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Single Layer Armour Systems: Toe, Crest and Roundhead Details

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SINGLE LAYER ARMOUR SYSTEMS – TOE, CREST AND ROUNDHEAD DETAILS

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Summary

Over the last few years, HR Wallingford (HRW) and Concrete Layer Innovations (CLI) have worked together analysing, designing and testing armoured revetments and breakwaters all around the world. This paper has been written to provide consultants, interested in breakwater and revetment design, with additional information to deal with design details in difficult situations.

Introduction

The primary objective of any armouring is to protect the underlayers and core of the rubble mound, and to minimise overtopping discharge and reflections. There are several single layer armour units available, the most popular being CORE-LOC™, ACCROPODE™ and Stabits. Units such as Cobs, Sheds, Seabees, N blocks and wave walkers have also been used where conditions are less severe. This paper focuses on the former type of units, which can be used under severe conditions and locations with difficult bathymetry and ground conditions. An example ACCROPODE™ revetment under construction in Malta is shown in Plate 1 (Reference 1).

The ability of the armour system to bind together to form an interlocking structure is very important. If properly designed, the armouring can withstand very severe conditions. Design wave heights of 8-10m are encountered at times. A number of structures, for example in the Caribbean, have been designed for hurricane offshore waves of great magnitude.

Nearly all single layer armour units are laid to a specific laying pattern and therefore placement density. The most critical areas are the design of the toe, crest and roundhead detail.

Acceptability design criteria

Prior to designing any structure, it is important to review all design issues such as design life, storm return periods and acceptance criteria, which includes armour movement and overtopping discharge. These criteria can be used during physical modelling to assess whether the breakwater/revetment design is appropriate. The acceptable criteria for armour stability and overtopping performance are described below.

Single layer armour movement

As single layer armoured structures are more brittle than equivalent structures armoured with rock or two layer armour units, less armour movement is allowed. The following criteria can be used for a structure armoured with a single layer of units.

1. No significant movement during a “service event”, the service event could have a return period of between 1:5 and 1:10 years.
2. Slight movement and consolidation of the armour can be accepted for the “design event”. This could be a 1:100 or 1:200 year condition depending on the type of harbour or facility. Settlement is generally limited to less than 0.3 times the

height of a unit. It is important to note that settlement is not well modelled in the laboratory and is difficult to estimate accurately.

3. Greater displacements are acceptable during an overload condition, however no extractions of the units are allowed.

Overtopping discharge

Prior to any design refinement, it is important to establish acceptable mean overtopping discharges for given storm return periods. These limits are then compared with measured (or calculated) overtopping discharges. Both “service” and “design” tolerable discharge can be considered. Presently accepted guidelines are summarised in the new European manual of overtopping (Reference 2) and discussed below.

For a “service” condition a return period of between 1:1 to 1:10 years may be appropriate. An allowable mean discharge of 1-10 l/s/m could be applied. This will allow trained staff to service structures where overtopping water passes below knee levels only. A general limit of 0.1 l/s/m has also been specified and assumes pedestrians can see the incident waves and flows again pass below knee level. This limit drops to 0.03 l/s/m where pedestrians have no clear view of incoming waves.

During the “design condition” which could have a return period of 1:50 to 1:200 years the overtopping discharge could be limited to 200 l/s/m to reduce the risk of failure of the crest and rear slope. If buildings or equipment are located behind the seawall then the discharge should be further limited to avoid damage.

The engineering solutions made by designers are based on an understanding of the overall details of the project and its design, the employer's risk tolerance, maintenance requirements, and budget constraints. While there are always "limits" established for elements such as the number of rows, settlement of units, rocking, etc., performance is a sliding scale - not a black or white limit. The closer that a structure is "optimised" to the limits (presumably to generate cost savings), the greater the risk of non-performance increases. This is complicated by the fact that the design in total is made up of many such decisions. This process can only be managed by the professional judgement of the designers.

