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E-mail	
Page	1 of 6
Subject	**Risks of Accroberm toe protection**
Projectnumber	**968000**

To whom it may concern,

From time to time DMC receives questions about the application the Accroberm™ concrete unit without a rock toe in front of it and why DMC doesn't apply such a solution with Xbloc. The Accroberm™ solution is presented by CLI as a substitute for a rock toe and as a substantial cost saving.

In this letter DMC's opinion about this technology is presented.

Xbase patent (2006)

DMC developed a similar technology under the name Xbase (patent filed in 2006). This unit has been applied on multiple project with a rock toe in front of the armour layer.

The Xbase patent comprises a shape which is very similar to the Accroberm™. These can be seen in Fig16, Fig17, Fig18 and Fig19 from the granted patent (see Figure 1 below).

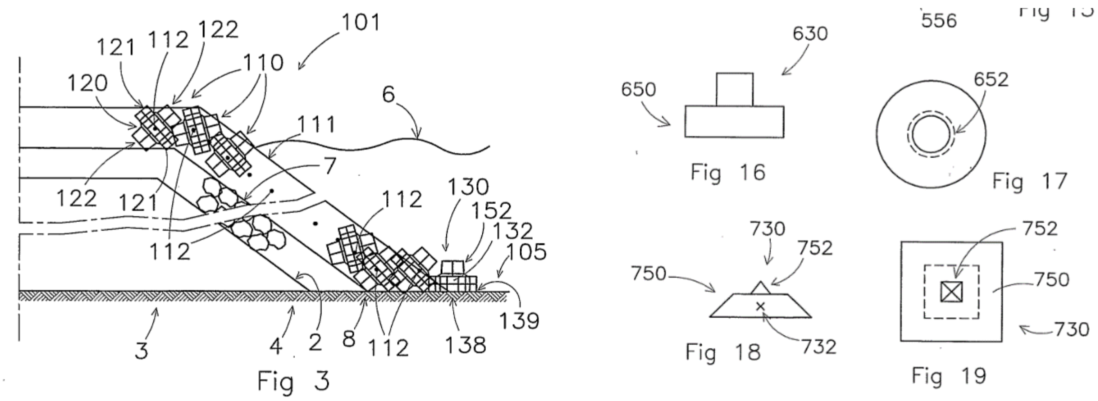

Figure 1: Figures from the Xbase Patent PCT/NL2006/000366

It is important to note that DMC developed the Xbase with the objective to facilitate placement of the armour units in the first row. The Xbase is applied in combination with a rock toe.

Risk of breakwater instability without a rock toe
In 2014, CLI presented a paper at the ICCE conference in Seoul stating that a design without a rock toe to support the first row of armour units leads to risk of instability of the armour layer. (A fragment of this paper which deals with the toe stability is added to this letter.)

At the time the paper was written back in 2014, the Accroberm™ was not yet developed by CLI, but the paper clearly puts emphasize on the connection between the first and second row of armour units.

Importance of block placement row 1 and 2
If no rock is placed in front of the first row of armour units (e.g. Accroberm™), the connection between of the first 2 rows of armour units is very important. If the interlocking connection is not strong, the Accroberm™ can move seawards which can lead to more settlements and instability of the armour layer.

For good accurate placement and a good connection between the first 2 rows, it helps if the rocks underneath the Accroberm™ unit are small, as shown in Figure 2. However, in this situation the fine rocks will be washed away by the waves and eventually the Accroberm™ units will be undermined. (See also section below about the trial project with Accroberm™.)

If the Accroberm™ is placed on larger rocks as shown in Figure 3, the rocks will be more stable against the waves. However from projects with Xbase we know that placement on top of larger rocks becomes more difficult. Therefore the connection between the Accroberm™ and the Accropodes™ row is expected to be more difficult when placed on large rocks. This in its turn leads to risk of instability.

Figure 2: example Accroberm™ on very fine stones (from CLI website)

Figure 3: Accroberm™ placed on large rocks during model tests (CLI website)

Prototype trial with Accroberm

A trial project was performed with Accroberm™ in the Cherloc project. Information can be found about this project online at https://www.unicaen.fr/projet-cherloc/.

Some photos are shown below where it can be seen that the Accroberm™ blocks have shifted seawards. In this case the blocks seem to be placed on a gravel layer on a beach. It may be possible that the shifting of these blocks is due to undermining of the beach in front of the structure. However the trial does demonstrate the risk of instability if the bedding layer underneath the Accroberm™ is undermined.

Figure 4: Photos of Accroberm prototype project in France

Physical model tests with Accroberm

For the stability of the toe, 2D tests are not considered the most critical tests. Therefore 3D model tests with oblique, breaking waves in shallow water are considered more relevant. To our knowledge the publications about 3D physical model tests with Accroberm™ are limited.

During the SCACR in Istanbul in 2023 a paper about 3D model tests with Accroberm™ was presented by Leone et. al. The presentation can be found at https://www.scacr2023.org/en/. A pdf of the presentation is included in the attachment.

The tests consisted of repeated test with waves of 120% of the design wave height. Such overload conditions are commonly applied during physical model tests with single layer armour units to prove the resilience of the design against higher waves. Typically a duration is applied of 1000 waves or a prototype duration of 6 hours which would contain 1728 waves in these tests. During the first tests with only 500 waves however, several displacements of Accroberm™ units and failure of the breakwater roundhead was observed.

Figure 5: Photo of as-built section of roundhead and damage after test series 1

During the subsequent test series, failure of the trunk was also observed. The tests show that the Accroberm™ does not provide resilience against the tested overload conditions.

