BERTH SCOUR PROTECTION DESIGN FOR AZIPODS, FALLING HINGED EDGES & MAINTENANCE DREDGING

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ABSTRACT

The paper seeks to advance knowledge to three important aspects of berth scour protection.

Azipods are increasingly being used particularly to large cruise vessels yet there is presently no established design method for scour protection subject to their action. These vessels can create high flow velocity to berths which makes rock protection impractical. Following scale model testing, design methods for scour protection will be presented for single and multiple azipods.

A 'falling hinged' edge detail has been developed for high velocity flows and as an alternative to rock falling edge aprons. The detail is used with insitu concrete mattress protection and comprises heavy in-situ concrete blocks which are linked to fall with edge scour. The relative merits of hinged edges and rock edges will be reviewed. A basis for the design and use of falling hinged edges is presented.

Maintenance dredging to berths with scour protection is an increasing issue with developing vessel size and often lower hull clearances, yet little up to date guidance is available. Views for the selection of resilient scour protection are given for common maintenance dredging actions with reference to PIANC WG22 (1997).

Key words: Berth Scour Protection, Hinged Edge, Maintenance Dredging, Concrete Mattress

1 INTRODUCTION

1.1 Azipods

Azipods are driven by electric motors in the rotational hub behind the propeller. The rotational facility gives vessels good manoeuvrability hence azipods are often used on cruise vessels. Azipods are often used in pairs with 3 or 4 azipods being common on larger cruise vessels. Previous scale model testing of propellers has now been extended to azipods. This includes testing of rock and in-situ concrete mattress. The testing demonstrated that azipods are similar to propellers and similar design methods can be used. These design methods are presented initially allowing comparison of the test results.

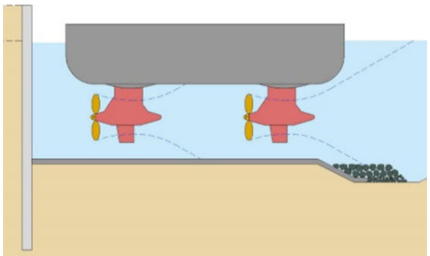

Figure 1. Twin Azipods

Figure 2. Azipod

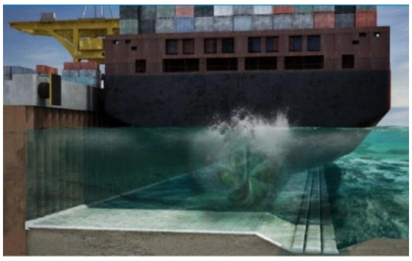

Figure 3. Falling Hinged Edge

Figure 4.Testing

1.2 Falling Hinged Edges

Edge protection is important to prevent damaging underscour of scour protection. Falling hinged edge arrangements have been developed following scale model testing under propeller azipod flow. This has demonstrated its performance to react to edge scour and allow a design method to be proposed for its falling protection depth. A method by Raes *et al* (1996) for the thickness design of hinged edge blocks to resist uplift is also presented.

1.3 Scour Protection Resilience for Maintenance Dredging

Maintenance dredging to remove siltation is frequently required to maintain vessel clearance. Near quay structures, siltation removal is needed over the top scour protection. Scour protection should be resilient to maintenance dredging methods likely to be used within the design life. The selection and design of scour protection needs to consider resilience to proposed dredging actions and bed levels to allow effective siltation management and removal.

1.4 Readership

The paper may assist with design and construction of berth scour protection, aid further testing, and development of design guidance. The paper may be of use to port authorities, design engineers, contractors, operators plus research and guidance authorities.

2 INDEX

3 NOMENCLATURE

V_o	Max. propeller jet velocity	V_b	Bed velocity	Δ	Buoyant relative density
(c)	Propeller type, open/ducted	H_p	Height of propeller axis from bed	C_F	Stability coefficient for flow
f	Ratio of engine power at berth	D_{min}	Design protection thickness	L	Azipod axial spacing
P	Engine power	u	Surface undulation	S	Azipod spacing
ρ	Density	w	Width between undulations	SF	Safety factor
D_p	Propeller diameter	I_Q	Surface undulation factor	C_L	Stability Coefficient (Raes *et al*, 1996)
C	Propeller tip clearance	C_S	Stability coefficient for suction	D_{S50}	Rock size (sphere), 50%
R	Propeller radius	g	Acceleration due to gravity	B_S	Stone stability coefficient

4 FLOW FROM AZIPODS

4.1 Introduction

Azipods are often capable of rotating 360˚ which aids moveability of vessels such as cruise ships (Figure 1). On larger cruise vessels 2 or more azipods are common with a pair of rotating Azipods and often additional fixed Azipods (Figure 5).

Figure 5. Azipods in Dry Dock

Velocities from azipods are similar to open propellers as demonstrated by the testing (Section 7) and can be taken as follows: -

4.2 Jet Velocity From Azipods

The jet velocity from azipods can be taken from the established formula (1) for propellers: -

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

Where:

Coefficient for open propellers	(c) = 1.48
Propeller diameter (m)	D_p
Engine power (kW)	P
Ratio of engine power at berth	f
Water density, Sea water 1.03 t/m3	ρ

Azipods are capable of high velocities at berth. The percentage of power used at berth should be obtained relative to each design vessel for both straight and rotated azipods.

4.3 Bed Velocity From Azipods

Bed Velocity is influenced by the number of azipods, the propeller tip clearance, azipod positions, fixed or rotating and the presence of a bottom fin to the hub of the azipod.

From the testing shown in Section 7, azipods with a bottom fin as Figure 6, were found to create bed velocities similar to an open propeller with a central rudder as Figure 7. Azipods with no bottom fin as Figure 8, produce bed velocities similar to an open propeller without a central rudder as Figure 9. The presence of a bottom fin splits the rotational propeller flow into two jets and creates higher bed velocities similar to a central rudder.

Figure 6. Azipod With Fin

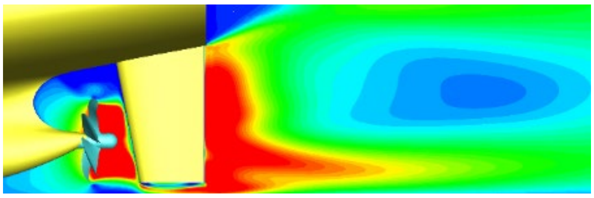

Figure 7. Velocity - With Straight Rudder

Figure 8. Azipod Without Fin

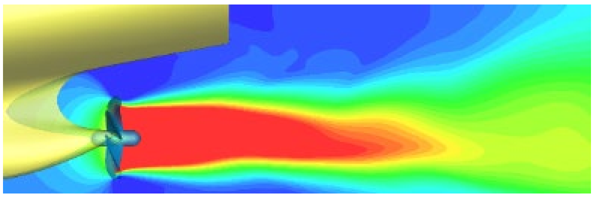

Figure 9. Velocity - No Rudder

Bed velocities for various arrangements of azipods can be taken from Figure 10 following the scale model testing in Section 7.

