Testing of Partially Constructed Breakwater Damage

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Summary

Breakwaters constructed in exposed locations are subjected to damage from wave action during the construction phase. A series of physical model tests were undertaken to quantify ambient and storm damage to a partially constructed breakwater. The 2.5km long breakwater extends out to a 25m water depth. The tests examined rates and patterns of erosion along three simulated construction faces of the breakwater (causeway, trunk and head). The results indicated the importance of armouring both the seaward face and the exposed core construction face, to prevent rapid and on-going core loss. For the breakwater examined, 3000-6000 m^3 of material could be lost during poor ambient conditions, increasing to 34000-42000 m^3 for larger storm events.

Background

The project site is exposed to year round energetic ambient and storm conditions. With an estimated construction duration of 18-24 months; the potential material loss, rebuild expense and schedule impact posed a significant risk to the project.

Accordingly, the construction contractor needs to understand the risk of damage to the partially constructed breakwater from the ambient and storm conditions. Forecasting of some storm conditions will be possible, especially cyclonic events, with reasonable warning (i.e. 3-5 days or more) however severe ambient and winter storms will arrive with limited warning (i.e. 0.5-2 days). This limits options for the Contractor to “armour up” the exposed core and filter layers.

An understanding of the likely damage to the partially constructed breakwater was developed through a 3D basin test at a scale of 1:55. The testing consisted of three simulated construction faces along the breakwater in a large (30m x 50m) wave basin. These included the shore-normal causeway (subject to end-on wave attack) and the shore-parallel trunk and roundhead (both subject to normal wave attack). Typical pre- and post-test images of the breakwater trunk are shown in Figures 1 and 2.


Figure 1. Trunk, Pre-Test


Figure 2. Trunk, Post-Test

It was observed that the breakwater underwent significant erosion of the unprotected core. This is a damage level beyond reshaping and is more akin to progressive ongoing erosion, depending upon the wave conditions. Accordingly, the primary aim of the testing was to provide information for the construction contractor on partially constructed breakwater stability and repair rework quantities for the range of ambient and storm conditions. For the project manager the same information allows planning and management of the projects remedial work requirements and overall risk and schedule management. The testing was not specifically structured to facilitate derivation of new design relationships on breakwater reshaping and core erosion, however it is hoped that the information contained herein is of relevance to other coastal engineers faced with similar project challenges.

Related Past Work

The study of the construction phase of breakwater projects has been presented by several authors in the past, and relevant papers are discussed below.

In "Construction Sequence Modeling for Harbour Breakwater", Hendry (1983) presented basin model studies undertaken to assess the optimum sequence of construction for breakwater extensions and new breakwaters, forming the Gansbaai Harbour in South Africa, East of Cape Town. The stability of both partially constructed rubble and caisson style breakwaters was observed under varying sea states. With respect to the rubble breakwater, "severe damage" and "advancing face destroyed" observations were made when Hs exceeded 2-4m when the breakwater was only 1/3 or 2/3 of its final construction length. The breakwater consisted of 50-500kg rubble and 1-3t armour rock. During construction, risks were reduced by construction of the caisson breakwater prior to the rubble breakwater and by limiting the length of exposed rubble without armour protection. This paper seeks to explore and quantify the extent of rubble damage, as observed by Hendry.

The St. George Breakwater in Alaska has been widely published and Gilman (1987) presents results of damage to the North Breakwater roundhead when half constructed. The roundhead berm was approximately half the design width (9.1m vs. 18m) and not at full height (+3.7m vs. +4.9m MLLW datum). The mass armour stone was a 2-10 T grading. The 1986-87 winter storms (5 of), which occurred during construction, had maximum deepwater Hs values of 6.1 – 9.1m and approached the design intensity of 11.2m. Shoaling and wave breaking modify the actual wave heights at the roundhead and these values are not presented.

However the results of pre- and post-storm survey measurements at St. George indicated little damage to the roundhead, with some limited subsidence of the berm (related to underlying sand layer) and consolidation of the mass armour under wave attack. These findings supported the performance of the mass armoured berm breakwater concept used and illustrate that if the breakwater core material mass is sufficient, it can act as a mass armoured breakwater with reduced damage during the construction phase, compared to a more finely graded core material.