Plate 1: Partially completed ACCROPODE™ section

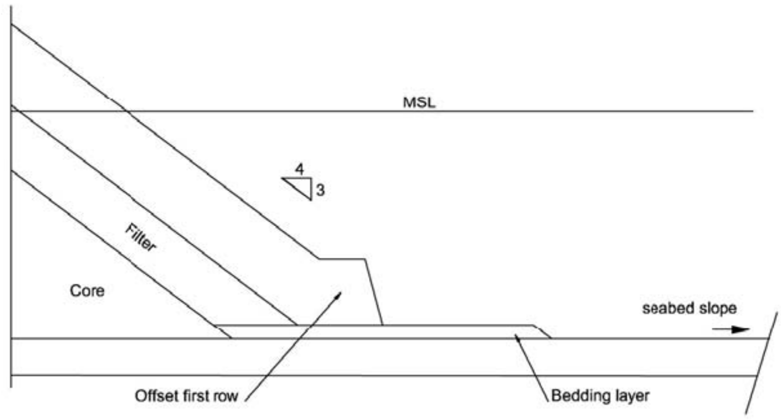

Plate 2: Typical toe on soft ground

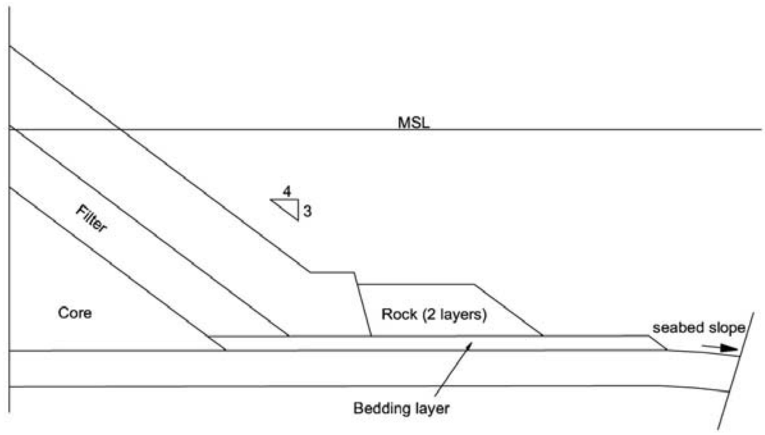

Plate 3: Typical toe, with additional support provided by rock

Design details

Toe details

A number of options are viable at the toe of a structure. The options depend on the slope and the material making up the bed. Various types of toes will be described each one adapted to specific seabed slope, bed material and type of wave attack.

Existing loose material at bed

The Standard toe can be used where the existing bed is relatively loose, but will not move under wave action. To avoid movement of the existing bed, a thin bedding layer is first placed at the toe. The initial armour unit is placed on the bedding layer and the rest of the units are placed to a strict placement pattern up the slope. If movement of the loose bed under storm conditions is expected then a large scour apron can be included to protect the area. Scour aprons could be 20 to 30m wide.

CLI does not usually recommended this toe design due to the possibility of poor placement of the first row of ACROPODES™ under water. The CLI and physical model experience shows that bad placement of the first row can generate future movement of the armour, it is one of the reasons why it is best to place a straight and level two layer thick rock bund in front of the first row of units to line up the ACCROPODES™.

The standard toe can be improved in two ways. If the bedding layer can move or the lowest armour units can move under breaking waves then the stability can be improved by placing a two layer thick by two units wide rock layer in front of the ACCROPODE™ toe. For this type of structure it is important that the rock is big enough not to be picked up by the waves and thrown onto the toe as this is likely to break the concrete units.

The second design shown in Plate 5 would be to construct a trench to contain the toe and rock fill. This stabilises the initial row of units but more rows of units are required.

