Berth Scour Protection For Fast Ferry Jets

Martin Hawkswood Proserve Ltd, Kenilworth, UK
Gareth Evans Seawork Marine Services Ltd, Southampton, UK
George Hawkswood KV Consultores, Madrid, Spain

Summary

Vehicle carrying Fast Ferries have often caused significant erosion and damage to berths since their introduction in 1990. During berthing, the high speed propulsion jets are deflected under the vessel and cause direct scour of the bed with scour holes up to 9m deep. Many Berthing structures have been underscoured or destabilized and scour protection damaged. This action is usually much more significant than traditional propeller action and requires the design and provision of appropriate scour protection.

Figure 1: Reversing Vessel

Published advice only recently started to become available[1,2,3] and the paper will seek to outline a current understanding gained from scour case histories and corresponding computational modelling. Scour protection types appropriate for high velocity jetting action will also be outlined and a basis for their design will be presented. The paper may be of use to Port Authorities, Design Engineers, Manufactures and Operators.

Introduction

The scour action of Fast Ferries is not commonly understood. The behaviour of the vessels, jets and deflection buckets during berthing will be outlined. Mooring jetting action with a high scour potential is particularly generated by vehicle carrying Roll on, Roll off (Ro Ro) Fast Ferries which stern berth. Smaller passenger Fast Ferries mainly berth against the side of the vessel without this effect. Peak jet scour action normally occurs whilst the vessel temporarily pushes onto it's stern berthing structure as it is being securely moored (Fig 2). Bed scour profiles corresponding to this mooring jetting action will be presented in the case histories. Experienced gained for the design and arrangement of effective scour protection will be presented.

Case Histories
    Poole
    Dover
    Stranraer
    Belfast
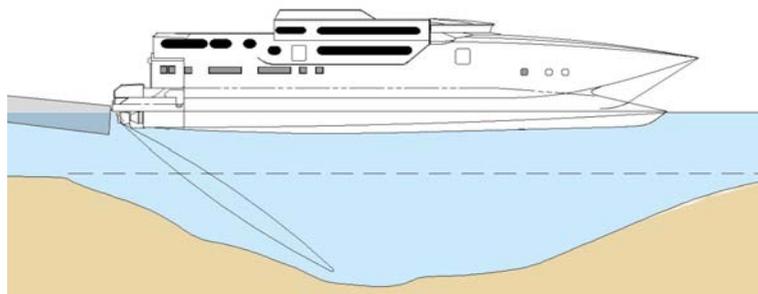   Portsmouth Berth 1
    St Helier
    Weymouth

Figure 2: Mooring Jetting and Scour

Areas requiring additional information/confirmation are identified and will hopefully promote input from other Engineers. Pianc WG 48 are currently preparing guidance which will include Fast Ferries.

Fast Ferry Vessels, Jets & Deflection Buckets

Larger vehicle carrying Fast Ferries were first used in 1990 in the UK. They are usually catamaran vessels with wave piercing hulls, built in aluminium and are typically some 47 m to 113 m long[4,6]. Vessels above some 60 m long usually have twin ducted propulsion jets in each hull similar to Figs 3 and 4. To berth, the vessels usually reverse onto floating roll on, roll off (Ro Ro) linkspan structures for stern mooring (Figs 1 & 2).

Figure 3: Fast Ferry Hull and Jets

These ducted propulsion jets usually have exit diameters up to 1.0 m and typically have mooring jet exit velocities U_o from 15 m/s to 23 m/s (Table 1). The ducted impellers are not reversed but deflection buckets divert the jet under the hull for reversal and mooring (Figs 2, 6 & 7). This is the case for all the Ro Ro Fast Ferry vessels considered in the case histories.
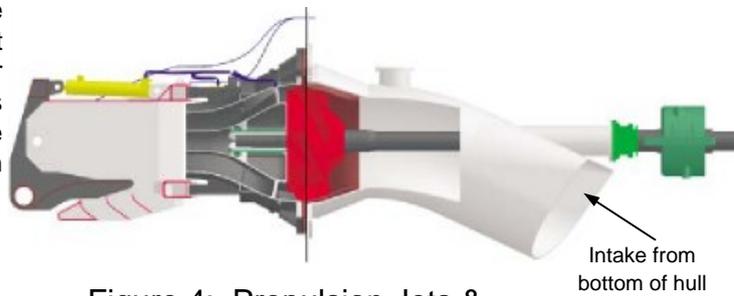

Intake from bottom of hull

Figure 4: Propulsion Jets & Deflection Buckets

The main manufacturers of Ro Ro Fast Ferries are Incat[4] and Austal[6]. Incat vessels are mostly equipped with Wärtsilä[5] jets & buckets (Figs 4-8) and Austal with Kamewa[7] jets & buckets.

The deflection buckets allow a variable proportion of the jet to be deflected under the vessel. The open bucket position (Fig 5) is used for forward motion. Partial jet deflection by the deflection plate (Fig 6) allows manoeuvring and slow reversing which can be seen in Fig 1. Plan rotation of the buckets is common up to some 30° as shown in Fig 8 which aids manoeuvring control of the vessel and can certainly be applied during mooring jetting for the Wärtsilä bucket system.
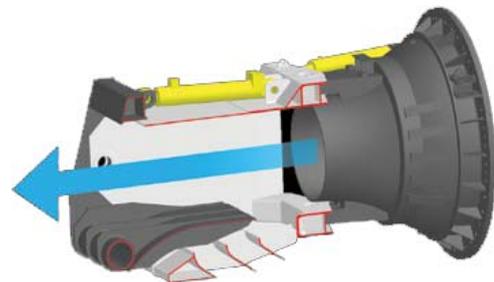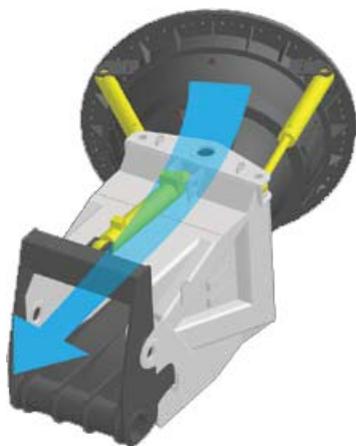

Figure 5: Forward Thrust

Figure 8: Steering
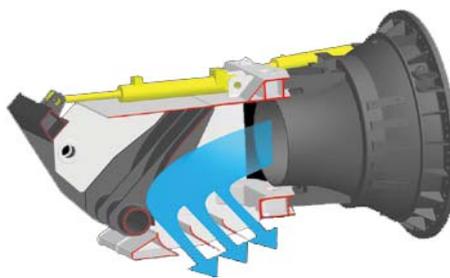
(Figs 4-8 courtesy Wärtsilä[5])

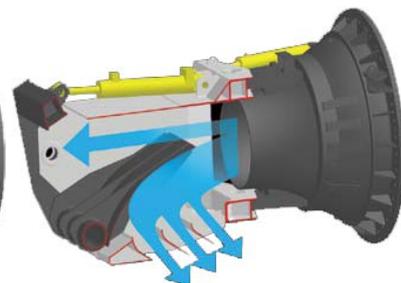Figure 7: Reverse Thrust/ Mooring Jetting

Figure 6: Zero Thrust/ Manoeuvring/ Reversing

Figs 4-8 show the bucket system by Wärtsilä. Buckets by Kamewa are of a similar concept but with a rotating bottom plate instead of the exit grills. It is important to determine bucket types as the Hamilton bucket type often used on small vessels splits the flow into two jets.