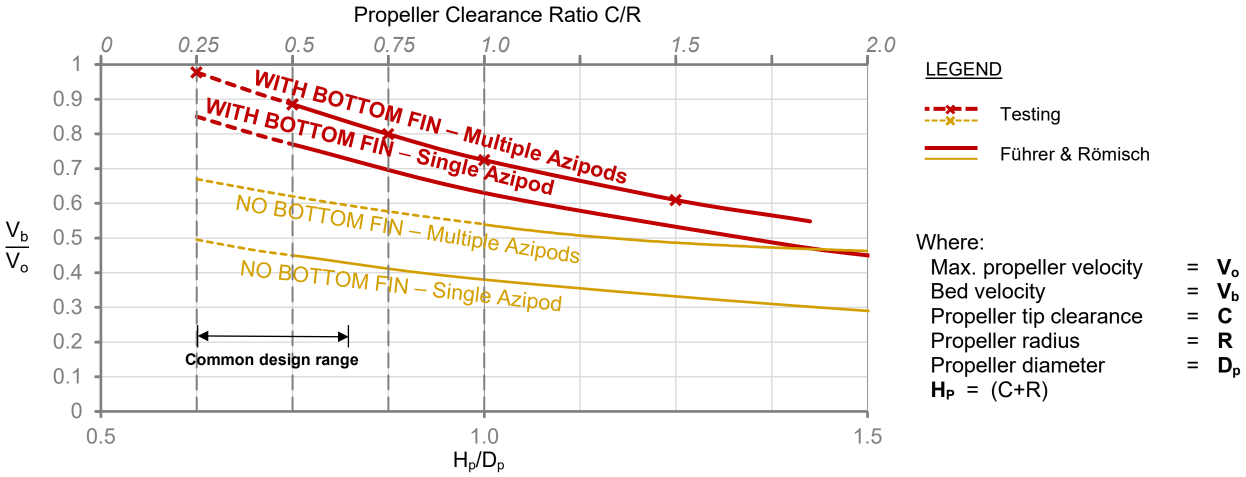

Figure 10. Bed Velocity, V_b Graph for Azipods

For single azipods bed velocities are similar to single propellers following the original work by FÜHRER & RÖMISCH (1977) and PIANC BULLETIN 109 (2002). For multiple azipods, bed velocities were found to be similar to advice for twin propellers from HAWKSWOOD, GROOM & HAWKSWOOD (2018). This comparison for flow action from azipods is summarised: -

Azipod with bottom fin	=	Propeller with Rudder
Azipod with bottom no fin	=	Propeller with Rudder
Multiple Azipods	=	Twin Propellers
		(See Section 7.2 for minimum azipod spacing.)

5 ROCK DESIGN FOR AZIPODS

5.1 Introduction

This section outlines the design method for rock bottom protection under azipod propelled vessels. Rock protection generally comprises two layers of rip rap or armour stone upon a bedding/filter stone layer and often a geotextile filter membrane as typically shown in Figure 11. Rock protection often needs to be grouted at walls and structures to prevent wash out from flow down or along walls, Figure 11. The rock construction depth can have a significant effect on structures, increasing the effective span height to piled walls and increasing the depth of gravity walls.

Design of rock for no movement is particularly important where rock movement would cause grounding or loss of berthing clearance. Bed velocities from larger azipods can often be too high for a rock solution to be feasible or practical.

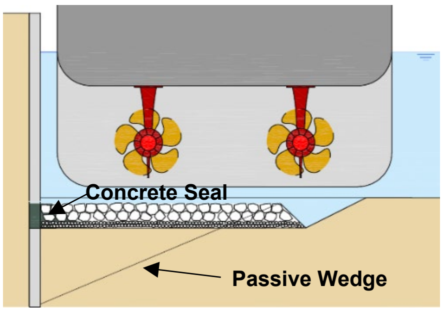

Figure 11. Rock Protection to Quay Wall

5.2 Level Rock Protection under Azipods

Design methods for rock stability have generally been based upon the 'threshold of motion' for no movement or scour with effectively a safety factor = 1.0. The most common design method emanates from the original testing work of FÜHRER & RÖMISCH (1977) who produced curves for bed velocity Vb for single propellers included within Figure 10. They also provided a design method for the size of rock protection as Equation (2) BAW (2005). The testing has shown Equation (2) can be used for azipods, with bed velocities taken from Figure 10 for single or multiple azipods with or without a bottom fin:-

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

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

Azipod With A Bottom Fin	$B_S = 0.64$	(With Rudder, FÜHRER & RÖMISCH (1977), BAW (2005))
Azipod Without Bottom Fin	$B_S = 1.55$	(No Rudder, HAWKSWOOD, FLIERMAN *et al* (2016))

The above method and stability coefficients were well supported by the testing in Section 7. The stability coefficient for an azipod with no bottom fin of $B_s = 1.23$ by FÜHRER & RÖMISCH (1977) was found to be too low and $B_s = 1.55$ is proposed. This is similar to the case of a propeller without a rudder, HAWKSWOOD, GROOM & HAWKSWOOD (2016).

The relationships of rock size D_{s50} to bed velocity V_b are shown in Figure 12 for the general case with a bottom fin, and with no bottom fin. The higher stability coefficient B_s for no bottom fin is created by the increased rotation and turbulence within the critical area of the flow acting upon the bed. For berths with low clearance which would be affected by rock movement, designers should consider increasing the safety factor or possibly using a mattress type scour protection.

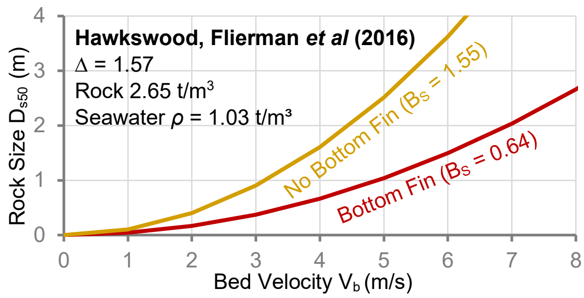

Figure 12. Stone Size for Azipod Flow

The testing by HAWKSWOOD, FLIERMAN *et al* (2016) also showed that the design tip clearance C can be taken from the centre of the top layer of rocks as Figure 13. This takes into account the increasing stability effect for larger rock sizes which has also been demonstrated in the testing for azipod action (section 7). This effect can make a useful saving to larger rock sizes.

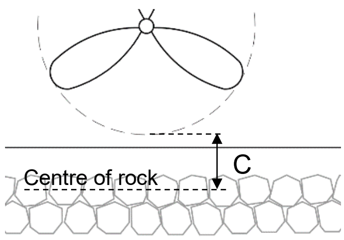

Figure 13 Propeller Tip Clearance, C.

5.3 Slopes and Piles

The increase in rock size needed for slopes can be obtained using a slope factor by Pilarczyk, PIANC Report 180 (2015). The increased flow and turbulence around piles can cause rock stability failure. A pile effect factor estimated by Van Doorn, interpreted from PIANC Report 180 (2015) can be used. Slope protection under piled quays is also described in more detail in HAWKSWOOD & KING (2016).

5.4 Rock Falling Edge Aprons

For azipod 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. Their design is the same as for propeller flow as outlined in Section 8.5 of HAWKSWOOD, GROOM & HAWKSWOOD (2018).

Rock falling aprons provide an effective way to manage the risk of edge scour. They are particularly useful when used in conjunction with insitu concrete or mattress protection types where 'sealed' edges are required. Falling edge aprons can achieve a relatively high protective depth (VAN VELZEN *et al* 2014) and importantly can be monitored and maintained. Rock aprons start to deploy when the edge scour exceeds the trench embedment depth as shown in Figure 14. Before aprons fully deploy and possibly fail, additional rock can be placed to any local scour areas. The rock size for falling edge aprons can be designed as Section 6.2.