The typical cross sections of this Arenella Project can be found at https://va.mite.gov.it/. It is relevant that this design contains a rock toe in front of the Accroberm™ units.

Conclusions
Based on DMC's experience with Xbloc and Xbase and based on the available information about the Accroberm™, DMC draws the following conclusions:

- The Accroberm™ technology introduces substantial risks to a project.
- The toe of a breakwater is the most critical part and repairs are practically impossible.
- DMC recommends to place a rock toe with a thickness of at least 1 D_{n50} of the toe rock in front of the first row of armour units.

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Fragment about toe stability taken from CLI paper Giraudel et.al., 2014, "Single-layer breakwater armouring: feedback on the AccropodeTM technology from site experience"

Toe units stability

In the first decade of use, the code of practices did not mention the necessity of a toe reinforcement made of heavy rocks in front of the first row of concrete units (Figure 10). After several years of use, and considering the potential unstability of the first row in case of settlements, it was recommended to buttressing the first row of armour units with rocks. This issue was not predictable earlier since the feed-back from the site was very poor and no issue at the design stage was seen. Physical modeling tests did not show significant impact on the armour stability in case of absence of toe reinforcement. This practice allows to minimizing the adverse effects in case of construction defects when placing the first row of units. When the interlocking between the first and the second row of units is efficient, the units of the first row remain stable in many of cases. However, this wise practice is an additional safety for the long life of the structure (settlement of the armouring, settlement of the underlayers), until new enhanced placing methods or toe alternatives are defined.

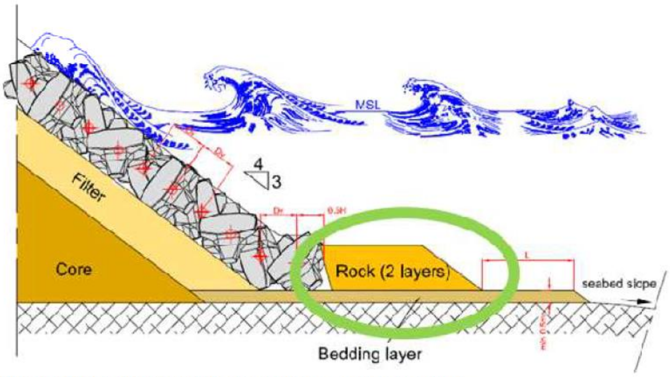

Figure 10. Basic principle for rock toe reinforcement.

The inspections have confirmed that the unsupported units can tilt over and become disconnected from the armouring. On several structures, the first row of ACCROPODE™ units was found to be no longer in contact with the rest of the layer (Figure 11). Therefore, the armour layer remains unsupported by the toe units and is sometimes "hanging" above the first row without touching it. It was not possible to determine when the isolated first row of units was extracted (at the construction or afterward). Such disconnection can take place when placing the second row of units, under storm conditions, or later when the lower layers (bedding layer for example) settle. The inspections have revealed that, the contact between the rocks and the first row of units is important to secure the units and prevent them to move away or tilt over. Specific attention is to be paid when placing the rocks in contact with the concrete units.

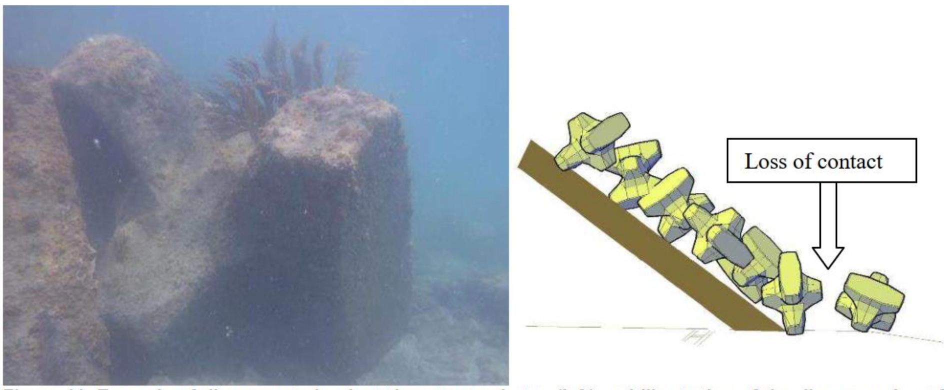

Figure 11. Example of disconnected unit at the structure's toe (left) and illustration of the disconnection of the first row of units (right).

Presentation by Leone et.al. 2023, "damage progression of a rubble mound breakwater with Accropodes II and Accroberm I armour units using image-based approaches"

SCACR 2023
10th Short Course/Conference on Applied Coastal Research
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DAMAGE PROGRESSION OF A RUBBLE MOUND BREAKWATER WITH ACCROPODES II AND ACCROBERM I ARMOUR UNITS USING IMAGE-BASED APPROACHES

Elisa Leone[1], Alberica Brancasi[1], Antonio Francone[1], Agostino Lauria[1], Andrea Paglialunga[2], Elio Ciralli[3], Leonardo Tallo[4], Antonino Viviano[4], Giuseppe R. Tomasicchio[1]

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UNIVERSITÀ DEL SALENTO
L'Ateneo tra i due mari

Tuesday, 5th September
Dedeman Istanbul Hotel, ISTANBUL/TURKEY

EUMER
EUropean Maritime & Environmental Research

- **Rubble mound breakwaters** are built for coastal protection and wave energy dissipation.

- **Accropode II** units' unique design ensures robust interlocking, minimizing wave-induced shifting or dislodgment.

