

Concrete mattress used for berth scour protection

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ABSTRACT

Geosynthetic concrete mattress systems are regularly used underwater to provide reliable insitu concrete protection. As vessel sizes and propulsion types advance, bed scour velocities in berths are increasing. Concrete mattress provides high scour resistance due to its interlocked slab nature, with experience of protection against jet flows presently up to 12.5 m/s. Design methods will be presented for the following actions in berths :-

- Propeller
- Jet (by reference)
- Side Thruster
- Current
- Wave

Concrete mattress has been used for berth scour protection for some 50 years providing a good understanding of performance. The technology and relative merits of the system will be outlined along with case history examples of usage in Africa as listed below :-

- Cotonou, Benin
- Abidjan, Ivory Coast
- Tanzania

This paper may be of interest to Port Authorities, Design Engineers, Contractors and Operators.

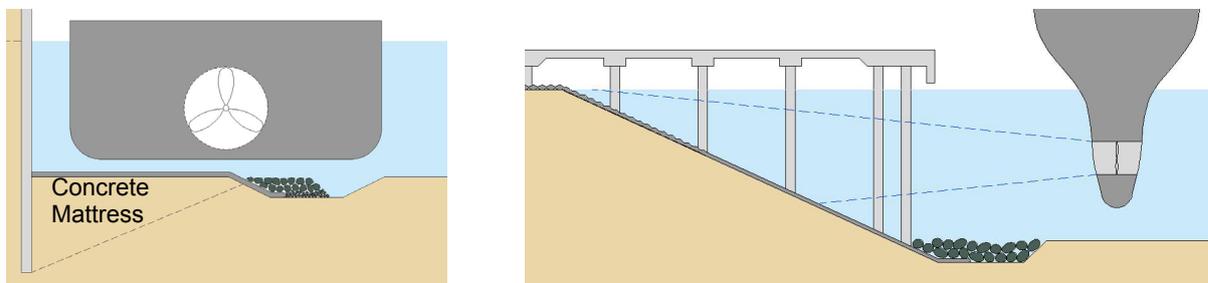


Figure 1. Berth Protection Examples

1. INTRODUCTION TO CONCRETE MATTRESS SYSTEMS

Concrete mattress aprons are formed by divers rolling out geosynthetic mattress fabric underwater which is zipped together and pump filled with highly fluid small aggregate concrete. The fluid concrete is protected from wash from currents and low wave action out by the mattress fabric. The system typically comprises two layers of interconnected woven fabric as shown in figures 2 and 3 which allows use on level beds or slopes.

Joints between mattress panels are formed using zipped or sewn 'ball and socket' shear joints (figure 2). This produces an apron of interlocked concrete slabs underwater, which gives a high resilience against currents, propeller and jet flows (Hawkswood, et al., 2013). Mattresses are typically pump filled with a sand: cement micro concrete mix of 35 N/mm² strength which has proven durable over 50 years to date.

1.1. Constant Thickness Mattress CT

This mattress is normally used to resist vessel actions on harbour beds and permanently submerged slopes. It is also often known as uniform mattress. Mattress aprons readily cope with high propeller and jet velocities with relatively low thickness when compared with rock protection. Thicknesses of 100mm to 600mm are generally available although 150-300mm thicknesses are most commonly used. A 200mm minimum thickness is recommended to berth beds where controlled maintenance dredging by large dredging vessels is likely. Weep holes are incorporated to cope with any residual ground water movement (see 4.3).