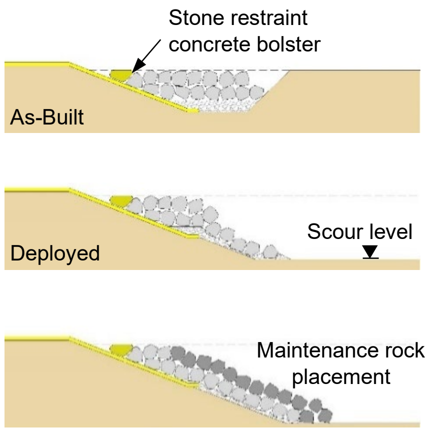

Figure 14. Falling Edge Apron

6 ROCK STABILITY TESTING FOR AZIPODS

6.1 Test Arrangements

Scale model testing of rock was undertaken using 150 mm diameter azipods at various clearances, both with and without bottom fins, see Figure 6 and Figure 8. The azipod propeller rotation to initiate movement of various rock sizes was determined. To replicate actions in berths, the following effects were tested: -

- Single Azipod (Figure 15)
- twin Azipods straight (Figure 16)
- twin Azipods rotated (Figure 17)
- three Azipods straight (Figure 18 & Figure 19)

Figure 15. Test, Single Azipod

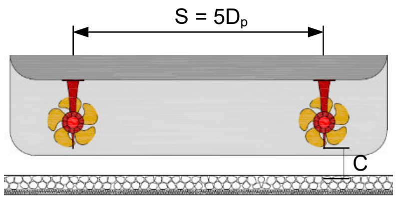

Figure 16. Twin Azipod Straight

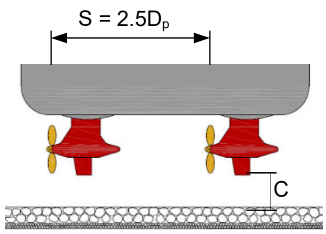

Figure 17. Twin Azipods Rotated

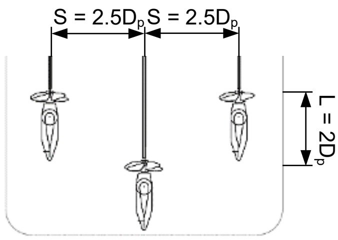

Figure 18. Test Plan – 3 Azipods Straight

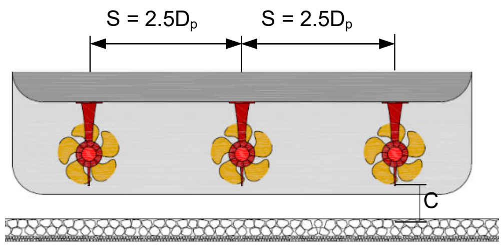

Figure 19. Test Section – 3 Azipods Straight

The testing was carried out with a range of model rock sizes with W_{85}/W_{15} ratios from 1.8 to 2.6. This testing was an extension of a previous testing programme for single propellers, HAWKSWOOD, FLIERMAN *et al* (2016) and twin propellers, HAWKSWOOD, GROOM & HAWKSWOOD (2018). It has allowed the effect of azipods to be demonstrated and appropriate design guidance suggested. The testing covered a common range of low clearance ratios using propellers with 5 blades. The propellers were produced by MARIN with a K_T value of 0.587 which is now common. The azipod hubs were produced by 3D printing in plastic. For large azipods with 6m diameter propellers, the relevant model scale would be 1:40.

6.2 Test Results and Findings

Results for rock stability are shown in Figure 21 and Figure 22 based upon bed velocities shown in Figure 10. Figure 10 is based upon bed velocities for single and twin propellers taken from HAWKSWOOD, GROOM & HAWKSWOOD (2018). Rock Stability compared well with rock design equation (2) with stability coefficients as outlined below: -

Azipod with Bottom fin	Figure 21	$B_s = 0.64$
Azipod with no Bottom fin	Figure 22	$B_s = 1.55$

Scale model testing for single azipods was found to be similar to single propellers. An azipod with a bottom fin was found to be similar to an open propeller with a central rudder and an azipod with no fin similar to an open propeller with no central rudder, HAWKSWOOD, FLIERMAN *et al* (2016).

Testing with multiple azipods with twin azipods straight as Figure 16, twin azipods rotated as Figure 17, plus three azipods straight as Figure 19, were all found to be safely comparable with previous guidance for twin propellers, HAWKSWOOD, GROOM & HAWKSWOOD (2018). The addition of a 3rd azipod with an axial offset of 2D as Figure 18 and Figure 19 was found to make little difference perhaps due to the drop in velocity due to the axial offset L. This confirms the design method can be used for 3 Azipods with a spacing S > 2.5 D_p and L = 2 D_p.

Some of the largest cruise vessels have 4 azipods (Figure 20). The trend in the results would suggest that the design method for 2 to 3 azipods would be safe for 4 azipods if the average azipod spacing S > 1.5 D_p and L > 3 D_p. Cruise ships typically have smaller Azipod propellers that are relatively more spaced out than larger twin propeller vessels.

Where azipods are closer together than the test arrangements or advise above, an increased velocity could be suitably allowed, based upon interpretation from the testing or further testing undertaken.