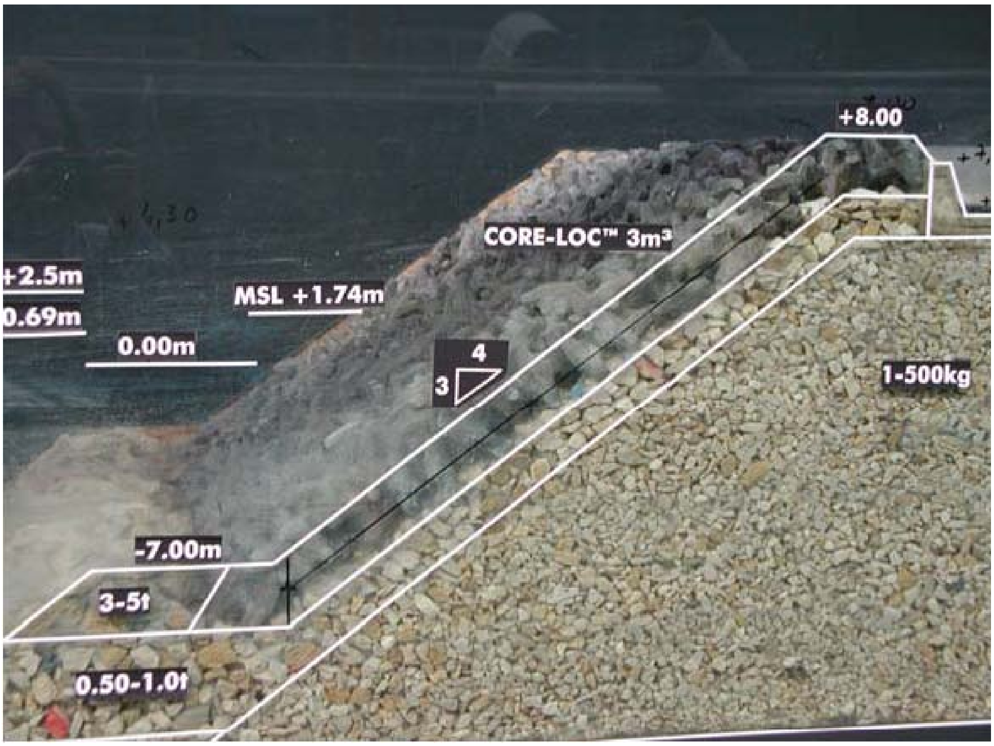

Plate 4: Typical toe, with additional support provided by rock

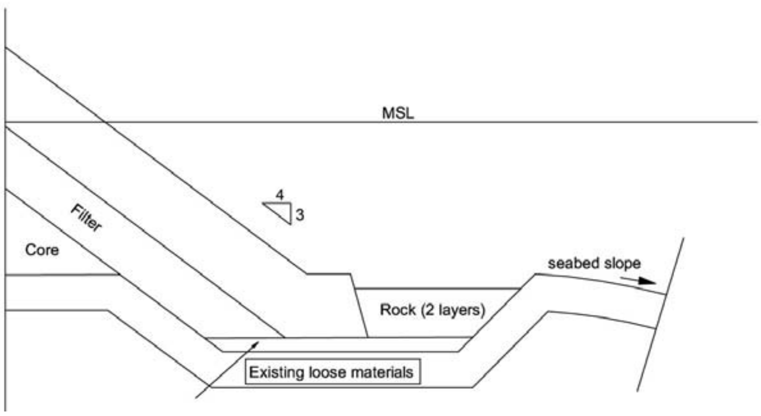

Plate 5: Typical toe constructed in trench

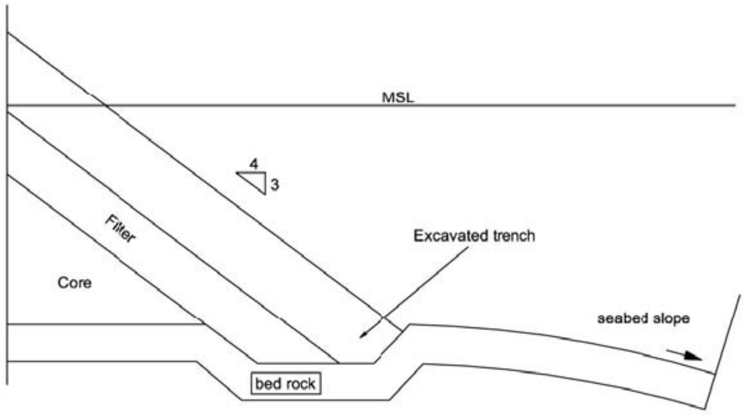

Plate 6: Typical toe in hard ground

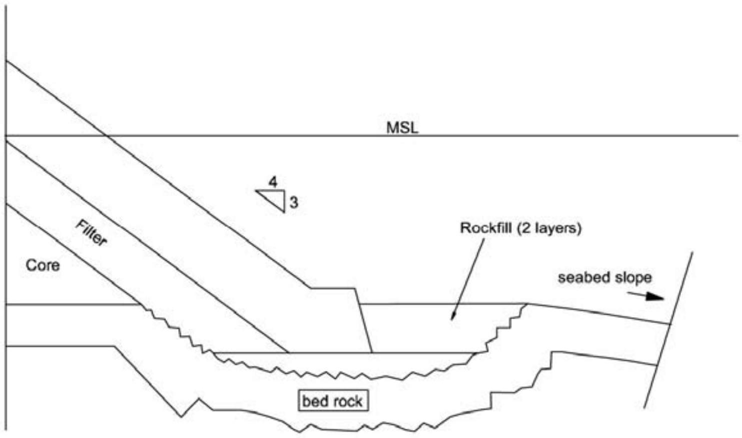

Plate 7: Typical toe in hard ground with rock fill

Rock foundation

The foundation of the revetment or breakwater is even more important when it is to be constructed on a rock bed due to possible slip of the units. There are two details that can be used. These are an embedded toe with excavated trench with no rock fill (Plate 6) or an embedded toe with an excavated trench and rock fill (Plate 7).

Piled / cubed / other

It is possible that excavating a trench is not allowed due to the stability of adjacent cliffs, buildings etc. For this type of location it may be possible to drill piles at a specific spacing for the size of armour units used. Alternatively it is possible to use cubes anchored to the bed. Ranasinghe et al 2009 showed that relatively large Tetrapods could be used to support CORE-LOCTM units on the slope. A number of solutions were assessed which included two sizes of Tetrapods, 12.5T and 20T placed at the rugged toe. Proper interlocking of the Tetrapods was not gained during the tests due to the rock outcrops and incident wave conditions. However, the packing arrangements of the CORE-LOCTM units were strong enough to withstand the design wave conditions. HR Wallingford has recently used 26t cubes and rock to protect the toe in a similar manner at the Port of Toga. Another study at Cirkewwa, Malta, showed that support provided by grouted cubes was superior to the trench used in previous tests. This was another location where the ACCROPODESTM armouring was extended around the roundhead onto the rear of the trunk to protect the rear of the breakwater.

Waves breaking directly onto toe

On some occasions it is possible that waves, which are limited by the depth of water, plunge directly onto the first two or three rows of armour. Due to this wave energy it is possible that armour units in the bottom two rows will be extracted. The only way around this is to make the incident waves approaching the toe less severe. The toe could be designed with a wide berm to break the waves before reaching the structure. Alternatively the toe could be positioned so that it is either higher or lower so that the design waves do not plunge onto the toe. It is possible that reducing the steepness of the bathymetry will also have the same effect.

Seismic zone

