PROPELLER ACTION AND BERTH SCOUR PROTECTION

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1.0 ABSTRACT

Effective scour protection is usually needed to protect berthing structures from vessels actions with increasing size and power. For seagoing vessels, use of propellers is usually the dominant vessel action for berth scour protection and the paper will focus on this and improving understanding & guidance.

Factors affecting scour actions at berths will be explored and a probabilistic method to aid design will be outlined. The results of scale model testing of rock protection will be presented and compared to methods in present guidance. A timescale relationship is proposed which has allowed consideration of scour duration upon rock stability. Suggestions will be presented for improved efficiency in the use of rock, for further testing and also for collection of information from working harbours.

Rock falling edge aprons have also been model tested and compared to deployed apron performance, which has allowed initial guidance to be proposed relating to propeller action.

The performance and constructability of rock, insitu concrete and mattress protection types will be reviewed. The differing performance of 'sealed' and 'open' protection types will be presented and supported by comparison to relevant testing and design methods. The benefits of a design and constructability approach will be outlined along with the use of a quality control process suitable for construction underwater.

2.0 INTRODUCTION

2.1 Scour Protection to Berthing Structures

Berthing structures are usually vertical quay walls as shown in Figure 1 or open piled quays as Figure 2. The cost of these structures is influenced by the depth of the berth and this often results in low vessel clearances with increasing hydrodynamic action and scour upon the bed. In erodible soils, scour protection is usually needed to ensure the stability of berthing structures. Scour protection may also be needed for the control of scour mounding to maintain vessel access, and to reduce maintenance dredging.

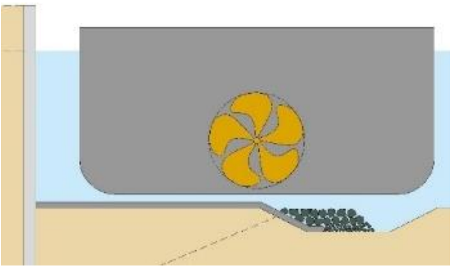

Figure 1. Vertical Quay Wall

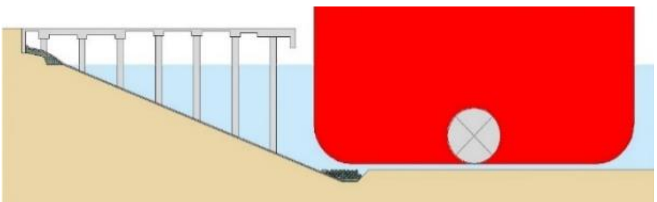

Figure 2. Open Piled Quays

The provision of reliable scour protection generally relies upon the following aspects which will be explored:-

- ***vessel actions***
- ***bed scour***
- ***constructability and design***
- ***reliability of construction underwater***

A greater understanding of these areas is needed for improvements to be made.

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2.2 Vessel Actions

Propeller actions are dynamic and are affected by a wide range of factors which will be outlined along with a probabilistic method to aid assessment of design events.

2.3 Bed Scour

An estimation of scour depths at berths is needed for effective design but these depths can be difficult to obtain for the combined variability of vessel actions and soil conditions. Present guidance by PIANC Report 180 (2015) will be referred to; particularly the overestimation of scour depths in fine grained soils. The need for practical guidance based upon scour behaviour experience will be outlined.

2.4 Scour Protection Design

The usual design process for scour protection is outlined below in Figure 3.

1. **PARAMETERS** (*propeller diameter, clearance, engine power/rps, rudder, etc.)*
   ⇩
2. **propeller velocity**
   ⇩
3. **bed velocity and turbulence or hydrodynamic forces**
   ⇩
4. **DESIGN AND CONSTRUCTABILITY**

Figure 3. Scour Protection Design Process

This relies upon determination of key parameters and following a design process to obtain adequate scour protection. For rock protections, these design methods have generally been based upon historical testing undertaken using scale models of propeller flow. The paper aims to increase understanding by scale model testing to confirm previous performance and to explore new topics which would be useful to design engineers and researchers.

2.5 Rock Protection

Historically, rock protection has mainly been used to berths, however with increasing propeller action, larger rock sizes have become impractical and less cost effective. For vertical quay walls (Figure 1), the construction depth of rock usually has a significant effect on the span height of the wall and thinner mattress or insitu concrete protection types are often preferred. For open piled quays (Figure 2), guidance in PIANC Report 180 (2015) results in larger rock sizes to cater for slope and pile effects. This is however increasingly difficult to place, and a wider consideration of other scour protection options is often useful.

2.6 Rock Stability Testing

Scale model testing of rock stability was undertaken for various clearance ratios, rudder conditions, ahead and astern which typically occur at berths. Testing was undertaken on level rock protection (Figure 4) to initially explore the relationship between rock size and it's threshold velocity for no movement. Subsequently, the relationship between rock movement and exposure time was explored based upon Froudian scale modelling of the timescale in the tests. The tests have allowed a comparison of test performance to the original work by Fuehrer & Römisch (1977) and present design guidance principally in PIANC Report 180 (2015) and PIANC WG22 (1997). Testing was also undertaken for flow deflected by the rudder towards the berthing face which is typically needed for the design of rock protection to the toe of open piled quays (Figure 2).

Figure 4. Test Arrangement

2.7 Rock Falling Edge Aprons

Rock falling edge aprons are now increasingly being used as edge protection to mattress and insitu concrete protection types to prevent underscour (Figure 5).

Little has been published on their performance under propeller flow, particularly for varying angles of attack to the edge. The results of the scale model testing undertaken will be presented and compared with some present guidance and deployed apron performance. The benefit of using rock falling edge aprons with appropriate monitoring and maintenance will be outlined to manage the risk of variability in erosion depth.

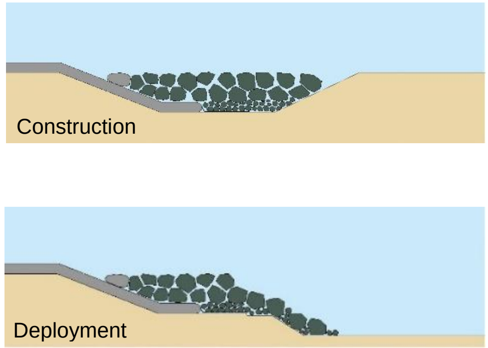

Figure 5. Rock Falling Edge Apron

2.8 Scour Protection Types

Various types of protection can be characterised by their nature, failure modes, constructability and reliability of performance into three general protection groups, as shown below, which will be reviewed:-

Rock; Insitu Concrete; Preformed Mattress.

The performance of insitu concrete protection and preformed mattress types generally depends upon the reliability of joints and edges and whether flow can get under the protection to create high uplift pressures. This aspect is not well understood and some failures have occurred. Design methods will be referred to for situations where joints and edges are effectively 'sealed' and secure against flow entry and also for where they are 'open' and prone to trapped flow pressure. This will be supported by some initial scale model testing of generic protection types of flexible mattress and insitu concrete mattress, with the results compared to design methods.

2.9 Reliability of Construction Underwater

The construction of reliable scour protection underwater has to overcome difficulties in marine working conditions and access usually limited to divers. The constructability and reliability of common protection types will be outlined for marine working conditions often occurring in harbours. The need for an integrated design and construction approach will be further discussed with the benefits of using a risk management based quality control system appropriate for the underwater construction of the protection type being used.

2.10 Readership

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

2.11 Nomenclature

rps	Revolutions per second	D_{S50}	Rock size (sphere), 50% passing	D	Rock size
V_o	Max. propeller flow velocity	W_{50}	Weight of rock, 50% passing	Δ	Buoyant relative density
C	Propeller clearance	L/T	Rock shape 'blockiness'	*Re*	Reynold's number
R	Propeller radius	K_T	Propeller thrust coefficient	L_m	Characteristic length scale
C/R	Propeller clearance ratio	ρ	Density	v	Kinematic fluid viscosity
V_b	Bed velocity	n	No. of propeller revolutions/ second	B_S	Stone stability factor
D_p	Propeller diameter	Fr	Froude's number	C_L	Stability Coefficient (Raes *et al,* 1996)
H_p	Height of propeller axis from bed	v	Flow velocity	Y	Offset distance
D_w	Water depth above propeller			P_y	Factor for stone size position

3.0 PROPELLER ACTION

3.1 Introduction

Seagoing vessels are most commonly propelled by a single open propeller with a central rudder. This basic arrangement is the main focus of the paper. These propeller actions have grown significantly with increasing vessel size, and are usually the critical design action for scour protection when compared with transverse thruster action, as typically shown in Figure 6.