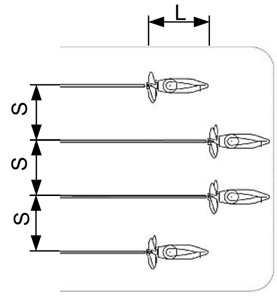

Figure 20. 4 Azipod Vessel

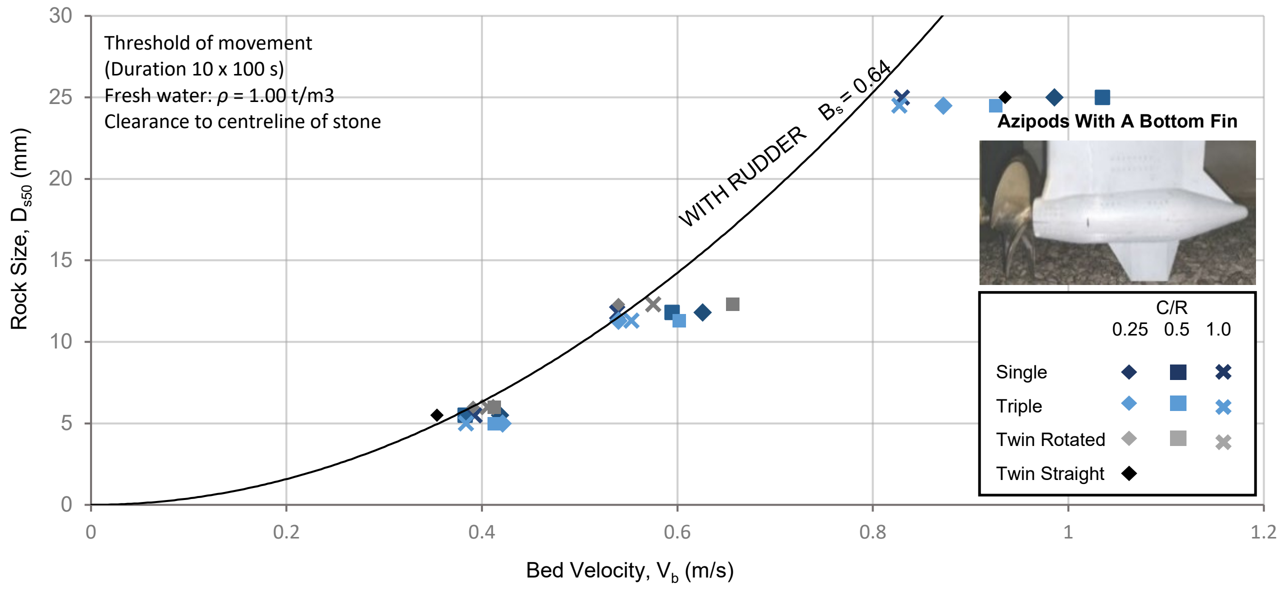

Figure 21. Azipods With A Bottom Fin

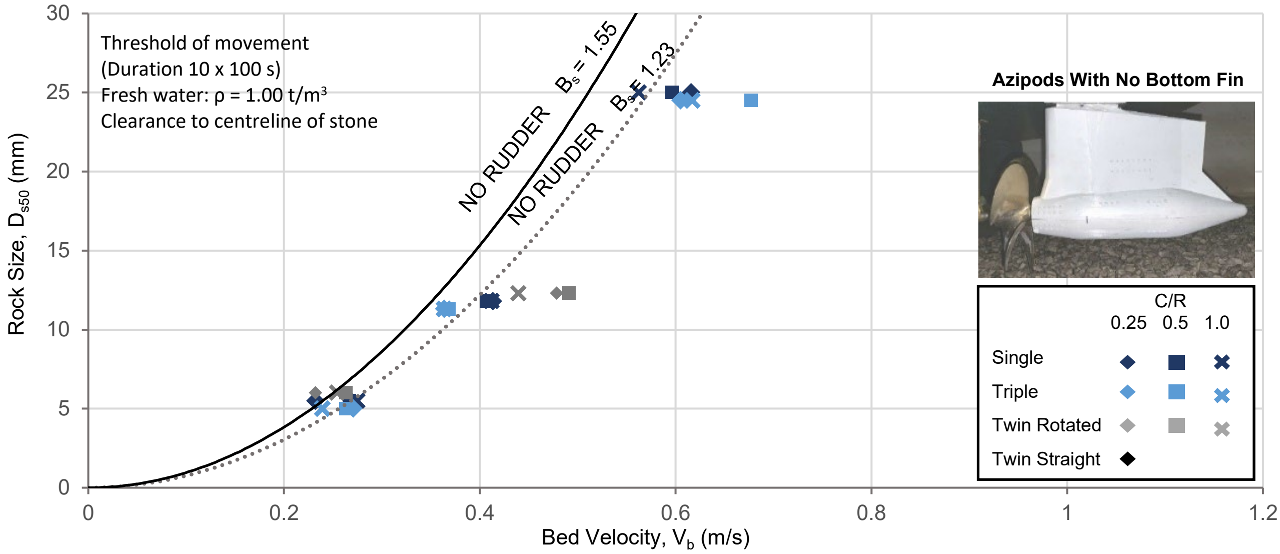

Figure 22. Azipods With No Bottom Fin

7 INSITU CONCRETE MATTRESS DESIGN UNDER AZIPODS

7.1 Introduction

Figure 23 shows a typical concrete mattress arrangement under an azipod propelled vessel. Insitu concrete mattress aprons can resist high velocity actions such as azipods and have a much lower thickness than rock. This can lead to significant savings in quay structures as outlined in HAWKSWOOD, GROOM & HAWKSWOOD (2018). This protection has also been used for high velocity inclined jet action from HSS vessels up to 12.5m/s HAWKSWOOD, EVANS & HAWKSWOOD (2013).

Constant Thickness Mattress types (CT) as Figure 24 are normally used to beds and permanently submerged slopes. Porous mattress types are needed to wave zones, HAWKSWOOD & ASSINDER (2013).

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 concrete. High performance joints between mattress panels are formed using zipped ‘ball and socket’ concrete shear joints, Figure 24. CT mattresses are typically pump filled with a sand: cement micro concrete mix of 35 N/mm² strength. This produces an apron of interlocked plain concrete slabs underwater. The fabric mattress is essentially a temporary works system. Seals to walls are achieved by using a concrete bolster detail as Figure 25.

Further background information on insitu concrete mattress is given in HAWKSWOOD, GROOM & HAWKSWOOD (2018) along with guidance for installation using an established marine quality control system.

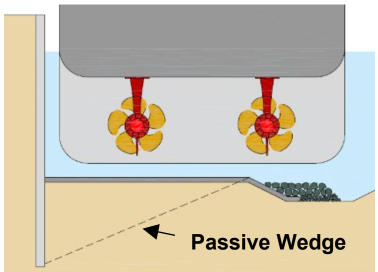

Figure 23. Typical Section

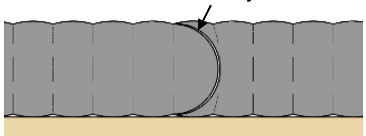

Figure 24. Constant Thickness Mattress (CT)

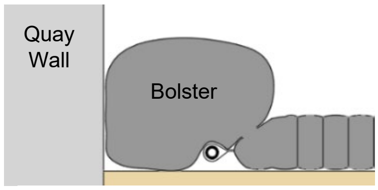

Figure 25. Wall Bolster Seal

7.2 Design Introduction

Insitu concrete mattress under azipod propellers should be designed for: -

- Azipod propeller suction
- Azipod propeller flow

Design methods for both suction and flow can be taken from comparable situations for open propellers from HAWKSWOOD, GROOM & HAWKSWOOD (2018). The design methods relate to ‘sealed’ protection with the following parameters: -

- Sealed joints and edges (protected from underscour)
- Concrete panels 3 to 5m wide between interlocked joints
- Concrete strength 35 N/mm² (MPa)

At lower clearance ratios C/R, suction is usually the design condition for azipod actions. Where protection is offset from propeller locations, design of suitable edge details are very important to prevent underscour and can be rock falling edge aprons as Section 6 or falling hinged edges as Section 12.

7.3 Mattress Surface Undulation Factor I_Q

The spacing of mattress thickness ties *w* controls the surface undulation u as shown in Figure 26 and Figure 27. The surface undulation ratio is given by *u/w*. Higher surface undulation increases hydrodynamic loading and reduces load distribution ability due to stress concentrations, HAWKSWOOD, LAFEBER & HAWKSWOOD (2014). Figure 28 shows an example of low surface undulation ratio with spacing of thickness ties at 100 mm centres.

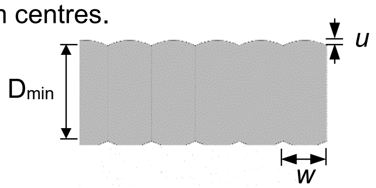

Figure 26. Low Surface Undulation

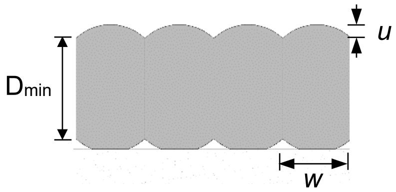

Figure 27. High Surface Undulation

Figure 28. Low Surface Undulation

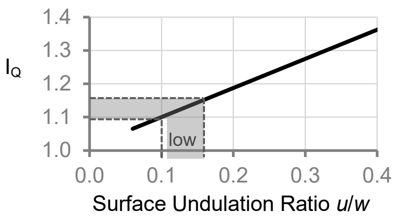

Figure 29. Surface Undulation Factor I_Q

The surface undulation factor I_Q for design is taken from Figure 29 and is related to the undulation ratio *u/w*. Mattress with low surface undulation ratio of 0.1 to 0.16 as Figure 26 are preferred and should be specified as they are subject to lower suction loads and distribute loading better. Mattress types with higher undulation ratios as Figure 27 are less effective and need a greater thickness. Insitu concrete mattress is specified by design thickness D_{min} and I_Q factor.

7.4 Design for Azipod Propeller Suction

Insitu concrete mattress creates an apron of plain interlocked concrete slabs which have good load distribution properties and can be designed for the large area of bed suction which occurs to the intake side of a propeller as outlined in Figure 30.