Ref. https://www.concretelayer.com/

- The **progression of damage** and failure modes plays a pivotal role in maintenance and repair efforts.

- Research helps identify **vulnerabilities**, **limitations**, and mechanisms contributing to breakwater failures.

About 150 references on this topic, chronologically discussed over almost a century of history

DAMAGE MODELS

- **Van der Meer (1988)**: linked "no-damage" and failure criteria to different values of eroded area, *S,* depending on breakwater slope.
- **Melby and Kobayashi (1998)**: introduced iterative damage model allowing non-zero initial damage, with slower increase over time.
- **Van Gent et al. (2003)**: enhanced Van der Meer's work with new shallow water data.
- **Castillo et al. (2012)**: introduced a versatile stochastic damage model without predefined functions, using properties-based equations instead.

MEASUREMENT OF DAMAGE

Damage definition:

- **Losada et al. (1986)** defined three qualitative damage levels;
- **Vidal et al. (1991)** added a fourth stage (initiation of destruction).

Damage parameterization:

- ***S** : d*imensionless eroded area related to the qualitative structure respo $S = A_e / D_{n50}^2$;
- ***N_o** :* number of units displaced out of the armor layer within a strip width of one equivalent armour length;
- ***E, L*** : dimensionless eroded depth and dimensionless eroded length.

Damage measurement:

- **visual Approach**: fixed camera (photo overlays, flicker technique);
- **measuring Approach**: mechanical profilers, LIDAR, DSP, SfM, RGB-D cameras, and

1. Laboratory Investigation :
- EUMER laboratory;
- small-scale rubble mound breakwater;
- experimental set-up.

2. Methodology :
- definition of sectors and initial volume calculation;
- volume changes between wave steps;
- extraction of cross-sections.

3. Results :
- accretion and erosion maps;
- time-varying evolution damage;
- evaluation of cross-section profiles.

4. Conclusion :
- enhanced maintenance and repair insights;
- identification of vulnerabilities.

LABORATORY INVESTIGATION – 3D PHYSICAL MODEL

EUMER laboratory
(EUropean Maritime Environmental Research)
University of Salento (Lecce, IT).
(www.eumer.eu)

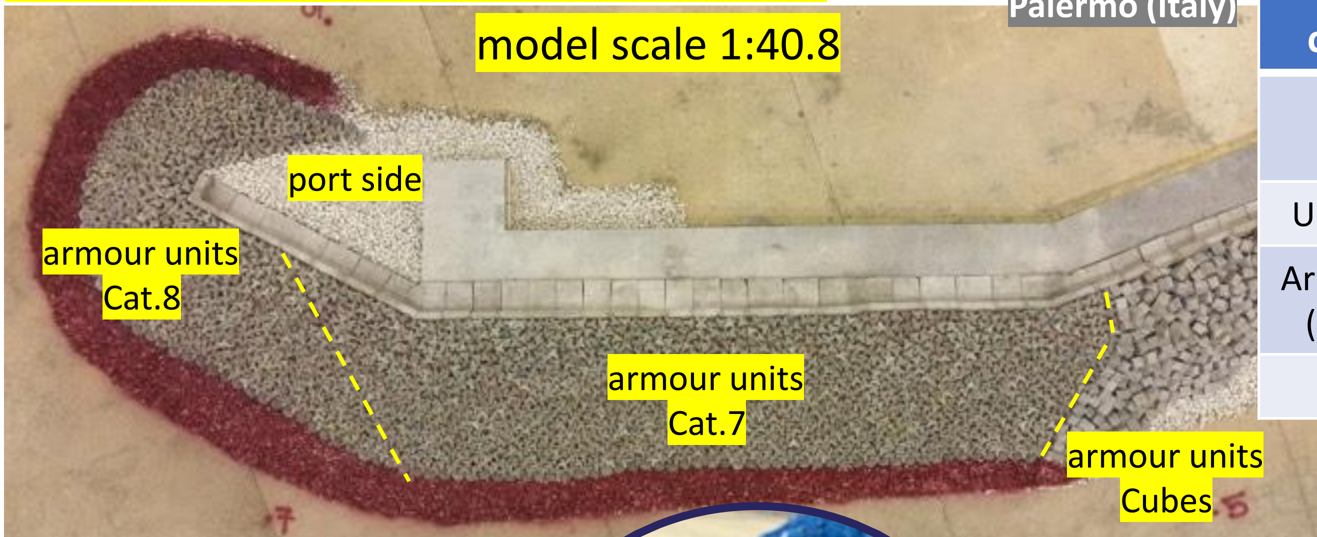
3D Wave Basin

- 29.5 m long, 28 m wide and 1.6 m deep;
- piston-type wave generator;
- spending beach at the end of the basin.

Unidirectional and directional wave fields, regular waves and wave spectra.

