

REALISTIC NUMERICAL PLACEMENT OF ARMOR LAYERS OF MOUND BREAKWATERS

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INTRODUCTION

Placement grid design is a key element for the construction of the armor layers of mound breakwaters. An optimum placement grid design in small-scale tests have to be feasible at prototype-scale. To this end, realistic small-scale physical placement tests have been used to check the feasibility of given placement grids. Nevertheless, these physical tests are time-consuming and, require specific equipment and trained small-scale crane operators.

Numerical models arise as a useful tool to analyze the suitability of placement grids for breakwaters. Numerical models can simulate the placement procedure and they may be classified in two main groups: (1) models based on finite and discrete element methods (FEMDEM) and (2) physics engines that are commonly used for videogames and animation. The FEMDEM models are complex with a high computational cost. In contrast, physics engines are much simpler and computationally time-efficient.

The Bullet Physics Engine (BPE), used in this study, is an open-source, robust and low time-consuming physics engine; it is based on rigid body physics and the Newton's laws of motion. BPE is adequate for the realistic simulation of the motion of multiple rigid bodies such as armor units in mound breakwaters. Numerical placement tests using BPE were validated with small-scale physical tests of Cubipod Homogeneous Low-Crested Structures (HLCS) to measure layer coefficients (Molines et al., 2021).

Cubipods (and other armor units) are placed following X-Y placement grid coordinates with crawler cranes or slings at a controlled placement velocity using a GPS differential system (Medina & Gómez-Martín, 2016). The GPS precision error and other errors that occur during the placement process may result on grid deformations or even the loss of armor units during the construction of mound breakwaters, or other typologies. The X-Y positioning errors of lower layers in HLCS may induce errors in upper layers. As a consequence, the constructed placement grid shape may be too distant from its theoretical design; that is: the porosity, layer coefficients or other key parameters may be different and affect the functionality of the breakwater.

HLCS (see Figure 1) are a typology of Low-Crested Structures (LCS) constructed by homogeneous armor unit types (rocks or concrete units) that are designed to be placed on retreating coral reef areas. In addition, the fewer environmental impacts and the high porosity of HLCS favor coral reef colonization and foster marine fauna whilst protecting the shoreline (Odériz et al., 2018; Medina et al., 2019).

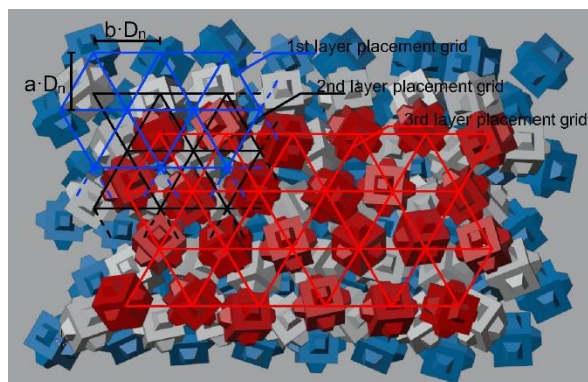


Figure 1 - 3-layer HLCS formed by a triangular placement grid with a grid spacing $\{a \cdot D_n, b \cdot D_n\}$.

This study presents a numerical methodology with the physics engine BPE to simulate the placement procedure of armor units following placement grids. This numerical model is based on the Bullet Physics Engine (BPE), which considers the Newton's laws of motion and rigid body physics. A numerical crawler crane is proposed to place armor units using realistic placement conditions: placement velocity and GPS error positioning. The methodology is applied to Cubipod Homogeneous Low-Crested Structures (HLCS) where a series of numerical placement tests are carried out for 3-layer Cubipod HLCS. Measured positioning errors are analyzed to assess the performance of the numerical simulations.

NUMERICAL PLACEMENT PROCEDURE WITH BPE

The BPE physics engine is based on Newton's laws of motion and uses Euler's Method to estimate the motion properties of all objects during the simulation. The BPE uses a Collision detection system to estimate the time step when every collision takes place; thereby motion properties are updated for the next time step of the simulation (linear and angular velocities and accelerations). BPE includes two synthetic parameters that slow the physical response of objects; these are named linear damping ld and angular damping ad .