Research into the 3-dimensional stability of reshaping breakwaters was presented by Burcharth and Frigaard (1988) shortly after the above work. This examined erosion of the roundhead and characterized the "banana shaped pattern" that develops as erosion proceeds. The work also indicated that there is an almost linear relationship between recession of the roundhead (central crest end) and number of waves. Initial guidelines for the design of roundheads with moderate damage were proposed, with $Hs/\Delta Dn50 < 3$. Accordingly this work contains relevant findings on the roundhead recession erosion rate and erosion patterns which can be compared to the new work presented herein.

In more recent work, Van Gent and Van Der Werf (2010) focus on the temporary stability of the submerged portion of a breakwater roundhead, often placed by floating plant, while the upper part of the breakwater is constructed by land based equipment. The paper looks at the need to ensure stability of the temporary portion and to understand the influence of the temporary section on wave conditions affecting the stability of the upper part of the breakwater during a winter storm season. Areas of varying damage level for different wave heights and angles of attack are determined and provide useful insights to help design armour in these areas. The focus is on assessing overall stability with moderate levels of damage, with Nd (number of stones displaced/number of stones in layer) often < 0.15.

Mulders and Verhagen (2012) have modeled damage to breakwater cores under wave attack. The focus was to assess the influence of stone grading on core deformation and longshore transport under differing wave heights and angles of attack. The work showed an increase in deformation and transport for wider graded cores, typical of quarry run material. Two-dimensional deformation of the core along the trunk was correlated against currently available formulas. Analysis of core volume loss on the roundhead itself is not presented and it was outside of the scope of the underlying work by Mulders (2010). It is this core volume loss that is presented herein.

Breakwater Details

The breakwater tested was an Icelandic berm breakwater design (JFA, 2011). The design had been refined through an extended 2D and 3D test program. It consisted of various core and filter layers underlying the primary armour on the berm, as shown in Figure 3 for the Breakwater Trunk.

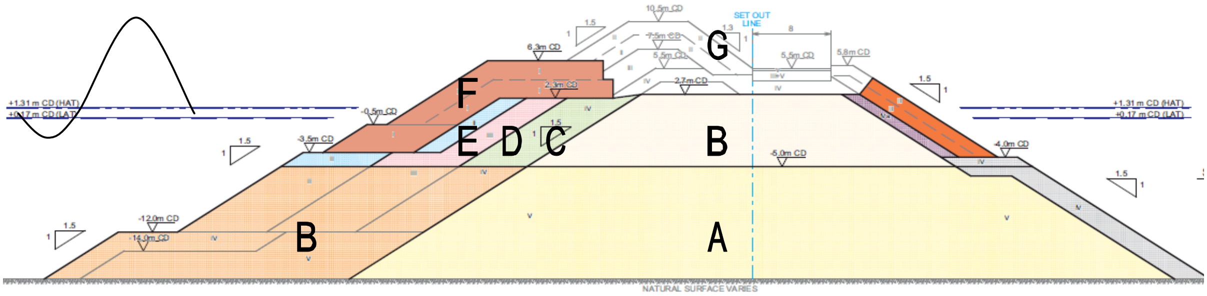

Figure 3. Typical Breakwater Cross Section, Construction Phases A to G shown

Seven phases of the breakwater construction process were selected for modeling, as shown in the Figure above. These included low level to high level core placement, and various filters and armour layers. Each phase was modeled at 30m long (prototype) together with a 40m long completed design section. The construction phases are summarized below:

- Phase A – Core below-5m Chart Datum (CD), placed by marine plant
- Phase B – Core above -5mCD and remaining Filters/Armour below -5mCD
- Phase C – First filter above -5mCD
- Phase D – Second filter above -5mCD
- Phase E – First Primary Armour
- Phase F – Remaining Primary Armour
- Phase G – Completed Crest

Testing Objectives and Program

The objectives of the testing were to gain an understanding of, and quantify where possible:

- Stability of the partially constructed sections under varying wave loads
- Material loss from the sections during the modeled ambient and storm conditions
- Rework quantities of accreted material on the lee side of the breakwater
- Cross contamination of materials once mobilized by wave action
- Overtopping and loss of construction platforms on the partially armoured sections

The testing program (WorleyParsons, 2010) included a wave calibration phase to establish the ambient sea states, with the storm conditions previously established from prior 3D modeling work on the project. Sea states were random Jonswap spectra with long crested waves. Three test sections were constructed within the basin, as the breakwater was long enough to allow separation of these test sections with no influence on the wave conditions impacting the adjacent test panel. One wave direction was tested, as described below:

- Roundhead at -23mCD, shore parallel and subject to normal angle wave attack,
- Trunk at -16mCD, shore parallel and subject to normal angle wave attack, and
- Causeway at -12mCD, shore normal and subject to end on wave attack.

Figures 4-6 (HRWallingford, 2011) show these test sections and associated construction phases, as described above. The arrow indicates approximate angle of wave attack.

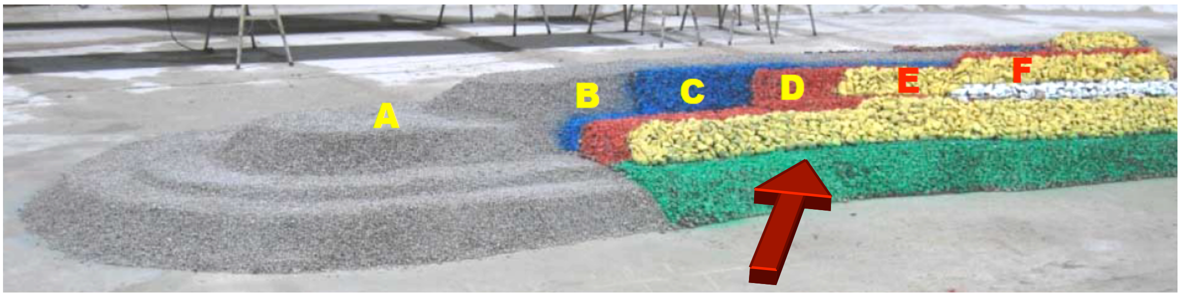

Figure 4. Roundhead, Pre-Test

Figure 5. Trunk, Pre-Test

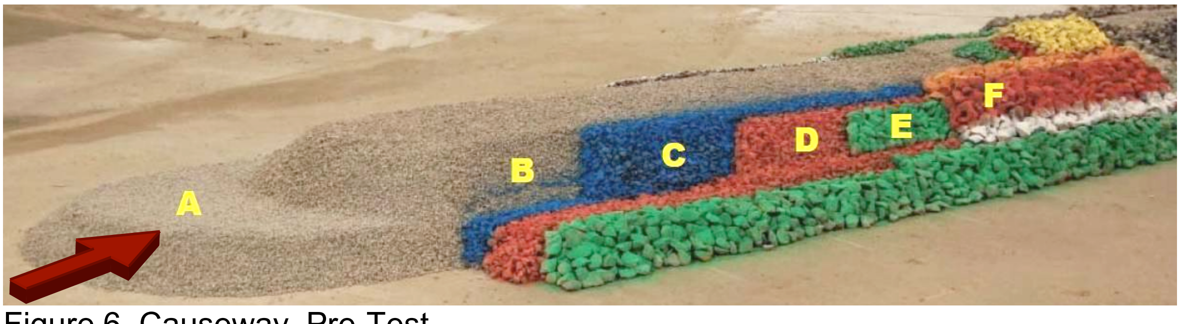

Figure 6. Causeway, Pre-Test

Metocean Conditions

Wave conditions vary between the sections with the shallower seabed at the trunk and causeway sections leading to an increased number of breaking and broken waves respectively. For the varying wave conditions and core/filter/armour gradings across the test sections, the dimensionless Stability Number (Van Der Meer, 1987) parameter ($N_s = Hs/\Delta D_{n50}$) data are shown in Table 1 below. The D_{n50} value adopted is that of the material about the water level (rather than that below -5mCD for example) and first exposed to wave attack, together with the finer core material. The wave period varied between 12 to 16 seconds across the range of ambient to storm conditions. All test conditions were run for 6 hours (prototype).