LABORATORY INVESTIGATION – 3D PHYSICAL MODEL

Small-scale rubble mound breakwater



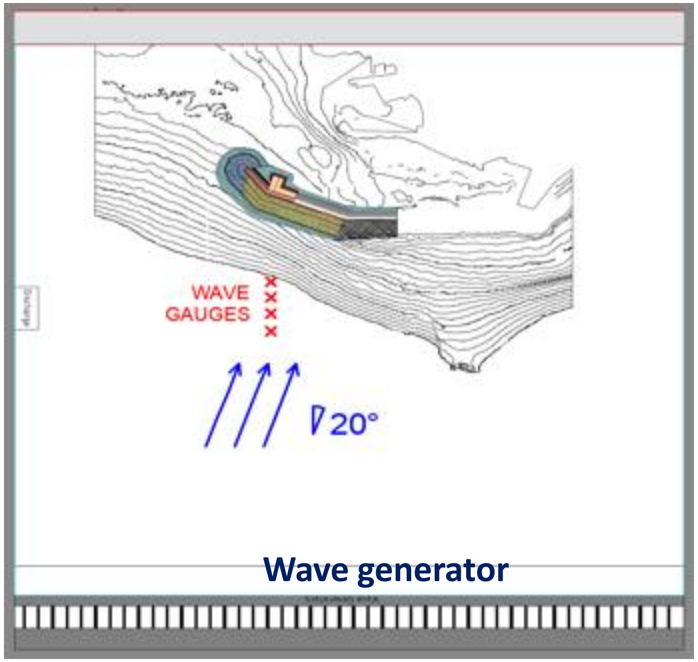
Rock category	D_{n50} (cm)	M (g)
Core	0.1 – 0.3 0.3 – 1.8	0.1 – 0.9 0.9 – 16.0
Under Layer	1.8 – 2.3	16.0 – 31.6
Armour Layer (port side)	2.2 – 2.4	19.5 – 34.4
Toe	1.8 – 2.3	11.5 – 23.0

Armour units	V (cm^3)	M (g)
ACCROPODE II Cat.7	87.7	205.3
ACCROBERM I Cat.7	89.4	205.5
ACCROPODE II Cat.8	116.4	273.0
ACCROBERM I Cat.8	118.0	271.2

Experimental set-up

Potential extreme scenario

Target wave characteristics T_r = 100y Dir = 20 deg					
Model scale			Prototype scale		
H_s (m)	T_p (s)	h (m)	H_s (m)	T_p (s)	h (m)
0.197	1.96	0.629	8.04	12.5	25.66



	N. waves	Duration (s)
Wave step 1	500	1078
Wave step 2	500	1078
Wave step 3	1000	2056
Wave step 4	2000	4012
Wave step 5	2000	4012
total	6000	12236

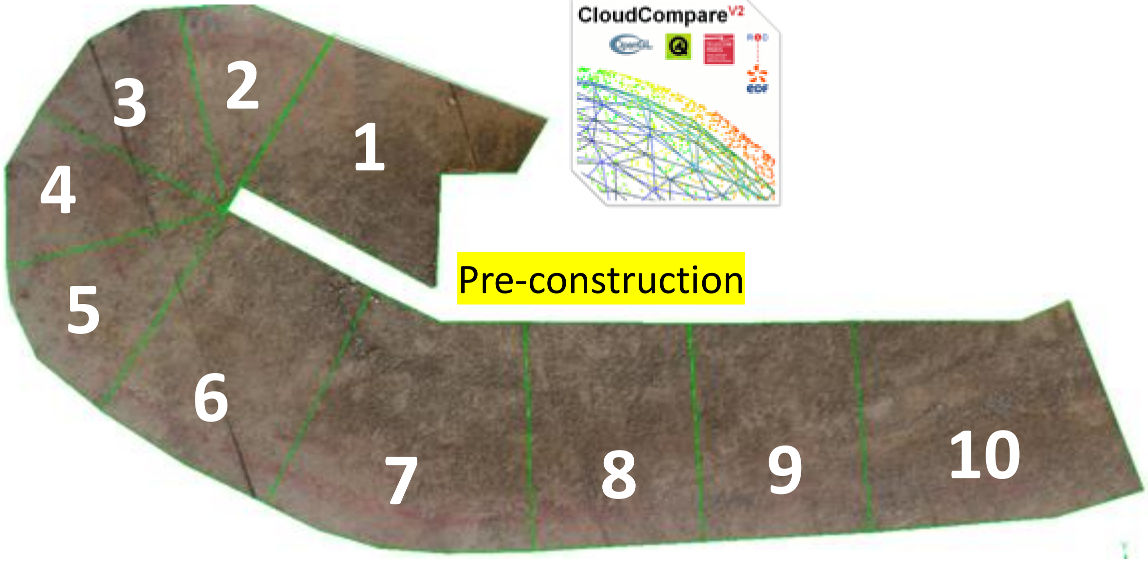
Survey with Unmanned Aerial Vehicle (UAV) equipped with a high-resolution camera after each wave step

Sector definition

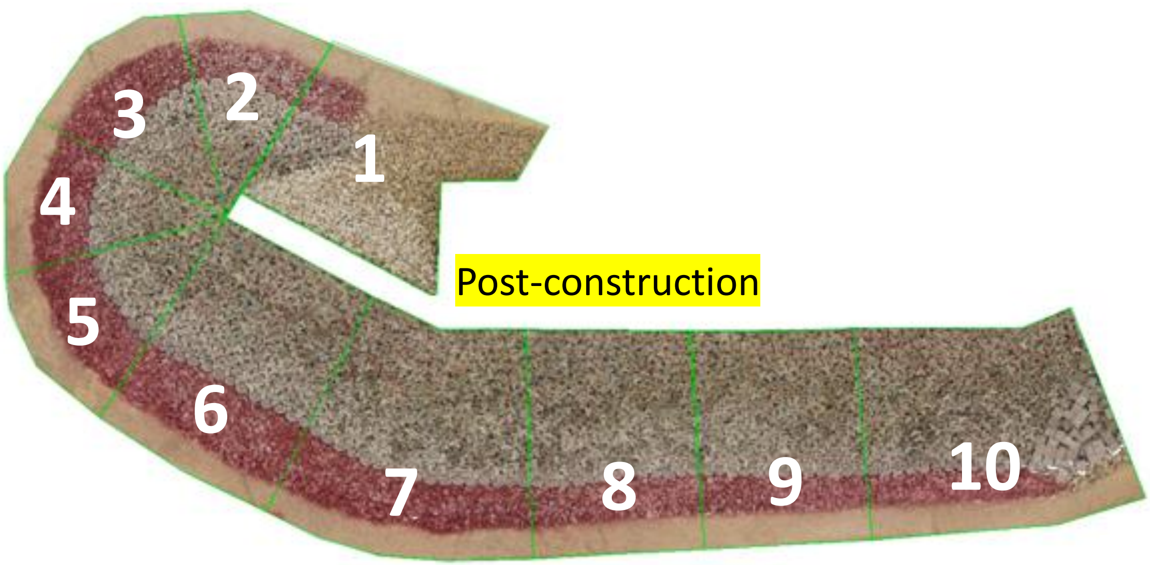
- model footprint division into 10 sectors (circular sectors at roundhead).