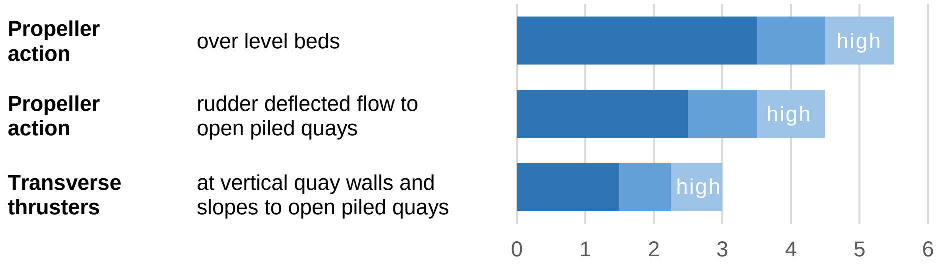

Figure 6. Typical Bed Velocities V_b (m/s)

Propeller scour actions are dynamic and generally influenced by the following basic parameters: -

- *vessel type*
- *engine power at berth/propeller rps*
- *maximum propeller flow velocity V_o*
- *rudder effects*
- *propeller clearance ratio (C/R)*
- *rudder deflected flow*
- *vessel duration/speed of event*
- *frequency of event*

Updated guidance in PIANC Report 180 (2015) suggests design engine powers/propeller revolutions at berths for a range of vessel types, along with established formulas for the maximum flow velocity V_o behind an open propeller at the constriction in the jet flow, (Equations 8-26 and 8-23 in PIANC Report 180). The selection of design vessels for the future design life of a berthing facility should be carefully considered. Also, during the design life of a berth, many unexpected vessel berthing manoeuvres and conditions may occur, including rudder deflected flow and various propeller orientations and distance to the berthing structure. Many vessels may use short bursts of power ahead or astern with rudder deployment to manoeuvre at a berth. Even when tugs are used to aid the manoeuvring of larger vessels at berths, the main propeller can still be used as needed with any range of rudder deployment and ahead or astern propulsion. PIANC WG22 (1997) gives general advice that designers should allow for rudder deployment at berths. Some ports do however have policies to handle vessels using tugs.

3.2 Bed Velocity from Fuehrer & Römisch (1977)

Original testing work by Fuehrer & Römisch (1977) demonstrated the significant effect that a central rudder has upon the bed scour velocity V_b, as shown in Figure 7. This effect is caused by the rudder splitting the rotational flow. This effect is well established and is graphically shown in Figures 8 and 9 from CFD modelling.

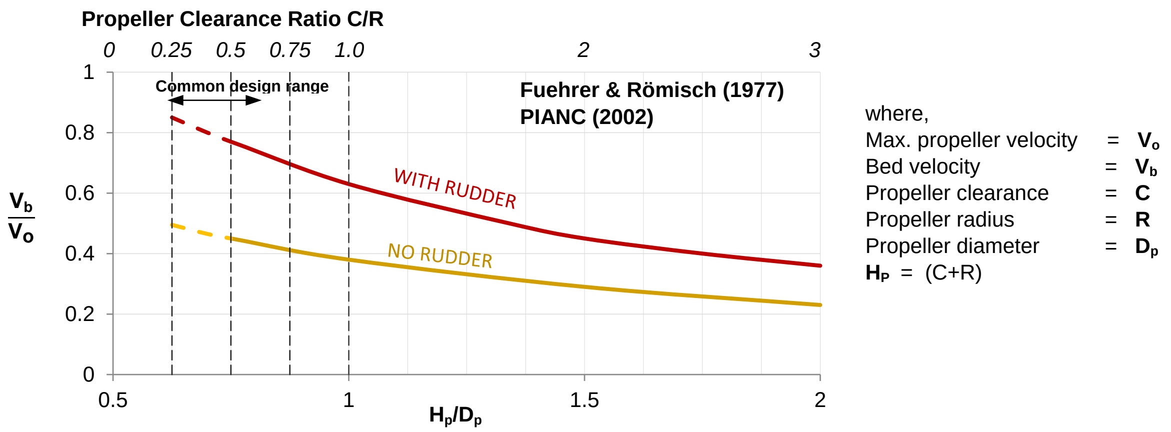

Figure 7. Bed Velocity, V_b

The relationship between propeller clearance C and bed velocity V_b is also shown in Figure 7. For the common arrangement of a propeller with a central rudder, Figure 7 shows a reduction in clearance of 0.1 x R corresponds to a reduction in bed velocity V_b of some 4% for the common design range shown.

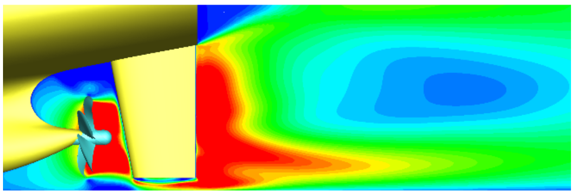

Figure 8. Velocity - *With Straight Rudder*

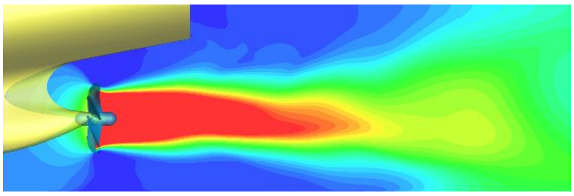

Figure 9. Velocity - *With No Rudder*

The condition of a propeller with no rudder is uncommon, however the flow field is similar to Azimuthal Thrusters.

3.3 Rudder Deflected Flow

For open piled quays (Figure 2), rudder deflected flow is usually of greater velocity than more frequent action from transverse thrusters, as outlined in Figure 6. This action may occur infrequently but it should be designed for as outlined in PIANC WG22 (1997), improved guidance is however needed for this condition. Some scale model testing of rock stability under rudder deflected flow has been undertaken to help develop more effective design guidance.

3.4 Vessel Movement

The maximum bed scour velocity V_b most commonly occurs when vessels are unberthing from a stationary position. As vessels gain speed, the effective bed scour velocity V_b reduces as shown by BAW (2005) Equation 5.8. This suggests the duration of a scour event can be taken as the time for a vessel to move by the length of the initial scour area as shown in Figure 10 typically taken as some 2 x D_p from the testing. For large slow moving vessels such as container vessels with propeller diameters of the order of 9.2 m, the duration of the scour event is estimated to be some 120 seconds from vessel simulations. For smaller vessels, the duration of this local scour event would reduce.

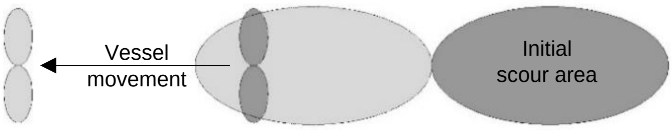

Figure 10. Plan of Scour Area and Vessel Movement

3.5 Probability of a Design Scour Event

The consideration of a design scour event at a berth can be aided by a probabilistic assessment of its occurrence within the design life as outlined in Table 1. This may be undertaken formally with estimation of the probability of multiple events or may be more simply interpreted for increased understanding.

Probability **P =**	**N° of berthing movements for design life**	×	**Probability of low clearance occurrence**	×	**Probability of critical vessel action**
	– Design life period		– Tidal levels		– Vessel type
	– Berthing frequency		– Vessel draught / loading		– Harbour arrangement
					– Berthing manoeuvres
					– Wind speed & direction
					– Currents
					– Captains behaviour
					– Rudder deployment
					– Use of tugs
					– Vessel speed

Table 1. Probability of a Design Event

4.0 BED SCOUR

4.1 Introduction

An understanding of the erodability of natural bed strata is needed for both present and possible future vessel actions at a berth. For vertical quay walls (as Figure 1), scour at the base of the wall is most threatening from repetitive bow thruster action or from propeller flow deflected by the rudder. Vertical quay structures can be designed to accommodate scour and this is often practical in clays or larger gravels. In sands and silts this is generally not practical, as the cost of the additional span height would often be many times greater than the scour protection cost. For open piled quays (as Figure 2), scour protection to the slope is usually needed for all erodable soils (except suitably resilient clays) to avoid embankment erosion and possible failure affecting the structure and usage of land at the top of the slope.

4.2 Scour Depths

Guidance on the erodability threshold levels of some soils are given in PIANC Report 180 (2015) and PIANC WG22 (1997). PIANC Report 180 (2015) now also provides guidance on scour depths which can be expected. However, for sands and silts, these scour depths appear to be an order of magnitude too high compared with scour levels, commonly experienced at berths. This guidance on scour depths may be based upon longer term scale model scour testing which is not comparable with the relatively short duration of critical vessel actions and their dynamic behaviour. Estimation of bed scour would appear to 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. Future guidance would be aided with the collection of previous scour behaviour experience.

