Research & Development in Berth Scour Protection

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Abstract: Advancement in berth scour protection has been mainly led by research and observation of performance in harbours. This paper seeks to review and summarize this research and development to provide a clearer understanding of the fundamental concepts and associated guidance. Hopefully this may be helpful to the engineering community and offers the prospect of improved protection to berths in compliance with PIANC guidance.

Keywords: Berth Scour Protection, Concepts, Design, Construction

1. Introduction

1.1 Scour Protection to Berthing Structures

Common types of berthing structures are shown in Figures 1 to 3.

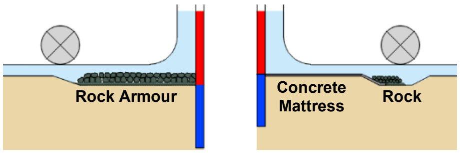

Figure 1. Piled Walls

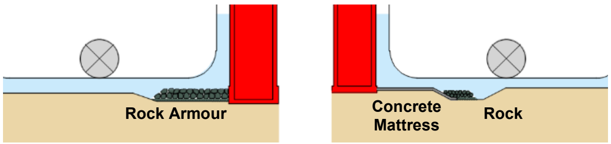

Figure 2. Caissons or Block Walls

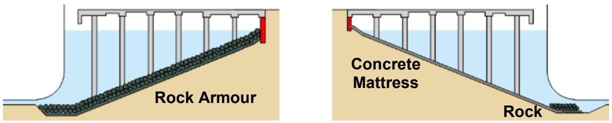

Figure 3. Open Piled Quays

Scour protection is principally required to ensure the stability of berthing structures from the threat of scour by vessel actions. Scour protection is needed to protect the geotechnically important areas to ensure stability of these structures.

Rock protection has historically been most commonly used to berths but larger rock sizes are now often needed for larger modern vessels. This increases the rock construction depth which can significantly increase the size of piled walls and gravity walls, Figures 1 and 2. Mattress construction, which is relatively thinner, is becoming increasingly used. The use of in-situ concrete mattress with rock falling edge aprons is often a beneficial combination. It is also effective for berth deepening projects to existing quay walls. In-situ concrete mattress can be installed under completed piled platforms (Figure 3) giving the prospect of savings in construction time.

The relative performance of preformed mattress types will be commented upon along with rock and in-situ concrete mattress protections. For these protections, stability concepts and design methods will be summarised based upon research and development.

1.2 PIANC Guidance

PIANC guidance is accepted as the worldwide standard for berth scour protection and should be complied with where appropriate. Presently guidance comprises of PIANC 180 (2015) [13] and PIANC WG22 (1997) [14] where its advice has not been superseded. A new combined guidance document is presently being prepared. PIANC guidance often includes developments in scour protection to berthing structures in its updates. PIANC guidance will not cover all situations and applications, yet it outlines suggested references or how modelling of solutions can be undertaken.

1.3 Research And Development

Research and development has led to the development of guidance and its improvement. Much of the research has been based on scale model testing. This research is often referenced in the paper with associated concepts presented.

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3. Nomenclature

V_o	Max. Propeller jet velocity	V_b	Bed velocity
(c)	Coefficient open/ducted propeller	H_p	Height of propeller axis from bed
f	% engine power at berth	D_{min}	Design protection thickness
P	Engine power (kW)	u	Surface undulation
ρ	Density	w	Width between undulations
D_p	Propeller diameter	I_Q	Surface undulation factor
C	Propeller tip clearance		Propeller radius
R	Propeller radius	Δ	Buoyant relative density
C_S	Suction Stability coefficient	C_F	Stability coefficient for flow
		B_S	Stone stability coefficient
D_{S50}	Rock size (sphere), 50%	g	Gravity

4. Extent of Protection

In principle the scour protection should cover the geotechnically important zones to ensure the stability of berthing structures. Figure 4, 5, & 6 show common types of berthing structures, their geotechnical zones and protection extents. These protection extents are normally defined by geotechnical design. Where the extent of the geotechnical zone is unknown, PIANC 180 (2015) [13] provides guidance for piled walls.

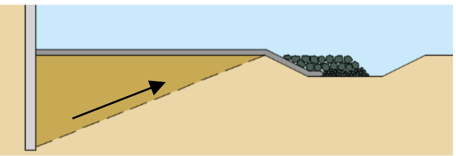

Figure 4. Protection Extent - Piled Walls

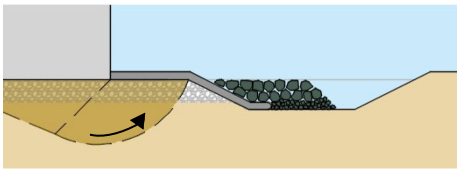

Figure 5. Protection Extent - Caissons or Block Wall

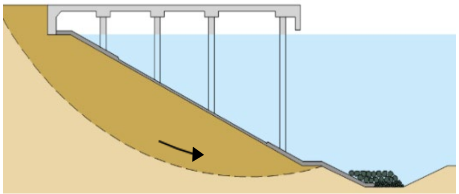

Figure 6. Protection Extent - Open Piled Quays

5. Propeller Action

5.1 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 from PIANC 180 (2015) [13] Equation (1):-

$$V_0 = (c)\left(\frac{fP}{\rho {D_p}^2}\right)^{\frac{1}{3}} \tag{1}$$

where V_0 = Maximum propellor jet velocity; c = coefficient for open propellors; f = Ratio of engine power at berth; P = Engine power (kW); ρ = Water density, Sea water 1.03 t/m^3; D_p = Propeller diameter (m)