If required, rock could be used in front of the toe to avoid slip circles.

Crest details

Crest details are generally more conventional. The most frequently occurring designs have a flat berm at the crest. The berm should ideally be at least 3 units wide to improve crest stability. In some cases, it may be acceptable to use rock at the crest of a concrete unit armoured revetment, as a lighter rock can be considered to have a similar stability at the crest.

The minimum 3 rows of units at the crest may improve the stability but the rule of minimum 3 rows is usually recommended for placement aspect (it is easier to place 3 rows in front of the crown wall).

For safety reasons, it is possible that a designer / architect may want to provide a boundary between structure and roadway that pedestrians / cars cannot cross. The usual method is to construct a wave return wall at the crest. This will also reduce overtopping discharge considerably as the water moving up the slope is blocked by the wall and percolates back through the crest armour. In tourist areas wave walls are generally constructed so that people standing on the promenade can see the sea. A wall height of approximately 1.0m is normally acceptable for this function.

Sometimes armour units are positioned above but supported by the rear wall, this again reduces discharge onto the roadway behind.

For deep water ports it is usual for the structure to be made out of caissons up to 30m high, it is unusual for single layer armour units to be placed as armour on this type of structure.

Number of rows in slope

The maximum number of rows on the slope, was initially established on the basis of systematic tests and experience. These tests were based on a reduction of the cumulative settlements of the units in physical model tests.

CLI's recommendation is as follows: *"The max number of rows must be less than 20 (the maximum limit but not the aim) along the armour slope.*

However, an advised value of max 16 rows is preferred taking into account works contingencies". The risk of settlement of the structure in prototype (that may not be observed in the model due to scale effects) increases as the number of rows increase. While 20 is CLI's suggested cut off limit, fewer rows are recommended if possible. The structure tolerance for settlement of the units needs to be considered in the context of the total design (i.e. the toe detail, the crest details, filter layer sizing, possible unit breakage, etc).

In case the number of rows is between 16 and 20, it is recommended to have a safety margin on the unit volume, as assessed by physical modelling.