Where scour protection is provided, the estimated scour depths at the edges of protection aprons are needed for the design of reliable edge details, such rock falling aprons or other secure details.

4.3 Mounding and Maintenance

Bed scour is also an important consideration in the operation and maintenance of berths. Scour action has an associated mounding consequence as indicated in Figure 11. Guidance on a range of considerations for under keel clearance (UKC) and depth allowance for siltation and maintenance dredging is presented in PIANC WG22 (1997). In order to save costs the depth of these allowances appears to be generally reducing in most modern berths even for progressively larger and more powerful vessels with greater scour potentional. Where mounding, siltation and ongoing maintenance is likely to be a problem, the extent of protection can be widened accordingly to reduce maintenance. Again, advice based upon collected experience of maintenance in ports would be useful.

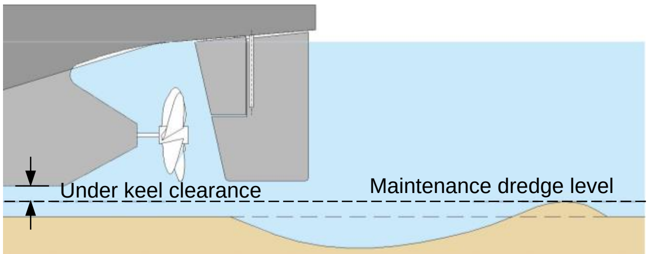

Figure 11. Scour Mounding

5.0 ROCK STABILITY TESTING ARRANGEMENTS

5.1 Test Arrangements

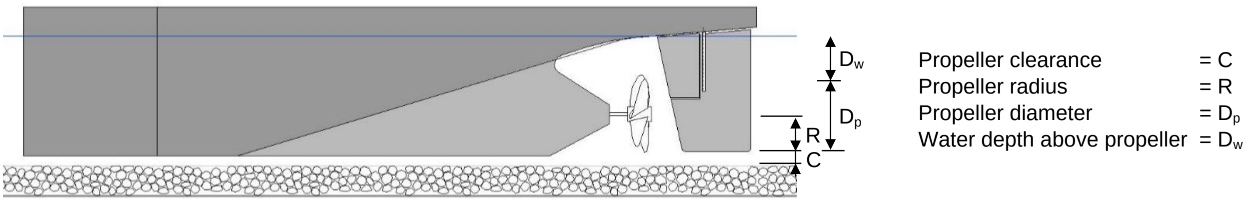

Figure 12. Test Arrangement Elevation (see also Figure 4)

Rock Size D_{S50} (mm)	Density ρ (t/m^3)	$\frac{W_{85}}{W_{15}}$	Shape L/T (average)	$\frac{D_{S50}}{R}$
5.5	2.590	2.0	2.0	0.072
11.8	2.640	2.6	1.9	0.155
18.1	2.560	2.3	2.0	0.238
25.4	2.570	2.3	2.1	0.334
37.1	2.670	1.8	1.9	0.488

Table 2. Test Rock

The scale model tests were conducted using a 152 mm diameter propeller as the arrangement shown in Figures 4 and 12. The tests were carried out in a 3.6 m x 2.4 m tank with the propeller mounted onto a scale model of the rear of a typical container hull which was stationary. Tests were initially conducted without the hull and its presence was subsequently found to have no discernible effect upon rock stability and propeller flow, but it did effectively slow the recirculating approach flow to the propeller. It appears that similar testing could be undertaken without a hull if the tank was considerably larger.

Stability testing of the five rock sizes shown in Table 2 was conducted after levelling to a maximum surface tolerance of plus zero and minus the rock size D_{s50}, as outlined in the Rock Manual (CIRIA, 2007). The tests were undertaken for various parameters of propeller actions expected in a berth as shown below:-

- *propeller revolutions rps / (variable power)*
- *various propeller clearance ratios C/R 0.25, 0.5, 0.75, 1.0*
- *rudder effects - straight, 35° deployment, no rudder*
- *rudder deflected flow*
- *ahead and reversal astern*
- *duration*

Stone stability and movement was observed via a Perspex side wall. A 5-blade propeller was used with parameters shown in Table 3. The K_T value has been estimated from the Wageningen test curves (Lammeren, 1969). The maximum flow velocity (V_o) behind the propeller was obtained by measurement of propeller revolutions using an optical rate of revolution counter and using the established formula (1). This velocity was confirmed by video measurement of the velocity of small plastic balls carried in the propeller flow and gave closely matching results.

Diameter D_p	152 mm
N^o of blades	5
Pitch ratio	1.170
Blade area ratio	1.035
Thrust coefficient, K_T	0.59

Table 3. Test Propeller

$$V_0 = 1.6\, n\, D_p \sqrt{K_T} \quad (1)$$

where, Maximum propeller velocity = V_o
N^o of revs. per second (rps) = n
Propeller thrust coefficient = K_T

5.2 Scaling Relationships

The testing scale was derived from the Froude Number relationship shown in (2) below:-

$$\text{Froude number} = \frac{V}{\sqrt{\Delta D}} \quad (2)$$

where, Flow velocity = V
Buoyant relative density = Δ
Rock size = D

The Froude number relationship is also the basis of present design methods for the design of rock protection (6) and allows ready comparison with scale model testing. In summary, the velocity scale is proportional to the $\sqrt{lengthscale}$. Similar dimensional analysis of the Froude Number also indicates that the timescale should also be proportional to the $\sqrt{lengthscale}$. This is less understood and accepted for propeller action. This is however supported by dimensional analysis of (1) which indicates the timescale is also proportional to propeller revolutions n and therefore the frequency of propeller blade pressure pulses passing over the bed. The hydrodynamic pulses from propeller blades were demonstrated in the scale model testing at Marin (Hawkswood *et al,* 2014) and are considered likely to affect rock stability according to the proposed timescale arrangement.

Examples of the test scale relationships to real vessel examples are shown in Table 4 below.

	Test	Real Vessel Examples	
Length Scale	**1:1**	**1:20**	**1:60**
Propeller Diameter	152.0 mm	3.00 m	9.20 m
Stone Size D_{s50}	37.1 mm	0.74 m	2.20 m
Stone Size D_{s50}	25.4 mm	0.51 m	1.50 m
Stone Size D_{s50}	18.1 mm	0.36 m	1.10 m
Stone Size D_{s50}	11.8 mm	0.24 m	0.71 m
Stone Size D_{s50}	5.5 mm	0.11 m	0.33 m
Velocity Scale	1	$\sqrt{20}$	$\sqrt{60}$
Timescale (approx.)	1	$\sqrt{20}$	$\sqrt{60}$

Table 4. Test Scale Relationships

The tests were conducted on rock sizes well above sand size where stability scaling problems are known to occur.

The Reynolds numbers (*Re*) for propellers and jet flow are given by:-

$$Re_{prop} = \frac{nD_pL_m}{\nu} \quad (3)$$

$$Re_{flow} = \frac{V_oD_p}{\nu} \quad (4)$$

where, Characteristic length scale $= L_m$
Kinematic fluid viscosity $= \nu$

Blaauw & Van de Kaa (1978) carried out early investigations into propeller jets and found that if the Reynolds Number for a propeller exceeds 7 x 10^4, and the Reynolds Number for the propeller jet is greater than 3 x 10^3, then effects due to viscosity can be ignored (Hamill et al., 2015). The lowest Reynolds Numbers used during testing for the general case with a rudder are shown in Table 5 relating to the test rock sizes.

Rock Size D_{s50} (mm)	**Propeller Revolutions (rps)**	**Reynolds Number (Propeller)**	**Reynolds Number (Jet)**
5.5	2.75	1.5 x 10^4	5.2 x 10^4
11.8	3.67	2.0 x 10^4	6.9 x 10^4
18.1	4.50	2.4 x 10^4	8.4 x 10^4
25.4	5.80	3.2 x 10^4	10.9 x 10^4
37.1	8.00	4.3 x 10^4	15.0 x 10^4

Table 5. Reynolds Number from Testing

In all the tests, the Reynolds Number for jet flow exceeded 3 x 10^3. The Reynold number range for propellers was 1.5 x 10^4 to 5 x 10^4, well below the originally proposed threshold of 7 x 10^4, however Blaauw & Van de Kaa (1978) and Verhey (1983) suggested these scale effects would be insignificant. This is supported by more recent testing by Hamill (2015), which has demonstrated that propeller velocity V_o is proportional to rotation down to Reynolds Numbers for propellers to a value of 1.4 x 10^4. This was further supported by velocities measured in the tests which compared well with the calculated velocities V_o from (1).

