IMPERMEABLE TOE PROTECTION TO CAISSON BREAKWATERS USING IN-SITU CONCRETE MATTRESS

M.G, Hawkswood [1] and G.M.P, Hawkswood [1]

[1]Proserve Ltd, Kenilworth, UK

ABSTRACT Porous rock armour or porous blocks have been generally used for toe protection to caisson breakwaters to date and smaller rock for caisson foundations. Recent developments have been made using impermeable toe protection of insitu concrete mattress to caisson breakwaters. Impermeable toe protection prevents flow and the transmission of wave pressures underneath caissons. The reduction in wave loading and uplift pressures to caissons will be described along with the prospect for more efficient breakwater structures.

Comparative stability guidance for concrete mattress thickness will be presented along with the need for further development by scale model testing under wave conditions. Initial comparisons with precast block and rock toe protection will be made particularly in terms of porosity, stability and flexibility.

Where bedrock is available, the use of in-situ concrete foundations can eliminate settlement allowing the prospect of interlocked caissons and more efficient breakwater structures to be considered.

1. Introduction

Vertical breakwaters are nowadays generally constructed using caissons or block structures on a rubble mound. Toe protection is generally with precast blocks or rock armour or a combination of both. The toe protection is porous along with the foundation stone layer which allows the movement of water under the caisson as outlined in Figure 1. This porosity also allows the transmission of wave pressures to the full depth of the caisson and underneath.

Figure 1 Porous Block and Rock Toe Protection

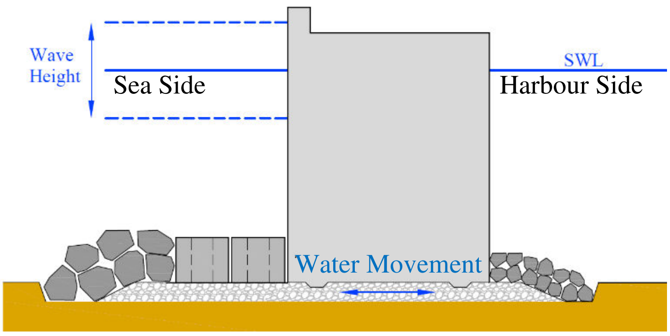
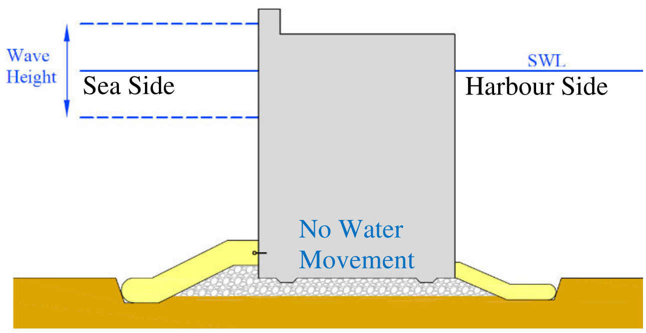


Figure 2 Impermeable Concrete Mattress Toe Protection



In comparison, impermeable toe protection using insitu concrete mattress as shown in Figure 2 does not allow water movement under caissons or the transmission of wave pressures. This produces improvements in caisson stability and the stability of the insitu concrete mattress protection, which will both be further outlined. The impermeable protection needs to be installed on both seaside and landside around the breakwater caissons to be effective.

Breakwaters are exposed to wave effects, Figure 3. They are subject to wave impact pressures with suction loading during wave reflection and also changes in water level to the seaward side from wave action as shown in Figures and 2.

Figure 3 Wave impact to Breakwaters

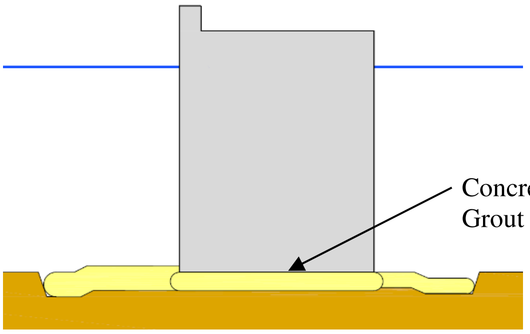
Wave effects need to be considered in the design of toe protection as well as for the breakwater caissons. The wave pressures acting on a vertical breakwater will be briefly reviewed with reference to Goda (2000). Ushijima's method of sizing precast toe blocks presented by Takahashi (2002) will also be reviewed along with an initial stability comparison method for the design of in-situ concrete mattress. The importance of reliable edge protection details will be reviewed to avoid underscour or sliding failure, and guidance for the robustness of impermeable concrete protection.