Initial volume calculation

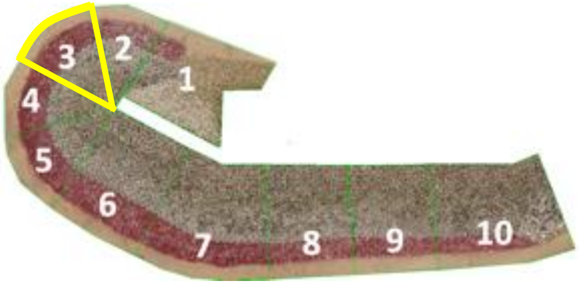
- pre-construction and post-construction point clouds gained by UAV-based bathymetry survey;
- statistical outlier remover;
- subtraction of point clouds for sector volumes.



Pre-construction

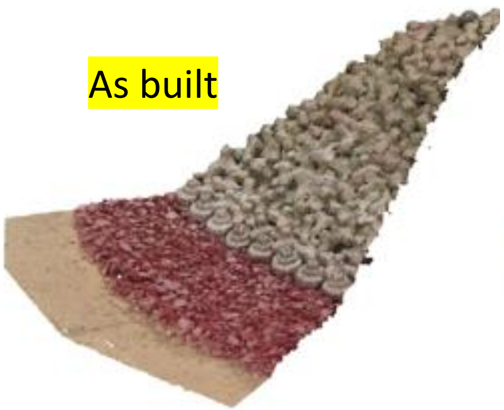


Post-construction



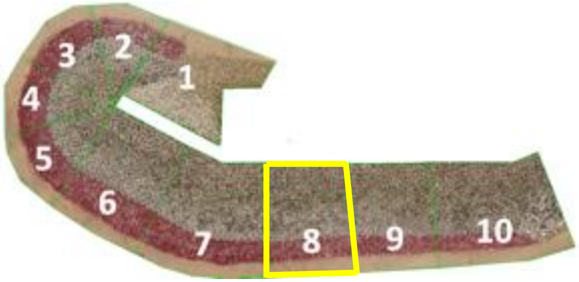
Volume calculation between wave steps

- volume calculated using parallelepiped volume summation, with base area as elementary cell area and height as z-coordinate difference (dV = grid step * grid step * distance);
- calibration, based on known-size armor units, determined optimal 1 mm grid step for volume computation, matching shifted armor units with observed count.



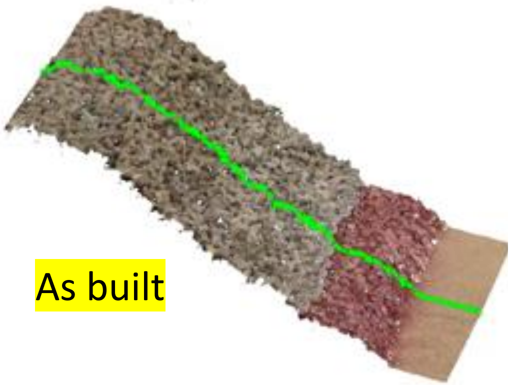
<u>empty cells filling</u>: Interpolation of points for empty cells using neighboring data

DAMAGE PROGRESSION ANALYSIS - METHODOLOGY

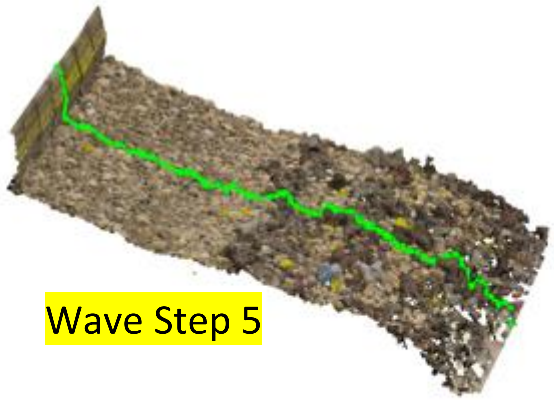


Cross-sections extraction

- definition of the central line for each sector;
- 2D contour extraction along the centerline from the point cloud of each section;
- repetition of the process for each survey.