The testing method used was to determine the maximum propeller revolutions n before any rock displacement occurred during 10 tests of 100 seconds duration, 1000 seconds total, for various parameters. This test period can be compared to the duration of a scour event as a vessel unberths from a stationary position as shown in Figure 10. For the example of a large slow moving container vessel with an estimated scour event duration of some 120 s (D_p = 9.2 m), the equivalent test duration can be estimated by the proposed relationship to the $\sqrt{length\ scale}$ as shown in (5) below.

$$\textit{Test scour duration} = 120\ s\ \sqrt{\frac{0.152\ m}{9.2\ m}} = 16\ \textit{seconds} \quad (5)$$

If this relationship is accurate, the total test timescale of 1,000 s is equivalent to some 60 (critical) vessel actions for the container vessel example (D_p = 9.2 m) and more for smaller vessels.

6.0 ROCK STABILITY

6.1 Fuehrer & Römisch (1977)

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 Fuehrer & Römisch (1977) who produced curves for bed velocity V_b as partly reproduced in Figure 7. They also provided a formula for rock protection size with no movement which is shown in PIANC WG 22 (1997) as (6).

Formula for rock size, with no movement

$$D_{s50} = B_s \frac{V_b^2}{g\Delta} \quad (6)$$

where, B_s = 0.64 *With rudder*
B_s = 1.23 *No rudder*

These relationships of rock size D_{s50} to bed velocity V_b are shown in Figure 13 for the general case with a central rudder behind the propeller, and with no rudder. The higher stability factor B_s for no rudder is understood to be due to the increased rotation and turbulence within the critical area of the flow acting upon the bed.

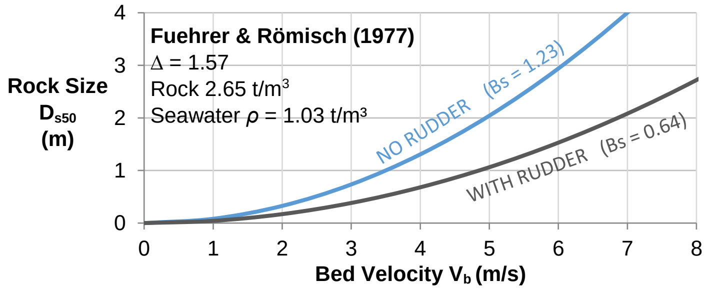

Figure 13. Stone Size for Vessel Actions

6.2 Testing with No Rock Movement

The test results with a straight rudder are shown in Figure 14, relative to Fuehrer & Römisch’s method. The results generally give a good, and safe correlation to this method, particularly in the common design range. This may be expected as Fuehrer & Römisch’s work was also largely based upon scale model testing. Larger rock size was found to become increasingly stable, with increasing D_{S50}/R ratio. The curve labelled ‘centre of top layer’ shows the stability relationship taking an increased clearance C to the centre of the top armour layer. This gives a closer match to the test results with the remaining margin possibly due to increase in bed roughness, for larger stones.

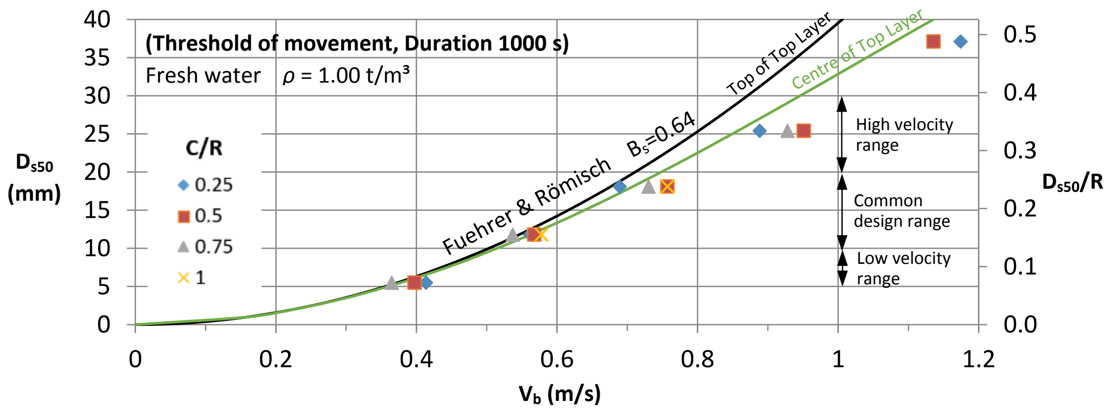

Figure 14. Testing - *With Straight Rudder*

Figure 15 shows quite similar results for 35° rudder deployment which indicates that rudder deployment appears to have only a slight effect at the threshold of movement.

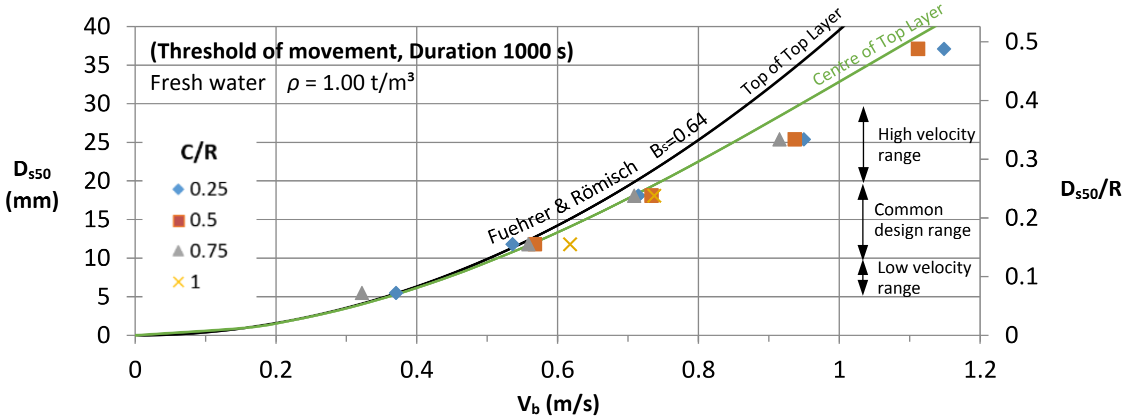

Figure 15. Testing - *With 35° Rudder*

The testing suggests that a design method based upon clearance to the centre of the top layer of armour could be reasonably used if supported by larger or full scale testing.

For the situation with no rudder (similar to Azimuthal thrusters), the test results are similarly compared as shown in Figure 16 and would suggest the stability factor B_s may need to be increased by some 20% to B_s=1.55 to ensure stability with no movement. Again, the testing suggests that the centre of the top layer could be considered as a basis of design.

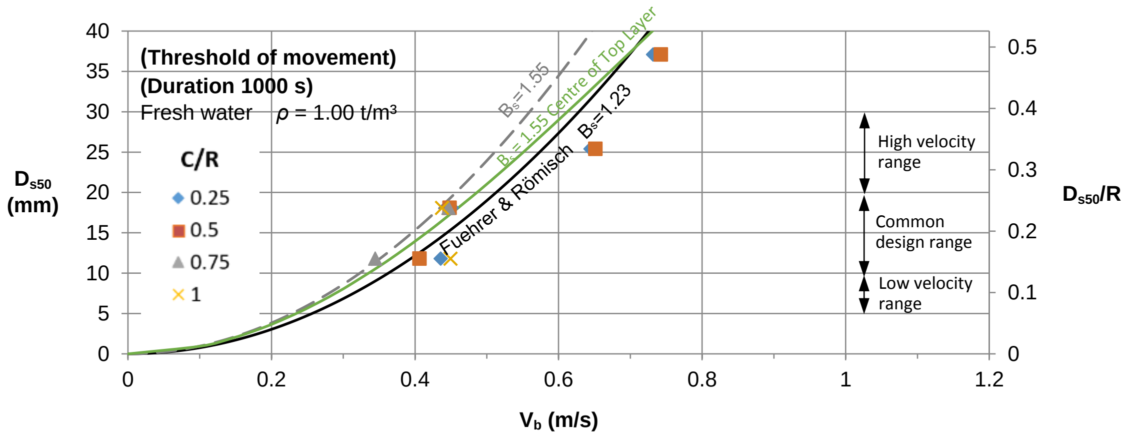

Figure 16. Testing - *With No Rudder*

Fuehrer & Römisch's work has been incorporated into various design guides PIANC WG22 (1997), PIANC Bulletin 109 (2002), EAU (2004), BAW (2005) and PIANC Report 180 (2015). It is suggested that bed velocities should be based on the original curves from Fuehrer & Römisch (1977) and not the E values proposed in PIANC Report 180 (2015) which overestimate bed velocity particularly at lower clearances (Hawkswood et al 2014). The definition of the rock size as D_{S50} in (6) is supported by the testing and earlier presentations of the method. The proposed use of D_{S85} instead of D_{S50} in PIANC Report 180 (2015) is not supported by the testing and original work by Fuehrer & Römisch (1977).

