3}\times\frac{1.15}{1.15} = 0.22\text{ m} \quad < 0.25\text{ m OK} \qquad (3)$$

Design for Flow: C_F = 0.12 *(Table 1)*

Bed velocity reduction factor: $\frac{V_b}{V_0} = 0.85$ *(Fig. 9)*

Bed velocity onto mattress: V_b = 0.85 x 6.5 m/s = 5.5 m/s

$$D_{min} = C_F\,\frac{V_b^2}{2\,g\,\Delta}\times\frac{I_Q}{1.15} = 0.12\,\frac{5.5^2}{2\,g\,1.3}\times\frac{1.15}{1.15} = 0.14\text{ m} \quad < 0.25\text{ m OK} \qquad (4)$$

Use Rock Falling Edge Apron 2 layers 1.5-3 t rock ($D_{s,50}$ = 1.18 m), with 0.5 m thick bedding stone layer

The top of rock is 0.5 m below maintenance dredging level (PIANC WG 22, 1997).

Prop. tip clearance ratio to centre of top rock: $\frac{C}{R} = \frac{1.3 + 0.5 + (1.18\text{ x }0.5)}{4.8} = 0.5$ $\left[\frac{H_P}{D_P} = 0.75\right]$

Bed velocity reduction factor: $\frac{V_b}{V_0} = 0.77$ *(Fig. 9)*

Velocity onto rock: V_b = 0.77 x 6.5 m/s = 5.0 m/s

Rock Stability Factor: B_S = 0.64 Single propeller with rudder

Rock size: (Δ = 1.57) $$D_{s,50} = B_S\,\frac{V_b^2}{g\,\Delta} = 0.64\,\frac{5.0^2}{g\,1.57} = 1.04\text{ m} \quad < 1.18\text{ m provided OK} \qquad (7)$$

10.2. Twin Propeller Vessel

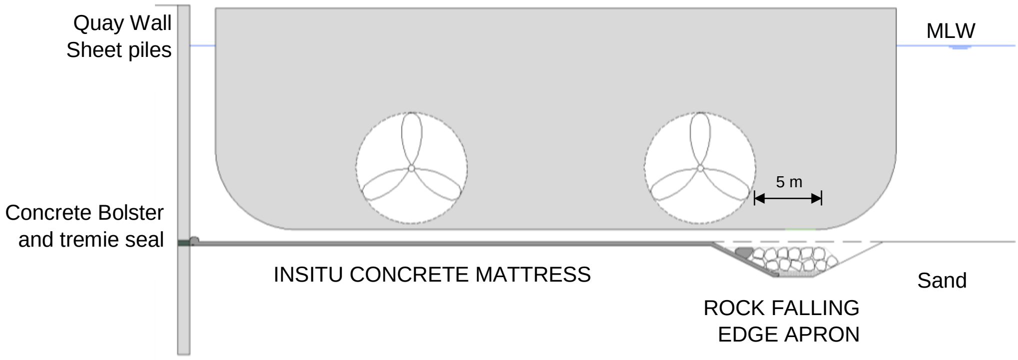

Figure 53. Design Section – Twin Propellers

Design Parameters: Container Vessel

Propeller type	Twin open propellers	
Propeller diameter (m)	D_p= 9.6 m	(R = 4.8 m)
Propeller axis separation (m)	S = 25 m	(25 m / 9.6 m = 2.6 D_p)
Engine power (kW)	P = 59,360 kW	
Rudder type and max. deflection	Standard rudders, 35º deploy range	
Ratio of Engine power at berth	f = 0.1	PIANC Report 180 (2015)
Propeller Tip Clearance to Bed	C = 1.3 m	at MLW

Max. jet velocity: $$V_0 = 1.48\sqrt[3]{\frac{0.1\times 59{,}360}{1.03\times 9.6^2}} = 5.9 \text{ m/s}$$ PIANC Report 180 (1)

Use 250 mm Thick Insitu Concrete Mattress (CT250) Tie spacing w = 100 mm, I_Q = 1.15 *(Fig. 19)*

Prop. tip clearance ratio to matt: $\frac{C}{R} = \frac{1.3}{4.8} = 0.27$ $\left[\frac{H_P}{D_P}=0.64\right]$

Design for Suction: C_S=0.15 *(Fig. 26)*

$$D_{min} = C_S \frac{V_o^2}{2\,g\,\Delta}\times\frac{I_Q}{1.15} = 0.15\,\frac{5.9^2}{2\,g\,1.3}\times\frac{1.15}{1.15} = 0.2 \text{ m}$$ < 0.25 m OK (3)

Design for Flow: C_F = 0.12 *(Table 1)*

Bed velocity reduction factor: $\frac{V_b}{V_0} = 0.97$ *(Fig. 9)*

Bed velocity onto mattress: V_b = 0.97 x 5.9 m/s = 5.7 m/s

$$D_{min} = C_F \frac{V_b^2}{2\,g\,\Delta}\times\frac{I_Q}{1.15} = 0.12\,\frac{5.7^2}{2\,g\,1.3}\times\frac{1.15}{1.15} = 0.15 \text{ m}$$ < 0.25 m OK (4)

Use Rock Falling Edge Apron – 2 layers 1.5–3 t rock, ($D_{s,50}$ = 1.18 m) with 0.5 m thick bedding stone layer
The top of rock is 0.5 m below maintenance dredging level (PIANC WG 22, 1997).