This equation is commonly used with guidance for the ratio of engine power at berth taken from PIANC 180 (2015) [13]. 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) [7].

5.2 Bed Velocity

The maximum bed velocity V_b is dependent upon the maximum propeller jet velocity, V_0, 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 Figure 7 and Figure 8 from CFD modelling by Marin, Hawkswood, Lafeber & Hawkswood (2014) [6].

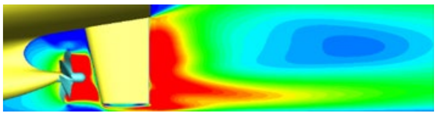

Figure 7. Velocity - With Straight Rudder

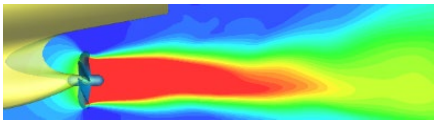

Figure 8. Velocity - No Rudder

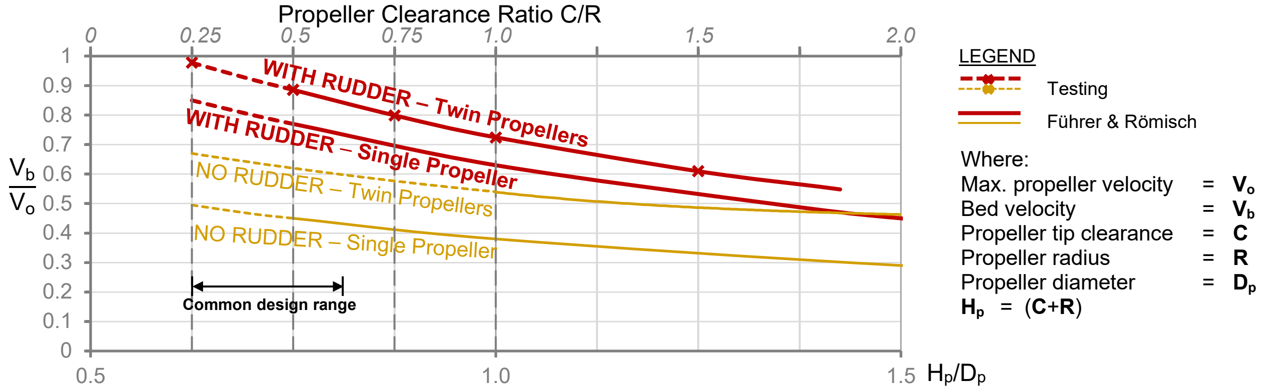

Figure 9. Bed Velocity, Vb Graph

For single propellers, bed velocities can be taken from Figure 9 based upon graphs from the scale model research work by Führer & Römisch (1977) [2] and PIANC Bulletin 109 (2002) [11]. This method adequately takes into account the significant effect of a central rudder as confirmed by scale model testing, Hawkswood, Flierman *et al* (2016) [7].

Twin propeller jets to vessels tend to combine and this creates higher bed velocities than for a single propeller. This is also shown in Figure 9 based upon testing by Hawkswood *et al* (2018) [9]. This testing showed that the use of a simple factor of √2 for twin propellers as suggested in PIANC 180 (2015) [13] is an overestimation for the normal spacing of propellers.

5.3 Rudder deflected Flow

Where protection is offset from the propeller, as often occurs with open piled quays, the protection should be designed for flow from deflected rudders, PIANC WG22 (1997) [14].

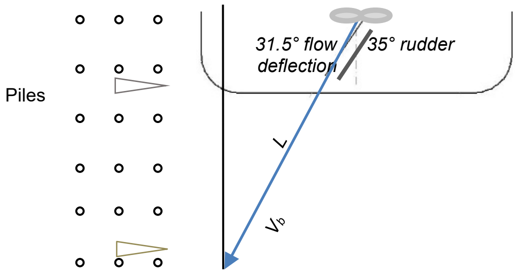

Figure 10. Plan Rudder Deflected Flow

A basis to calculate bed velocity from rudder deflection is provided in Hawkswood *et al* (2018) [9].

5.4 Hydrodynamic Bed Loads

Examples of hydrodynamic loads upon a bed are shown in Figure 11 from scale model testing conducted at Marin, Hawkswood, Lafeber & Hawkswood (2014) [6]. A large area of bed suction occurs in front of propellers and impermeable protections need to be designed for this effect.