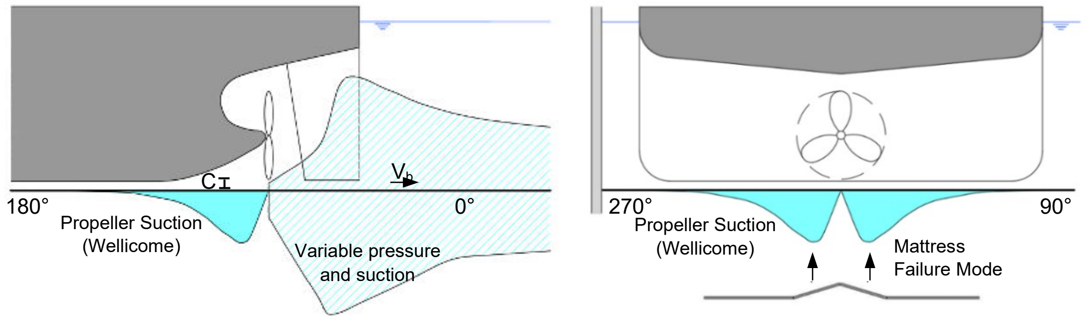

Figure 30. Propeller Suction

The testing in Section 7 established that azipods are comparable to open propellers therefore, the dead-weight design method for suction from open propellers by HAWKSWOOD, GROOM & HAWKSWOOD (2018) can be used for azipods for a 'sealed' protection. This method applies to azipod propellers with or without a bottom fin as this has no effect on propeller suction on the bed. The design method is based upon the propeller exit velocity V_o, and is presented in Equation (3): -

Simplified dead-weight design method
$$D_{min} = C_S \frac{V_o^2}{2 g \Delta} \times \frac{I_Q}{1.15} \qquad [3]$$

Where: Stability coefficient for insitu concrete mattress propeller suction C_s
Mattress surface undulation factor (Figure 29) I_Q

The stability coefficient for propeller suction C_S is taken from Figure 32. Propeller suction upon the bed reduces as the bed clearance ratio increases. Where two azipods are in line as Figure 31, the area of suction can combine, and suction coefficient can be taken from Figure 32.

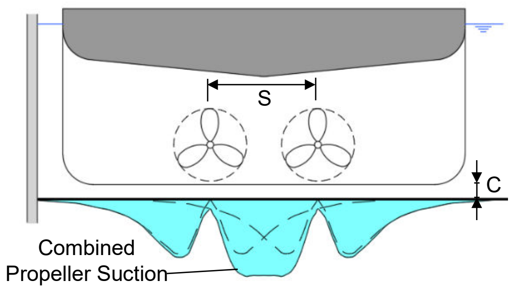

Figure 31. Suction Distribution - Twin Azipods

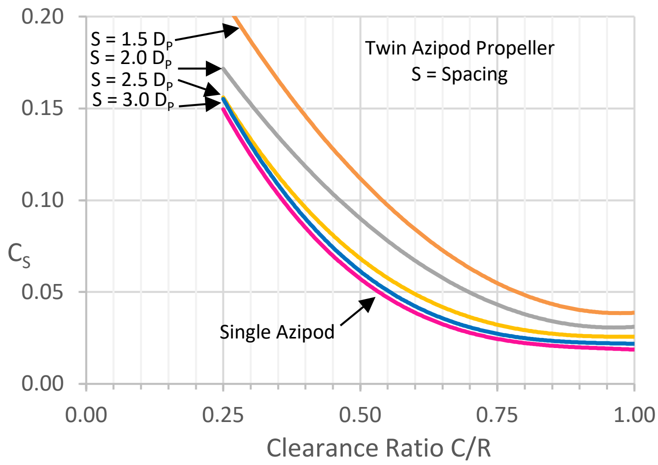

Figure 32. Suction Coefficient C_S

7.5 Design for Azipod Flow

The design method for 'sealed' insitu concrete mattress under Azipod flow, can be applied to both with a fin and without a fin as Equation (4):-

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

Where: Stability coefficient for insitu concrete mattress under propeller flow C_F
Mattress surface undulation factor (Figure 29) I_Q
The maximum bed velocity V_b is taken from Figure 10 for the appropriate fin arrangement and single or 2-3 Azipods V_b

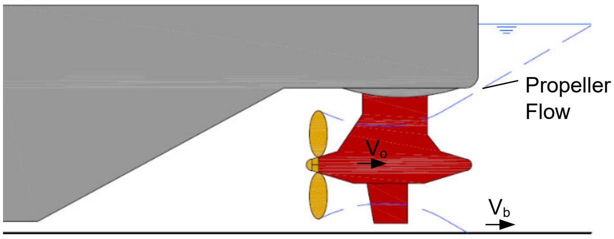

Figure 33. Propeller Flow

Design Condition	C_F
With fin, level beds	0.12
With fin, slopes and/or variable bottom	0.16
No fin, level beds	0.19
No fin, slopes and/or variable bottom	0.23

Table 1. Mattress Flow Coefficient C_F

The coefficient for azipod propeller flow C_F can be taken from Table 1. A variable bottom is assumed when bed undulations/ construction tolerances exceed 600mm. Where changes in bed levels cause large areas of accelerated flow and suction, uplift can be estimated using Bernoulli's equation or CFD Modelling and mattress thickness designed accordingly.

8 DESIGN OF SLOPING INSITU CONCRETE MATTRESS

8.1 Introduction

Where cruise vessels berth to open piled quays, insitu concrete mattress protection needs to be designed for the high flow conditions during unberthing from twin rotated azipods, Figure 34. Insitu concrete mattress is reliably installed to quay slopes and around piles with experienced engineering support, HAWKSWOOD & KING (2016).

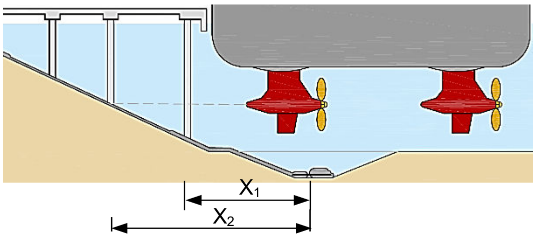

Figure 34. Azipods Rotated Towards Pile Quay

8.2 Velocity onto Slopes.

The worst flow case often occurs at the outer piles where the flow is increased by the blockage factor of the piles: -

$$\text{Pile Blockage Factor B.F} = \frac{\text{Pile Spacing}}{\text{Gap Between Piles}} \qquad [5]$$

The bed velocity at a distance of X_1 can be estimated from using Equation (6): -

$$\text{Velocity at pile (Row 1)} = V_{bMax} \times \frac{2.6 \times P \times D_p}{X_1} \times \text{B.F} \qquad [6]$$

Where, the max bed velocity V_{Bmax} is from Figure 10, the velocity decay factor $\frac{2.6 \times D_p}{X}$ for single propellers is reduced for twin azipods with factor P, with P = 1.15 for azipods with a bottom fin and P = 1.35 for azipods with no bottom fin.

The bed velocity to sloping mattress between piles near to the azipod axis can be estimated from Equation (7):-

$$\text{Velocity at pile (Row 2)} = V_{bMax} \times \frac{2.6 \times P \times D_p}{X_2} \times \text{B.F} \qquad [7]$$

The P factor has been estimated based upon the increase of bed velocity for twin azipods in comparison to single azipods, Figure 10. Velocity decay is greater for azipods with a bottom fin because the fin splits the flow. Equations 6 and 7 apply where: -

$X > 3\ D_p$ Azipods with a bottom fin.
$X > 3.5\ D_p$ Azipods with no bottom fin.

Concrete mattress thickness is often reduced after the first row of piles using the above equations.

As no dredging is likely to take place to slopes under piled platforms, a minimum thickness of 150mm is often adopted for nominal resilience.

8.3 Thickness Design to Slopes

Design thickness of insitu concrete mattress to slopes can be taken from Equation (4) with a stability coefficient for slopes C_F taken from Table 1. The stability coefficients for slopes include allowances for slopes and bed undulation as tolerances on slopes are often greater than 0.6m.

9 TESTING OF SLOPING INSITU CONCRETE MATTRESS

9.1 Test Arrangements

Scale model testing of sloping insitu concrete mattress was undertaken as described in HAWKSWOOD, GROOM & HAWKSWOOD (2018) for previous testing under twin propeller action. The test mattress had an effective thickness of 3.7mm plus a strength and Young's Modulus replicated approximately to scale with interlocking joints.

The test arrangement for twin rotated azipods creating flow of 1.65m/s onto a slope is shown in Figure 35. A safety factor of greater than 4 was obtained without failure being reached as shown in Figure 36. The comparison is based upon the design method given in Section 8.5.

The relatively high safety factor is in common with previous testing for effectively 'sealed' protection types.