In the event that a structure appears to be "optimised" to all of the "limits" - the number of rows, the observed movement of units in the model studies, the filter layer sizing, and the toe design, the collective risk of this structure requiring more maintenance in a design or near design event is greater than if a more conservative set of decisions were made. Certainly there are times when a highly refined design with minimal reserve capacity is warranted. However it is important that the designers understand the impacts that a collective set of decisions may have with respect to a structure performance.

Interlock of units on curved parts of the structures

The number of units in a column of single layer armour units will reduce where the breakwater changes direction. This occurs because the horizontal length of the structure is less at the crest than at the toe. Instead of the usual placement pattern, areas will have units which interlock with 5 units around a hole rather than the usual 4 points. These locations are usually a point of weakness and wherever possible should be incorporated into the structure outside areas of wave breaking etc. The minimum recommended radius for bends should be 10Hs. Regarding the placement mesh and taking into consideration armour unit size, height of the structure and armour slope, the radius must be between 10 and 25Hs in order not to influence significantly the placement mesh. (e.g.: for a project in Brazil, the elbow radius was as much as 35Hs). Tighter radii can be used but it is not recommended unless validated by means of physical modelling).

Joints between units and solid walls

It is inevitable that at some locations new breakwaters, armoured with single layer armour units, will abut to old blockwork or concrete seawalls. These inevitably occur in areas where waves are focused onto the connection If the incident waves at this point are similar to the rest of the structure the lack of interlock with the wall is likely to cause movement of the armour units and failure of the slope. There are generally two solutions.

1. Extend the new breakwater into a more sheltered area where the wave conditions are less severe.
2. Provide a trench in the wall along the line of the armour units to make sure there is interlock between the seawall and the armour units.

Plate 8: Typical curved structure

Plate 9: Joint between existing vertical wall and new CORE-LOC™ armoured structure

Plate 10: Joint between single layer ACCROPODE™ armouring and two layers of Antifer Cubes (coloured)

Plate 11: Construction of an ACCROPODE™ armoured breakwater

Using concrete to fill holes is generally not acceptable if the remediation bonds the surrounding units together. It is possible however to insert the concrete into bags to improve interlock without connection to the surrounding units.

Roundheads

CLI provides clear design guidance for CORE-LOC™ and ACCROPODE™ roundheads stating that the minimum radius of the roundhead should be 2.5Hs measured at the High Water Line.

Care should be taken at the rear of the roundhead. This is usually the location where waves break over the roundhead and pull units from the structure. Best practise would include shaping the roundhead gently into the rear trunk and taking the transition of the single layer armour units back 50m along the trunk (top) from the centre of the roundhead. The transition to smaller units or rock should be diagonal with the larger units/rock below the transition.