The following case histories will outline the application of the concrete mattress system in each case:

- Pittenweem, Scotland (2016)
- Porto do Topo, Azores (2020)

For Pittenweem and Porto do Topo, the in-situ concrete toe protection thickness was 1m and 1.2m respectively to the seaward side and 0.5 m thick to the landside. The mattress formwork system creates plain slabs of concrete with interlocking joints. It also prevents wash out of fluid concrete during installation. The system is installed by divers and pump filled with a fluid self-compacting concrete.

Figure 4 Insitu Concrete Foundations to Caissons



Breakwater caissons are typically founded onto crushed rock bedding layers. Where bedrock is available, an in-situ concrete foundation can be considered as shown in Figure 4. This limits settlement movement, and allows the prospect of a more interlocked and efficient caisson structure to be developed, which will be further described. The impermeable foundation layer also provides additional resilience to the impermeable toe protection.

2. Pittenweem breakwater repairs

Engineer: AECOM, *Contractor: Farrans* *Dive Contractor: Aberdeen Marine Services*

The historic masonry breakwater was extended in 1992 by four reinforced concrete caissons, see Figure 5. The caissons were founded on a crushed rock bedding layer placed onto bedrock. A tremie concrete layer was used as a toe protection. The significant wave height to the extension was considered to be some 4.5m.

Figure 5 Pittenweem Breakwater Extension

The original tremie concrete toe protection layer failed allowing some significant wash out of the bedding stone layer and settlement damage, with caisson 3 dropping by some 0.2m as Figure 6. The tremie concrete layer was found to be generally weak & poor quality.

Figure 6 Pittenweem Breakwater Settlement

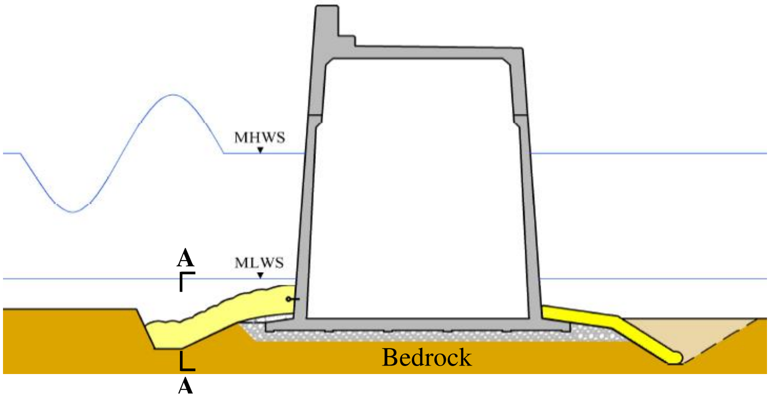
The project team considered the working conditions and preferred plant available and developed a repair method:-

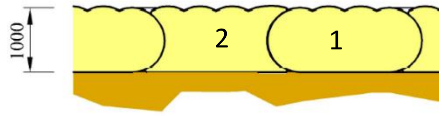
1. Survey of the extent of voids by drilling.
2. Perimeter seal to voids by grout bags
3. Progressive grouting of voids from drill holes.
4. Excavation for toe protection by excavator on a barge.
5. Toe protection by concrete mattress.
6. Repairs to deck and structure.

The works were undertaken in 2015 & 2016 summer seasons and were occasionally interrupted when wave heights exceeded some 1m.

A 1m concrete mattress thickness was preferred as toe protection to the seaward slope. Woven mattress thickness by looms is presently limited to 0.56m so a hand fabricated mattress for 1m thickness was developed and tested using higher strength thickness ties at 0.5m centres. The 1m thick concrete mattress was installed to the outer breakwater for wave action Hs of 4.5m, Figure 7. Mattress edges were toed into the variable mudstone/sandstone bedrock to protect edges from future scour. The mattress was tied into the breakwater wall using heavy steel eye bolts to resist breaking wave loads, particularly suction uplift. The concrete mattresses were fabricated in compartments of 10m³ filling volume for constructability, with robust ball and socket shear joints between panels as Figure 7 Section A-A.