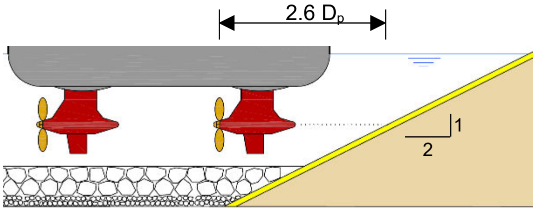

Figure 35. Test, Twin Azipods Rotated Onto Slope

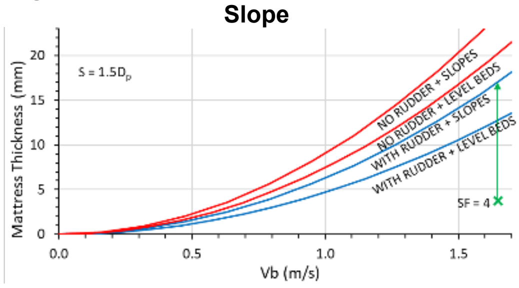

Figure 36. Test Safety Factors

10 DESIGN OF FALLING HINGED EDGES

10.1 Introduction

Falling edges are often used with edge embedment trenches to provide edge scour protection, Figure 3 and Figure 34. A falling hinged edge solution to insitu concrete mattress protection can often be preferred to a rock falling edge apron where: -

- Rock size is not practical in high velocities.
- Rock costs are high.
- Saves additional plant/ process of rock laying.

Falling hinged edges are formed with insitu concrete as part of insitu concrete mattress installation. Falling hinged edges react to edge scour and can be formed in 1 row of hinged blocks as Figure 37 and in 2 rows as Figure 38.

The heavy edge blocks are hinge connected with pairs of strong webbing or geotextile to allow them to fall in reaction to any edge scour below the embedment trench. The blocks are spaced apart with gaps of some 25% of the block thickness to allow for articulation during falling.

A robust geotextile is provided to the bottom of the blocks to prevent washout, Figure 38. Importantly additional geotextile is provided to the gaps to allow differential articulation of the hinged edge blocks. A thickened toe beam to anchor the blocks is usually provided.

Falling hinged edge details are formed in insitu concrete using fabric mattress panels. The edges can be formed using various sizes and numbers of blocks. In particularly, heavy block sizes can be used to ensure stability in high flows such as cruise ships with Azipods, where large rock size may not be viable.

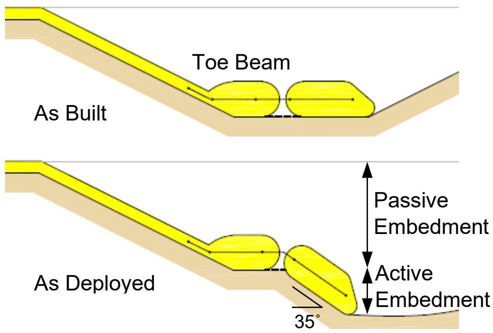

Figure 37. 1 Row Hinged Edge Block

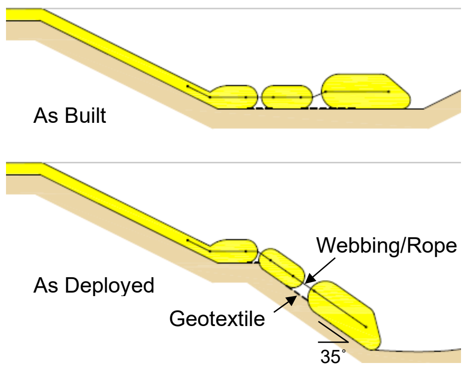

Figure 38. 2 Rows Hinged Edge Blocks

10.2 Falling Hinged Edge Block Design

Edge block thickness is designed as an 'open' protection to resist trapped flow pressure uplift from flow into scour voids under the blocks, Figure 39, by propellers or azipods, HAWKSWOOD, GROOM & HAWKSWOOD (2018). An established formula by RAES *et al* (1996) can be used as Equation (8) for open edges:-

$$\text{Thickness } D_{min} = \frac{C_L \times V_b^2}{2\Delta g} \quad [8]$$

Where $C_L = 1.0$ Flow angle 30°- 90° to edge
$C_L = 0.5$ Flow angle 0°- 30° to edge

The use of $C_L = 0.5$ up to a 30˚ flow angle to the protection edge is based upon the pressure coefficient for flow impact on surfaces at 30˚ being 0.5 (sin30˚) plus also testing of edges. As the test arrangements, block lengths should typically be 2m to 2.5m and block widths should be greater than 2m. As a general guide the thickness of the toe beam and a second row of blocks is typically 2/3 of the edge block thickness as shown in Figure 38. The hinge connection capacity should be greater than the block weight.

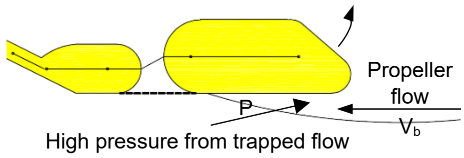

Figure 39. Uplift Pressure From Edge Block Under Scour

In design, an allowance for the extent of under scour voids can be made relative to the worst-case situation for any block. This can give a slight saving in thickness. For design, the critical condition is when the edge blocks are level, stability increases as the blocks hinge and fall. The edge block nosing can be shaped to increase stability in the critical level condition. The design method applies to flow from propellers and azipods.

10.3 Edge Protection Depth

Estimations of edge scour depths would appear to be best formed by comparison to similar vessels and bed soils. Often, scour experience in local or similar harbours is useful with reference to bathymetric survey records. This can aid selection and agreement of a design scour depth, preferably with a backup edge maintenance plan. An example back up plan could be rock placement locally to a deployed hinged edge as shown in Figure 40. This arrangement can effectively manage the uncertainty and risk of edge scour during the design life.

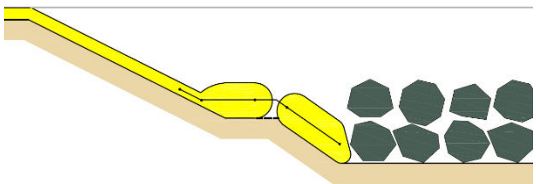

Figure 40. Falling Hinged Edge Maintenance

Once a design scour depth is agreed, the edge arrangement can be engineered. Passive edge embedment has the best durability and is normally proposed for at least 50% of the edge scour depth as Figure 37. A reactive falling hinged edge can be designed for the remainder of the design scour depth. The length of single or twin rows of hinged blocks can be determined using a deployed slope angle of 35˚ as demonstrated in the tests.

11 TESTING OF FALLING HINGED EDGES

11.1 Testing Arrangements

Falling hinged edge arrangements of 1 row and 2 rows of blocks where made to a scale of 1:40 in precast concrete with scaled components of webbing tie connections and geotextile. The hinged edges were arranged in an edge trench with concrete mattress on a medium sand. The testing was principally to develop a reliable edge detail that was reactive to edge scour. The thickness design method by RAES *et al* (1996) for uplift stability had previously been tested and confirmed in HAWKSWOOD, GROOM & HAWKSWOOD (2018).

The test flow was created by twin rotated or in line azipods 150mm diameter with bottom fins as this created the worst case flow conditions. The azipod spacing was 2.5 D_p which is considered an effective worst case for rotated azipods of cruise vessels, which have been found to range between 2.6 D_p to 5 D_p. The bed velocity was taken from Figure 10 and relatively scaled.

11.2 Testing Results

The following testing was undertaken: -

Tests 1 and 2	Hinged edge	1 Row	Flow 90°	Figures 41-44
Tests 3 and 4	Hinged edge	1 Row	Flow 0°	Figures 45-50
Test 5	Hinged edge	2 Row	Flow 0°	Figures 51-54

The edge block test thickness of 22.5mm was relative to 900mm thickness at full scale to the 1 row of block Tests 1-4. For 2 rows of blocks as Test 5, the 15mm edge block test thickness was relative to 600mm at full scale. Edge block thickness typically ranges from 400 to 900mm.