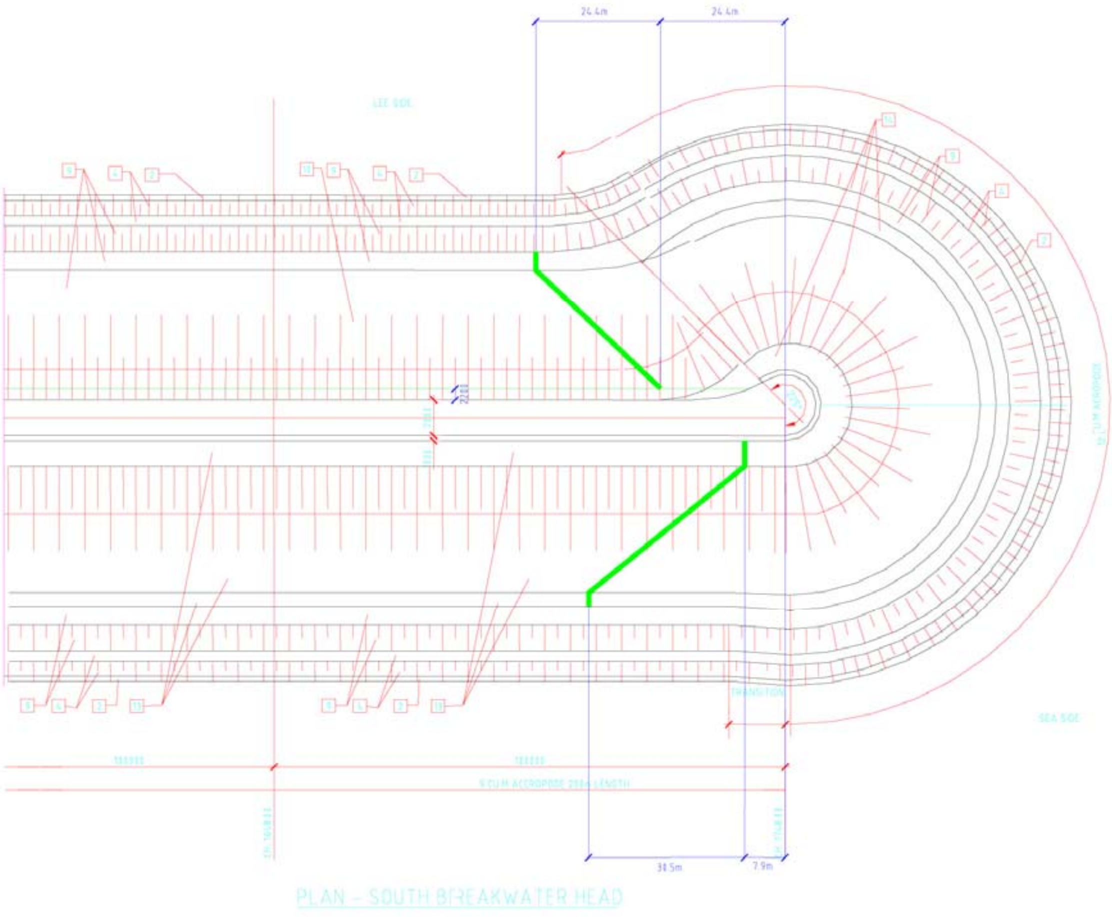

Plate 12: Extended armour detail (green) around the rear face of the breakwater

Plate 13: Construction of a model roundhead

Placement of armour units

Over the last two years the techniques used to place armour units to the correct patterns and orientation have improved. This is important to allow placement at night and also provides an as built drawing for the placement of the armouring.

The main placement rules for CORE-LOC™ are as follows.

a) Units are placed in a single layer.
b) The units are placed according to a diamond shaped grid pattern.
c) Slinging of the units must be varied and tilting of the units preferred.
d) Units shall be placed in deliberately random orientation, with neighbouring units having different orientations.
e) Two neighbouring units within the same horizontal row should not be in contact.
f) Each unit must be in contact with the filter layer.
g) Each unit must key in between two units in the row below.
h) Two adjacent units shall not have their flukes parallel.
i) Packing density shall be at least 100% of the theoretical packing density.
j) There should be no more than 15 rows in total along the armour slope.

Posibloc is primarily an assistance tool to help achieve suitable interlocking underwater. This recent measuring device can be attached to the armour unit during placement, which will provide the placement location and orientation so that in the final structure the interlock between units is correct. This device is an improvement on old methods which used divers to ensure interlock. This is often difficult due to poor visibility and lack of experience.

The main advantages of the system are described below.

1. Reproduces the overall armour configuration with actual unit geometry (as-built)
2. Increases placement output (cost effective)
3. Can operate 24 hours per day.
4. Minimises the use of divers control (safety and accuracy)
5. Initial placement can be compared with armour locations at any time thereafter.
6. Full length survey, worst situation

Physical modelling

The overall complexity of a site and the wave/structure interaction generally advocates the use of a 3d model. The parameters measured during a model study include wave agitation, armour stability, overtopping discharges, pressures inside and outside rubble mound structures and sometimes wave transmission through and around the breakwater. The effect of the modifications on each of these variables can be fully investigated.

Physical model tests are an economical method to assess a number of toe, crest and roundhead layouts to ensure that the most appropriate structure, in terms of armour stability, cost and constructability, is proposed.

For the study shown in Plate 14, a number of solutions were assessed. These included, varying the size of the toe berm rock and introducing a trenched toe (below the level of breaking wave action).

The study concluded that the most effective solution was to introduce a large rubble mound to cover part of the existing 30m deep scour hole, the new rubble mound would be used to support the single layer armouring. Along the trunk, the toe of the breakwater was submerged to keep the rock armoured toe outside the influence of breaking waves.