The conditions that the partially constructed breakwater sections are exposed to thus vary from quite benign Ambient 1 conditions in the N_s 1-4 range where unprotected Phase B core should behave as a stable slope, increasing in mobility even in the Ambient 2 conditions to the N_s 3-6 S-shaped and berm breakwaters range. Under Storm conditions, the Core material is expected to be highly mobile and behave as a rock slope/beach for N_s 6-20. As the Metocean conditions increase, the exposed filter and armour layers also become increasing mobile, especially in Phases C & D. The complete cross section, Phases F & G, is designed to be statically stable.

As a comparison, the previously discussed work of Burcharth and Frigaard (1988) suggested a design guideline, at the Roundhead, of $Hs/\Delta D_{n50} < 3$ for moderate damage, a value exceeded in this case under Ambient 2 conditions.

Table 1. Metocean Conditions, Stability Number (N_s) shown

Test Section	Construction Phase	Ambient 1		Ambient 2		Storm 1		Storm 2		Storm 3	
		Exposed Filter or Armour	Core	Exposed Filter or Armour	Core	Exposed Filter or Armour	Core	Exposed Filter or Armour	Core	Exposed Filter or Armour	Core
Roundhead	A*		2.7		4.4		5.6		8.9		10.3
	B		2.7		4.4		5.6		8.9		10.3
	C	1.2	2.6	1.9	4.2	2.4	5.3	3.8	8.5	4.4	9.9
	D	0.8	2.6	1.3	4.2	1.6	5.3	2.6	8.5	3.0	9.9
	E	0.5	2.6	0.8	4.2	1.0	5.3	1.6	8.5	1.8	9.9
	F	0.4	2.6	0.6	4.2	0.8	5.3	1.3	8.5	1.5	9.9
	G	0.4	2.6	0.6	4.2	0.8	5.3	1.3	8.5	1.5	9.9
Trunk	A*		2.9		4.7		6.1		9.5		11.5
	B		2.9		4.7		6.1		9.5		11.5
	C	1.2	2.8	2.0	4.6	2.6	5.9	4.1	9.2	4.9	11.0
	D	0.8	2.8	1.4	4.6	1.8	5.9	2.8	9.2	3.3	11.0
	E	0.6	2.8	1.0	4.6	1.3	5.9	2.0	9.2	2.4	11.0
	F	0.4	2.8	0.7	4.6	1.0	5.9	1.5	9.2	1.8	11.0
	G	0.4	2.8	0.7	4.6	1.0	5.9	1.5	9.2	1.8	11.0
Causeway	A*		2.5		4.2		5.7		9.4		10.8
	B		2.5		4.2		5.7		9.4		10.8
	C	1.1	2.4	1.8	4.0	2.4	5.4	4.1	9.1	4.6	10.4
	D	0.7	2.4	1.2	4.0	1.6	5.4	2.7	9.1	3.1	10.4
	E	0.5	2.4	0.9	4.0	1.2	5.4	2.0	9.1	2.2	10.4
	F	0.5	2.4	0.9	4.0	1.2	5.4	2.0	9.1	2.2	10.4
	G	0.5	2.4	0.9	4.0	1.2	5.4	2.0	9.1	2.2	10.4

* Top of Core is below -5mCD

Testing Results

Photography, laser scanning and digital surface models (HRWallingford, 2011) were used to assess the changes in the model from each sea state. Erosion/accretion volumes were then determined using the 'Surfer' software and are presented in Table 2.

Table 2. Cumulative Erosion & Accretion Volumes, m^3 (prototype units)

Test Section	Ambient 1		Ambient 2		Storm 1		Storm 2		Storm 3	
	Erosion	Accretion	Erosion	Accretion	Erosion	Accretion	Erosion	Accretion	Erosion	Accretion
Roundhead	500	700	2700	3000	7700	9600	29600	28100	43200	42000
Trunk	1100	800	4400	5300	9800	10800	31500	31700	40500	39600
Causeway	600	600	5900	6200	11300	13600	31200	28900	42000	33700

It can be seen that the material losses can be substantial. By dividing these volumes by the cross sectional area of the breakwater, and assuming a two-year construction duration, lost progress and recovery time can be around 2-4 days for an Ambient 2 event and 2-4 weeks for a larger Storm event.