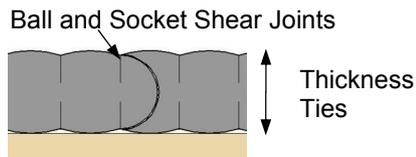


Figure 2. Constant Thickness Mattress

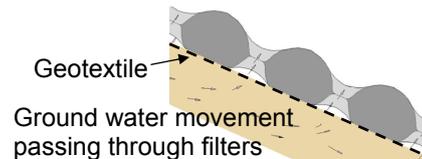


Figure 3. Filter Point Mattress

1.2. Filter Point Mattress FP

The porosity of the woven in filters allows use on slopes in tidal ranges and for wave heights (H_s) typically below 1 to 1.5m. Filter Point (FP) mattresses commonly have an overall thickness of 150mm to 250mm, with an average thickness of 100mm and 166mm respectively. A geotextile fabric is required under the mattress to protect against filter loss. These mattresses are not generally used in lower zones of direct jetting action where filter point and geotextile may be lost by abrasion from suspended particles.

1.3. Settlement and Flexibility

Most berths are dredged into natural ground strata where bed soils will have been previously over consolidated and are therefore not generally prone to settlement. In these cases, no precautions for mattress flexibility have been required, with mattress panels extending the width of the apron. In filled ground, or other cases where settlement is an issue, the mattress panel size can be reduced to increase flexibility see 3.2.

1.4. Edge Details

The concrete mattress system requires robust edge details to prevent under-scour failure. This is best achieved with in-filled edge toe trench details. Falling riprap edge details are generally preferred (figure 4) although in stiff clays a concrete trench infill bolster can also be considered (figure 5). Falling apron edge details consisting of 3 layers of stone are acknowledged solutions that can be designed to overcome the estimated local edge scour (d_p) and can be readily monitored and maintained to overcome any unexpected vessel action or bed strata, etc.



Figure 4. Edge Detail with Falling RipRap



Figure 5. Bolster Edge Protection to Clays

2. CONCRETE MATTRESS DESIGN

To protect quay structures or prevent disruption to berthing operations, berth scour protection can be required to resist the actions shown in Table 1 and prevent the damage shown in Table 2.

Table 1.

Actions
Propeller
Ro Ro Fast Ferry Jets
Side Thruster
Current Flows
Waves

Table 2.

Damage
An increase to quay structures span heights
Loss of quay wall embedment or underscour
Loss of passive support
Slope erosion and failure
Scour mounding

Concrete mattress can be efficiently designed and constructed to prevent these actions. Unlike rock armour, concrete mattress does not fail in rolling or sliding particle displacement, but generally in panel failure due to suction and uplift pressure. Areas of bed suction or uplift are outlined in Table 3. Design methods are available to determine these suction and uplift effects, allowing mattress thickness to be designed for its deadweight and panel action resistance.

Table 3.

Areas of Hydrodynamic Bed Suction or Uplift
Under propellers (figure 7)
Around jet impact
Around bridge piers/ structures from accelerated flow
Bed undulations to current flow
Uplift from wave run down

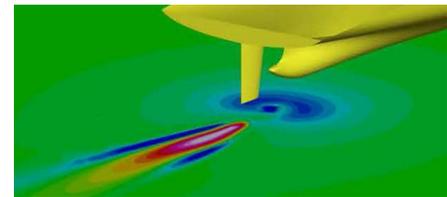


Figure 6. Propeller Bed Loadings by Marin

2.1. Propeller Action

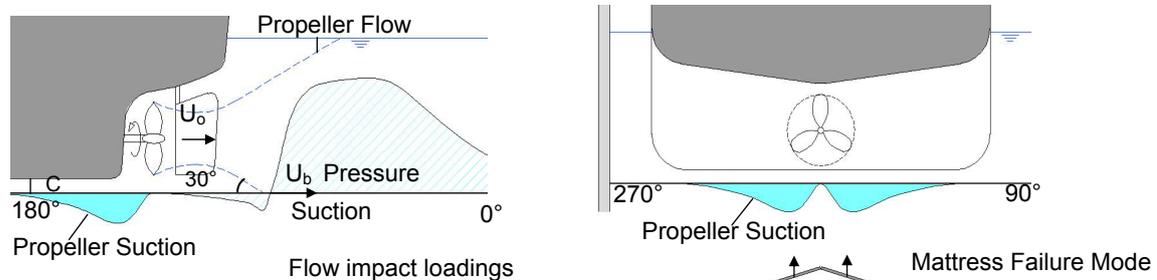


Figure 7. Propeller Flow, Bed Loadings and Mattress Failure Mode

2.1.1. Suction Under Propeller

The propeller suction shown in figure 7 can be determined by Wellicome (1981), supported by modelling commissioned at Marin 2013, which now also outlines the flow impact loadings shown in figures 6 and 7.