Figure 7 Pittenweem Cross Sections





Section A-A, filling compartments

The concrete mattress panels were filled in-situ with highly fluid sand:cement micro concrete delivered by ready mix, Figure 8 & Figure 9. The mattress panels were installed in pairs with the outer panel filled first so side filling pressures are balanced as Section A-A, Figure 4. The mix was pumped using a Putzmeister 1000D piston pump up to 270m along the breakwater in 100mm steel pipes into a secondary worm pump at the worksite with 50mm rubber grouting hose for diver handling. Hose pumping trials where an important part of the development work for the project. A total of 1,100m² of concrete mattress was installed by the team of divers in suitable weather windows.

Figure 8 Picture Of Concrete Mattress (At Low Tide)

An established marine quality control system was used for the overall concrete mattress installation works along with specialist engineer support visits. A 0.5m thick concrete mattress was installed to the Harbour Side to create an apron of impermeable protection around the breakwater and to cater for lower wave action and effects of local fishing vessel traffic. Since 2016, the toe protection has been inspected annually and is reported to be performing well to date.

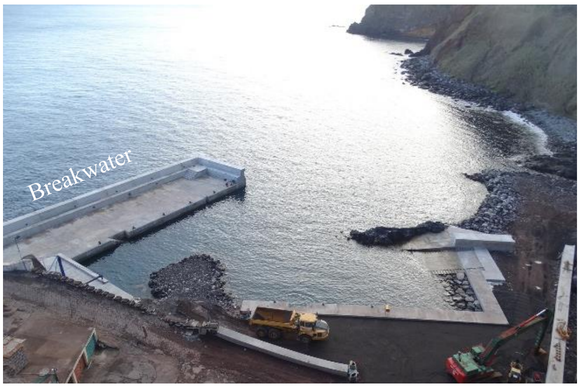
Figure 9 Concrete Pumping 270m

3. Porto do Topo, Azores

Contractor: Mota-Engil/Etermar JV

Porto do Topo is on the exposed westward coast to the Azores. A sheltered harbour was formed by a breakwater of one long reinforced concrete caisson, Figure 10. The significant wave height was considered to be some 5.5m (Hmax some 10m).

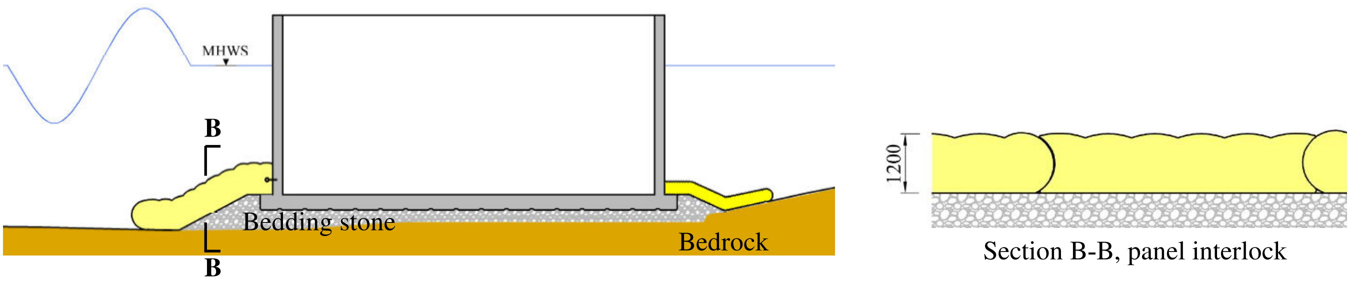
Figure 10 Caisson Breakwater, Porto Do Topo



An impermeable concrete mattress system was chosen as toe protection to be used on 3 sides of the caisson. For the seaward side it was considered to have the following features to enhance stability:

- Anchor bolts from concrete mattress to caissons.
- Large panels 5m x 5m with interlocking joints.
- Impermeable protection prevents water movement to cause uplift failure of the protection.