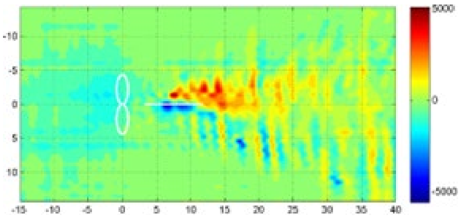

Figure 11. Hydrodynamic Loads - Propeller With Rudder

Behind the propeller, hydrodynamic loads upon the bed are higher but more variable. 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.

5.5 Azipods

Research by Hawkswood *et al* (2023) [10] found where Azipods have bottom fins, they are similar to propellers with rudders. Where cruise vessels berth to open piled quays, scour protection needs to be designed for the high flow conditions during unberthing from twin rotated Azipods, Figure 12.

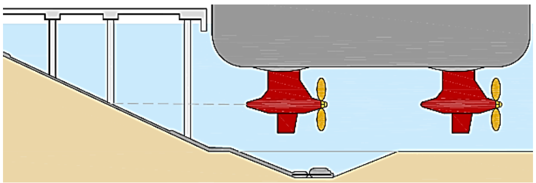

Figure 12. Azipods rotated towards pile quay

Design methods based on scale model testing for this and other conditions are shown in Hawkswood *et al* (2023) [10].

5.6 Other Propulsions

Research was carried out for jet propulsion common to catamaran vehicle ferries, Hawkswood *et al* (2013) [5] by CFD modelling which assisted with the development of some general guidance, given in PIANC 180 (2015) [13]. For Voith Schneider propulsors, velocity fields can often be provided by manufacturers.

6. Bow Thruster Action

Bow thrusters act on scour protection mostly during unberthing as outlined in Figure 13.

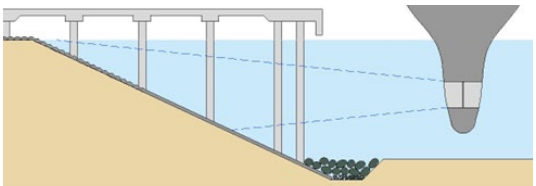

Figure 13. Bow Thruster

Multiple bow thrusters are often used on vessels. These jets are generally closer together than twin propellers and readily combine to produce higher velocities as advised in PIANC 180 (2015) [13].

7. Scour at Edges

Scour occurs when bed velocity from vessel actions exceeds the stability threshold level for the bed material. Once the extent of protection has been decided, the major issue is to determine the design edge scour depth likely to reasonably occur at protection edges.

Estimation of scour at edges can be best determined by a comparison of scour behaviour of similar vessel actions and bed soil conditions. Presently this may be best achieved by interpretation from locally available experience and records in harbours as Figure 14, coupled with more general experience.

Figure 14. Harbour Bathymetric Scour Records

Formulas to predict scour by vessels have not been found to be reliable so far by the authors. For sand and silt bed materials Table 1 shows some general experience of design scour depths presently being used.

Table 1. Vessel types and typical scour depths

Definition	**Design Edge Scour Depth**
Container Vessels to 16m draft	4m – 5m
Ferry Vessels to 7m draft twin propellers, very frequent	5m – 6m
Cruise Vessels to 10m draft azipods, daily	4m – 5m

For example, ferry vessels with frequent berthing each day can quickly cause significant scour up to 5m-6m in sands which often reaches a scour equilibrium in 1-2 years. By comparison, scour from container vessels takes much longer to reach equilibrium and higher siltation rates can act to reduce scour depths.

For smaller vessels, the likely scour depths are reduced. Scour experience from other engineers would be welcome.

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 15).

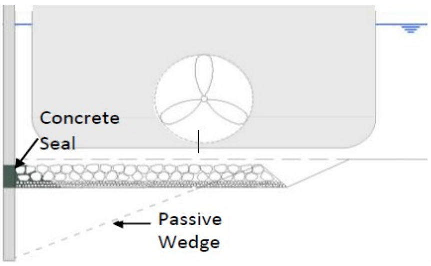

Figure 15. Rock Protection

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 15). Rock protection can be installed in modest currents.

8.2 Rock Design - Level Bed Protection

Design methods for rock stability have generally been based upon the 'threshold of motion' for no movement or scour. Design of rock for no movement is particularly important where rock movement would cause obstructions, grounding or loss of berthing clearance. The most common design method emanates from the original testing work of Führer and Römisch (1977) [2] 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) [1] as (2) below: -

$$D_{s50} = B_s \frac{V_b^2}{g\Delta} \tag{2}$$

Where D_{s50} = Rock size, with no movement; Bs = stability coefficient, V_b = bed velocity, g is gravity, Δ is buoyant relative density.

Extensive scale model testing of rock stability was undertaken by Hawkswood, Flierman *et al* (2016) [7] as Figure 16.