Mooring Jetting

Ro Ro Fast Ferries reverse slowly onto their linkspan moorings under a modest fairly constant power with control from deflection bucket operation as Fig 6.
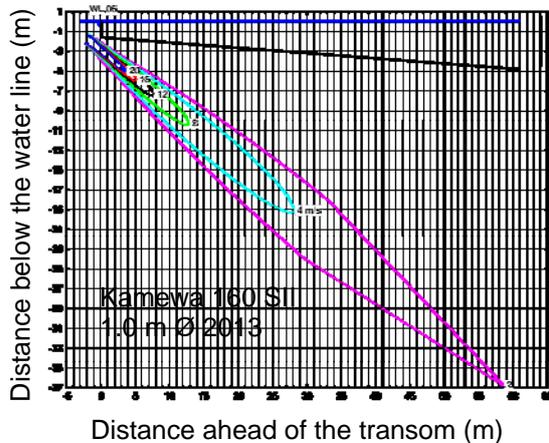

Figure 9: Velocities in the Submerged Jet

The case histories show that peak jet scour action typically occurs when the vessel makes contact with the linkspan berthing face as shown in Fig 2. Vessels usually 'push on' with significant power (Table 1) with the deflection buckets in full reversal mode as Fig 7, for some 30 to 45 seconds. This 'mooring jetting' is to temporarily maintain the vessels position whilst mechanical mooring linkages or similar are secured. The maximum reverse or mooring jetting exit velocities are best obtained from the manufacturers as the velocities are normally limited by impeller cavitational effects for particular jet types.

For the vessels used in the case histories (Table 1), Kamewa's advice for velocities in the submerged free jet are shown in Figs 9 and 10 (Belfast—Stranraer) and Wärtsilä's advice is shown in Fig 10. Computational Fluid Dynamics (CFD) modelling was undertaken by the Wolfson Unit initially in 2003[8] and further in 2013[13] to consider bucket effects, check and provide velocity fields and compute bed suctions and pressures. The Wärtsilä buckets were accurately measured and modelled showing a typical bucket back pressure of 60 kN/m² and a 20% forward flow escape to the open area between the circular jet and open square bucket. The large Kamewa buckets were only approximately modelled and showed a typical bucket pressure some 3 to 4 times higher and a very approximate forward escape of some 26%. (Fig 11)
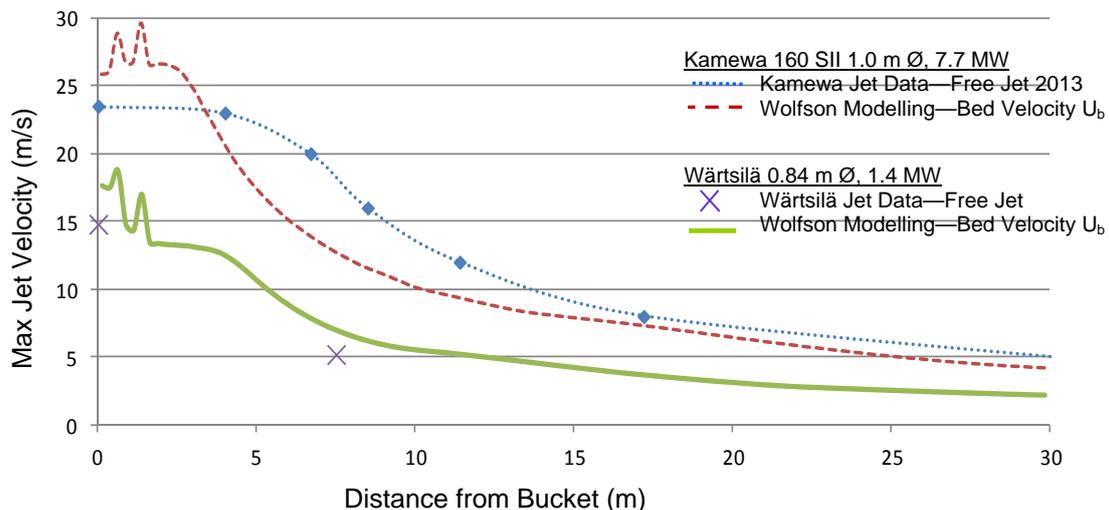

Figure 10: Max Jet Velocity vs. Jet Length

The modelling was based upon an approximation of velocity loss due to other bucket effects, comprising deflection plate gaps (2.5%) and estimated jet velocity suppression from the bucket reversal pressure of 7.5% for Wärtsilä and 12.5% for Kamewa. The presence of the bed shown in Fig 11 was found to reduce the bed velocity U_b typically by a reduction factor of 0.89 when compared to a free jet. The resulting CFD modelling of bed velocity U_b compared to jet length is shown in Fig 10. In comparison with the Kamewa profile, the bucket effect initially accelerates the peak exit flow, then lower velocities establish due to the reduced flow rate and bucket effects, before the twin jets merge together and approach the Kamewa profile. Compared to Wärtsilä's advice, the modelling shows bed velocity some 33% higher than the Wärtsilä reference data point, which may be unsafe. Further work and confirmation of bed velocities is however needed particularly addressing flow suppression from bucket pressure and also covering a wider range of jet types and sizes.