Damage Evolution

The evolution of the roundhead and trunk sections over the five consecutive tests is shown in Figure 7 and the causeway in Figure 8. The breakwater model was not rebuilt between tests, so cumulative damage is shown. The arrow indicates approximate angle of wave attack.

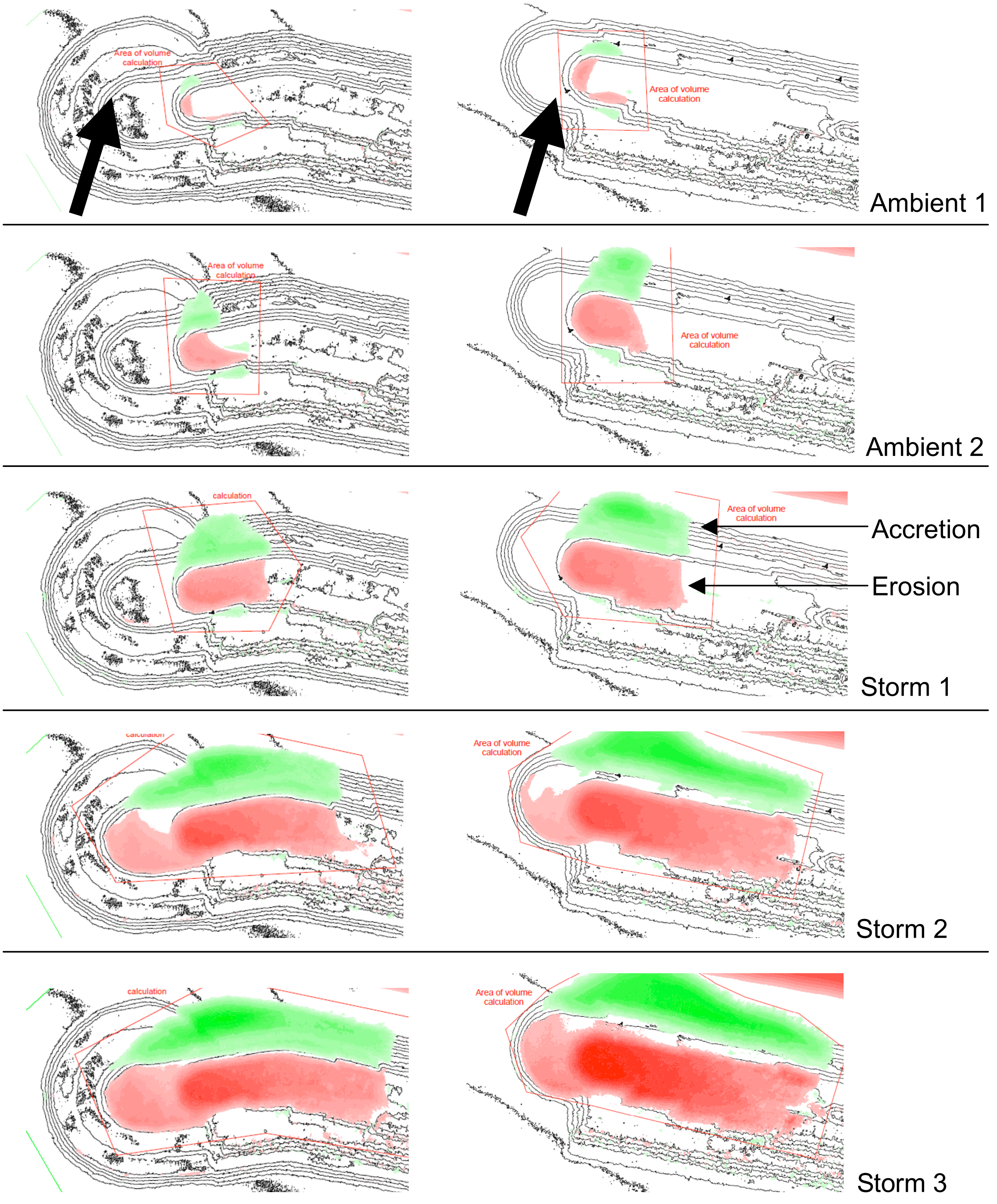

Figure 7. Damage Evolution, Roundhead (left), Trunk (right).