Figure 16. Scale Model Test Arrangements

Following the testing, the following stability coefficients Bs where proposed as Table 2: -

Table 2. Stability Coefficients For Rock Bed Protection

With Rudder	Bs = 0.64	Führer and Römisch (1977) [3], BAW (2005) [1]
No Rudder	Bs = 1.55	Hawkswood and Flierman *et al* (2016) [6]

The stability coefficient for no rudder of Bs = 1.23 by Führer and Römisch (1977) [2] was found to be too low.

The relationships of rock size D_{s50} to bed velocity V_b are shown in Figure 17 for the general case with a central rudder behind the propeller, and with no rudder. The need for a higher stability coefficient Bs for no rudder is created by the increased rotation and turbulence within the critical area of the flow acting upon the bed.

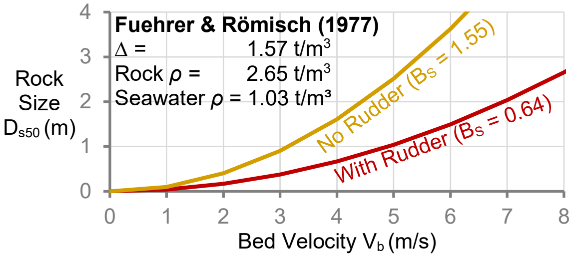

Figure 17 - Stone Size & Bed Velocity

The testing covered lower clearances which are now more common and also showed that propeller tip clearance C can be taken from the centre of the top layer of rocks as Figure 18. 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.

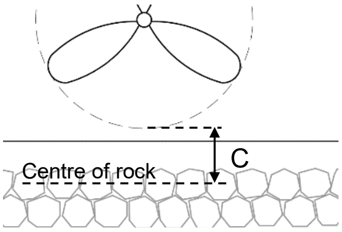

Figure 18. Propeller Tip Clearance, C

The method following Führer & Römisch's original work is termed the 'German Method' in PIANC 180 (2015) [13] 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) [7].

Rock armour becomes more stable where partially embedded in siltation. This is known to occur with high siltation rates and where vessel actions are lower and less frequent. Initial diver inspection of ferry berths has shown the top layer of rock is often clear of siltation in areas under high and frequent propellor flow. Future research may be worthwhile.

8.3 Rock Design - Rudder Deflected Flow

Where rock protection is offset from the propeller, which is common to open piled quays as Figure 19, the stone size should be designed for rudder deflected flow as outlined in PIANC WG22 (1997) [14]. Rock sizes can be reduced for offset using a method by Hawkswood *et al* (2018) [9] following scale model testing.

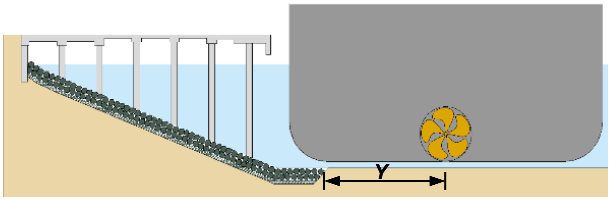

Figure 19 - Open Piled Quay, Section

8.4 Slopes and Piles

The increase in rock size needed for slopes can be obtained using a slope factor by Pilarczyk (2000) [15]. The increased flow and turbulence around piles can cause rock stability failure. A pile effect factor estimated from research by Van Doorn, interpreted from PIANC 180 (2015) [13] can be used. Slope protection under piled quays is also described in Hawkswood & King (2016) [8].

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 following testing, experience and guidance by Hawkswood, Flierman *et al* (2016) [7]. A fully deployed apron as outlined in Figure 20, is likely to slowly regress in the short term due to the risk of suffusion between the layer of dispersed armour and bedding stones. Where longer term performance is required, some additional 50% of rock is suggested along with monitoring and maintenance where needed.

Rock falling aprons are particularly useful when used in conjunction with in-situ concrete or mattress protection types where 'Sealed' edges are required. The rock size can be designed as for level beds following testing and guidance by Hawkswood, Flierman *et al* (2016) [7]. A stone restraint concrete bolster is cast in-situ to restrain edge rocks from movement, as shown in Figure 20.

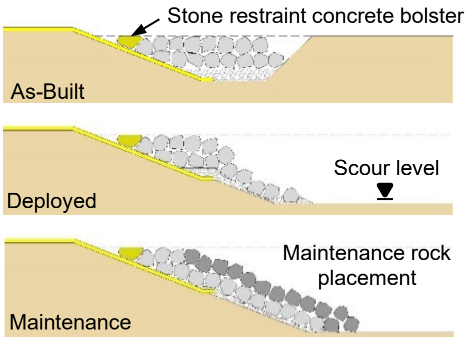

Figure 20. Falling Edge Apron Maintenance

9. Mattress Stability Principle

The stability principle for mattress protection types largely depends upon whether it is 'Sealed' to flow entry as shown in Figure 21 or with 'Open' joints and edges where higher trapped flow pressures can occur as also shown in Figure 21. These stability principles were initially established from testing by Raes *et al* (1996) [16] and further confirmed by scale model testing undertaken by Hawkswood and Flierman *et al* (2016) [7]. This principle significantly affects performance, the protection thickness needed and the design method to be used.