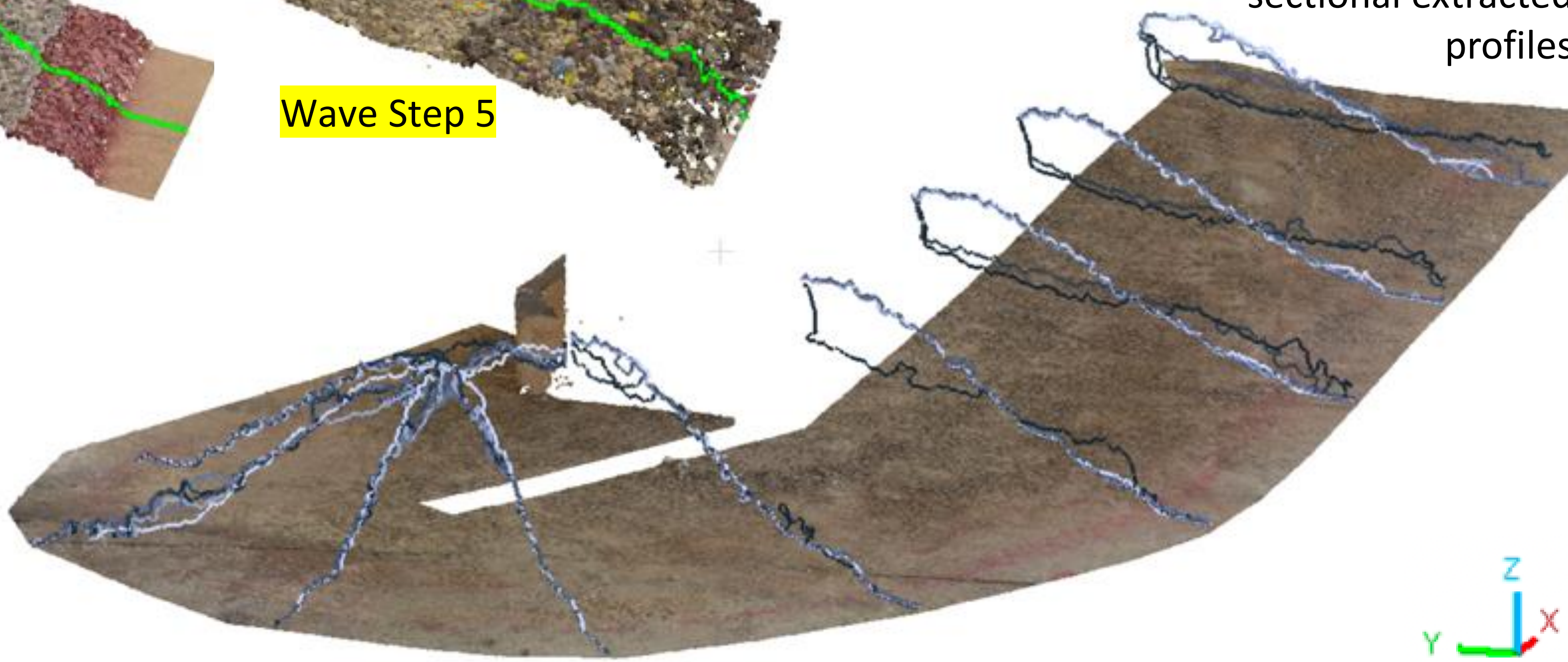


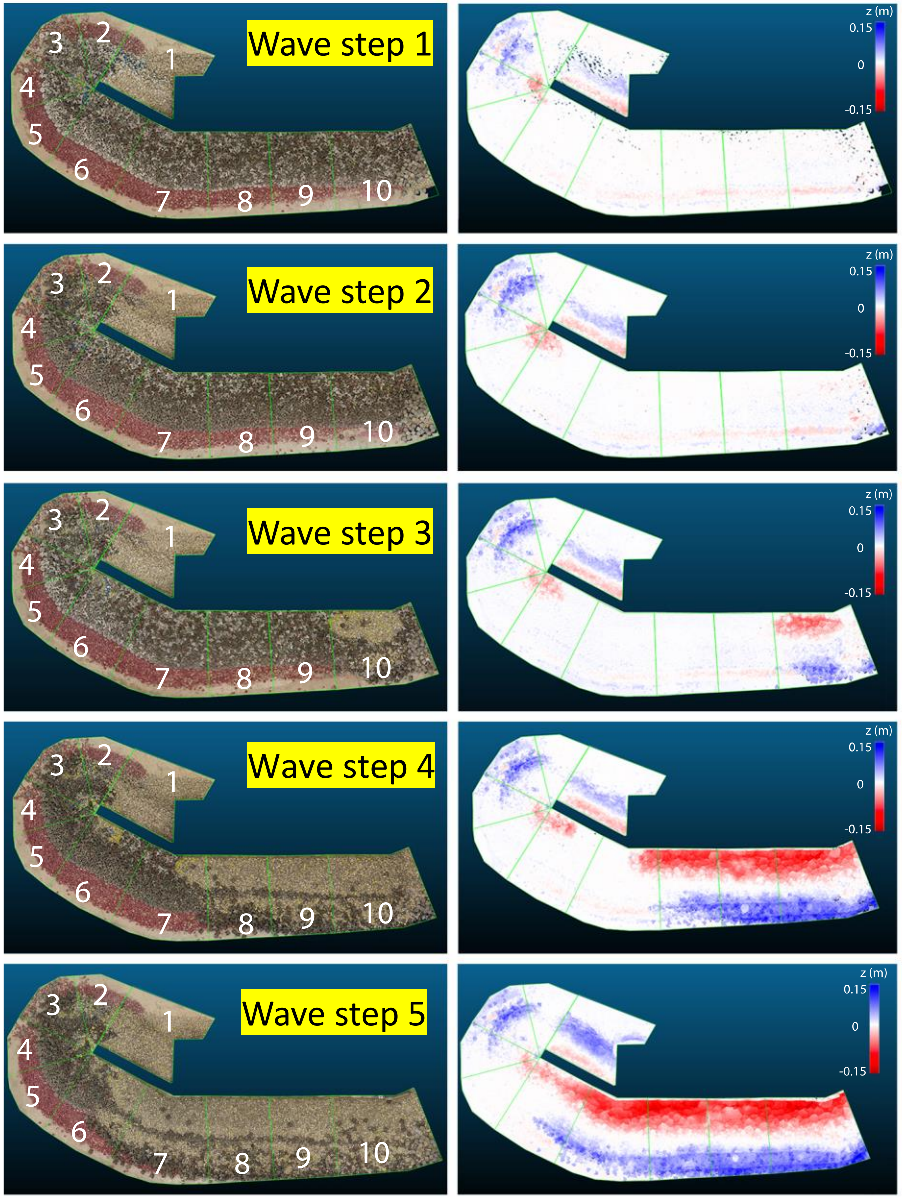
As built



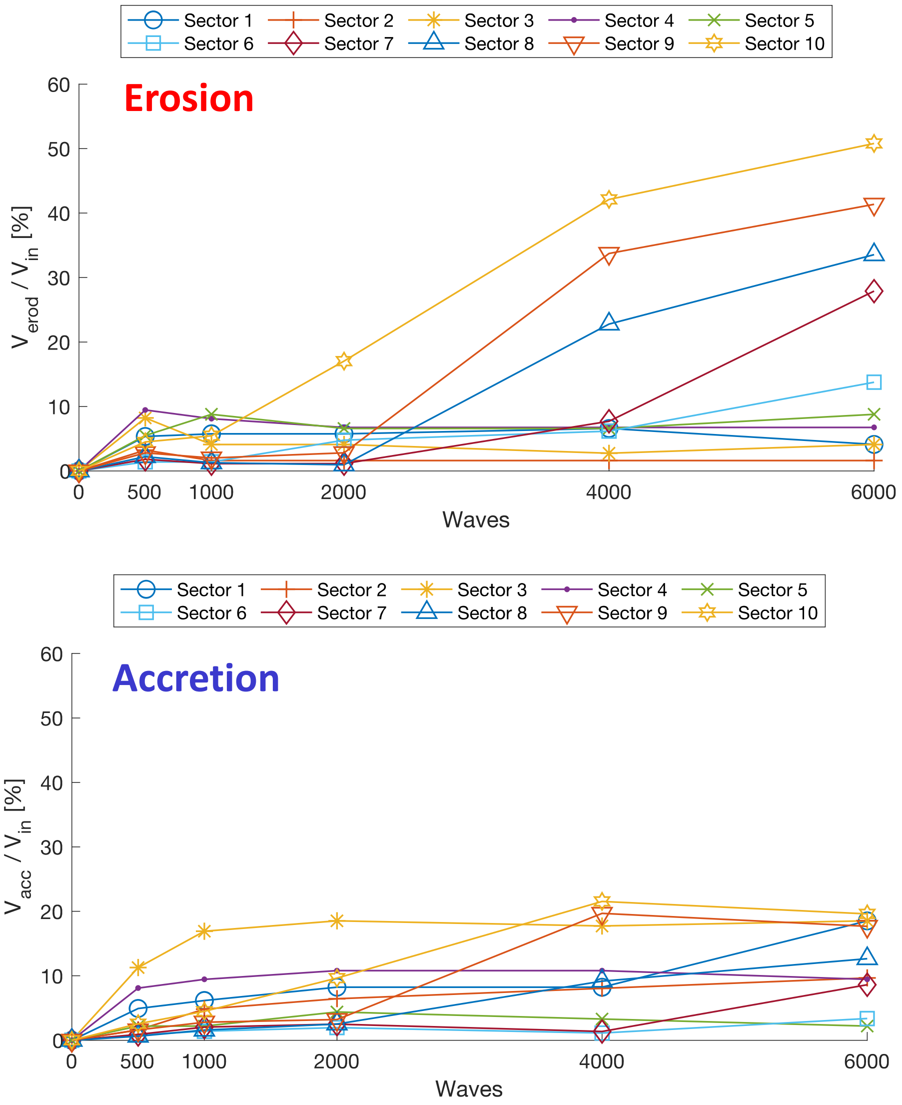
Wave Step 5

3D view of all cross-sectional extracted profiles

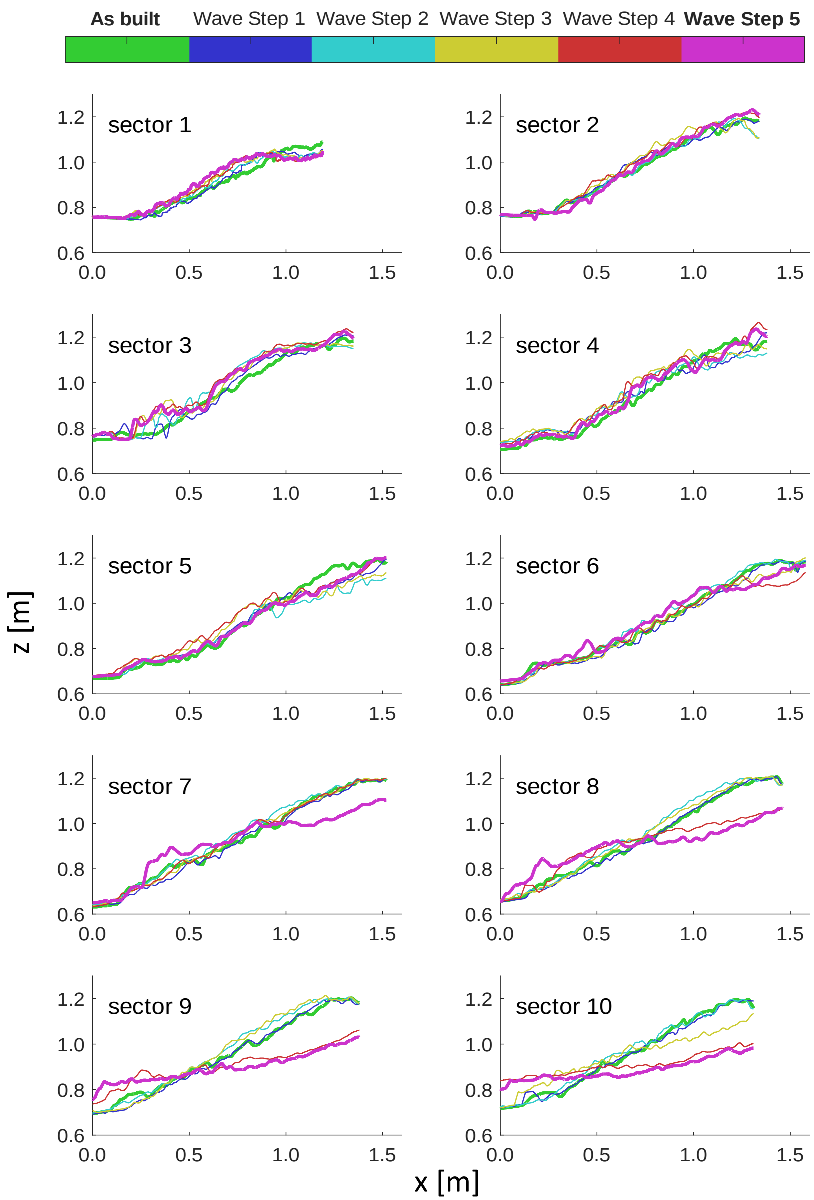




Erosion - accretion maps



DAMAGE PROGRESSION ANALYSIS - RESULTS



Eroded area [m^2]

	Wave step 1	Wave step 2	Wave step 3	Wave step 4	Wave step 5
Sector 1	0.01	0.01	0.01	0.02	0.02
Sector 2	0.01	0.01	0.01	0.01	0.01
Sector 3	0.02	0.01	0.01	0.01	0.01
Sector 4	0.03	0.03	0.03	0.03	0.03
Sector 5	0.03	0.04	0.03	0.03	0.03
Sector 6	0.02	0.02	0.04	0.05	0.05
Sector 7	0.02	0.02	0.02	0.02	0.08
Sector 8	0.01	0.01	0.02	0.07	0.09
Sector 9	0.01	0.01	0.02	0.09	0.11
Sector 10	0.01	0.01	0.05	0.10	0.12

Accretion area [m^2]

	Wave step 1	Wave step 2	Wave step 3	Wave step 4	Wave step 5
Sector 1	0.01	0.02	0.02	0.03	0.04
Sector 2	0.01	0.01	0.01	0.01	0.02
Sector 3	0.02	0.04	0.04	0.06	0.06
Sector 4	0.01	0.01	0.01	0.01	0.02
Sector 5	0.01	0.01	0.01	0.02	0.01
Sector 6	0.01	0.01	0.01	0.01	0.04
Sector 7	0.01	0.01	0.01	0.01	0.04