Similar trends can be seen for the Roundhead and the Trunk, with slightly greater movement on the Trunk being consistent with the high N_s values. Initially there is slight reshaping of the exposed Phase B Core under Ambient 1 conditions increasing to complete Phase B core loss in Ambient 2 conditions with N_s in the range of 4.4-4.7. This initiates failure of the Phase C, which is complete after the Storm 1 condition. Damage continues to increase as Storm conditions increase. It is notable that the Phase A Core at -5mCD is quite stable especially at the Roundhead. This allows flexibility in terms of advancing marine plant based construction well in front of subsequent land based Phases, with little risk of the material being reshaped during Ambient and Storm conditions.

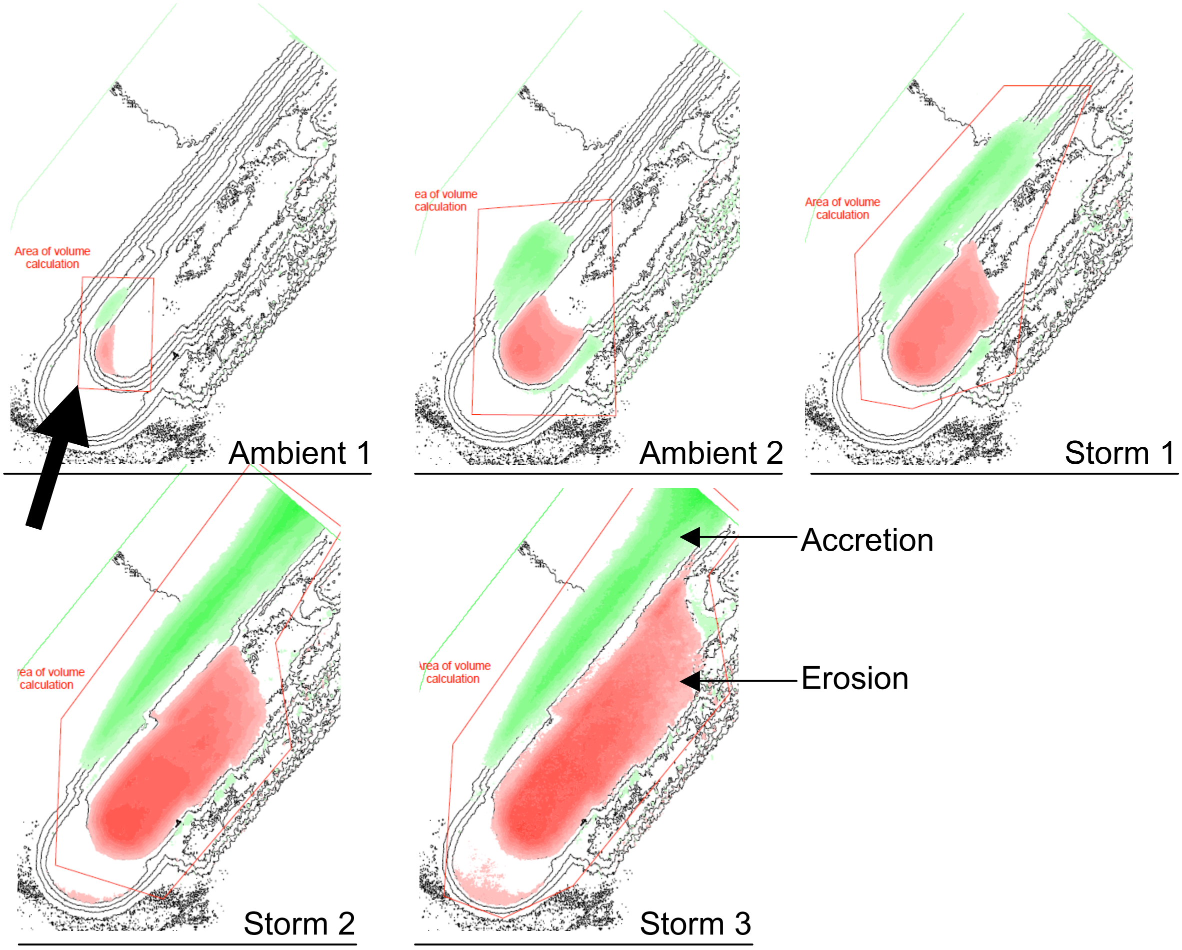

Figure 8. Damage Evolution, Causeway.