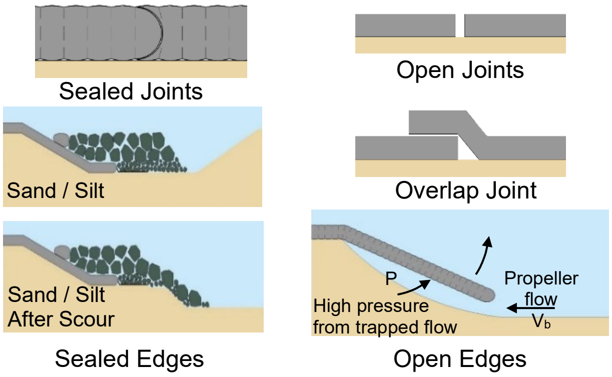

Figure 21. Sealed vs Open Protections

10. In-situ Concrete Mattress

10.1 Introduction

In-situ concrete mattress aprons have been developed and used as scour protection to quay structures as shown in Figures 1 to 3 for 50 years. A rock falling edge apron or reactive hinged edge are often used to provide a 'Sealed' edge detail.

Constant Thickness Mattress (Incomat) is normally used to beds and permanently submerged slopes. Porous mattress types have been developed for use in wave zones as Section 10.8.

In-situ concrete mattress aprons are formed by divers rolling out mattress panels underwater which are 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 22.

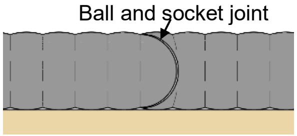

Figure 22. Constant Thickness Mattress (Incomat)

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 22. This produces an apron of interlocked plain concrete slabs underwater. Concrete mattresses are typically pump filled with a sand: cement micro concrete mix of 35 N/mm² strength for long-term durability.

Seals to walls are achieved by using a concrete bolster detail as Figure 23. For sheet piled and combi walls, any inpans are infilled with tremie concrete.

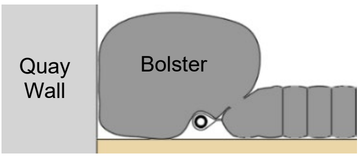

Figure 23. Wall Bolster Seal

Most berths are dredged into natural ground strata where bed soils strata is overconsolidated and usually not prone to settlement. In filled ground, or other cases where settlement is an issue, the mattress panel size can be reduced to increase flexibility or a flex mattress outlined in Section 10.9.

The in-situ concrete mattress system is further described in Hawkswood *et al (2018)* [9]. Design guidance for berth maintenance actions is outlined in Hawkswood *et al* (2023) [10]

10.2 Mattress Surface Undulation

Mattresses with a low surface undulation are preferred as they are subject to lower hydrodynamic suction loads and distribute loading better. Mattress types with higher undulation ratios as Figure 24 are less effective and need a greater thickness. The surface undulation factor I_Q for design is taken from Figure 25 and is related to the undulation ratio u/w.

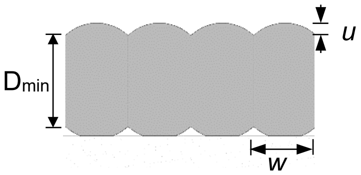

Figure 24. Surface Undulation

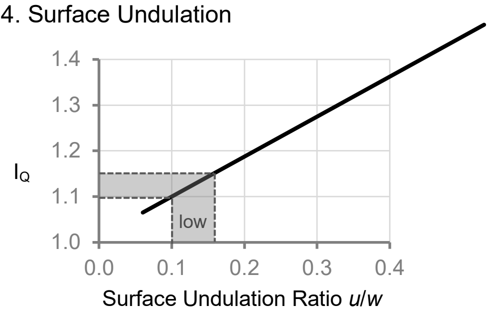

Figure 25. Surface Undulation Factor IQ

10.3 Design

In-situ concrete mattress under propellers should be designed for propeller suction and propeller flow. Design methods for both propeller suction and propeller flow are shown in Hawkswood *et al* (2018) [9] based upon scale model testing and performance experience.

10.4 Design for Propeller Suction

Design for propeller suction is based upon the original work by Wellicome provided in Hawkswood & Assinder (2013) [4] as referred to in PIANC 180 (2015) [13]. At lower clearance ratios C/R, suction is usually the design condition for propeller actions. In-situ 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 26 and previously in Figure 11.