6.3 Dutch Method

PIANC Report 180 (2015) now incorporates an alternative method known as the 'Dutch Method'. This method appears to be based upon unobstructed jet flow development leading to an underestimation of bed velocity particularly by not taking into account the effect of the rudder, and also the effect of the bed.

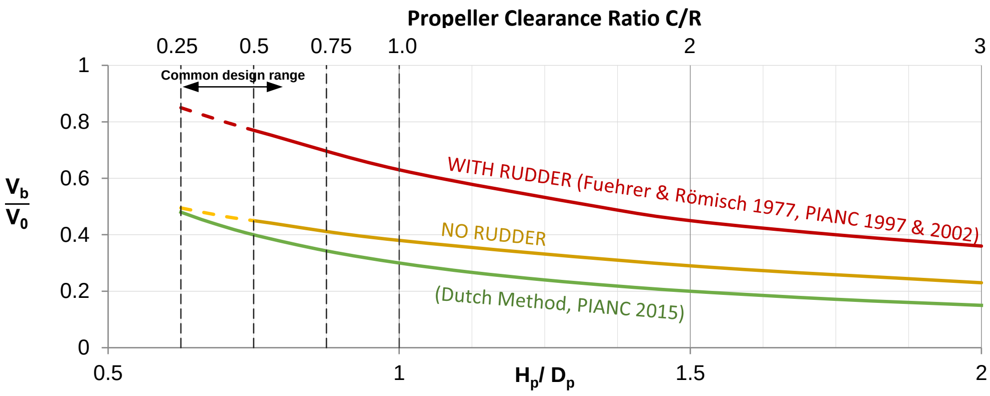

Figure 17. Bed Velocity

The underestimation of bed velocity by this method is shown in Figure 17 relative to the bed velocity curves provided by Fuehrer & Römisch (1977). Stone sizes D_{S50} given by the Dutch method are reduced to some 0.42 - 0.27 times the sizes obtained by the Fuehrer & Römisch (1977) method, for C/R values between 0.25 and 1.0 respectively. Rock weight W_{50} is comparatively reduced to some 0.07 - 0.02. Stone size D_{S50} with no rudder is comparatively reduced to some 0.58 - 0.39.

Figure 18. Testing to the Dutch Method

Figure 18 shows a picture of testing of 18.1mm rock protection subjected to a bed velocity based upon the Dutch Method. Local loss of the top layer occurred after 8s and loss of the bottom stone layer and the bedding layer occured after 16s of testing. Design to this method would appear inappropriate based upon the testing undertaken.

6.4 Tests with Rock Movement

Rock movement was explored for higher bed velocities than the threshold of motion for various C/R ratios and three different rudder conditions as typically shown in Figure 19. Typically the rudder presence is shown to cause stone failure closer to the propellor. As clearance ratio C/R increases, the zones of failure generally move further away from the propellor as expected.

Tests on the five various stone sizes were undertaken to establish the velocity when some 10-20 Nº stones would be displaced in a combined test period of 1000 s. Figure 20 shows a typical view with the local displacement of some 20 stones. During the tests, no stone movement occurred for a few seconds and afterwards the rate of stone movement was reasonably linear with time.

Figure 20. 10-20 Rocks Displaced

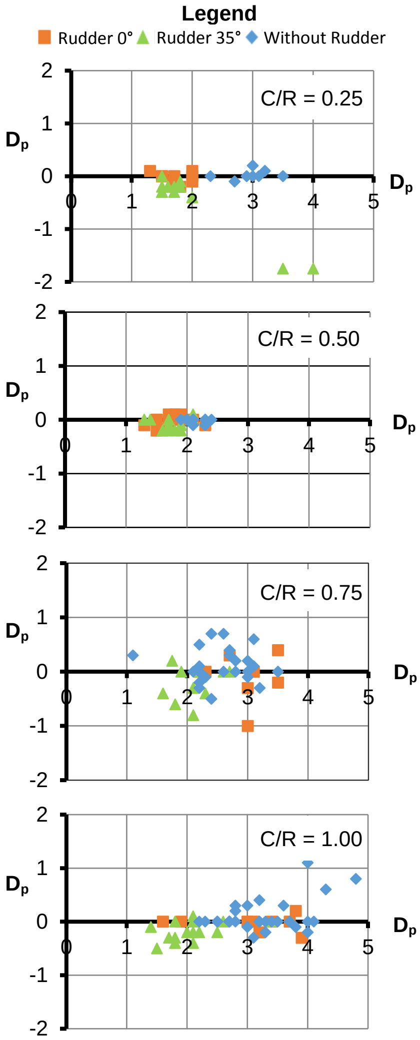

Figure 19. Plan of Rock Movement

6.5 Consideration of Allowable Movement

For the above test conditions, the top layer has failed locally but the second layer is stable and importantly continues to protect the bedding layer from failure. As outlined in section 5.2, this test period would relate to approximately 60 Nº design scour events for a vessel with a 9.2 m diameter propeller based upon the earlier proposed timescale arrangement. The results obtained are plotted in Figure 21 and suggest that for this level of stone movement, reduction in the stone size could be considered with further confirmation of this performance.

The retention of the second layer of stone is vital and Figure 21 shows a dotted line relating to the stability of this second layer. Using this criteria, local stone loss could be expected to be some 10 to 20 stones in a duration of 1000 s of testing. For example, this relates to some 60 Nº design scour events of a 9.2 m diameter propeller. Application of this potential method would be inappropriate to vessels with more repetitive berthing, such as ferries. A design method for allowable movement would also need to be confirmed by further testing to better establish rock stability with scale and timescale closer to reality. Tolerance to movement was also considered by Roubous *et al* (2007) which was based upon comparison to current flow.

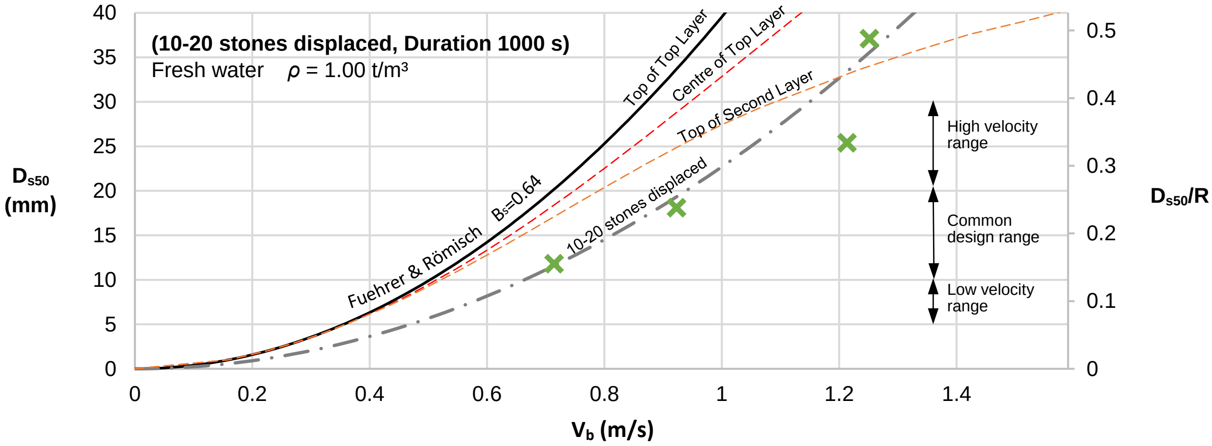

Figure 21. Tests with Rock Movement - *With a Straight Rudder*

6.6 Rock Mounding

Tolerance to stone movement is potentially a greater issue for rock mounding and loss of clearance (Figure 11). A suitable clearance depth would be needed to accommodate displaced stones. For sloping revetments (Figure 2) there is presently no guidance where displaced stones maybe deposited.

6.7 Siltation Effect

Stone stability can be improved by siltation. During diving inspections, it is generally observed that in zones of frequent propeller operation (such as ferries) the rock is flushed clean (no siltation), yet areas with infrequent propeller flow often silt up partially encapsulating the top layer stones and stabilising them. Collection of information on siltation behaviour and its effect in harbours may prove useful in developing further understanding.

6.8 Rudder Deflected Flow

Deflection of propeller flow by rudder deployment is commonplace at berths and should generally be allowed for in designs as outlined in section 4.7 of PIANC WG22 (1997). Although usually less frequent than bow thruster action, it is often of greater velocity as shown in Figure 6. It is particularly significant for sloping protection under piled quays as shown in Figure 2, where embankment stability is important.