Figure 11 shows the modelled jet flow through the deflection bucket and impact onto the bed. The CFD modelling[8,13] also produced estimates of bed suction and pressure distributions which are useful for the design and consideration of bed protection. The modelling gave reasonably common local suction/ pressure coefficients for the two jet examples as shown in Fig 12 with slight variation due to jet type and size in the suction zone and due to water depth in the pressure zone. The local pressure coefficients C_{pb} relate to the following equation derived from Bernoulli's Law:

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

Where: C_{pb} = Local Pressure or Suction Coefficient
             U_b = Max Jet Impact Bed Velocity
             ρ = Relative Density of Water
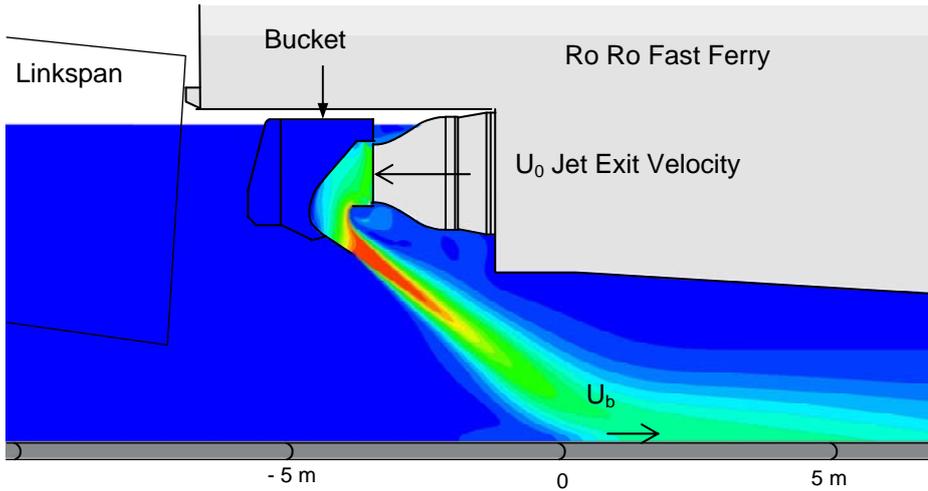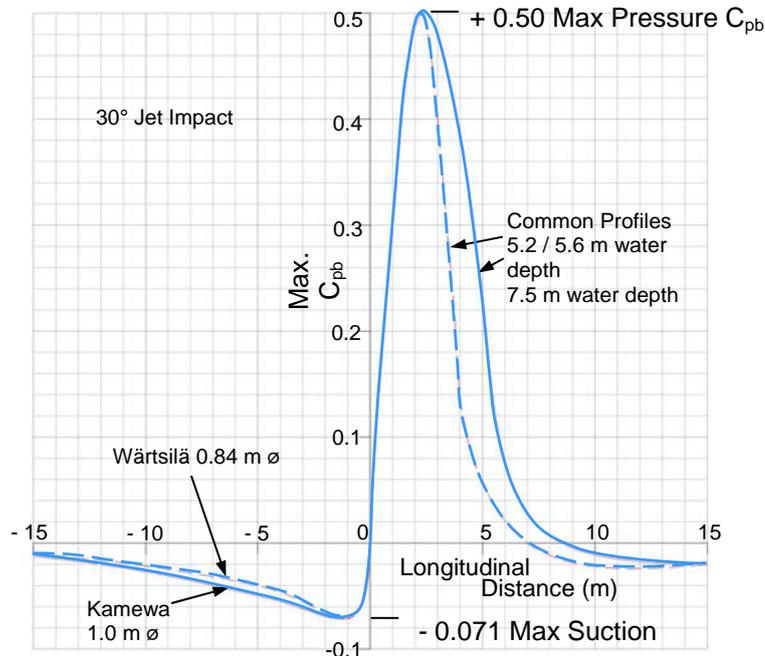

Figure 11: Modelled Mooring Jetting

Figure 12: Suction/ Pressure Coefficient Distribution

The modelled coefficients show that for jet impact at 30°, maximum pressure levels are some 7 times greater than suction levels. Examples of peak bed suction and pressures for Stranraer are −5.7 kN/m² and 40 kN/m² (U_b = 12.5 m/s), Portsmouth −1.7 kN/m² and 12.2 kN/m² (U_b = 7.3 m/s).

Bed Scour

The mooring jetting action corresponds well with the position of the worst case bed scour observed for the Ro Ro Fast Ferry case histories, which are shown in Figs 13, 18–24.The scour holes consistently align with the mooring jetting positions at a 30° submerged angle and at low water where the peak bed velocities occur (Fig 14). The submerged jetting angle of 30° would appear to be a better estimate than Wärtsilä's advice of 35°. Some scour hole positions such as Weymouth (Fig 23) and St Helier also indicate a plan rotation of some 15°-30° to the Wärtsilä jets, which may also be deployed to further secure the vessel during mooring. This effect is not observed for the Kamewa deflection buckets[7] used at Stranraer & Belfast, but could be used in other berthing and wind conditions.

Mooring jetting exposes the bed to much higher flow velocities than traditional propeller action. Also the direct jetting action is considered more erosive than current or propeller flow of similar velocity due to the angle of incidence of the jet with the bed. Soft deposits (silts, sands and soft clays) have been eroded to some 6 m depth at Belfast and 9 m at Stranraer below seabed level (Fig 13) by the high powered Stena vessel with Kamewa jets. At Weymouth, a 6 m scour depth in stiff clay has occurred in 16 years by the Incat vessel with Wärtsilä jets and buckets (Fig 23). Stiff clays and weak fragmented rock have been eroded to some 2 m depth at Portsmouth Berth 1 (Fig 22) and St Helier (Fig 24) respectively for short term periods also under Wärtsilä jets. Table 1 shows a review schedule of scour depth, exposure period, bed material or protection along with jet and vessel details for the case history sites. For soft deposits, scour equilibrium is normally achieved in a few years, but for stiffer clays the period is proving to be much longer as shown at Weymouth.
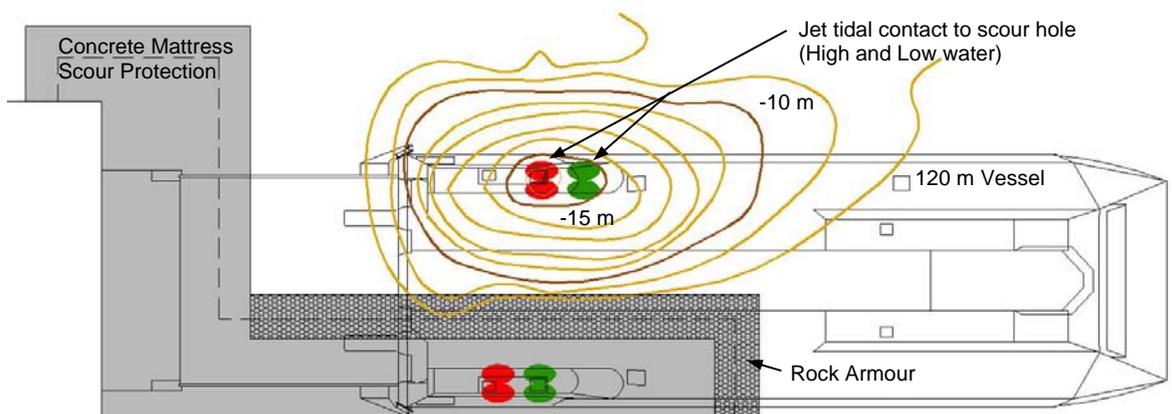