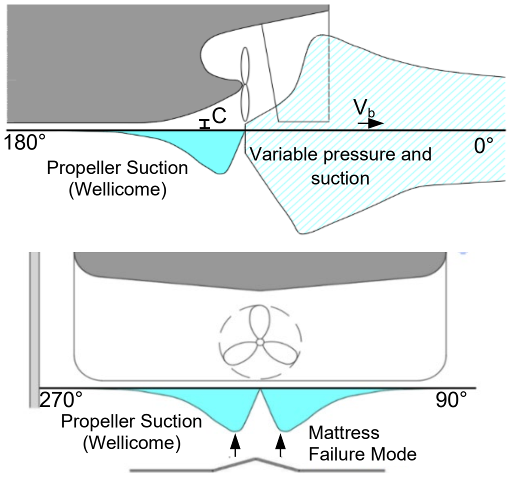

Figure 26. Propellor Suction

The dead-weight design method is used for ‘Sealed’ protection, based upon the propeller exit velocity V_o, and is presented in a simplified format from Hawkswood *et al* (2018) [9] in Equation (3) below: -

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

Where D_{min} is the design minimum concrete thickness, C_S = Stability coefficient for in-situ concrete mattress propeller suction; I_Q = Mattress surface undulation factor (Figure 25).

The stability coefficient for single propeller suction C_S is taken from Figure 27. Propeller suction upon the bed reduces as the bed clearance ratio increases. This method applies to open propellers with or without a rudder. For twin propellers, the design method in Hawkswood *et al* (2018) [9] can be used.

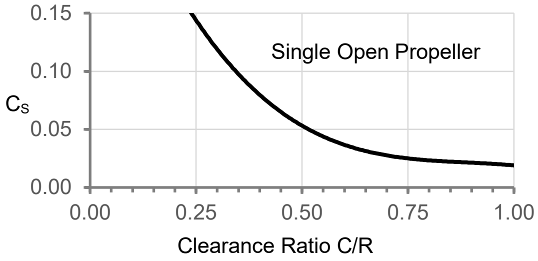

Figure 27. Propeller Suction Coefficient Cs

10.5 Design for Flow

The design method for ‘Sealed’ in-situ concrete mattress under propeller flow as Figure 28 is based upon the maximum bed velocity V_b as Equation (4) below:-

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

Where D_{min} is the design minimum concrete thickness, C_F = Stability coefficient for in-situ concrete; I_Q = Mattress surface undulation factor; V_b = maximum bed velocity.

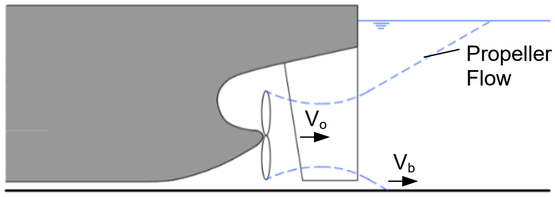

Figure 28. Propeller Flow

The bed velocity V_b can be taken from Figure 9 for either single or twin propellers and the coefficient for propeller flow C_F can be taken from Table 3.

Table 3. Mattress Flow Coefficient C_F

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

This is based upon performance examples by Pilarczyk (2000) [15] plus testing for single propellers as shown in Figure 29 by Hawkswood, Flierman *et al* (2016) [7] and testing for twin propellers as Figure 30 by Hawkswood *et al* (2018) [9]. The method includes a minimum safety factor S.F. of 1.5. A variable bottom is assumed when bed undulations/ construction tolerances exceed 600mm.

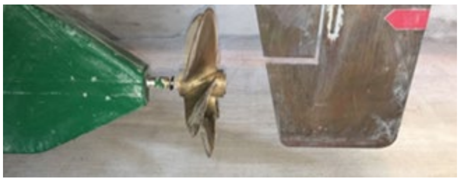

Figure 29. Single Propeller Test – In-situ Concrete Mattress

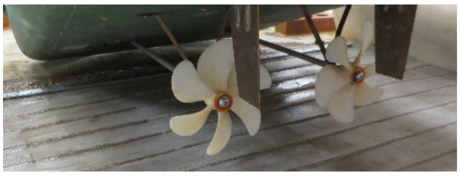

Figure 30. Twin Propeller Test – In-situ Concrete Mattress

10.6 Open Piled Jetties

In-situ concrete mattress is often used to open piled jetties as it can be readily installed to slopes around piles and under platforms as Figure 3, Figure 34 and Figure 35. To design in-situ concrete mattress around piles, the increased local velocity due to blockage of the piles should be computed Hawkswood *et al* (2023) [10] and a conservative average velocity over an effective mattress panel used in Equation (3) for thickness design.

Where vessel jets impact onto slopes, a stabilising positive pressure is created and a slope factor is not required. Concrete mattress should be installed on stable slopes as it does not contribute to slope stability.

10.7 Hinged Edge To In-situ Concrete Mattress

Recently a partially embedded and scour reactive Hinged Edge solution has been developed by scale model testing for use in granular soils as shown in Figure 31 and Figure 32, Hawkswood *et al* 2023,.