Propeller diameter D_P Engine power at berth P_B
Max Propeller Velocity at Constriction (PIANC WG22, 1997) :-

$$U_o = c (P_B / D_P^2)^{1/3} \quad [1]$$

Standard Propeller $c = 1.48$ (Ducted propeller $c = 1.17$)

Velocity at Propeller :-

$$U_P = U_o / 2 \quad [2]$$

Propeller Thrust t (kN/ m²) :-

$$t = 2\rho_w U_p^2 \times 10^{-3} \quad [3]$$

Water Density (seawater) $\rho_w = 1030\text{kg/m}^3$

Propeller clearance C

Propeller radius R

The peak suction pressure under the propeller S_p is taken from figure 8, (derived from Wellicome for a flat bed) for varying C/R . S_p is then multiplied by I_Q (mattress quilting factor, Table 4) to give the max design suction S_D [kN/m²].

$$S_D = S_p \times I_Q \quad [4]$$

I_Q relates to the surface quilting effect of flow over the bed (Wellicome, 1981). The quilted profile is measured by undulation height / undulation length. For propeller suction, other bed undulation effects are usually ineffective providing the minimum propeller clearance C is maintained (using a (Proserve Technical Note, 2013). The propeller suction distribution is taken as radial to three sides from 45° to 315° and can be taken from Wellicome’s dimensionless suction distributions (Figure 9) with the max design suction S_p assigned as above.

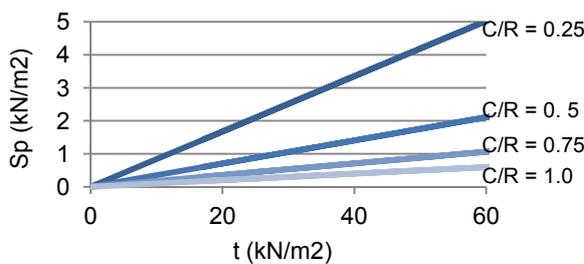


Figure 8. Peak Suction, S_p vs Propeller Thrust, t

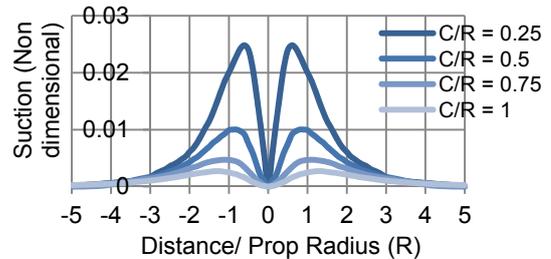


Figure 9. Wellicomes Suction Distributions

Concrete mattress thickness should be designed using a robust safety factor >2.0 (to limit the likelihood of repairs), using worst case combination of water level/clearance and applied engine power. This is particularly important to under jetty slope protection and berths in continual use. For simple design, the thickness deadweight can be solely used to resist the max suction (S_D).

Table 4. Surface Quilting Factor

	Quilting	I_Q
Constant thickness mattress	0.16	1.15
Other cases/ FP Mattress	0.33	1.30

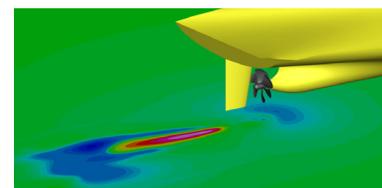


Figure 10. Bed Loadings $C/R = 1$

More rigorous panel analysis can be used where dead weight and panel flexural strengths are used to resist the effective suction distribution over the panel. For unreinforced concrete panels, analysis to masonry codes (BS 5628, etc) or yield line methods can be applied. Using a $SF > 2$, at working loads, concrete flexural stresses are generally very low compared to allowable design levels and installed concrete mattress has performed well to date.