On the Causeway, slight erosion of the exposed core can be seen after the Ambient 1 condition. This erosion rapidly increases with increasing Metocean conditions, and in a quite different pattern to that of the roundhead and trunk. Under Ambient 2 and Storm 1 conditions the erosion volume is greater than that for the Roundhead and Trunk.

Another noticeable feature is the extensive distribution of the eroded material down the entire lee side of the causeway, as the angle of wave attack was slightly off a true end-on angle. This highlights a particular material contamination issue, as any complete armouring on that side of the causeway will be contaminated with finer core material. To a much smaller extent this also occurs on the seaward side combined with loss of filter and armour rock due to the extensive core loss.

Conclusions

The testing program undertaken has allowed quantification of erosion volumes along the partially built breakwater and these can be seen to be significant, in terms of lost construction value, recovery and repair costs, and project schedule delays.

- The patterns of material loss and accretion conform loosely to the banana shaped pattern identified by Burcharth and Frigaard (1988), especially at lower levels of damage.
- The complete loss of core and subsequently any protective armour stone correlate with the observations of Hendry (1983), with additional definition and better volume data now available due to improved laboratory tools, such as laser scanning.
- The loss of core material occurs at the exposed construction face, with a distinct wash away line that cuts across the breakwater in the direction of wave propagation, as shown in Figure 9 for Ambient 2 and Storm 1 post-test conditions. The location and progression of the wash-away line is shown as a dashed line.

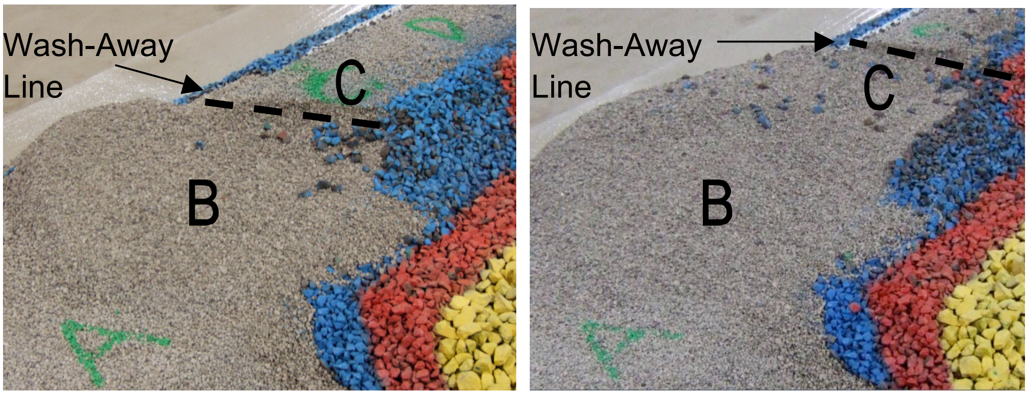

Figure 9. Core loss undermining armour layer, Trunk - Phase B and C.

- Core is lost along this wash-away line, rapidly undermining any suitably sized filter or armour rock on the exposed seaward face of the breakwater.
- The filter and armour stone, once displaced from the seaward face of the breakwater, mix with the core material and are transported across the breakwater to the lee side. They do not provide any noticeable stability to the top of core area.
- The loss of core from the -5mCD level was limited, at least until the most severe storm conditions, thus allowing increased flexibility in construction scheduling with marine based plant.
- The angle of wave attack is also clearly important. In this test program, only one angle of attack was tested (correlating to most frequent ambient and winter storm direction). The differing damage evolution on the Causeway Section provides an indication of erosion patterns during end-on wave attack.

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