Figure 13: Jet Bed Contact & Scour Plan (Stranraer)

After the jet contacts the bed, the CFD modelling shows a radial flow distribution largely forward and sideways . The radial flow helps create the extent of the scour hole as is well shown in Figure 13 and has the ability to cause sideways wash out under structures (St Helier, Fig 24, Weymouth, Fig 23) and under scour protection aprons (Belfast Fig 21). For estimation of potential scour hole depth and extent, soil type parameters and depths at the berth are needed with associated interpretation of their erodability. Information on the scour threshold velocities of some bed types are given by Pianc WG22[9] (4.15) for turbulent propeller flow, as below:-

Firm clay bottom   *1.2 m/s*
Fine, loosely packed sandy bottom *0.5 m/s*

Theoretically, scour hole erosion will reach long term equilibrium where the jet velocity matches the threshold scour velocity of the bed material for inclined jet action. For the 16 year old scour hole at Weymouth, the modelled max jet velocity (U_b) at the bed of 3.2 m/s is indicated from the velocity profile (Fig 10). This suggests the scour hole may not yet have reached equilibrium and be completely mature when compared with an estimated scour threshold velocity of some 2 m/s for a very stiff clay. For soft deposits at Stranraer and Belfast, the maximum jet bed velocities (U_b) of 4.7 m/s and 5.3 m/s respectively from the modelled velocity profile (Fig 10) do not compare well with an estimated scour threshold velocity of some 0.5 to 1.2 m/s for the relative strata. This large difference may be due to jet velocities being overestimated or seldom used, short scour durations, rock or boulders armouring the bottom of scour holes (Stranraer and Weymouth), or variation in ground conditions (Belfast), however further work and understanding is needed.

Sand bed types without any cohesion allow scour holes to develop rapidly and can be expected to create much larger scour holes. At Poole a localised unprotected area of sand bed eroded some 5 m in depth in a single vessel visit. Further scour examples in sand would be welcome. Estimates of potential scour hole depths and extents for the inclined jet action, are currently best based upon scour hole experience for similar jets and bed material (where information is available), coupled with estimated velocities and scour resilience.

The case histories show little evidence of bed scour to the berth reversal area (Fig 1). Mounding in front of large mooring jetting scour holes (Fig 23) has often had to be dredged away showing that reverse manoeuvring jetting has a much lower effect.

Berth Scour Aprons

Unless the bed is competent rock, some form of bed protection will usually be the only practical course of action for scour control under these Ro Ro Fast Ferries. To consider the apron size, the mooring jetting contact zones on the bed can be plotted for the tidal range as shown on Fig 14. Plan bucket rotation, which accommodates for a range of wind conditions, should also be included where applicable (Fig 23). The case histories show the mooring jetting action will usually require scour protection to at least the inner hull jetting zones unless the bed is competent rock or the berth is unusually deep.

In soft deposits, such as silts, sands and soft clays, the area under the outer hull jets will usually require protection to safely avoid short term edge underscour into the zone under the inner hull as suggested from Stranraer, Belfast and Dover.

For stiff clays, Weymouth (Fig 23), suggests the outer hull zone should be protected, unless the protection is short term and is supported by regular edge inspection and maintenance. (Portsmouth)
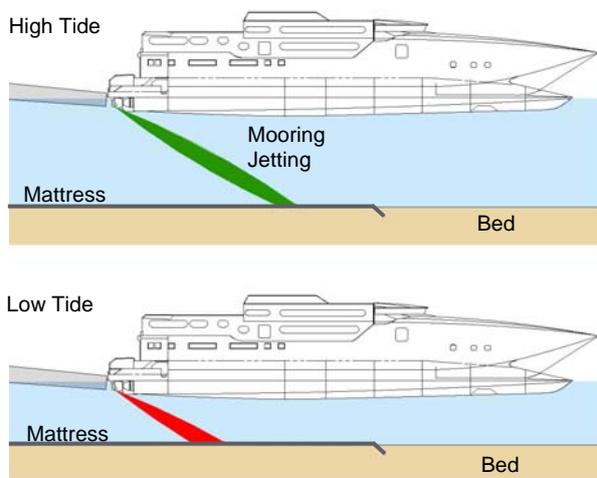

Figure 14: Mooring Jetting

The protection apron also needs to cater for the significant scour potential from unberthing action. Typically, the jets can strike the linkspan face and deflect into a radial flow. The apron should extend well beyond the linkspan face to protect against this down wash. Where unberthing jetting impacts onto quay wall structures (which deflect a proportion of the flow down onto the bed, particularly within piling recess), protection should be provided against the quay wall.

Scour apron levels are important for Ro Ro Fast Ferry berths. The vessels are more easily manoeuvred with greater draught clearance.

Also low clearance is prone to cause expensive impellor damage from ingestion of loose bed material during berthing, particularly under mooring jetting. For the HSC Incat 86 m vessels, the manufacturer advises a minimum 3.5 m clearance, whereas operators have in the past accepted a lower minimum working clearance of some 2 to 2.5 m.

Rock Protection

Rock protection is not commonly used to protect the mooring jetting area for Ro Ro Fast Ferries in the UK. Initial experience at Poole[1] showed 4 t armour stones with a D_{50} of 1.4 m were readily displaced by mooring jetting with bed velocities estimated by the CFD modelling at some 5.8 to 5.5 m/s depending upon the tidal depth (6.2 to 7.2 m).

At Dover, the 60 kg to 300 kg granite rock with a D_{50} of 0.45 m was laid as a repair over the scoured bed profile from previous mooring jetting (Fig 19). It subsequently performed without any apparent disturbance but as berthing power was restricted, the performance bed velocities are unknown.

No authoritative guidance is presently known for rock design against Fast Ferry jet action. It is expected that rock sizes for mooring jetting will need to be comparatively larger than for similar propeller velocities[1,9]. Design guidance or further performance experience would be welcome, however the performance at Poole indicates that larger stable rock sizes are likely to be impractical for the case history range of Fast Ferries and usual bed levels. Where flows are more modest, such as deeper berths at Dover, or for smaller vessels and less exposed zones away from mooring jetting (Belfast, Stranraer), rock protection becomes more viable.