Test 1 was ceased when the edge blocks where held up by catenary action of the tight geotextile, allowing under scour under the blocks, Figure 43. This is a well-known problem and was clearly demonstrated. For Test 2 and all subsequent tests, 8mm of additional geotextile was added to the side gaps to allow edge blocks to effectively fall with differential movement between blocks. Figure 44 shows the additional geotextile allows effective falling at a block rotation of 35°, underscour began at the toe beam.

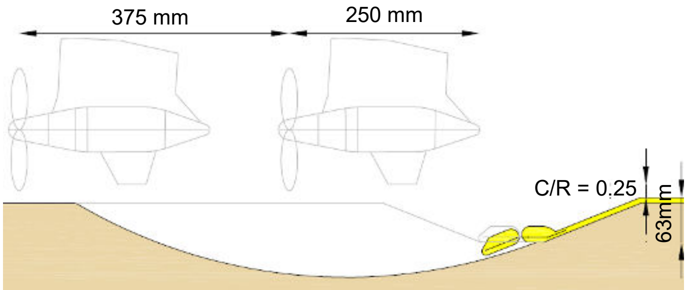

Figure 41. Test 1 Section

Figure 42. Test 1, As Constructed

Figure 43. Test 1, Deployed, Tight Geotextile

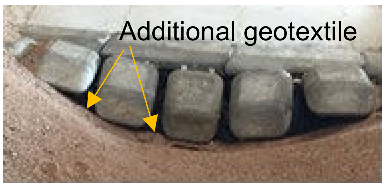

Figure 44. Test 2, Deployed, Surplus Fabric

During Test 3, the toe beam panels slipped when the edge blocks had rotated to 35° as shown in Figure 48. This was due to the toe beam panels not being connected to the concrete mattress and sliding due to the slope and assisted by the pulsing effect of flow from the propeller. In subsequent tests the toe beam was glued to the mattress. This occurrence shows the need to take the webbing reinforcement into the concrete mattress.

Test 4 demonstrated good reactive performance with no slippage, Figure 49. The surplus geotextile was seen to be working well allowing differential movement between the blocks, Figure 50. The hinged edge block rotation was up to 45°, Figure 46. At the end of the test and when the edge detail was removed, no underscour of the toe beam had occurred. Block contact with the sand was demonstrated to be typically more than half of the block area (better than for direct flow at 90°). In tests 2 and 3, no underscour of toe beam had also occurred, with rotation up to 35°. The testing indicates the single row hinged edge detail is effective for a design block rotation to 35°.

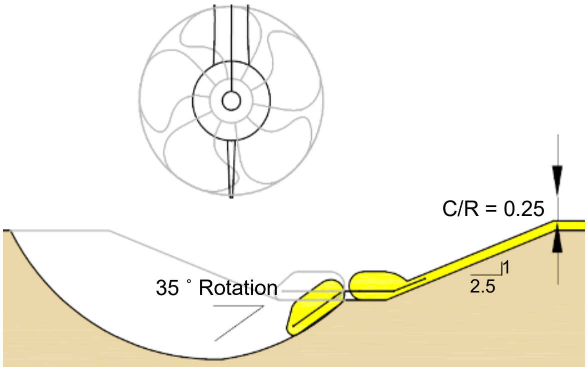

Figure 45. Test 3 Section

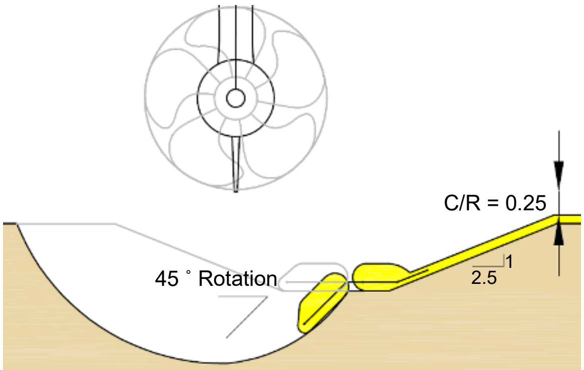

Figure 46. Test 4 Section

Figure 47. Test 3, As Constructed

Figure 48. Test 3, Toe Beam Slip

Figure 49. Test 4, Edge Deployed Top View

Figure 50. Test 4, Edge Deployed Side View

Test 5 was for 2 rows of hinged edge blocks as Figure 51 for an extended test period of 900 s. The edge blocks where 15mm thick (600mm) and the central block and toe edge beam both 10mm (400mm). This arrangement reacted well to edge scour as shown in Figure 53 and Figure 54. The block rotation was generally to 35° with a maximum of 45˚ with a falling depth of 90mm (3.6m). Following the tests, the 2 row falling hinged edge detail is also considered effective for a design block rotation up to 35° during edge scour.

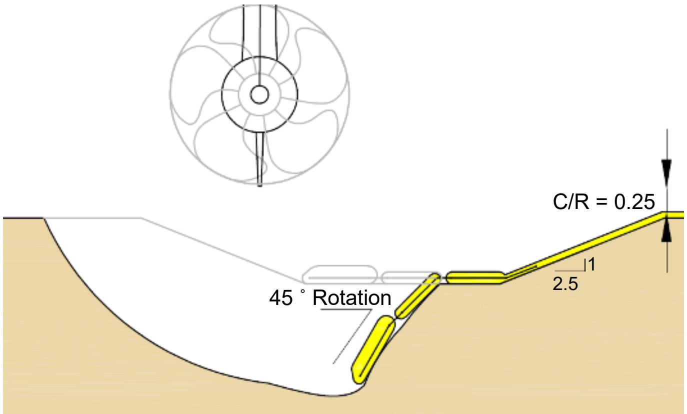

Figure 51. Test 5 Section

Figure 52. Test 5, As Constructed

Figure 53. Test 5, Edge Deployed Side View

Figure 54. Test 5, Edge Deployed Front View

The testing was conducted with propeller rotation of 400 rpm. During testing the stability of the edge blocks in comparison to the design thickness from the method by RAES *et al* (1996) equation (8) is expressed below:-

			Design Thickness RAES *et al* (1996)
Tests 1-2	22mm Thick edge blocks	Flow 90°	28 mm
Tests 3-4	22mm Thick edge blocks	Flow 0°	14 mm
Tests 9	15mm Thick edge blocks	Flow 0°	15 mm

No blocks where observed to fail in uplift due to flow. Previous testing of open edges by HAWKSWOOD, GROOM & HAWKSWOOD (2018) suggested the RAES *et al* (1996) method had a nominal SF = 1.5.

11.3 Summary

The development and testing of the falling hinged edge has shown: -

- Ability to fall in reation to edge scour and continue to provide scour protection
- Differential edge block movement is enabled by hinging and additional geotixtile
- Thickened edges can be desiged by the RAES *et al* (1996) method to resist uplift

The hinged edge system manages some problems encountered with block or ashphalt mattress types namley rolling up of edges and the opening of joints in falling deployment.

12 SCOUR PROTECTION RESILIENCE FOR MAINTENANCE DREDGING

12.1 Introduction

Maintenance dredging to remove siltation from berths is needed to most ports to maintain bed clearance for vessels. Quays with high vessel occupancy often need fast dredging methods to limit loss from downtime. Guidance in PIANC WG22 (1997) identified the three main aspects to be considered, vessel clearance, maintenance dredging allowances and clearance to scour protection as outlined in Figure 55.

PIANC (1997) guidance suggests an under-keel clearance of 1m preferred and 0.6m minimum. The siltation depth allowed for maintenance dredging and rate of siltation determines the likely dredging periods. For maintenance dredging clearance to scour protection, PIANC (1997) recommends 0.75m or 0.45m minimum including tolerances.