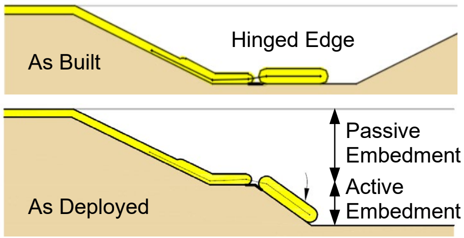

Figure 31. Hinged Edge Performance

This avoids the use of additional marine plant needed with rock falling edge aprons.

Figure 32. Scale Model development – Hinged Edges

To resist uplift from trapped flow pressure whilst reacting to scour, the Raes method from PIANC Report 180 (2015) is used as equation (5).

$$\textit{Edge Block Thickness} \qquad D = \frac{C_L \times V_b{}^2}{2\,g\,\Delta} \qquad (5)$$

Where V_b is the max bed velocity (m/s), Δ is relative density of concrete; g is acceleration due to gravity (9.81 m/s^2), C_L is edge stability coefficient $C_L = 1.0$ for flow angles 30°-90° to edge, $C_L = 0.5$ for flow angles 0°-30°

This formula is based upon trapped flow pressure as Bernoulli Equation which was validated by the scale model testing. Importantly for Hinged Edge operation, the blocks need to rotate and react to scour independently with surplus geotextile provided to the underside, Figure 32.

Figure 33. Surplus Geotextile Provided to Allow Rotation

10.8 Open Hole Mattress

Open Hole mattress has been developed over the last 10 years to protect slopes from wave action. The system is typically used under piled jetties as Figure 34 and Figure 35 where it can be installed before or after the platform.

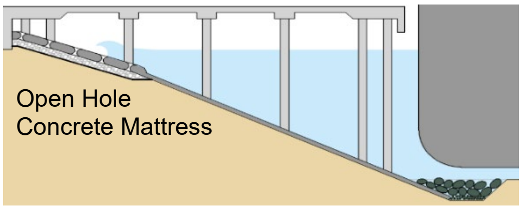

Figure 34. Open Hole Concrete Mattress Protection Below Pile Jetty

Figure 35. Open Hole Concrete Mattress, Puerto Quetzal, Guatemala

It is also used to general revetments. Open hole mattress is normally laid on a filter stone layer and geotextile, which acts as temporary protection during construction, Figure 36.

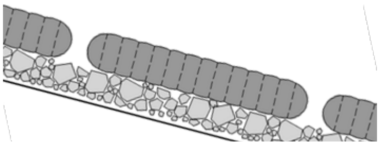

Figure 36. Open Hole Concrete Mattress, Filter Layer and Geotextile

A design method for porous concrete slabs by Yarde *et al* (1996) [18] based upon wave flume testing at HR Wallingford can be followed for design as outlined in Furborough *et al* (2024) [3]. This design method covers wind waves and also long period swell waves.

10.9 Flexible Mattress

Where relative ground settlement to slopes exceeds 70mm (Hawkswood & Assinder, 2013 [4]) a flexible mattress type has been developed as shown in Figure 37 to cater with settlement.

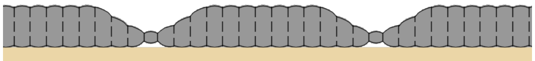

Figure 37. Flex Mattress

The Flex mattress allows slight cracking of flex areas to accommodate the relative settlement that could occur. Connection between the mattress panels is provided by shear interlock through this slight cracking. The mattress thickness can be varied to suit, up to a maximum of 350mm. In wave zones, the combination of Open Hole and Flex mattress types can be used, Figure 38.

Figure 38. Open Hole Flex Mattress, Freeport, Texas

For this combination, a relatively thicker mattress can be designed by the Yarde *et al* (1996) [18] method taking a reduced panel width into account. Flex mattress protection provides a continuous concrete layer of variable thickness with good long term durability. Other flexible mattress types may include areas of only fabric which can abrade and degrade.

11. Preformed Mattress Types

Prefabricated mattress types such as concrete block mattresses and asphalt mattresses are generally not a generic or 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.

PIANC 180 (2015) [13] advises joints to block mattress and asphalt mattress should be grout sealed when wider than 3cm. Reliable joints underwater are difficult to form. Scale model testing of block mattress was undertaken at Deltares as Van Velzen and De Jong (2016) [17] which reported that design by Pilarzcyk's method was unsafe particularly for 'open' edges. The design method by Raes *et al* (1996) [16] for open edges has been further tested and found to be reliable Hawkswood and Flierman (2016) [7] and Hawkswood *et al* (2023) [10], Figure 39.

Figure 39. Testing of Preformed Mattress Types

The Raes method results in much thicker edges to overcome the trapped flow pressures predicted by Bernoulli's equation.

Historically, it has been quite common for concrete block mattress edges and asphalt mattress edges to be installed without embedment. This has led to a high level of maintenance and edge failure see Figure 40.