Concrete Mattress Protection

Concrete mattress has been the main type of scour protection used against Fast Ferry jets in the UK and is proving to be effective as shown by the case histories and at other locations. The performance summary Table 1 provides a review of the short term exposure and performance with bed velocities (U_b) up to 12.5 m/s at Stranraer. Concrete mattress aprons provide a continuous protection layer with interlocking joints which importantly does not allow jet entry and high under pressures, creating an effective bed protection.

Mattress aprons are formed by divers rolling out mattress fabric underwater which is zipped together before being pump filled with highly fluid small aggregate concrete, which forms good quality concrete slabs underwater[10,11,14].
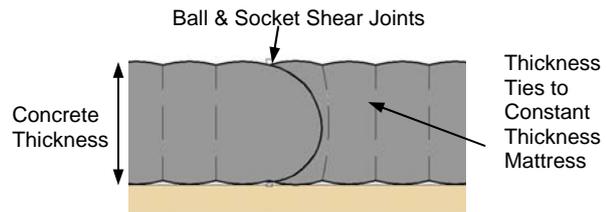

Figure 15: Concrete Mattress Detail

For thickness design, the failure mode for central sections of concrete mattress is generally due to suction uplift[10,12,13,16] as mattress slabs cannot generally slide or roll. Thickness design has been based upon CFD modelling of suction uplift[8,13] with yield line panel analysis[12] used to account for the distribution capability of concrete slabs. The method uses average suction values over the panel size with concrete panel strength conservatively estimated from masonry codes and confirmed with flexural tests. Mattress thickness from the design method is shown in Fig 16 relative to bed velocities and suctions based upon the 2013 Wolfson modelling[13]. The design method is now supported by the short term performance of the case histories. The key reference sites being 300 mm thickness used at Stranraer (22.5 m/s jet exit velocity & 1.0 m Ø, 5.6 m min water depth, Stena vessel, Kamewa buckets) and 200 mm thickness at Portsmouth Berth 1, (14.8 m/s jet exit velocity & 0.84 m Ø, 5.2 m min water depth, Incat vessel, Wärtsilä buckets). Where a longer design life is required in comparison to the case history performance, a suitable factor for increased exposure[12] could be applied. Due allowance should also be made for possible different vessel behaviour in different ports. In very soft soils the bearing capacity or mattress thickness should be checked for jet pressure.effects[8,13] as per the Belfast case history.
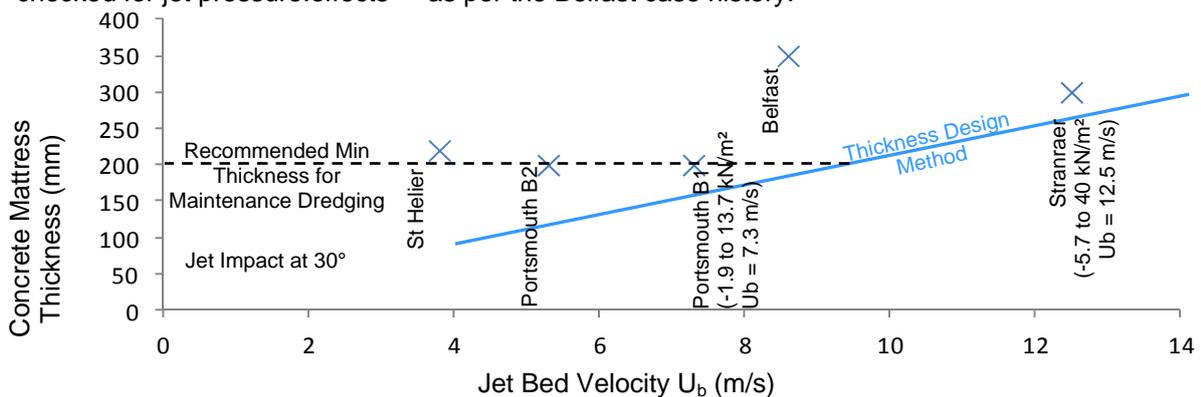

Figure 16: Mattress Thickness vs. Jet Bed Velocity U_b

A minimum mattress thickness of 200 mm[12] is recommended for robustness against appropriately controlled dredging. Concrete mattress thickness is modest compared to traditional rock armour, this can allow existing berths to be retrofitted where draughts are limited (Belfast, Alderney) and create significant savings in the design of quay wall structures from:-
- Reduced pile span or structure height
- Reduced pile or structure embedment
- Reduced dredging volumes

Edge details should be located away from the direct action of the mooring jets to protect against uplift from jetting pressures getting underneath any mattress slabs. Edge protection depths should be designed to safely exceed the scour potential in that area. For stiff clays, an edge protection trench with an infill concrete bolster is a good protective detail. (Fig 22) For soft deposits, edge trench infill with 3 layers of suitably sized rock usually provides a good falling apron edge detail[15].

Most berths are dredged into natural ground strata where bed soils are not generally prone to settlement. In filled ground, the mattress panel size can be reduced to increase flexibility[12, 14]. Porosity weep holes[12] are usually provided for permeable soils to cater for any residual water flow under quay structures generated from tidal movement.

Precast Blocks

A system of precast blocks was developed for Poole[1] and installed after the failure of the rock armour protection. The concrete blocks were 1.8 x 0.6 x 0.6 m deep, some 1.5 t each, and laid in a single layer upon filter geotextile onto an infilled sand layer. Crucially sets of 5 blocks were linked together and tied to neighbouring blocks which produced a significant gain in stability. Side details were formed in precast finger blocks

Figure 17: Precast Blocks

allowing edges to rotate. The system allows for easy removal, but is diver intensive to install.

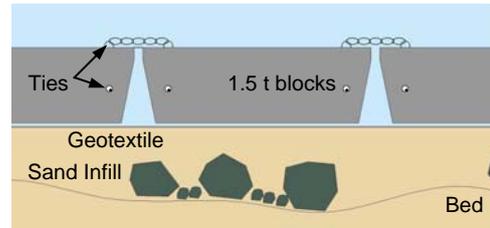## Tremie concrete

Tremie concrete could create good protection against jet action. Practically, tremie slabs often need to be at least 0.5 m thick to cope with bed and tremie surface laying tolerances to level areas, it cannot be used to sloping areas and also there are also some construction and environmental difficulties to overcome:-

- Panel joints
- Toe trench slopes for edge details
- Weep holes

- Quality control
- Unconfined concrete into marine habitats
- Flexibility

Grouted rock

A rock layer can be grouted typically with concrete or asphalt for modest flows. This system has been used for propeller berth protection. For reliable protection against inclined Fast Ferry jets, complete plan grouting of voids must be achieved to prevent wash out failure and this may be difficult to achieve or inspect, along with some of the above points.

