

REPAIR AND REHABILITATION OF CUBE-ARMORED MOUND BREAKWATERS

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Hundreds of breakwaters will exceed their service lifetime during the next decades, and will have to be repaired, rehabilitated or dismantled. The placement of heavy units is usually a challenging construction problem of mound breakwaters because wind, waves and crane operators have a relevant influence on the actual positioning of new units. The construction of new breakwaters and the repair and rehabilitation of old ones can be better planned using realistic numerical placement simulations more efficient than realistic physical placement tests. A new proprietary software named PLACSIM[®] is described in this paper as a realistic numerical simulator of the placement process of armor units. This simulator uses the open-source software for video games PhysX to apply the laws of the Classical Mechanics on rigid bodies; movements and collisions of armor units during the placement process are realistically simulated. This software can be used to analyze the feasibility and results of different placement grids to optimize the placement procedure of a given breakwater in given environmental conditions.

Keywords: rubble-mound breakwater; armor unit placement; numerical simulator; optimization; feasibility analysis

INTRODUCTION

During the last century, thousands of mound breakwaters have been built around the world contributing to the economic and social development of many countries. The attention of the engineering community has been focused on the construction and exploitation of new breakwaters; however, repair and rehabilitation of existing breakwaters require increasing attention due to the large number of aging breakwaters still in service (see Stagnitti et al., 2023). Numerous mound breakwaters have suffered different levels of damage during their service time (see Edge and Magoon, 1979, and database by Allsop et al., 2010) which sometimes have required costly and urgent repair works. In addition to under-performed design or construction and degradation in time, Climate Change (CC) and Sea Level Rise (SLR) increase the design wave loads (see Isobe, 2011) for existing breakwaters and coastal structures. Structural damage, flood risks (see Muis *et al.*, 2020) and environmental impacts will increase in coastal areas resulting in higher design waves and overtopping, coastal flooding, etc.; the design loads and the risk of existing breakwaters in service will rise.

Service lifetime of breakwaters sheltering harbors usually ranges 25 to 50 years (see ROM 1.0-09) and, during the next decades, developed countries will face the problem of repair, rehabilitate or dismantle hundreds of breakwaters exceeding their service time. However, the scientific and technical information for the repair of mound breakwaters are limited and mostly related to the rehabilitation of old breakwaters after lifetime or related to the repair and reconstruction works after unexpected breakwater failures during construction and the first years of service time in the 70s and 80s (Sines, Bilbao, San Ciprián, Giona Tauro, Arzew, Tripoli, Diablo Canyon, etc.). The damage of breakwaters in the 90s and later was not rare but it has been less frequent than they were in the 70s and 80s. It is very difficult to obtain reliable information of breakwater failures in recent times (see Allsop et al., 2010), and most rehabilitation and reconstruction of large breakwaters during service lifetime are usually related to unexpected high costs, legal disputes and lawsuits, as well as confidential reports not described in the literature. It is not easy to rationalize design guidelines for adequate repair and reconstruction works of damaged breakwaters when most relevant information about real experiences is confidential.

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In addition to the need of new methodologies to upgrade and rehabilitate old breakwaters in service, during the next decades, hundreds of new breakwaters are expected to be built in the world because of the economic growth of many developing countries and the new waterways requirements. Global Gross Domestic Product (GDP) is strongly correlated to marine trade (see UNCTAD, 2022); world GDP growth and maritime transportation will grow and so the need for additional coastal infrastructure. Figure 1 shows the evolution of global maritime trade by cargo type over the last decades. In the last two decades, the number of Twenty-foot Equivalent Unit (TEU) transported by sea has increased 3-fold as well as the maximum size of containerships; the largest containerships in 2023 (Length \approx 400 m, Breadth \approx 60 m and Draft \approx 16 m for 24,000 TEU) are conditioned by the new geometry of the Suez Canal, just as the new locks limit the New Panamax vessels (16,000 TEU). Larger ships and an increase in world maritime transportation will require new breakwaters and port infrastructures. In the last two decades, the global containerized trade in TEU has been growing at an average annual rate of +4.9% and the world GDP only +2.9%. These trends in global maritime trade are stressing the management and competition of many port infrastructures.