2.1.2. Propeller Jet Loadings onto Level Beds

Flow impact from propellers with a rudder (figure 6) creates positive pressure due to flow impact which is much greater than suction loadings. For low clearances as Figure 7, the suction under the propeller is generally the worst case, but with increasing clearance (Figure 10) the suction zone after flow impact becomes the design case. Estimation of this suction is given in the Proserve Technical Note.

2.1.3. Propeller Race Loadings onto Slopes

After determination of the maximum propeller velocity on the slope U_b (BAW, 2005), the design process in the previous sections can be repeated to obtain slope suction/ pressures and mattress thickness for slopes up to 30° . Mattress deadweight uplift resistance on slopes is multiplied by $\cos \alpha$. (Figure 11)

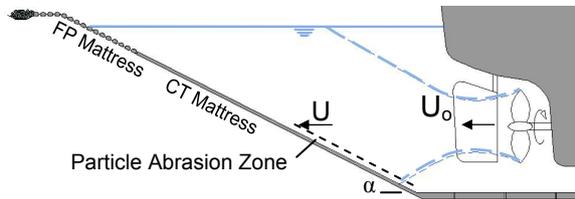


Figure 11. Propeller Action

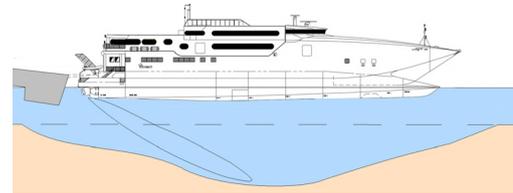


Figure 12. Fast Ferry Jet Action

2.2. Ro Ro Fast Ferry Jet Action

Mooring jetting has created bed scour holes up to 9 m deep (Figure 12). Concrete mattress has been used to many berths for bed jet flow to 12.5 m/s. See Hawkswood et al 2013 for further details and design methods.

2.3. Side Thruster Action

Side thruster action onto quay walls (Figure 13) can cause significant erosion from deflected downwash. Where concrete mattress protection is used the downflow produces mainly positive pressure with little need for analysis other than the provision of mattress of nominal thickness with a robust edge seal. Side thruster actions onto slopes are over much smaller areas than propellers, the slope velocity of which can be calculated from Pianc WG22, 1997/BAW 2005 and a design appraisal made as for propellers.

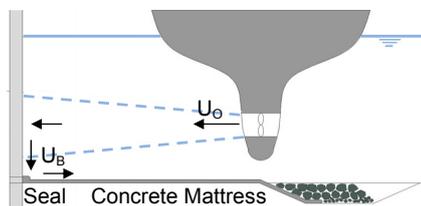


Figure 13. Side Thruster Action

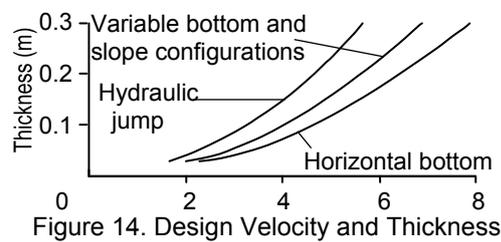


Figure 14. Design Velocity and Thickness

2.4. Current Action

For current flow parallel to beds, slopes and straight channels, figure 14 can be used for constant thickness mattress depth (Pilarczyk, 2000). Suction uplift is the limiting failure mode, which is primarily dependent upon velocity, construction undulations and mattress surface profile. Figure 14 can be used for filter point mattress average thickness with a 15% increase to allow for greater surface quilting. A suitable geotextile should be provided under FP mattress to guard against filter point loss and washout, unless protection is short term and flow and abrasion levels are low.