Conclusion

An outline of the berthing and unberthing operation is presented for Ro Ro Fast Ferries and their high speed jets with deflection buckets used for reversal. The case histories show that "mooring jetting" is their dominant scour action. This action is much more extreme than for conventional vessels with scour holes forming up to 9 m depth in the bed and many berths suffering damage.

More recent CFD modelling of "mooring jetting" has demonstrated that the deflection buckets and presence of the bed have a slowing effect on the bed velocity (U_b) compared to that of a free jet. This has produced a closer correlation between higher modelled bed velocities and expected threshold scour velocities for the lower power Wärtsilä jets. Modelled estimates of velocity and suction/ pressures on the bed are presented for consideration and design of protection types. Further supporting work is needed however, particularly addressing flow suppression from bucket pressure and coverage of a wider range of jet types. Lessons learnt from the case histories are presented, including the extent of scour aprons and location/ detailing of edges to resist underscour. The modelling shows that the bed pressures created are much greater than bed suction and therefore protection types which reliably prevent jet entry give better performance.

The case history experience shows concrete mattress is well suited to resist the principle mooring jetting action and the design method used is presented. Heavy close fitting concrete blocks which are tied together can also be used. Other monolithic protection types such as tremi concrete or concrete grouted rock construction could be considered where their limitations can be overcome. Rock protection is not generally practical within the mooring jetting zones, due to the poor stability of individual rocks under inclined and higher jet velocities. An authoritive design guide is also needed.

Case Histories

A summary table of vessels, jetting, scour and scour protection performance is shown below.

Table 1: Case Histories Performance Review Summary

Location	Vessel & Manufacturer	Jet & Bucket Details	Max Jet Velocity into Bucket for Reversal U_o (m/s)	Scour Protection	Low Water depth [Scour Depth] (m)	Velocity at Protection (m/s) [Bed scour Velocity at lowest scour level] U_b (m/s)	Protection Exposure Period [Bed Exposure period]	Notes
Poole	Condor Express 86 m Ferry Incat	Wärtsilä (Lips) Jets 4 N° x 1.4 m Ø impeller (0.84 m Ø exit) 6.9 MW Wärtsilä Buckets	14.8 m/s (manu.) 0.84 m Ø (340 rpm, 1.4 MW)	**Inner & Outer Hulls** 1997-2001 4 t Rock D_{50} 1.4 m 2000 – present Linked Concrete Blocks 0.6 m deep	6.2 m / 6.2 m	5.8 m/s 4 t rock / 5.8 m/s	4 yrs / 10 yrs	Rock failure under mooring jetting and of quay wall edges. Replaced by larger concrete blocks linked together which require some tie and edge monitoring. Sand strata.
Dover	81 m Incat (74 m initially) Incat	Wärtsilä (Lips) Jets 6.9 MW Wärtsilä buckets	14.8 m/s Estimated	**Inner & Outer Hulls** 1993-2003 Unprotected 2003-2005 Rock D_{50} 0.45 m	5.3 m rock [6.7 m scour] / 10.2 m	[3.0 m/s at 12 m] / < 3.7 m/s	10 yrs / [2 yrs]	6.7 m max scour in river deposits before rock protection D_{50} = 0.45 m installed on scour profile which was stable with engine power reduction.
Stranraer	Voyager HSS 1500 126 m Stena (Finyards)	Kamewa Jets 4 N° x 1 m Ø exit 17 MW Kamewa Buckets	23.5 m/s (manu.) 1.0 m Ø (336 rpm, 7.7 MW approx)	**Inner Hull** 300 mm concrete mattress / **Outer Hull** Unprotected Bed	5.6 m to mattress / [9 m scour]	12.5 m/s / [4.7 m/s at -15m]	15 yrs (2011) / [9 yrs] (2005)	HSS started 1996, removed 2011. Survey 2008 – outer hull erosion 9 m into soft deposits, mattress in good condition measured at 300 mm thickness.
Belfast VT4	Voyager HSS 1500 126 m Stena (Finyards)	Kamewa Jets 4 No x 1 m Ø exit 17 MW Kamewa Buckets	23.5 m/s (manu.) 1.0 m Ø (336 rpm, 7.7 MW approx)	**Inner Hull** 350 mm concrete mattress / **Outer Hull** Unprotected Bed	-8.4 (7.4 m design) mattress / [5 m scour]	8.6 m/s / [5.3 m/s at -13.7 m]	2 ½ yrs / [2 ½ yrs] (2011)	Dive survey shows mattress has good resistance to mooring jetting. Outer Hull erosion 5 m into soft deposits. HSS removed 2011.
Portsmouth Berth1	Portsmouth Express 91 m Ferry Incat	Wärtsilä (Lips) Jets 4 N° x 1.4 m Ø impeller (0.84 m Ø exit) 7.2 MW Wärtsilä Buckets	14.8 m/s (manu.) 0.84 m Ø (340 rpm, 1.4 MW)	**Inner Hull** 200 mm concrete mattress / **Outer Hull** Unprotected Bed	5.2 m to mattress / [2 m scour] −7 m to −9.2 m	7.3 m/s / [4.2 m/s at −9.2 m]	7 yrs / [5 yrs] (2010)	Yearly Inspection and occasional maintenance by concrete tremie to local edge scour. Outer hull scour some 2 m in stiff London clays. (survey 2010)
St Helier	Condor Express 86 m Ferry Incat	Wärtsilä (Lips) Jets 4 N° x 1.4 m Ø impeller (0.84 m Ø exit) 6.9 MW Wärtsilä Buckets	14.8 m/s (manu.) 0.84 m Ø (340 rpm, 1.4 MW)	**Inner Hull** 220 mm concrete mattress / **Outer Hull** Unprotected	10.1 m mattress / 10.1 m with [2 m scour]	3.8 m/s / 3.8 m/s	2 yrs	Protection laid after erosion of fragmented rock bed. Had caused under-scour of pier bases.
Weymouth	Condor Vitesse Condor Rapide 86 m Ferry Incat	Wärtsilä (Lips) Jets 4 N° x 1.4 m Ø impeller (0.84 m Ø exit) 6.9 MW Wärtsilä Buckets	14.8 m/s (manu.) 0.84 m Ø (340 rpm, 1.4 MW)	**Inner Hull** Existing 100mm concrete mattress / **Outer Hull** Unprotected stiff London Clay	5.3 m mattress / [6 m scour]	8.7 m/s / [3.2 m/s at -11.3 m]	16 yrs / [16 yrs]	Existing 100 mm concrete mattress under inner hull was formerly propeller protection. Quay wall and old scour protection found underscoured by survey 2012. 6 m erosion in stiff clay under outer hull. Concrete mattress protection installed in 2013 at 5.7m+.