Sector 8	0.01	0.01	0.01	0.05	0.06
Sector 9	0.01	0.01	0.02	0.06	0.06
Sector 10	0.01	0.01	0.04	0.06	0.07

CONCLUSIONS

Key findings:

- **Objective:** Investigation on damage progression of a rubble mound breakwater with ACCROPODE II and ACCROBERM I armour units under extreme wave conditions.

- **Testing approach:**
  1. laboratory investigation on a rubble mound breakwater with ACCROPODE II and ACCROBERM I armour units linked to existing cubic rock mound (transition zone at Sector 10);
  2. small-scale model tested under severe wave conditions, repeated for 5 iterations, up to 6000 waves;
  3. UAV surveys carried out after each test.

- **Data processing:**
  1. *CloudCompare* used for data analysis;
  2. detailed erosion and accretion maps in terms of volumes (point cloud analysis) and areas (cross-sectional profiles extraction).

- **Critical points identified:**
  1. **port side:** erosion up to 15% and accretion up to 20% at sector 1 (accretion from sectors 6 and 7);
  2. **roundhead:** distributed erosion within 1000 waves at sectors 4, 5 and 6 up to 10% for each sector and accretion up to 20% at sector 3;
  3. **trunk:** critical transition zone (cubic rocks to innovative units):
     - within 2000 and 6000 waves: progressive erosion from sector 10 to 6;
     - at 6000 waves: maximum erosion of 50% and accretion of 20% at sector 10 (some armour units and part of the filter layer beyond assessment domain).

CONCLUSIONS

Significance and contributions

- Quantification of erosion and accretion volumes through point cloud analysis.
- Extraction of detailed cross-sectional profiles for area analysis.
- Introduction of an innovative study highlighting the application of image-based approaches for assessing damage progression under extreme wave conditions.

Implications and future directions

- Validation of technique effectiveness in laboratory environments.
- Enhancement of port maintenance strategies through identification of structural vulnerabilities.
- Establishment of a precedent for UAV utilization in coastal engineering research.

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Thank you for your attention!