A plan view of a typical marina is shown in Plate 15. The bathymetry in the area was hard rock. All elements of the toes were embedded to avoid extraction of the armour. An interesting design is shown at the roundhead. This design shows the roundhead as a stepped concrete structure which supports the armour units. The armour units are placed up to the wall which reduces the number of units compared to a conventional roundhead but that can generate unwanted pressure action leading to possibly dislodging the units located close to the wall. Wave probes spread throughout the harbour provides wave heights and periods to assess yacht movement under relatively frequently occurring conditions

Plate 14: Hydraulic model of a CORE-LOC™ armoured structure

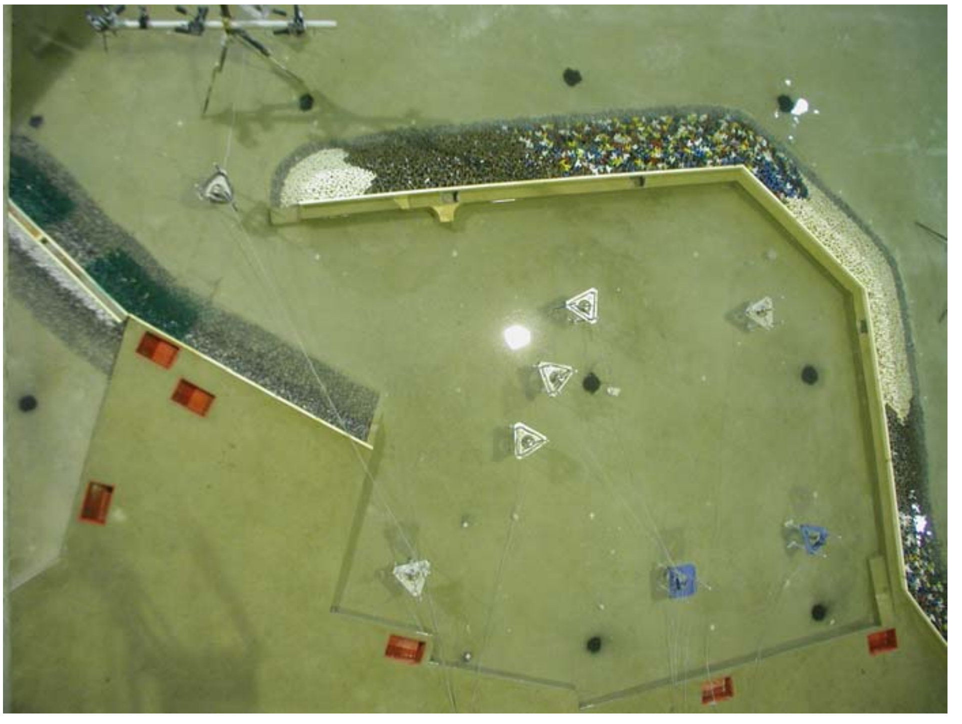

Plate 15: Typical plan layout of physical model

Plate 16: Typical revetment under final construction

As built structures

The structure shown in Plate 16 shows the completion of a typical cross-section. It should be noted that the rear wall is keyed and will therefore provide good support to wave slam forces on the crest units. The structure has two rows at the crest. Note that a minimum of 3 rows of units is usually preferred.

There are some armour units with defects such as concrete chipped off corners, these could have occurred during construction, moving or placement of the units. The number of these damaged units should be minimised.

Conclusions

Unfortunately, there is no such thing as a standard design as each design will be dependent on the prevailing conditions and geographical location. The design of the crest, toe and roundhead detail of a number of structures have been discussed above.

The engineering solutions made by designers are based on an understanding of the overall details of the project and its design, the employer's risk tolerance, maintenance requirements, and budget constraints. While there are always "limits" established for elements such as the number of rows, settlement of units, rocking, etc., performance is a sliding scale - not a black or white limit. The closer that a structure is "optimised" to the limits (presumably to generate cost savings), the greater the risk of non-performance increases. This is complicated by the fact that the design in total is made up of many such decisions. This process can only be managed by the professional judgement of the designers.

Beyond the guidance given in this paper, the designers must reach their own solutions. This will be based on engineering judgement, the project and employer's objectives and risks tolerance, the understanding of the limitations of the modelling processes, and the uncertainty of marine construction.

For projects where some solutions may be innovative and untried we would highly recommend the use of physical models to assess armour stability, hydraulic performance or the interaction of the toe with sediment transport.

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