Poole

In 1997 conventional rock armouring of the seabed commenced with 2 layers of 4 t rocks (D_{50} = 1.4 m) overlaying a geotextile membrane. Daily monitoring showed continual rock displacement in the mooring jetting zone and associated forward mounding, both requiring intensive maintenance. In 2001/2 the failing area was replaced with precast concrete blocks (0.6 m x 1.8 m x 0.6 m deep) as shown in Fig 17.These blocks were linked together by steel cable run through internal ducts in the blocks to form sets of 5 units. These 7.5 t block sets were themselves interconnected with chains. The system has been monitored over the last 12 years and has generally remained stable. The precast block solution was adopted to allow easy removal for future changes to the berth structures.

Laboratory modelling[1] of block systems revealed the following:-

- The flow from the jets is highly turbulent and is subject to high frequency pressure variations.
- Block uplift occurs immediately outside the footprint of the jet impact.
- The use of individual block (or rock) units in the impact zone is unlikely to be successful, and inter-block connections are essential.
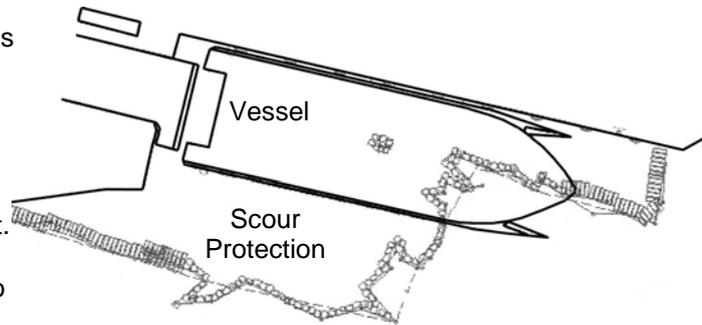

Figure 18: Poole Plan

The sand bed was particularly prone to erosion from unberthing downwash against the sheet piles. A robust tied in tremie concrete seal was successfully used.

Dover

Incat 74 m vessel use started in 1993 with Reno mattress protection under the link span area. By 2003 the scour profile into river bed deposits had formed due to mooring jetting and possible deflected downflow from unberthing. Two layers of rock protection were laid onto the scour profile, with the top armour layer consisting of 0.8 m of 60 to 300 kg granite, D_{50} = 0.45 m. The rock protection performed adequately under later Incat 84 m vessels, but with berthing power restriction until the service stopped in 2005.
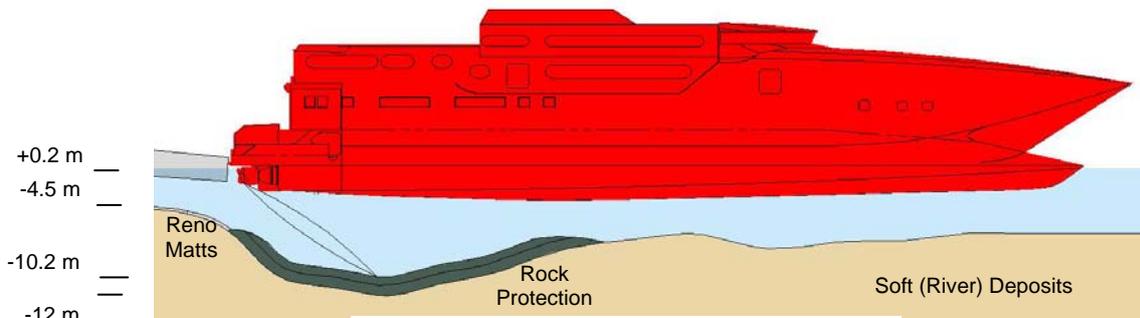

Figure 19: Dover

Stranraer

A designed mattress thickness of 350 mm was installed in 1996 to protect the scour zones under the inner hull for the new vessel. A detailed bed and mattress diver survey in 2005 showed the outer hull scour hole to be 9 m deep below design dredge depth and just approaching the mattress toe with no sign of the edge rock armour. The dive survey measured the average mattress thickness to be 300 mm. The large HSS vessels use stopped in late 2011.
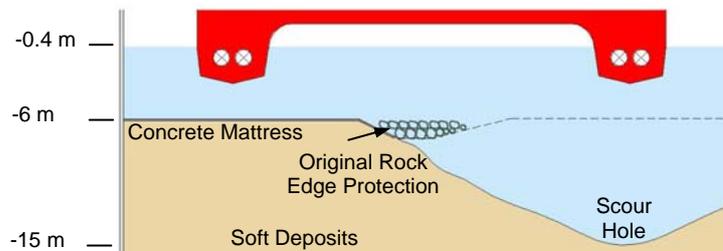

Figure 20: Stranraer (9 years)

Belfast VT4

A mattress thickness of 350 mm was installed to protect the passive support areas to the quay wall. Unprotected areas under the mooring jetting of the outer hull were eroded some 5 m in 18 months into initial soft deposits. A layer of very soft clay (sleech) at design formation level was removed

Figure 21: Belfast (1 1/2 years)

to ensure necessary support to the concrete mattress apron to withstand the jetting contact pressures. Mattress panels were limited to 10 m long as a precaution against any slight settlement.
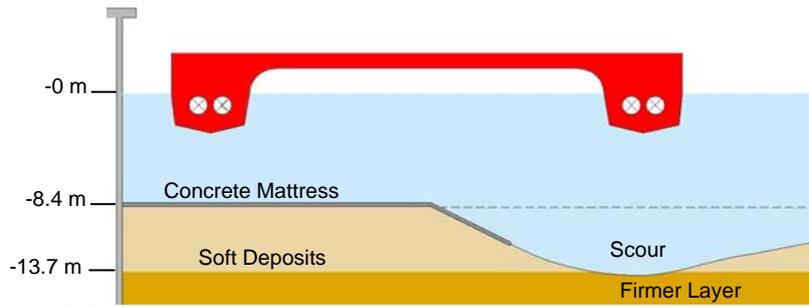
Portsmouth Berth 1

Fig 22 shows the concrete mattress protection arrangement to the inner hull zones. A 1 m deep toe trench and concrete bolster edge detail was installed into stiff London clay. Erosion under the outer hull by mooring jetting is of the order of 2 m and after 7 years is still ongoing. Occasional edge protection maintenance is undertaken in stiff fibrous tremie concrete. The mattress was laid onto an existing graded rock layer without any provision for settlement or mattress flexibility.