Figure 11 Azores Breakwater Cross Section



The thickness of the concrete mattress to the seaward side was undertaken by comparison to Ushijima's stability method for individual blocks as presented in Takahashi (2002) and outlined in Section 5 and 6. Ushijima's method suggested a block thickness of some 2.1m. After a stability comparison of individual blocks and concrete mattress, taking into account anchor bolts provided to the caisson and larger concrete panels with interlock, a concrete mattress thickness of 1.2m was selected. The reduction in water movement under the impermeable protection was not considered, to be conservative. Testing would be needed to determine this effect.

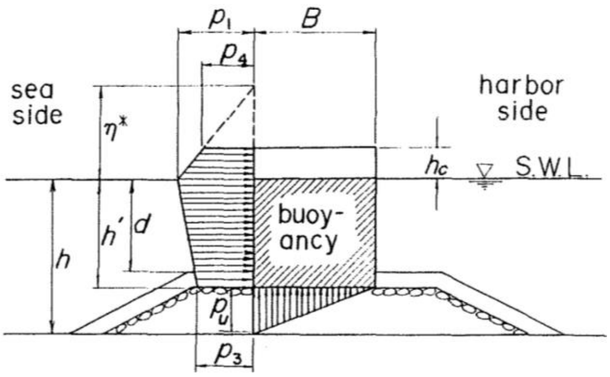
The hard bedrock was considered unlikely to erode and therefore a concrete mattress overlap joint was selected instead of the more usual toe trench.

The site was exposed with construction planned for the summer season when wave conditions allowed. The caisson was placed at the end of the 2019 season and temporary edge rock placed to secure the caisson and bedding stone over the winter. The contractor removed the temporary rock and installed the concrete mattress in the 2020 summer season. With hindsight, the contractor would have preferred a concrete foundation to the caissons as described in Figure 4. A 0.5m thick mattress was installed as bed protection to the landwards side.

4. Wave loads with a porous protection & bed

Wave pressure distributions for vertical breakwater caissons can be taken from Goda (2000) as typically shown in Figure 12 for positive wave loads. Similar suction distributions are available for wave reflection. These distributions apply to caissons with a porous protection layer and a porous bedding stone layer, allowing transmission of a positive pressure under the caisson.

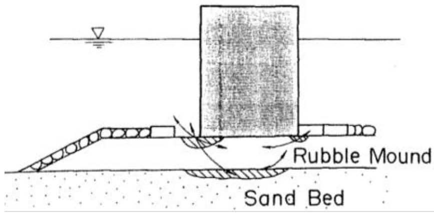
Figure 12 Goda Pressure Distribution



5. Toe protection blocks

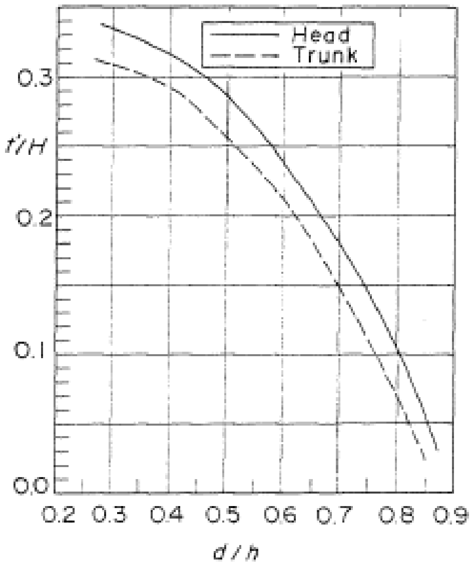
Precast concrete blocks have been used as toe protection to caisson breakwaters and a stability method from testing undertaken by Ushijima was published by Takahashi (2002) Figure 10.

Figure 13 Failure Due To Damage To Toe Protection (Takahashi, 2002)

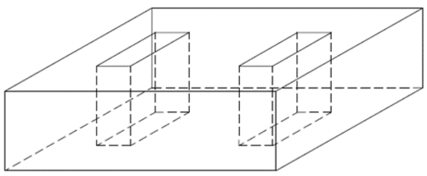


Ushijima determined stability graphs for thickness of foot blocks with a porous area of 10% as shown in Figure 14. The design wave height is advised as H_{max}.