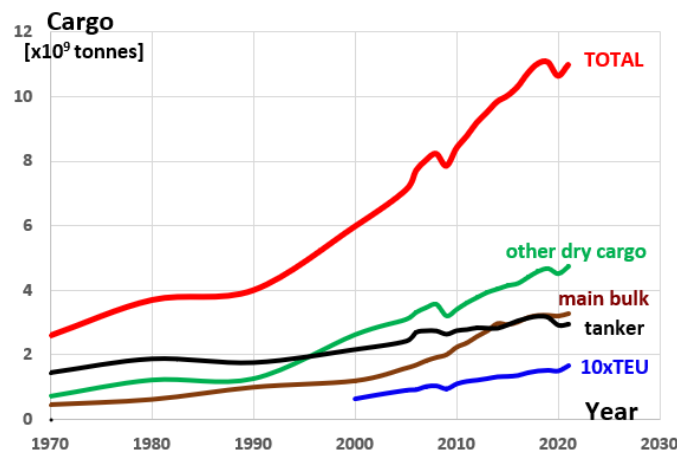


Figure 1. Marine trade by cargo type (UNCTAD, 2022).

A long-term growing of marine trade and shipping fleet (see UNCTAD, 2024) is indicating the need of the construction of hundreds of new breakwaters and the rehabilitation of old breakwaters during the next decades. The main objective of this paper is to describe the construction simulator PLACSIM[®] (www.placsim.com), a new proprietary software to optimize construction procedures of mound breakwaters, adequate for constructing new breakwaters as well as upgrading and rehabilitation of old maritime structures. 3D realistic numerical placement tests carried out using PLACSIM[®] can be used for feasibility analysis of breakwater construction in different environmental conditions.

MONITORING OF BREAKWATERS

There are hundreds of breakwaters in service whose original lifetime is exceeded or close to being exceeded in the coming years. To properly assess the risk associated with a given breakwater, a monitoring program has to be implemented during construction and also service lifetime. Some monitoring has been usually implemented for most coastal structures (see Magoon *et al.*, 1983) such as periodic visual inspection in the past and specific surveys and wave climate studies to describe the evolution in time of wave loads and structural characteristics. During the last decade, new low-cost and high precision surveying techniques are available and a variety of monitoring schemes and surveys have been used in monitoring breakwaters. In addition to visual inspection, aerial photogrammetry, terrestrial and drone

LiDAR can be used for the emerged part of the breakwater, and the submerged part can be surveyed with side-scan sonar and multi-beam echosounders. The quality of surveys has been rising while the costs have been reducing in time so there is a global tendency to improve the monitoring programs during service time.

The goal of a monitoring program is to estimate the evolution in time of the risk to failure. Periodic 3D high precision Digital Terrain Model (DTM) of the breakwater is necessary to estimate breakwater damages and bottom erosion. The settlements of the crown wall and the movement of blocks within the armor are usually the main indicators of incipient damage which may lead to an increase of risk to failure and the need of repair mound breakwaters. In addition to the direct information from the prototype, it is necessary to take into consideration three main sources of uncertainty affecting the performance of a mound breakwater and the expected levels of damage during service time: (1) characterization of environmental variables and loads, (2) foundation, materials and construction process, and (3) design.

The estimation of extreme waves, water levels, seismic loads and other environmental variables at the construction site is a key factor to properly estimate the breakwater damage levels and the probability of failure during service time. Sea Level Rise (SLR) due to CC is modifying the water levels and CC may also be changing the extreme waves estimated in the past, under the hypothesis of a stationarity. In addition to a proper description of the foundation to prevent geotechnical failure models, materials usually downgrade in time and, sometimes, break (slender armor units) changing the hypothesis assumed during the design process.

Although the foundation was well analyzed and material degradation and breakage were prevented, the construction process at prototype scale is always significantly different than construction process in laboratory for small-scale tests. The construction process of small-scale models is unrestricted with perfect view and hand placement; a conventional double-layer cube armor with a given packing density is relatively easy to build-up. However, at prototype scale, with wind and waves affecting the crane, cables and units to be placed, and a poor view of the submerged part of the breakwater, armor porosity tends to be higher than designed and armor randomness is reduced (face-to-face fitting). Settlements and other differences between prototype and small-scale models may be relevant, and differences between prototype and small-scale model tested during the design process (model effects) must be considered. 3D realistic numerical placement tests carried out using PLACSIM[®] can be used to estimate realistic placement conditions of given prototypes.