A constant placement velocity can be achieved by setting an arbitrary ld value (Figure 2). Due the non-linear behavior of the ld , a different geometrical scale can be set between prototype and model scale to simulate lower placement velocities. The criterion followed to calculate the adequate geometric scale is to maintain a constant ratio between potential and kinetic energy in model and prototype. The change in scale is defined by:

$$kp = \frac{E_{kinetic}}{E_{potential}} = \dots = \frac{v^2}{2gD_n} \rightarrow kp \cdot \frac{v_p^2}{2gD_{n,p}} = \frac{v_n^2}{2gD_{n,n}} \quad (1)$$

where kp is the kinetic-to-potential energy ratio, v is the placement velocity (v_p prototype and v_n numerical), D_n is the nominal diameter of the Cubipod ($D_{n,p}$ prototype and $D_{n,n}$ numerical) and g is the gravity acceleration. Therefore, by defining a prototype-scale size and placement velocity $\{D_{n,p}, v_p\}$, the numerical nominal diameter $D_{n,n}$ can be calculated with Eq. (1) once a ld is established, which corresponds to a numerical placement velocity v_n , as indicated in Figure 2.

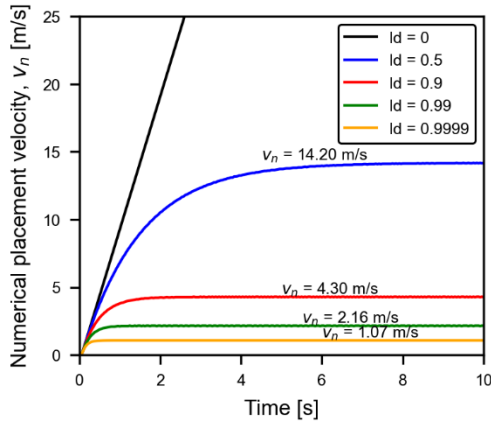


Figure 2 - Placement velocity over time for different linear damping values (ld).

GPS positioning errors on the simulated crawler crane are defined by a dimensionless crane spatial deviation (Δ/D_n) which correspond to the variance of the error positioning. This deviation modifies slightly and randomly the theoretical placement position on the placement grid. The spatial deviation proposed in this study is a theoretical approach to consider all placement errors.

RESULTS

A series of numerical simulations are completed for HLCS formed by equilateral triangular placement grids for different grid porosities $\{a \cdot D_n, b \cdot D_n\}$, bottom seabed slopes (m) and different combinations of placement conditions $\{kp, \Delta/D_n\}$. Cubipod armor units are placed one by one following the order dictated by the placement grid. Positioning errors (ε) are the deviations of the armor units compared to the theoretical placement grid. Two estimators are defined to quantify the quality of the construction: ε_{rms} which is the root mean squared of ε and, $N_{\%}$ as the percentage of significant deviations, $\varepsilon/D_n \geq 1$, from the theoretical placement grid. By defining a target threshold of unacceptable levels, feasible handling conditions can be determined for the construction of HLCS, see Figure 3. For instance, $\varepsilon_{rms}/D_n=0.30$ is associated with unacceptable levels $N_{\%} \leq 2\%$ (in orange). By slowing the placement procedure or improving the GPS tolerance, the better are the performance indicators (in green). Otherwise, the

worse are the handling conditions, fastest or more GPS imprecision, the worse (in red). This region of feasible handling conditions can be tabulated to provide guidance depending on the HLCS geometry, construction cycles or weather conditions at construction site (see Figure 3).

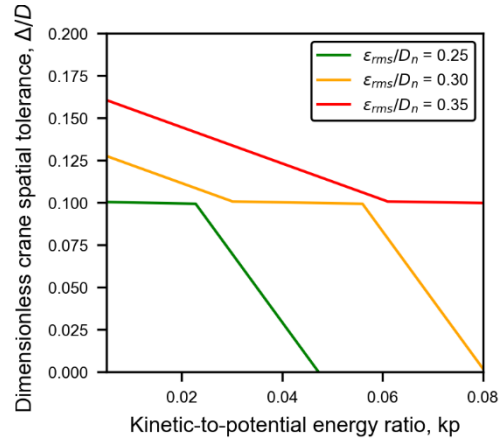


Figure 3 - Feasible handling conditions for three thresholds of ε_{rms}/D_n : {0.25, green; 0.30, orange; 0.35, red}. For the construction of a Cubipod HLCS with a grid spacing $\{1,32 \cdot D_n, 1,52 \cdot D_n\}$ over a bottom slope $m=0.04$.

CONCLUSIONS

A numerical methodology is proposed to simulate a realistic placement procedure of armor units on mound breakwaters. In this study, a series of simulations for 3-layer Cubipod HLCS were carried out. The numerical simulations helped to understand the uncertainty of the construction procedure. The initial deviations measured were used to estimate the quality of the construction and the feasibility range of crane operations.

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