Figure 11 Thickness For Foot Protection Blocks by Ushijima's Method (Takahashi, 2002)



Where:
t' = Block thickness
H = Design Wave Height (Hmax)
d = Water depth in front of caisson (See Figure 12)
h = Water depth at protection toe (See Figure 12)



The block thickness is influenced by the depth ratio d/h which has a significant effect, therefore it appears the failure mode is due to the net uplift suction during wave reflection. Uplift is a common mode of failure for concrete blocks in wave action. As flow under caissons during a wave trough is related to Hmax/2, this suggests that flow under the caissons during wave rundown is not a critical condition for blocks with a porous area of 10%.

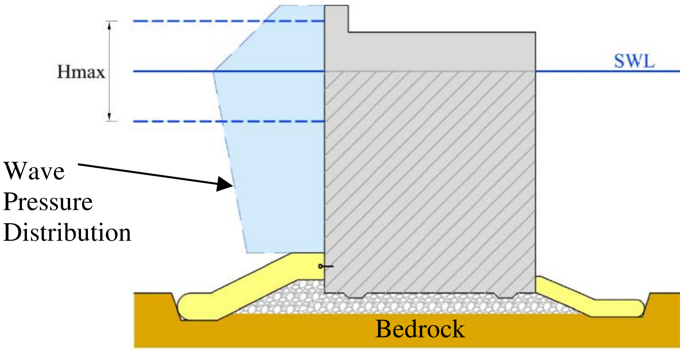
The use of secure edge details is important to avoid edge failure to blocks reported by Takahashi (2002). Some edge failure was also reported at Peterhead (Figure 15) to 50t solid concrete blocks although after a significant service period, (Tomlinson *et al,* 2003*)*. At transitions between foot blocks and rock armour, at a simple butt joint it has been common for rock movement to allow underscour and sliding of edge blocks. The rock movement appears to be due to wave return flow. Overlapped or grouted joints are typically considered more secure with suitably sized rock.

Figure 15 Plan Survey Of Edge Scour To Precast Block Toe Protection (Tomlinson *et al*, 2003)

6. Concrete mattress toe protection

The change from porous toe protection to impermeable concrete creates a significant change in performance of the protection and the caisson breakwater under wave load. Where an impermeable toe protection layer is used such as concrete mattress, the pressure distribution on caissons outlined in Figure 12 only exists above the impermeable layer, as shown in Figure 16. This reduces the sliding force to the face of the caisson and eliminates the uplift force on the bottom of the caisson offering the prospect of saving in the mass of the caisson structure.

Figure 16 Concrete Mattress Toe Protection



With impermeable protection on both sides of the caisson breakwater, the flow of water under the caissons is prevented during wave run up and run down. Significantly, during wave run down to the sea side, the concrete mattress theoretically has no movement of water able to lift it. The static water head pressure across the mattress can approach $H_{max}/2$, but water is not free to move under the impermeable layer to promote failure by uplift.

To develop a specific design method for concrete mattress protection taking the above aspects into account, scale model testing is proposed for impermeable protection in a similar way to Ushijima's work for the design of porous toe blocks. The testing is intended to cover the following:

- Varying d/h ratio
- Rock foundations to caissons
- Concrete foundations to caissons
- With and without anchorage ties to caissons on the seaward side

Presently, it is suggested that toe protection mattress thickness can be estimated by safe comparison to Ushijima's method for toe blocks as outlined in Section 3, taking into account the following aspects:

- Anchoring to caisson
- Larger panels with interlock

This comparison method is considered conservative as the impermeable toe protection seaside and landside does not allow water movement that is often a contribution to uplift failure. This is likely to create an element of robustness in the comparison method.