Prop. tip clearance ratio to centre of top rock: $\frac{C}{R} = \frac{1.3 + 0.5 + (1.18 \times 0.5)}{4.8} = 0.5$ $\left[\frac{H_P}{D_P} = 0.75\right]$

Bed velocity reduction factor: $\frac{V_b}{V_0} = 0.89$ *(Fig. 9)*

Velocity onto rock: V_b = 0.89 x 5.9 m/s = 5.2 m/s

Rock Stability Factor: B_S = 0.64 Twin props with rudders

Rock size: (Δ = 1.57) $$D_{s,50} = B_S\frac{V_b^2}{g\,\Delta} = 0.64\,\frac{5.2^2}{g\,1.57} = 1.12 \text{ m} < 1.18 \text{ m provided OK}$$ (7)

10.3. Insitu Concrete Mattress Parameters

– Use a proven Marine Quality Control System for ‘Sealed’ protection construction	Section 5.2
– Use CT mattress with tie spacing w = 100 mm (surface undulation ratio < 0.16)	Section 5.4
– Use Ball and Socket Joints between mattress panels	Figure 5
– Panel width 4.4 m typically	Section 5.3
– Concrete strength 35 N/mm^2 (MPa) C28/35	Section 5.3
– 250mm thickness > 200mm minimum thickness recommended for maintenance dredging and robustness	Section 5.1
– Use Concrete bolster seal to wall with tremie concrete infill to inpans, 0.3 m thick	Figure 52
– Use 1 row of 90 mm Ø weep holes @ 4.5 m centres along wall for nominal tidal water movement under wall in fine/medium sand	Section 5.1

10.4. Use 4.5m Wide Rock Falling Edge Apron

The extent of Scour Protection is to be 5 m beyond outer propeller. PIANC Report 180 (2015), p114. Provide Stone Restraint Bolster to secure edge rocks upon mattress.

From scour assessment experience, twin propeller vessels are the worst case, design rock falling edge apron for 5 m scour depth.

Top of rock depressed 0.5 m below maintenance dredge level M.D.L. to avoid damage, PIANC WG22 (1997).

Rock apron construction thickness take
(2 × 1.18 m × 0.8) + 0.5 m bedding layer = 2.4 m

Provide rock apron average length L = 4.4 m

The deployed apron depth is calculated for a single layer of rock protection on a 3:1 slope, 25% allowance as short term protection

Passive embedment: 2.4 m + 0.5 m = 2.9 m

Active deployment: $2 \times \frac{4.5\text{ m}}{1.25\text{ m}} \times \frac{1}{3.16} = \frac{\sim 2.3\text{ m}}{5.2\text{ m}} < 5\text{ m}$ OK

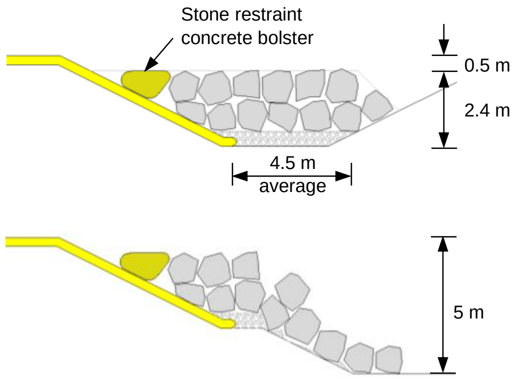

Figure 54. Falling Edge Apron Deployment

Rock edge to be monitored by annual bathymetric surveys. Any areas approaching ultimate deployment are to be inspected by diver and if required maintained locally with additional rock, HAWKSWOOD, FLIERMAN et al (2016).

11. CONCLUSIONS

Significant savings can often be made to piled and gravity quay wall structures using thinner scour protection than traditional rock construction, Figures 1 and 2.

The stability of thinner scour protections depends upon whether they are ‘Open’ or ‘Sealed’ to flow entry. A ‘Sealed’ protection has better performance and is normally more economic. Insitu concrete mattress protection is often used in conjunction with rock falling edge aprons and can be reliably installed as a ‘Sealed’ protection using a proven marine quality control system. Simplified design methods are now available for single propeller action, which have now been extended to twin propeller action following the research testing which has been presented. The formation of reliably ‘Sealed’ joints and edges using prefabricated mattress lowered onto harbour beds is more difficult to achieve. Prefabricated mattress designed as an ‘Open’ protection can be conservatively used.

The previous testing programme for rock protection generally supported use of the original method by FÜHRER & RÖMISCH (1997) for single propeller action, but with a stability coefficient B_S = 1.55 for the no rudder condition and propeller clearance taken to the centre of the top rocks (Figure 37). Further testing for twin propeller action has allowed an extension of the method to cover twin propeller action. Compared to PIANC Report 180 (2015), this shows significant savings in rock size to be made for twin propellers with rudders by a factor of some 1.5.

The number of large container vessels, cruise ships and ferries with twin propellers is growing and designers should take this into account. Vessels with twin propellers may need an increase in scour protection size and an increase in protection width to protect under both propellers. The testing has shown that bed velocities for twin propellers with rudders are lower than estimated by PIANC Report 180 (2015) and this results in savings in rock size by a factor of some 1.5.

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