Figure 40 - Edge failure due to lifting

Failure from the edges is normally progressive. It has been quite common for these mattress edges to be flipped or rolled up, which has been reported in many ports. This has caused obstruction to vessel mooring and a temporary loss of the berth whilst significant repairs are carried out. For precast block mattresses, leading guidance by HEC23 (2009) [12] provides clear guidance that edges should be embedded below the scour depth, see Figure 41. This authoritative guidance confirms that block mattresses are not suitable to be reactive to scour in higher flows.

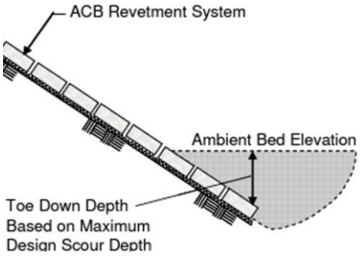

Figure 41 – Edge Embedment – Block Mattress

More research and development of these mattress types appears to be needed to achieve reliable edges. Edge failure can lead to progressive failure across the mattress scour apron.

12. Conclusion

Research testing has largely led to the development of the present PIANC guidance and will influence potential updates. Research has also allowed developments to bed velocities, in-situ concrete mattress protection plus aspects of rock protection. Further development work appears to be needed for preformed mattress types particularly to form reliable edges and joints.

The paper shows some of the wide-ranging research undertaken and its development to guidance and understanding. Hopefully future research can continue this development.

13. Acknowledgements

This paper presents the views of the authors, not necessarily their employers, clients or organisations however, no liability or responsibility of any kind can be accepted in this respect by the publishers or the authors. Any subsequent amendments will be listed at www.proserveltd.co.uk

14. References

[1] BAW (2005), Principals for the Design of Bank and Bottom Protection for Inland waterways, Bulletin 85, Karlsruhe, Germany.

[2] Führer M., Römisch (1977), Effects of Modern Ship Traffic on Inland and Ocean Waterways, 24th International Navigation Congress, PIANC, Leningrad, Russia, pg. 236-244.

[3] Furborough M., Hawkswood M.G., and G.M Hawkswood (2024), Design of Concrete Mattress with Porous Open Holes for Wave Protection to Harbour Slopes. PIANC World Congress, Cape Town, South Africa

[4] Hawkswood, M.G., and Assinder, P., (2013) Concrete mattress used for berth scour protection, GhIGS GeoAfrica, Accra, Ghana.

[5] Hawkswood, M.G., Evans G., and Hawkswood G.M. (2013) Berth Scour Protection for Fast Ferry Jets. ICE Marine Structures and Breakwaters.

[6] Hawkswood, M.G. Lafeber, F.H., Hawkswood, G.M., (2014) Berth Scour Protection for Modern Vessels, PIANC World Congress, San Francisco, USA.

[7] Hawkswood, M.G., Flierman M., De Haan R., King M., and Groom J. (2016) Propeller Action and Berth Scour Protection. PIANC-COPEDEX IX Rio de Janeiro, Brazil.

[8] Hawkswood, M.G., King, M. (2016), Slope Protection Under Piled Quays, ASCE COPRI Ports 2016, New Orleans, U.S.A.

[9] Hawkswood, M.G., Groom J., and Hawkswood G.M. (2018) Berth Scour Protection for Single and Twin Propellers. PIANC-World Congress Panama City, Panama.

[10] Hawkswood, M.G., Hawkswood G.M. and Groom J. (2023) Berth Scour Protection Design for Azipods falling Hinged Edges and maintenance dredging. PIANC America.

[11] PIANC Bulletin 109, (2002).,Input Data of Propeller Inducted Velocities for Dimensioning of Bed Protection Near Quay Walls, Römisch, K. & Hering, W.

[12] HEC 23 (2009). Bridge Scour and Stream Instability Countermeasures Experience, Selection, and Design Guidance (3rd ed., Vol. 2). National Highway Institute.

[13] PIANC Report 180, (2015) Guidelines for Protecting Berthing Structures from Scour Caused by Ships.

[14] PIANC Report of Working Group 22, Bulletin no 96 (1997), Guidelines for design of armoured slopes under open piled quay walls.

[15] Pilarczyk, K.W. (2000), Correspondence 02/08/2011

[16] Raes, L., Elskens, F., Römisch K.W. and Sas, M. (1996) The Effect of Ship Propellers on Bottom Velocities and on Scour Near Berths and Protection Methods Using Thin Flexible Revetments. Proceedings 11th International Harbour Congress, Antwerp – Belgium, pp. 433-443.

[17] Van Velzen G., De Jong M.P.C., Quataert, J.P., and Verheij H.J. (2016) The Stability of a Block Mattress in a Propeller Induced Jet. Scour and Erosion – Harris, Whitehouse and Moxon.

[18] Yarde, A.J., Banyard, L.S., & Allsop W.H. (1996). Reservoir Dams: Wave Conditions, Wave overtopping and Slab Protection, HR Wallingford.