Figure 17. Suction Uplift Condition

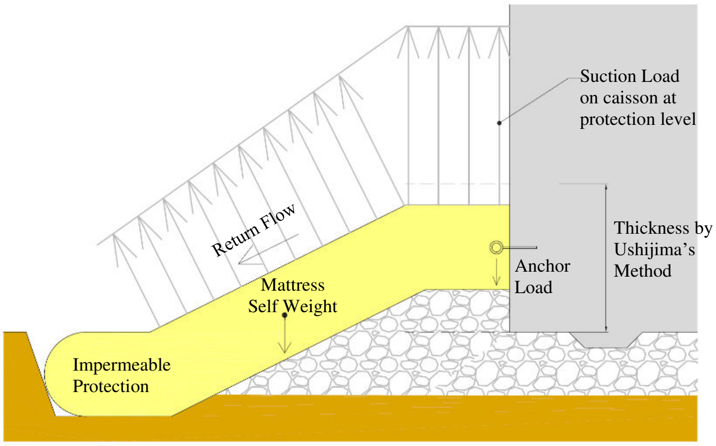
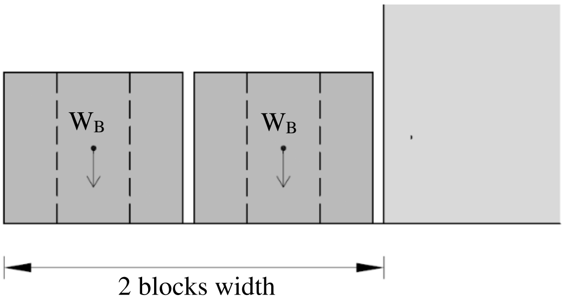


Figure 17 shows a schematic consideration of the loading conditions for suction due to wave reflection which acts for a short time period. The relative block thickness by Ushijima's method is also outlined. The suction loading at the bottom of the wall dissipates to seaward along the bed.

Figure 18. Comparison Design of Concrete Mattress to Blocks

Precast Blocks



Concrete Mattress

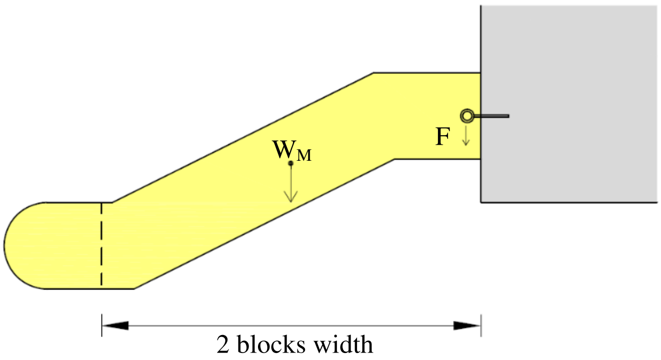


Figure 18 shows a comparison of the submerged weight of precast blocks and the submerged weight of concrete mattress and wall tie anchorage force. The precast blocks by Ushijima's method range from 1.5m to 2.5m wide and a 2 block width is generally used.

For simple design comparison Equation (1) below can be applied:-

$$W_M = 2 \times W_B \times d - F \qquad \text{Equation (1)}$$

Where

W_M = submerged concrete mattress weight (kN/m)

W_B = submerged block weight (kN/m)

d = load distribution factor suggested as 0.8 for interlock / load distribution over a larger area and for the reducing suction load towards the edge of protection.

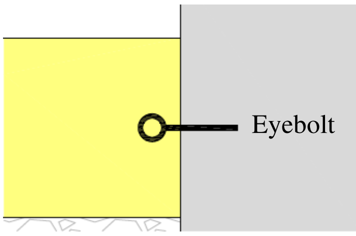
F = tie anchorage load (kN/m)

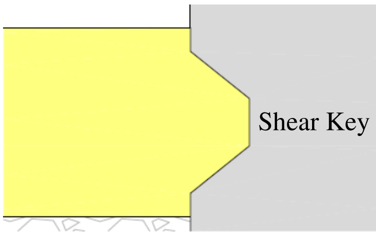
(F is limited to ⅓ of 2 x W_B x RF to maintain stability of the free mattress edge)

Equation (1) is applied to the submerged weight of blocks and concrete mattress over an equivalent area. For 2 rows of precast blocks, the blocks against the caisson face are most critical as suction pressures reduce away from the wall face. The load distribution factor d as been appraised based upon this reduction of suction loading and the ability of interlocking concrete mattress to distribute load in both directions. Where anchorage to the caisson is used, the plain concrete slabs can be checked and designed for low levels of flexural stress to BS EN 1992-1-1:2004 Table 3.1.

In both projects to date, large eyebolts have been used for anchorage to the caissons, typically as shown in Figure 19 with an alternative shear key also shown. Eyebolts are either drilled and resin anchored into caissons or cast into caissons. Eyebolts have been typically used at 1m centres. It is important that these anchorages are designed for forces from wave suction loading as the comparison method suggested above.