Where panel size may be reduced to provide flexibility for ground settlement, thickness needs to be increased. For relatively modest flow blockages up to 20% by piles or piers and for obstruction widths $< 7 \times$ Mattress Thickness (Proserve Technical Note, 2013), the increased mean velocity through the blockage can be used in Figure 14 and mattress thickness increased by the ratio of blockage velocity to approach velocity. Where greater flow acceleration occurs, the increase in suction loadings should be assessed by CFD modelling or by conservative comparison to existing modelling.

2.5. Wave Action onto Slopes

A permeable Filter Point mattress is generally used in the tidal range to release tidal water movement and uplift pressures during wave run down. The mattress thickness is principally dependent upon the

ratio of mattress permeability (k_m) to soil permeability (k_s) and the significant wave height (H_s). Where $k_m > k_s$, theoretically no uplift exists under the mattress as water can move through the mattress faster than through the soil. Where $k_m < k_s$, ground water uplift in the wave rundown zone is created as shown in figure 15, and a greater mattress thickness is needed to resist and distribute the net uplift load. Thickness can be determined from the following relationship derived from performance (Proserve Technical Note, 2013) (McConnell, 1998 [9.3 & figure 10.7]), where c is a stability coefficient dependent upon soil permeability as shown in table 5.

$$D = c \times H_s \quad [5]$$

The performance range is presently limited to $H_s < 1.5$ m and for slopes up to 30° . Initial mattress porosity is commonly some 10^{-3} but reduces with clogging to some 10^{-4} in clays/ silts and 5×10^{-4} in sands. Porous revetment construction should extend $2 \times H_s$ below low water level before lower porosity mattress is used. The slope angle α has been found to have little effect upon required mattress thickness as the uplift length decreases with increasing slope angle.

For mattress on slopes, toe embedment support is important to prevent wave induced sliding and underscour. Where no toe support is provided, design is often problematic and should preferably be avoided unless a specialist design is prepared with durable steel tension cables or similar provided to a secure top anchorage. For filter point mattress wave run up can be assessed (McConnell, 1998) using a surface run up factor of $r = 0.95$.

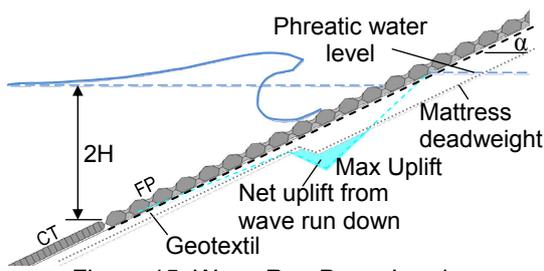


Figure 15. Wave Run Down Loads

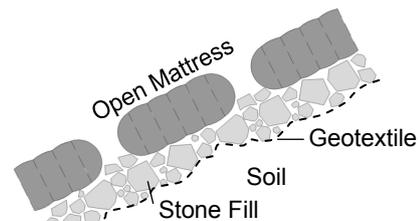


Figure 16. Open Mattress

For other than very short term usage, filter point mattress requires a geotextile filter underneath to protect against washout from filter point loss. For dynamic wave action, it is recommended that the opening size of the geotextile O_{90} (McConnell, 1998) should be typically reduced by 0.7 for cohesionless soils.

For efficient design the mattress permeability including clogging effects should be clearly greater than the underlying soil permeability, preferably with $k_m / k_s > 10$ to ensure this. For soils or stone fill materials with greater permeability, open mattress are effectively required without filter points. Open mattress permeability should be at least 1/10 of the sublayer where a stability coefficient of 1/6 is currently recommended for H_s up to 1.5m.