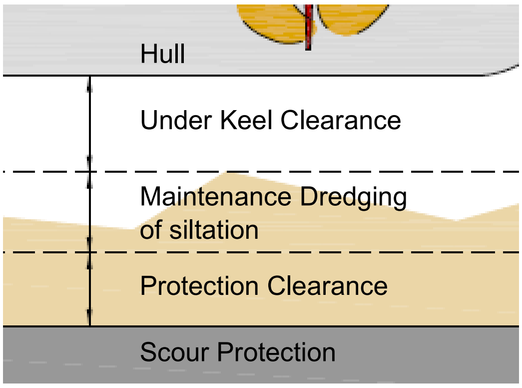

Figure 55. Scour Protection Clearance

The 1997 PIANC guidance mainly applied to rock protection and now needs to be updated for the present range of maintenance dredging actions and common types of scour protection. The selection of berth scour protection should consider:-

- Maintenance dredging actions
- Scour protection resilience
- Maintenance clearance to protection if needed.

12.2 Maintenance Dredging Actions

Common maintenance dredging actions are outlined as follows: -

12.2.1 Water Injection Dredging

Water injection dredging is increasingly being used as it uses relatively low velocity mass jetting to clear siltation. It appears only effective for silts and fine sands. Importantly it generally needs no protection clearance depth to scour protection and is relatively quick.

12.2.2 Air Lifting/ Dredging Pumping

These methods are relatively low action and generally require no clearance to scour protection. However they are relatively slow and usually impractical to most berths.

12.2.3 Ploughing

Ploughing is commonly used along with Trailing Suction Hopper (TSH) dredging. The plough is usually suspended from tugs with level control by winches and suspension cables. The plough is dragged and lowering some 100mm for each pass. The weight if ploughs typically varies from 0.5 t/m to 2 t/m.

Ploughs are often used to move siltation away from the quay face where a TSH dredger cannot approach. Also ploughs can move siltation from over the protection area to areas where the THS dredger operates.

Ploughing can be used for management of siltation high spots or mounding caused by vessel actions as an interim maintenance measure, HERMANS *et al* (2006).

Figure 56. Plough and Vessel

12.3 Trailing Suction Hopper Dredging

Trailing Suction Hopper (TSH) dredging is commonly used in ports in conjunction with ploughing. Normally, ploughing is used to berthing areas to work around moored vessels with dredgers operating outside the moored vessels. TSH dredgers can operate over berthing areas of scour protection when they are sufficiently clear. This should be made clear in maintenance plans so suitable allowance can be made.

The suction head is controlled for level and generally needs a clearance to the scour protection to avoid heavy abrasion and control of suction uplift.

12.4 Clam Shell / Excavator

The use of clam shell or excavator maintenance dredging to berths is less common as it poses risk of direct mechanical damage to protections unless there is a suitably large protection clearance depth.

12.5 Scour Protection Resilience

Resilience of scour protection to maintenance dredging is considered in terms of the following actions:-

- Abrasion/ drag
- Impact loading
- Suction uplift

The resilience of common scour protection types are considered as below: -

- Rock
- Insitu Concrete Mattress
- Precast Block Matts/ Asphalt Matts (Preformed Mattress)

12.6 Rock

Rock protection has very good resistance to impact loading and less resistance to drag and suction uplift. Ploughing can risk dislodging some rocks unless a suitable dredging clearance is allowed. For trailing hopper suction dredging, a suitable clearance is needed relative to the hopper suction power and rock size to avoid rocks being sucked up into the hopper.

12.7 Concrete Mattress

Insitu concrete mattress is effectively long plain concrete slabs with ball and socket interlock joints. Concrete strength C28/35 is usually recommended for durability for the design life. This protection has a good resilience to dragging abrasion and lower resilience to impact and suction uplift unless it is thickened. Ploughing can be used with a relatively low protection clearance. The mattress thickness relative to the plough weight is suggested below: -

Plough weight	0.9 t/m max	200mm Thickness
	2.6 t/m max	300mm Thickness

Larger and heavier ploughs are being developed to aid faster dredging.

For trailing suction hopper dredging, the clearance distance between the hopper and the concrete mattress needs to be controlled to limit the suction uplift force as shown in Figure 57. The minimum thickness for robustness of areas subject to maintenance dredging is 200mm HAWKSWOOD, GROOM & HAWKSWOOD (2018), PIANC 180 (2015).

Light weight clam shell dredging can be used directly onto the mattress where it is suitably thickened. Dredging by excavator or heavy clam shell should have the recommended 0.75m clearance where this is suitable.

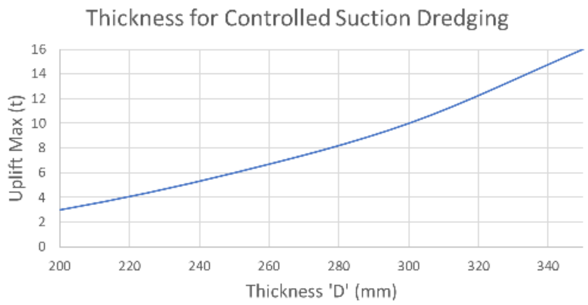

Figure 57. Suction Forces

12.7.1 Precast Block Matts/ Asphalt Matts

These mattresses are preformed and lowered into place underwater. Being comprised of panels of concrete blocks or asphalt with the likelihood of steps at joints, these systems have a low drag/ abrasion resilience. Ploughing with level control can be used with the recommended protection clearance 0.75m (0.45m minimum) where suitable.

For water injection dredging joints need to be effectively sealed. For maintenance dredging by TSH dredger, or clam shell/ excavator, the recommended protection clearance should be adopted where this is suitable.

13 CONCLUSIONS

13.1 Azipods

Design methods for azipod flow and scour protection design have been presented based upon the scale model testing. The testing has shown that azipods are similar to open propellers allowing design formulas and concepts for open propellers to be applied to azipods. In particular, azipod hubs with a bottom fin are similar to propellers with a central propeller as they split the flow and increase bed velocity. Azipod hubs without a bottom fin are similar to propellers without a rudder. Both types of hub are common to cruise vessels.

Arrangements of multiple azipods were tested that are common to cruise vessels including pairs of rotated azipods. A design method based upon a method for twin propellers has been proposed with limits suggested for azipod spacing. The proposed design methods can aid effective scour protection design for cruise berths particularly where flow velocity from azipods is typically higher than for conventional propeller vessels.

13.2 Falling Hinged Edges

A falling hinged edge arrangement that reacts to edge scour has been established from scale model testing. It is proposed that hinged edge detail is positioned within an edge protection trench to provide at least 50% of the design edge protection depth, with the hinged edge designed to fall the remainder, Figure 37. Following the tests, a 35˚ design rotation of the blocks is proposed for design of the deployed edge.

A design method for edge block thickness and stability against flow uplift by RAES *et al* (1996) is proposed. Guidance is given for the specification of the system, particular allowance of additional bottom geotextile at joints to allow differential movement.

The hinged edge can be useful with high velocities where rock is impractical such as large cruise berths. It is also useful where rock is expensive and where additional plant for rock placement is not desired.

13.3 Scour Protection Resilience For Maintenance Dredging

The review shows that updated guidance is needed to allow effective scour protection selection for current maintenance dredging methods. New dredging methods and scour protection types have emerged since the PIANC WG22 (1997) guidance. In particular, advice for maintenance dredging clearance is needed. Under keel clearance to scour protection in many berths is lower than minimum advice from PIANC WG22 (1997) leading to the prospect of increasing maintenance dredging damage to scour protection.

ACKNOWLEDGMENTS

This paper presents the views of the authors, not necessarily their employers, clients or organisations. The test rig was developed by P. Holloway and J. Groom with twin testing undertaken by J. Groom, T. Hart and D. Gomez. Every effort has been made to ensure that the statements made and the opinions expressed in this paper provide a safe and accurate guide; 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

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