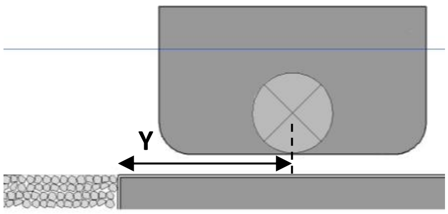

Figure 22. Test Arrangement

Presently, no authoritative guidance is known to be available for this condition. Testing was undertaken for this arrangement as shown in Figure 22 to establish the relationship between propeller rotation n, velocity and offset distance (Y) for the threshold of motion of various rock sizes. The results are shown in Figure 23, with a Stone Size Position Factor P_Y proposed based on the worst case test results. This factor can be applied to the D_{S50} rock size that would be required directly under the propeller. As offset distance Y increases, the rock size required for stability decreases.

The tests were conducted conservatively with a smooth (metal) bed under the propeller and with a level bed of rock offset 0 to 3.5 D_p from the centre line of the propeller. From earlier tests with larger rock under the propeller of instead a smooth bed, the effect of bed roughness slowing the flow was found to be of significant effect. During the tests it was observed that flow became progressively more turbulent after a flow distance of some 5 D_p directly from the propeller. This is demonstrated by the flattening of the curve for factor P_Y after Y = 2.5 D_p in Figure 23.

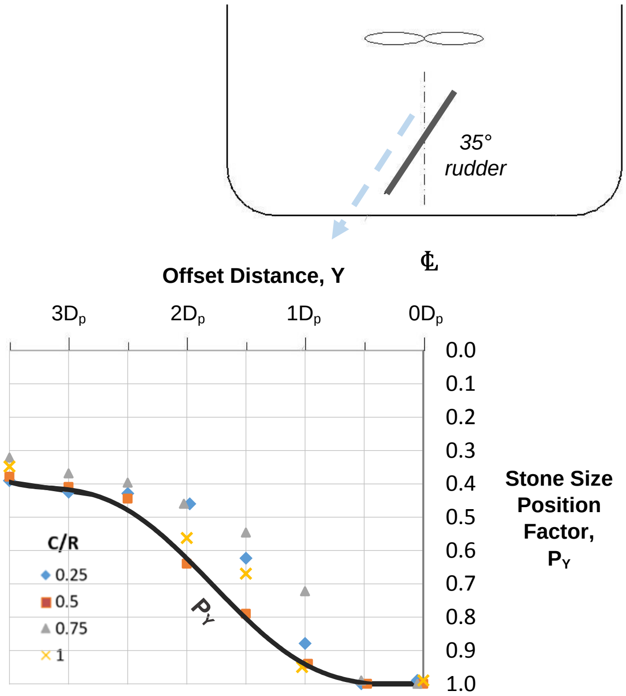

Figure 23. Stone Size Position Factor P_y for Rudder Deflected Flow at Offset Distance Y

Testing was undertaken with a 35º rudder angle which is typically a maximum for a common central rudder. During the testing, rudder deployment at 35º was found to be the worst case compared to other levels of partial deployment. Some vessels often have rudders with higher deployment such as two-stage Becker type rudders which are often used on oil vessels.

6.9 Reversal

Reverse rotation of propellers is commonly used upon berths for slowing and astern movement of vessels. Tests upon this action were conducted with a central rudder for various rock sizes and clearances based upon the threshold of motion for rock. The tests demonstrated that propeller rotation astern needed to be increased by 25-60% compared to propeller-ahead to create a similar effect. The results confirm that this action is likely to be non-critical for common hull shapes even at low clearances.

6.10 Water Depth over Propeller

The effect of water depth over the propeller D_w was found to have little effect upon rock stability for D_w between 0.25R and 1.5R. Generally, tests were conducted with a D_w values of 0.86R.

6.11 Further Testing

Further testing at a much larger scale or with real vessels is needed to confirm present guidance and also to confirm suggestions made for the design of rock protection outlined in earlier sections. Following this, suitably scaled testing could be undertaken for positions of reduced scour actions (P_Y, P_X), for slopes and slopes with piles, plus for other main propulsion actions such as twin propellers, ducted propellers, podded propulsors, and azimuthal thrusters, etc. A design method based upon variable factors for duration, required stability, position, slope and structure effects, etc. appears to be appropriate.

A CUR C208 committee has been formed and plans to undertake some testing and the publication of updated guidance for rock and other protections. Collaborative testing by other organisations would be useful to cover the array of main propulsors.

7.0 ROCK FALLING EDGE APRONS

7.1 Testing to Fuehrer & Römisch, 1977

Scaled arrangements of rock falling edge aprons were tested for propeller flow parallel to the protection edge as Figure 24 and for the less common condition of flow at 90º to the protection edge as Figure 25. The tests were conducted with a straight rudder, C/R ratio of 0.25, and at the threshold velocity for stone stability based upon the method by Fuehrer & Römisch (1977). The grading of materials used in the tests are shown in Table 6 and comply with the filter rules (Rock Manual, CIRIA, 2007). The stone edge detail was basically stable at the threshold velocity flow but was deployed as a falling edge apron by sand erosion at the edge.

The inner edge of the rock apron was stabilised using engineered clay to match the restraint of a concrete edge bolster which is common. Earlier testing had confirmed the need for this detail to restrain unsupported edge stones. The tests have demonstrated that the stone stability performance of falling edge aprons is effectively similar to performance for level beds.

	Size (mm)		
	D_{S15}	D_{S50}	D_{S85}
Armour Stone	15.9	18.1	21.0
Bedding Stone	0.7	1.4	3.2
Sand	0.3	0.4	0.8

Table 6. Test Rock

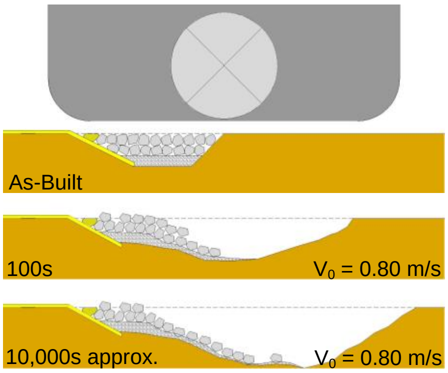

Figure 24. Flow as Fuehrer & Römisch Parallel to Edge

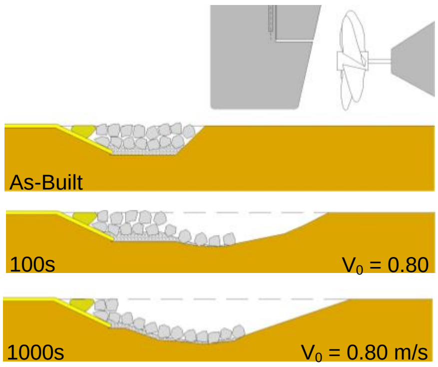

Figure 25. Flow as Fuehrer & Römisch 90° to Edge

7.2 Testing to the Dutch Method

The tests for flow at 90º to the edge were repeated for threshold velocity given by the Dutch Method from PIANC Report 180 (2015). The top layer of stones were quickly displaced in a few seconds and then the bottom layer of armour stones were moved apart with the bedding stone promptly lost. Subsequently, the remaining stones were progressively lowered due to suffusion of sand from between the stones; until underscour of the mattress edge occurred within the 100s test period, see Figure 26. This test along with previous testing suggests that stability performance is not likely to be adequate for this method, particularly when a central rudder is present.

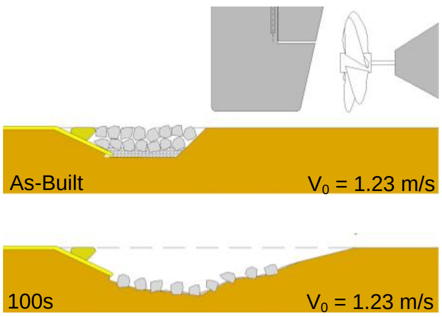

Figure 26. Flow as 'Dutch Method' 90° to Edge

7.3 Deployed Aprons

Figure 27 shows a recorded example of a deployed falling edge apron in sand/silt. An extreme level of edge scour was caused by the repetitive action of a twin propeller vessel turning a few times a day next to the berth edge with high rudder deployment (42º) and propellers operated ahead and astern with relatively high power. Some 5 m of bed scour lowering caused the apron to be fully deployed. The general

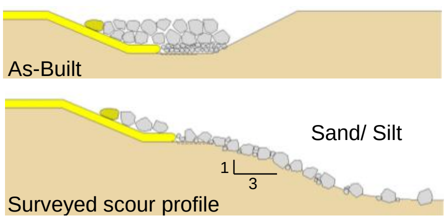

Figure 27. Deployed Apron Example

slope angle of the deployed apron was approximately 1:3. Relative model testing for flow parallel to the edge as shown in Figure 24 also indicated a deployed apron slope of approximately 1:3. Many authorities suggest a deployed falling apron slope of 1:2 for current flow (Verhagen, 2003). Rock falling edge aprons have performed well in berths with many case histories of rock use shown in PIANC WG 22 (1997) for example.