Table 5. Stability Coefficient c , FP Mattress

Particle Type	Range of Diameters (mm)	Order of permeability K_s (m/s)	Stability Coefficient (c)
Coarse Sand	2 - 0.5	10^{-3}	1/4
Medium Sand	0.5 - 0.25	10^{-3}	1/5
Sand & Gravel	10 - 0.05	10^{-4}	1/6
Fine Sand	0.25 - 0.05	10^{-5}	1/10
Silty Sand	2 - 0.005	10^{-6}	1/10
Sandy Clay	1 - 0.001	10^{-7}	1/10

It is important to provide secure toe, crest and edge details to mattress aprons. In cohesionless sands, that have no effective silt content (typically $D_{15} > 0.15$ mm), fines can be lost from potential water movement under the toe, this can typically occur where $k_m < k_s$ in larger wave action. For these cases an open mattress construction as shown in figure 16 can be used where the rock fill provides temporary protection.

3. CONSTRUCTION

3.1. Fabric Formwork Technology

The mattress system is lightweight and can readily be transported and used worldwide. Mattress panels are premade and rolled out by Divers and zipped together (Figure 17) for insitu filling underwater with highly fluid micro concrete; a 2:1 sand:cement mix.



Figure 17. Concrete Mattress Installation

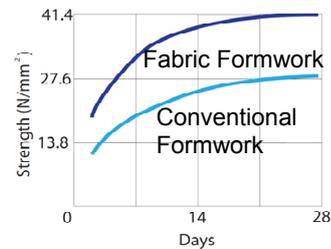


Figure 18. Free Water Bleed and Strength

Mattress forms are made from a porous yet grout tight woven fabric which causes free water in the mix to 'bleed out' during filling before initial set. This produces a lowering of the water: cement ratio in the surface zone until the mix ceases to be a fluid and reaches what is known as a mechanical set. This results in a significant rise in strength and abrasion resistance as shown in figure 18 (Hawkswood 2012).

A temporary works design should be prepared for fabric formwork strength and stability during the filling process. For micro concrete (sand:cement mix) the fabric opening size O_{90} is less than the D_{50} of sand in the mix to ensure micro concrete tightness. The fabric is woven in polyester/ polyamide and importantly is negatively buoyant. Mattress panel widths are typically some 3m to 4.8m from the weaving process. Concrete mattress is used for many other scour protection applications to channels, rivers and bridges. Fabric formwork systems are also used for concrete encasement pile repairs (Hawkswood 2011) and for foundations to precast marine structures (Hawkswood 2009).



Figure 19. Porous Woven Fabric

Table 6. Settlement and Panel Size

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

3.2. Settlement and Flexibility

Panel size can be reduced to cope with significant settlement usually associated with hydraulically placed sand fills as shown in Table 6 (Relative settlement is based across the apron width). For example a 1m panel size was used at Belawan and produced using crack failure lines (Loewy et al., 1984).

3.3. Porosity Weep Holes

Residual ground water movement may occur under quay structures, piling or slopes created by tidal movement etc. Weep holes can be provided in CT mattress (Figure 20) to provide low porosity to cater for these effects. For soils a geotextile should be provided to the bottom of the weep hole to retain fines, and the weep hole size and spacing designed to suit (Proserve Technical Note, 2013).

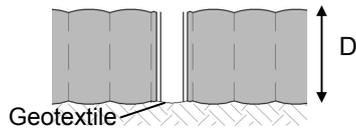


Figure 20. Weep Holes to CT Mattress

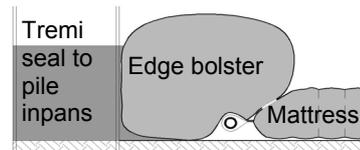


Figure 21. Wall Bolster and Tremi

3.4. Seals to Walls

To seal against piled profiles, a concrete edge thickening bolster is commonly used allowing a deeper tremi concrete infill seal to in pans. An edge thickening bolster can also be used to unprofiled walls with inspection and a tremi concrete infill seal to any gaps (Figure 21).

4. RELATIVE MERITS

Concrete mattress has a low relative thickness compared to other protection systems such as rock as shown in figure 22. This importantly creates significant savings in the design of quay wall structures reducing span heights, embedment and dredging volumes.