Figure 19. Shear connection to breakwater





Interlocking ball and socket joints are used between concrete mattress panels as Figure 20. They have a significant shear capacity which can be readily calculated and have a very good record of performance.

Figure 20. Interlocking Ball and Sock Shear Joint

The main risks to reliability and performance of concrete mattress toe protection are presently considered to be:-

- Edge underscour
- Gaps caused by caisson movement
- Need for further development testing and case history performance

Mattress edges need to be appropriately sealed to the bed material and protected from underscour. For bedrock prone to limited scour, a trench embedment detail as Figure 7 has been used and where rock is hard and not prone to scour an overlap seal has been used as Figure 11. In sand and granular beds, the concrete mattress may need to extend into deeper toe embedment trenches safely below the level of expected scour, or rock edge protection provided. In sands and granular material, a check would be needed to ensure no piping or erosion occurs between seaward and landward toe edges under the protection and the caisson.

For stability comparison, a lower thickness of insitu concrete mattress an be used than pre-cast blocks due to larger interlocked panels and anchorage to the caissons. Presently concrete mattress thickness is limited to 1.2 m thickness but with wall anchorage this can be equivalent to the thickest blocks of 2.2 m shown in Ushijima's method.

For a comparison of flexibility, protection with precast blocks and rock has a high flexibility for settlement yet an apron of relatively thick and interlocked concrete mattress slabs is fairly rigid. Where a degree of caisson settlement or settlement in higher rouble mounds is expected, additional longitudinal ball and socket joints can be incorporated where flexibility can be engineered to meet expected settlement. Caisson settlement is normally greatest at the landward side, and to allow a degree of relative settlement, anchor ties should not be used between the concrete mattress and the caisson to the landwards side.

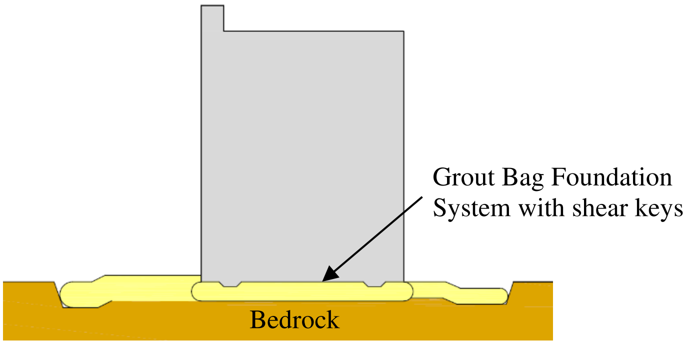
For comparison of porosity, relative to precast blocks and rock, insitu concrete mattress is relatively impermeable due to the nature of concrete and contact at joints. The use of anchor ties to caissons provides robustness against joints to caissons opening. There are benefits of impermeable protection which have been outlined and the concrete mattress needs to be designed and constructed adequately to ensure this to ensure that the benefits are achieved. A proven marine quality control system should be used as the case histories.

7. Caisson foundations in concrete

Historically caisson foundations have been formed with a layer of levelled rock. This has generally been a preferred marine construction method. It creates a porous layer beneath the caisson. An in-situ concrete foundation can be adopted as shown in Figure 21. Many caisson structures have been founded using this system, (Hawkswood & Allsop, 2009). In-situ concrete foundations are formed by pump filling grout bags prefixed to the underside of caissons,

Figure 22. The system caters for bed undulations. Caissons are temporarily supported on pre-levelled pads or supports. Shear keys may be incorporated into the bottom of the caisson as shown in Figure 21 to aid sliding resistance (Hawkswood & Allsop, 2009). Impermeable foundations in concrete are compatible with the use of impermeable concrete toe protection as shown in Figure 21.