7.4 Falling Edge Apron Design, Monitoring and Maintenance

For propeller flow, it would appear to be more appropriate to design the quantity of armour rock needed in falling edge aprons to give at least 1 layer of armour on a 3:1 slope down to the required scour protection level. A fully deployed apron is likely to function only in the short term due to the risk of potential suffusion between the stones. Where a longer performance is required, additional armour rock is suggested perhaps as outlined in Hawkswood et al (2014) where some additional 50% of rock is suggested (Figure 28, deployed). This also provides for greater robustness as edge scour depths are often difficult to estimate along with the use of future vessels.

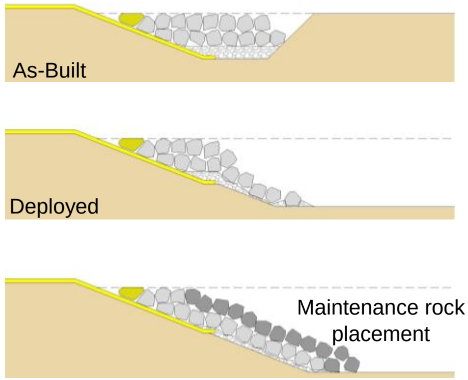

Figure 28. Falling Edge Apron Maintenance

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 progressive edge underscour needs to be avoided to prevent progressive edge failure. Falling edge aprons can achieve a relatively high protective depth (Van Velzen, 2014) and importantly can be monitored and maintained. In harbours, it is common to monitor performance of berth beds on an annual basis.

Monitoring can similarly be applied to edge aprons. Rock aprons start to deploy when the edge scour exceeds the trench embedment depth as shown in Figure 28. Before aprons fully deploy and possibly fail, additional rock can be placed to any local scour areas. This provides an enhanced protection depth if scour proceeds further. For designs including falling edge aprons, arrangements for appropriate future monitoring and maintenance should be discussed and arranged with clients. This helps avoid problems with unexpected scour often caused by soft spots or unusual vessel action.

8.0 SCOUR PROTECTION CONSTRUCTABILITY AND DESIGN

8.1 Introduction

PIANC Report 180 (2015) well describes the various protection types used for berth scour protection. The main scour protection types were characterised by their nature and failure modes by Hawkswood *et al* (2014) into 3 distinct groups outlined in Figure 29.

Type	Principle Failure Mode
· ROCK	Particle displacement [1]
· INSITU CONCRETE	Uplift panel failure [2]
- Concrete mattress	Edge underscour [3]
- Tremie concrete	
- Grouted rock	
· PREFABRICATED MATTRESS	Joint failures
- Concrete block mattress	Unit movement
- Asphalt mattress	Component failure
- Gabion/reno mattress	Edge underscour [3]
	Others

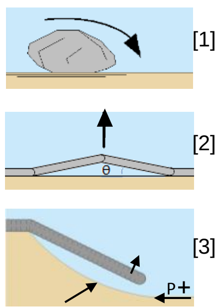

Figure 29. Principle Failure Modes

8.2 'Sealed' Protection

The main influence upon the performance of insitu concrete and preformed mattress types depends upon whether they are 'sealed' against the entry of flow and higher pressures. It is a key design and construction choice, whether to use a protection which is reliably flow sealed, generally thinner and more cost effective. Trapped flow pressure under protection is relatively much greater than suction caused by propellers or due to propeller flow over bed protection.

8.3 'Open' Protection

Raes, Elskens, Römisch & Sas (1996) provided a formula (7) for the stability of thin flexible bottom protections determined by experiment for overlapping or open joints and underscoured edges:-

$$\text{Thickness, } D_{min} = \frac{C_L V_b^2}{2\Delta g} \qquad (7)$$

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 30. This method can be compared to Bernoulli's equation applied to trapped flow pressure.

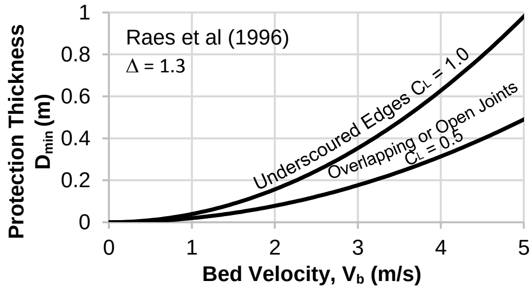

Figure 30. Open Mattress Stability

8.4 Constructability

Constructability and reliability of scour protection types often need to be considered at the design stage, involving some of the aspects listed below:-

- *safety*
- *limited access - divers, ROV's or automation*
- *access, land/marine construction*
- *sea working conditions*
- *influence of protection thickness*
- *joint and edge reliability ('sealed' or open')*
- *bed conditions*
- *working on slopes*
- *working around piles*
- *working under decks*
- *tolerances*
- *plant available*
- *materials available*
- *local factors*

Working conditions need to be established to ensure the selection of a scour protection type is constructable and can achieve the chosen level of 'sealed' or 'open' performance. Marine working conditions are far more onerous and variable than encountered on land, typically outlined below:-

- *currents*
- *waves and tidal range*
- *sediment transportation*
- *diver visibility*
- *environmental constraints*
- *noise, contamination, etc.ice flows*
- *vessel movements*
- *seabed strata type and profile*
- *obstructions*
- *bed surface conditions*
- *depth & other local factors*

Where currents are above some 0.5 m/s, divers generally cannot work effectively. In this case, automated placement of rock by plant is usually preferred, with a suitably constructable design. Scour protection levels are normally selected to achieve a minimum berth depth with only downward construction tolerances specified. Considering safety, where divers are needed to place preformed mattress or larger rock armour, the risk of diver entrapment needs to be recognised and managed. The constructability of scour protection types is outlined in the following sections.

8.5 Rock Protection

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 31). The design, specification and construction of the rock protection can follow authoritative guidance by Fuehrer & 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 etc. (Figure 31). Rip rap stone with a wider grading than armour is generally preferred as it can be mass placed by excavator bucket etc rather than individual placement of armour stone PIANC WG22, (1997).

For vertical quay walls, the rock construction depth usually increases the effective span height of piled walls when compared to thinner mattress types. Where caisson construction is being used, this effect also applies to the caisson depth. As quay structures usually have a dominant influence upon costs, thinner protection types are often preferred to these structures.

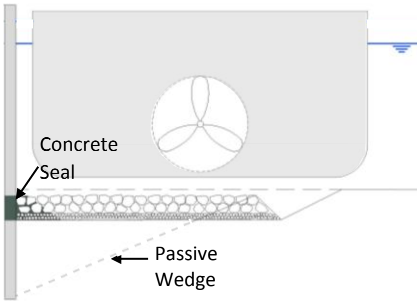

Figure 31. Rock Protection

For open piled quays, the increased flow and turbulence around piles on slopes has caused some rock stability failure. PIANC Report 180 (2015) suggests the use of a slope factor by Pilarczyk, and a pile effect factor estimated from Van Doorn. These combined effects result in relatively large rock protection sizes which become progressively difficult to place upon slopes and around piles (Hawkswood & King, 2016). Working upon slopes is more difficult than horizontal beds; layer thickness and surface preparation tolerances are usually increased accordingly. The Rock Manual suggests some 50 % increase in layer thickness for working upon slopes (CIRIA, 2007). The reliable use of geotextiles to piled slopes can be difficult underwater. In fine sand soils the use of multiple granular layers to comply with the filter rules is generally not practical.

8.6 Insitu Concrete Mattress

Insitu concrete mattress aprons are formed by divers rolling out mattress fabric underwater which is zipped together and pump filled with highly fluid small aggregate micro concrete typically of 35 N/mm² strength. The system forms reliable 'ball and socket' shear joints between concrete mattress panels, shown in Figure 32 for Constant Thickness mattress type (CT). This produces an apron of interlocked concrete slabs underwater, which gives high resilience against propeller suction and flow where edges are suitably protected.

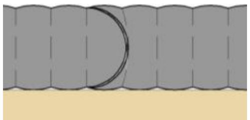

Figure 32. Ball and Socket Joint

The system can be designed and reliably constructed as 'sealed' protection with the use of a recognised marine quality control system which should usually be overseen by an experienced professional engineer. For this situation, PIANC Report 180 outlines that design can be based upon the suction generated in front of the propeller, as originally described by Wellicome, and following a method summarised by Hawkswood & Assinder (2013).