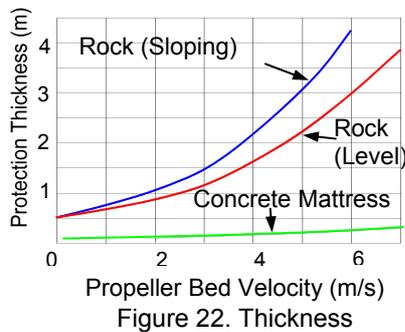


Figure 22. Thickness

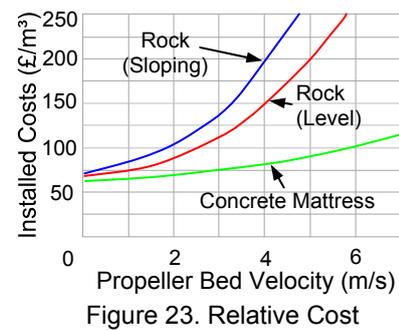


Figure 23. Relative Cost

Expensive marine plant is usually not needed as concrete mattress is normally installed by divers working from the quay wall or the top of revetment slopes. Uniquely, insitu concrete mattress systems can be used on slopes, allowing sloping toe trench edge details with stone falling aprons. The system can be used on undulating beds and slopes reducing the need for expensive bed levelling preparation associated with low tolerances. The mattress system is lightweight fabric, which makes it much safer for divers to install compared to heavy preformed systems which risk diver entrapment during lowering. Environmentally, it reduces dredging and material quantities and avoids washout of cement. Typical relative costs are shown for concrete mattress and rock armour in figure 23. Concrete mattress is likely to be more cost effective for flows above 2-3 m/s. (Example based upon: Rock £60/m³, Geotextile £8/m², Dredging £24/m³, 0.45m maintenance dredging depth.)

5. SPECIFICATION

In common with general maritime construction control, where mattress construction is largely underwater and cannot be readily visually observed or inspected, the marine works should be supervised by a suitably experienced professional engineer(s) using a proven marine quality control system. These details and the mattress system proposed should be submitted for approval with details of similar previous projects. Typically, the following information should be prepared for approval prior to mattress supplier selection / commencing work:-

- Proposed Supervision and Marine Quality Control System
- Mattress General Arrangement Details
- Installation Guidance by Supplier/ Supervising Engineer
- Contractors, Method Statement and Dive Plan

For significant projects the above should include:-

- Risk assessment of marine working conditions and environmental aspects
- Bed preparation methods and suitable marine construction tolerances
- Temporary works design
- Proposed mix development, testing and construction records
- Proposed as built record drawing and maintenance advice

The specified mattress thickness should be achieved with a tolerance of -0% and +10% typically. A sand:cement concrete mix is to be developed to achieve 35N/mm² strength at 28 days, with appropriate testing specified. Suitable management, supervision and recording is required to ensure and demonstrate that the concrete mattress apron achieves full coverage and thickness with ball and socket joints, level tolerance, wall seals and edge protection depths and infill (Proserve Technical Note, 2013).

6. CONCLUSIONS

Concrete mattress provides high performance protection against vessel actions with performance against jet flow to 12.5 m/s. It is likely to be more cost effective than rock armour for flows above 2-3 m/s due to the relatively low stability performance of rock armour.

Design methods have been presented with references to further aid engineering design and specification. It is important that concrete mattress aprons are provided with suitable edge protection. Often rip rap falling apron edge trenches are used which provide excellent edge protection along with the opportunity for future maintenance. In common with other marine works, the use of a quality control system to overcome marine working conditions is recommended along with experienced professional input to the process.

7. CASE STUDIES

7.1. Cotonou, Benin

2 new container berths have been constructed at the port of Cotonou by Bachy Soletanche, with a depth of 15m to accommodate larger container vessels. Proserve designed the scour protection apron (Figure 24), supplied the concrete mattress system and provided professional supervision along with a marine quality control system. The mattress was woven by Huesker. The scour apron was designed to resist the suction forces due to container vessel propeller action, 240mm and 150mm thick CT Constant Thickness mattresses were used. The lower construction thickness of concrete mattress provided a cost effective solution and importantly minimised the span height of the quay wall.