Figure 21 In-situ Concrete Foundation to Caissons



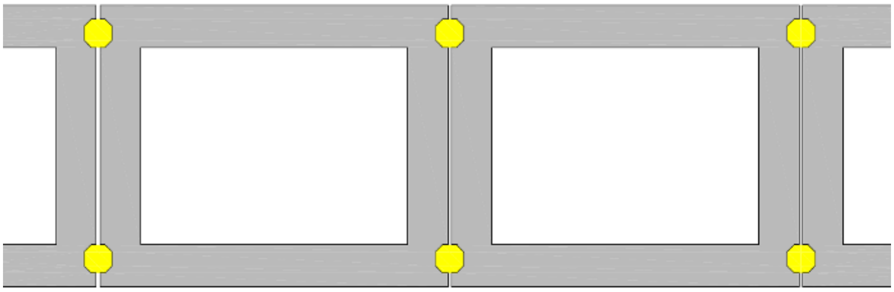
The system is particularly useful where bedrock is available, with concrete foundations offering the following advantages:-

- Founding directly onto bedrock, with little or no settlement
- Caissons can be interlocked and more efficiently designed with load sharing of wave actions
- Impermeable foundation.
- Avoids stone wash out risk and stone settlement.

Figure 22 Concrete Grout Bags Foundations To Caissons, (Second Severn Crossing, UK)

When founding directly onto bedrock, no settlement is likely to occur, so caissons can be interlocked together as indicted in Figure 23 to share and distribute wave loads into adjacent caissons.

Figure 23. Interlocked Caissons



The interlocking of caissons offers the prospect of reduced caisson mass particularly as sliding is a common design/failure mode. Shear keys can be formed using in-situ concrete and fabric formwork as shown in Figure 24, and the concrete can be designed to transfer the loads required.

Figure 24 In-situ Concrete Shear Keys, (Greystones, Ireland)

Shear keys can also be filled with compacted stone where a degree of flexibility is preferred (Lee *et al* 2020).

The use of an impermeable concrete foundation is compatible with the use of impermeable toe protection in the sense that there are 3 impermeable barriers to flow under the caisson which increases the robustness of the scour protection and caisson structure when founded on bedrock.

The use of concrete protection and foundations in other soils would be more complex and engineers may best approach with validation by scale model testing.

8. Conclusion

Initial comparisons with precast block and rock toe protection have been made, particularly in terms of porosity, stability and flexibility.

The initial development of impermeable toe protection using in-situ concrete mattress to breakwater caissons has been outlined with reference to two case history examples.

Impermeable protection prevents flow and the transmission of wave pressures under caissons. This allows the prospect of more efficient breakwater structures. Loads are significantly different to historical caisson construction using porous rock and offers an alternative for engineers to consider. Impermeable protection is considered most useful where bedrock exists.

The thickness design of concrete mattress protection can initially be estimated by comparison to Ushijima's method, (Takahashi, 2002), and an initial comparison design method has been presented for this. To develop a more specific design method, scale model testing of impermeable caisson toe protection under wave action is planned.

Consideration has also been given to the use of in-situ concrete foundations to caissons. This is envisaged as being particularly useful where bedrock exists and no settlement will occur. This allows the prospect of caissons being structurally interlocked together to form a more efficient structure that can distribute wave loads. It also provides increased robustness of an additional impermeable layer under caissons.

9. Acknowledgements

This paper presents the views of the authors, not necessarily their employers, clients or organisations. Thanks is given to Luis Teixeira of Etermar for supplying the photo in Figure 7. 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

10. References

BSI (British Standards Institution). (2004). *BS EN 1992-1-1:2004: Eurocode 2: Design of concrete structures. Part 1-1: General rules and rules for buildings.* London, UK: BSI.

Goda, Y. (2000). *Random Seas and Design of Maritime Structures* (2nd ed.). WORLD SCIENTIFIC.

Hawkswood, M., & Allsop, W. (2009). Foundations to Precast Marine Structures.

Lee, B. W., Jung, J.-S., Park, W.-S., & Yoon, J.-S. (2020). Wave Force Characteristics and Stability of Detached Breakwaters Consisting of Open Cell Caissons Interlocked via Crushed Stones. *Water, 12*(10), 2873.

Takahashi, S. (2002). *Design of Vertical Breakwaters.*

Tomlinson, B., Oliver, G., & Cooke, R. (2003). Emerging Acoustic Techniques for Monitoring the Condition and Performance of Underwater Structures - as applied to Peterhead Bay Breakwater. In *Breakwaters, Coastal Structures and Coastlines* (pp. 345-357).