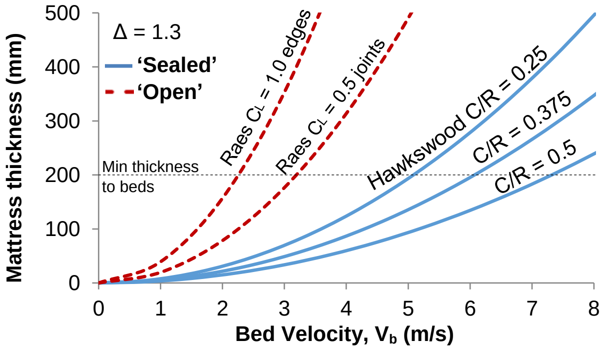

Figure 33. Matt Thickness for Propeller Action

Figure 33 shows mattress thickness based on this method using a simple deadweight design basis and a safety factor of 1.5 as shown in Hawkswood et al. (2014). Bed velocity is based on Fuehrer & Römisch (1977). For berths with level beds, a 200 mm minimum thickness of insitu concrete mattress is recommended for maintenance dredging and robustness. Figure 33 applies to interlocked panels greater than 3 m wide and of relatively constant thickness and surface profile with undulation < 30 mm. Figure 33 outlines the significant effect that 'sealed' protection has upon performance compared to 'open' protection. A proven marine quality control process should be specified and supervised as outlined in Hawkswood et al. (2014) and (2013). Scale model tests were conducted as shown in Figure 34 on insitu concrete mattress with a thickness of 3.7 mm which could not be failed. In comparison to the design method by Hawkswood et al (2014), shown in Figure 33, the tests indicate a safety factor >5 for this form of 'sealed' protection. Conservative design of 'sealed' protection is recommended as thickness is relatively low.

Insitu concrete mattress can be readily used to slopes and around piles under open piled quays (Hawkswood & Assinder, 2013), and (Hawkswood & King, 2016). The 2016 paper describes a 'Land Infill' construction method which has recently been developed to allow largely land based construction of open piled quay structures.

Figure 34. Insitu Concrete Mattress Test

Insitu concrete mattress used in the tidal range needs a degree of porosity. Filter Point type (Figure 35) or Open Hole type (Figure 36) can be used. The relative porosity of the mattress and underlayers is important to determine mattress thickness; design methods are outlined in Hawkswood and Assinder, (2013).

Insitu concrete mattress benefits from the use of rock falling edge aprons in erodible granular soils for edges to be both 'sealed' and effective.

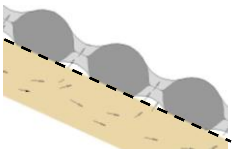

Figure 35. Filter Point

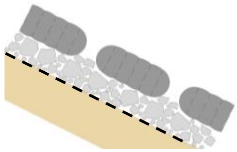

Figure 36. Open Hole

8.7 Tremie Concrete and Grouted Rock

These insitu protection types are outlined in PIANC Report 180 (2015). These methods are difficult to use on sloping areas and upon toe trench slopes to form important embedded edge details, Hawkswood et al (2014). Thickness often needs to be a minimum of 0.5-0.6m to cope with bed and tremie surface laying tolerances. Problems that may occur with siltation or fluid mud on the bed, quality control, environmental, and washout also need to be overcome along with other aspects. Where these constructability difficulties can be overcome, the thickness design methods can be based upon Hawkswood et al (2014), for 'sealed' protection with suitable allowances for joints and tolerances.

8.8 Preformed Mattress

The formation of reliable joints underwater is a major consideration as this generally defines whether protection can be considered as 'sealed' or an 'open' protection. The sealing of joints underwater is often diver reliant and particularly difficult in poor visibility, with a poorly prepared bed and where the bed is fluid or prone to siltation. A robust quality control system is needed to ensure reliable 'sealed' protection. Block mattress are also subject to higher local suction and pressure on smaller elements (Hawkswood *et al*, 2014).

Figure 37. Testing Block Matt

Flexible block mattresses were tested and compared with the method by Raes et al (1996) for both open/overlapped joints and unprotected edges. The test results are shown in Figure 38 and Figure 39. During the test, the joints and edges were moved to locate the worst case conditions. The tests show reasonable comparison to the Raes method with the safety factors generally in the range of 1.4 to 1.7. The tests also demonstrated that performance was affected by the flexibility, which suggests the Raes method may be conservative for mattress types with greater rigidity. (Test block size 0.25 to 0.3 x R)

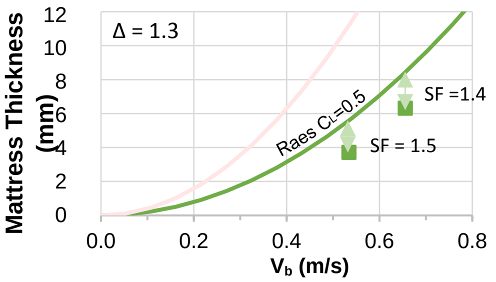

Figure 38. Testing of Block Matt - *Joints*

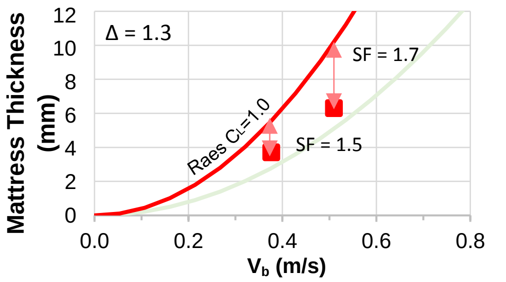

Figure 39. Testing of Block Matt - *Edges*

9.0 RELIABILITY OF CONSTRUCTION UNDERWATER

Risk management based quality control systems are often used for higher risk construction such as oil, gas and nuclear projects. This approach has general benefits for maritime construction underwater and has been used on many major projects. Where 'sealed' scour protection is proposed and the whole apron needs to be reliably constructed, quality control procedures are normally needed, as outlined below:-

- *performance parameters*
- *working conditions*
- *constructability, reliability and design*
- *risk assessment and management*
- *guidance documents and method statements*
- *control procedures*
- *as built records*

The suggested procedure should ensure that all risks are identified and suitably managed. Key performance points should be recognised and often a system of check control sheets is used by construction personnel and divers to ensure that reliable construction is achieved, recorded and demonstrated. Independent check diving is preferable. The process should be overseen by an experienced professional engineer.

10.0 CONCLUSIONS

Critical scour events for propeller action at berths have been further defined. A proposed timescale relationship between scale model testing and full size vessel actions has allowed consideration of the significant effect that scour duration time has upon rock stability. Also, a probability based approach to factors affecting a design scour event has been presented to aid the design of scour protection.

Scale model testing of rock has found that the original method by Fuehrer & Römisch (1977) is slightly conservative for no movement. The testing suggests that the clearance depth C could be taken to the centre of the top armour layer. This provides a significant reduction for larger rock sizes in higher velocity situations which would be most useful. Guidance could also be developed for further reductions in rock size where the vessel clearance can tolerate rock movement plus mounding and also where the overall scour exposure time for a berth is relatively low. Before any of these potential improvements could be adopted, they should be supported by confirmation from further testing or comparison to performance with real vessels. Collection of performance information from harbours for protection performance, bed scour, mounding, maintenance, and rock stabilisation by siltation may also aid future guidance and understanding. The tests have indicated that the Dutch Method of design significantly underestimates the rock size needed particularly for the common case of an open propeller with a central rudder.

Relative comparison of rock stability testing has more reliably determined that a rudder has a significant effect on rock stability; that propeller reversal is unlikely to be critical; and comparison has also allowed a design method for rudder deflected flow to be proposed.

The falling edge apron behaviour of rock construction under propeller action was tested using scale modelling and compared to real apron deployment. This has allowed a more conservative design method to be proposed compared to present guidance for current flow.

The performance and constructability of a common range of scour protection types has been outlined. For insitu concrete and preformed mattress types, the concept of 'sealed' and 'open' protection has been presented with widely differing performance. This has been supported by scale model testing of an 'open' protection of thin flexible block mattress with performance supporting the guidance by Raes et al (1996). The testing of edges has demonstrated that insitu concrete and mattress types will generally need rock falling edge aprons in order to form practical and reliable edges. Testing of 'sealed' insitu concrete mattress protection has suggested that design methods are conservative. The need for 'sealed' protection types to be reliably constructed underwater has been outlined with the proposed use of appropriate quality control procedures. The need for a combined design and constructability approach has been outlined for the reliability of various scour protection types.

11.0 ACKNOWLEDGMENTS

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