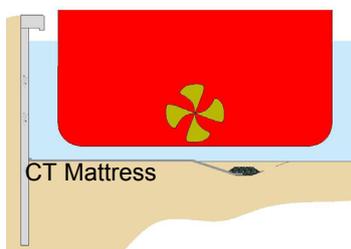


Figure 24. Propeller Scour



Figure 25. Lowering mattress to be rolled out by divers.



Figure 26. Mattress trial filling on site

A local micro concrete mix was developed with pumping and mattress filling trials. The mattress system was diver installed using the roll out technique and then pump filled automatically via pre-installed lay flat hoses. 15,000m² of mattress was installed in some 6 weeks using 2 large dive teams. A rip rap stone falling apron edge detail was provided to overcome edge scour in the sand and clay bed.

7.2. Abidjan, Ivory Coast

Harbour revetment slopes were protected with filter point mattress some 40 years ago to prevent scour to slopes. A local sand and cement mix was used and the mattress system was installed using local labour with professional supervision.



Figure 27. Ivory Coast, Berth

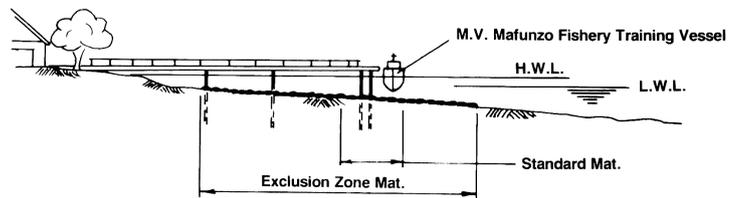


Figure 28. Tanzania

7.3. Tanzania; Berth Protection

Concrete mattress was used to protect a piled jetty berth from the effects of local bed growth fouling propellers. A standard mattress protected the bed to the end of the jetty from gravity and bed lowering and a lighter weight mattress with large filters was used in the growth exclusion zone.

ACKNOWLEDGEMENTS

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REFERENCES

- Hawkswood, M.G., Evans, G., and Hawkswood, G.M., (2013) Berth Protection for Fast Ferry Jets, *Coasts, Marine Structures and Breakwaters 2013*, ICE, Edinburgh, UK.
- Pilarczyk, K.W. (2000). *Geosynthetics and Geosystems in Hydraulic and Coastal Engineering*. Taylor and Francis, New York, USA.
- Wellicome J.F. (1981) Bottom Suction Loads due to Propeller Scour Action and Ship Movements, www.proserveltd.co.uk
- Marin, 26869: Seabed Suction Force Computations, Proserve Ltd., Preliminary Results, Version 2 2013-06-04, Lafeber, F.H.
- PIANC Report of Working Group 22, Bulletin no 96 (1997), Guidelines for design of armored slopes under open piled quay walls.
- Karlsruhe (2005) Principals for the Design of Bank and Bottom Protection for Inland waterways BAW
- Proserve Technical Note (2013) Berth Scour Protection Using Concrete Mattress, www.proserveltd.co.uk
- McConnel, K. (1998) *Revetment Systems Against Wave Attack*. HR Wallingford, Thomas Telford, London.
- Loewy, E., Burdall, A.C., Prentice, A.G., and Sir William Halcrow and Partners (1984), *Revetment Construction at Port of Belawan, Indonesia*, I.C.E. London
- Hawkswood M.G., (2012), *Fabric Formwork Systems Used in Marine Construction*, 2nd ICFF, ISFF, Bath, UK.
- Hawkswood, M.G., (2011), *Marine Pile Repairs by Concrete Encasement*, *Innovative Coastal Zone Management*, ICE, Belfast UK.
- Hawkswood, M.G., Allsop, W., (2009) *Foundations to Precast Marine Structures*, *Coasts, Marine Structures and Breakwaters 2009*, ICE, Edinburgh, UK.