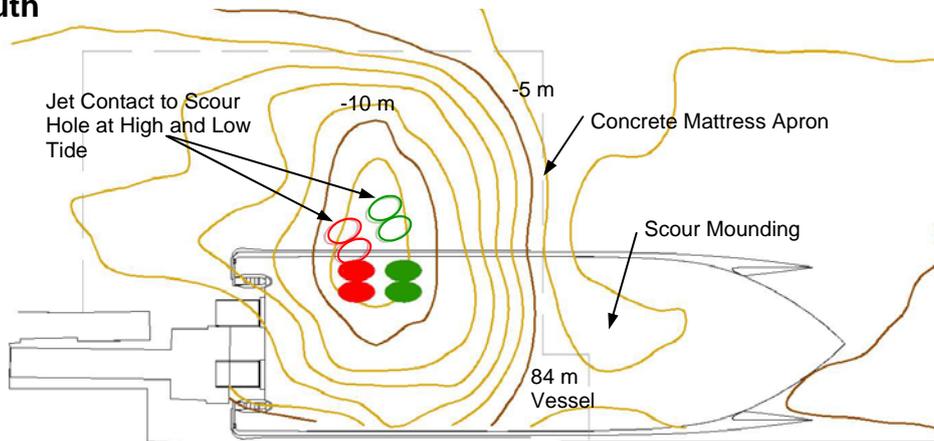Figure 22: Portsmouth Berth 1 (5 Years)

Weymouth

Figure 23: Weymouth (16 years)

A scour hole some 6 m deep formed in the stiff clay bed under the outer hull jetting area over some 16 years. The inner hull zones were protected initially by a previous propeller scour apron of 100 mm concrete mattress which suffered classical edge underscour and subsequent progressive failure. Subsequently this allowed or exacerbated underscour of the quay wall structure which had to be replaced. A new 220 mm thick concrete mattress protection apron has been designed and installed to protect both inner and outer hull jet contact zones. A 15 m width of the scour hole was infilled with a reasonably self compacting crushed rock before mattress installation.

St Helier, Jersey

The berth bed strata is a fragmented rock. The fast ferry operated for a number of years without bed protection. Scour up to some 2 m occurred from the mooring jetting and caused underscour to large pad foundations to the side walkway jetty. The pad foundations were underpinned with concrete using a large grout bag system. Concrete mattress protection was installed locally to the jet contact area of the inner hull jets. Due to the difficulty to excavate edge trenches in the fragmented rock and the relatively modest edge scour potential, a sacrificial tremie edge slab was adopted with regular monitoring and reactive maintenance.
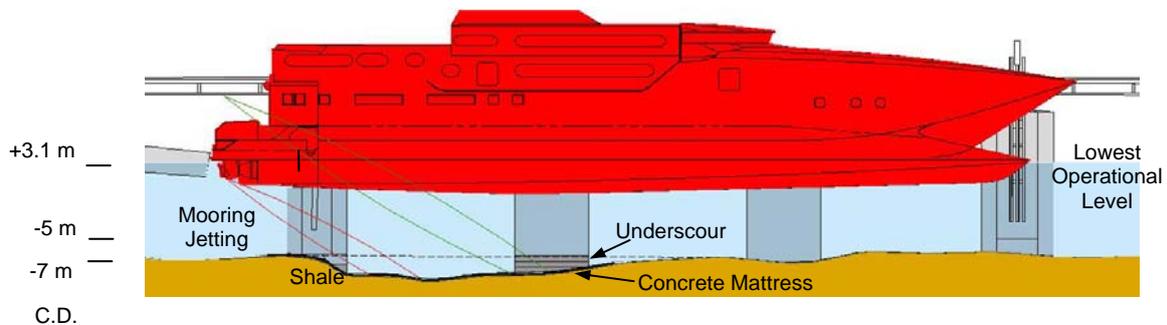

Figure 24: St Helier

Acknowledgements

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Chris Patterson, Jacobs UK: Does the bed material ever require to be improved prior to laying a scour mattress on soft seabed deposits?

Authors reply: Thank you for your question which raises issues regarding the flexibility of concrete mattress. Ground improvement is seldom used for concrete mattress scour protection. Firstly, ground improvement is usually relatively expensive in the marine environment and secondly, concrete mattress flexibility is usually increased to cope with any significant settlement associated with soft seabed deposits. Generally, mattress panel size is reduced to increase flexibility relative to estimated settlement as shown in Table 2[17].

Table 2. Settlement and Panel Size

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

(Relative settlement is based across the apron width)

This method has been adopted for many cases where settlement is expected such as hydraulic fills [14], soft silts and stone fills etc. This technique of reducing panel size to increase flexibility for settlement is commonly used for concrete slab design used on land. The concrete mattress system can be constructed on very soft sea bed materials. Any significant layers of sludge or fluid material should however be largely removed (Belfast VT4).

David Tresidder, Arup UK: Please can the speaker comment on the critical importance of concrete mattress edge details and in particular the vertical wall to mattress connection with regards to critical failure modes.

Authors reply: Your question is appreciated as it raises the important issues of edge protection to concrete mattress aprons.

Seals to quay walls are important as they are subject to deflected flow from jets which can cause significant underscour unless seals are effective. Reliable seal methods often used are shown in Fig 25 [17].
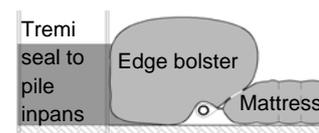

Figure 25: Wall Seal

Reliable methods of edge protection are also outlined in reference [17] as shown in Figs 26 and 27. Where appropriate, the use of edge toe trenches with rip rap falling edge aprons as Fig 26 are proving to be effective details. The toe embedment provides an initial element of 'passive' edge protection before the 'active' element of the rock falling apron is deployed. With usual periodic inspection, the edge detail can be further maintained should any areas be subject to any unusual vessel behaviour or soft spots. Historically, the underscour of concrete mattress apron edges has been the primary cause of failure commonly due to a lack of understanding of its importance. Underscouring edges are subject to uplift cracking failure from relatively high pressures created by flow into underscour voids.

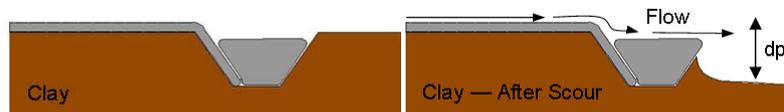Figure 26: Edge Detail with Falling RipRap

Figure 27: Bolster Edge Protection to Clays

Once appropriate edge details have been designed, it is important that they are reliably constructed using a quality control system appropriate for the marine environment under the supervision of a professional engineer experienced with the construction system. The development of 'as built' record drawings as construction proceeds is necessary to reference for monitoring inspections. These controls are generally good practice to all marine scour protection systems.

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