Finally, the breakwater design is also a source of uncertainty because of the difficulty and many restrictions of some construction procedures at prototype scale. It is usually easy to draw sections of a mound breakwater on paper, which may also be well constructed in laboratory ideal conditions, but it is very difficult to build the theoretical design with cranes under wind and waves at prototype scale. Some designs lead to relevant model effects and a relevant uncertainty on the structural performance should be taken into consideration. 3D realistic numerical placement tests provided by PLACSIM[®] can be used to analyze the feasibility of a given construction procedure in given environmental conditions.

Small-Scale Physical Tests

Functionality and risk to failure may significantly change in time if settlements (crown-wall and armor layer) and movement of armor units are relevant. Initial porosity of cube armors and actual crest freeboard affect overtopping rates and hydraulic stability of the armor layer (see Medina et al., 2014), crown-wall and rear side. The failure of a breakwater usually requires an “ad hoc” rehabilitation, but a repair is related to minor or moderate damages and requires a criterion to take the repair decision in a scenario of a continuous breakwater down-grading. An increase of overtopping rates affects the forces on the crown-wall (see Molines et al., 2018) and

settlements and cube heterogeneous packing affect the armor hydraulic stability and overtopping rates. Therefore, small-scale physical tests of realistic models with the actual crown-wall or crest elevation, packing density and unit randomness, are required to compare the overtopping rates and actual armor failure function with those assumed during the original breakwater design phase. Fig. 2 shows realistic small-scale physical placement tests in laboratory; the tests provide valuable information of the most adequate placement grids but they are time-consuming.

If the probability of failure increases compared to the assumptions taken during the original design phase, a repair work is required to upgrade the structure and regain the original safety and functionality levels. Small-scale physical tests of the repaired breakwater are always feasible in laboratory and the construction procedure may be also tested in laboratory, but the process is time-consuming (see Medina et al., 2010). It is not usually easy to find a reliable and feasible procedure to properly repair a damaged breakwater; a non-tested repair process may be unfeasible at prototype scale. In order to find a feasible and optimized procedure to repair cube-armed breakwaters, realistic numerical placement tests can be carried out using PhysX or Bullet Physics Engine (BPE) to apply the Newton's laws on rigid bodies to represent the construction or repair process of a cube-armed breakwater.



Figure 2. Realistic small-scale physical placement tests.

REALISTIC NUMERICAL PLACEMENT TESTS

The construction of new mound breakwaters and the repair or rehabilitation of existing breakwaters usually require the placement of heavy units using crawler cranes with GPS positioning. Wind, waves and ability of crane operator affect the uncertainty in placement horizontal coordinates (X,Y) of each heavy block. Realistic physical placement tests can be carried out in wave basins using small-scale crawler cranes (see Medina et al., 2010), but it is time-consuming. An alternative is to use numerical simulators which are faster and more efficient. There is open-source software to simulate the Newton's laws on rigid bodies used in videogames (Physics Game Engine) such as BPE.

Molines et al. (2021) used the results of physical tests corresponding to Cubipod Homogeneous Low-Crested Structures (HLCS) to calibrate the numerical software for placement simulation based on the open-source software Blender which uses the physics game engine BPE. The software applies the Newton's laws on rigid bodies with a collision detection system. Friction coefficient ($\mu=0.7$), bounciness, collision margin, damping and rotation coefficients were calibrated to fit the measurements observed in the physical test. Using these calibrated coefficients, Muñoz-Palao et al. (2024) improved the software to analyze the handling conditions or armor units (velocity and error positioning) to study the feasibility of construction for given crane and environmental conditions; the goal was to optimize placement grids for given environmental conditions. In this study, PLACSIM[®] uses PhysX on rigid bodies (crown wall, cubes, Cubipods and rocks) and the Newton's laws of classical mechanics similar to BPE. Analyzing the optimum placement grids for Cubipod HLCS, Molines et al. (2021) used a calibrated software for realistic 3D placement.

PLACSIM[®]: Proprietary Software Based on PhysX

The numerical placement software described above evolved to the proprietary software PLACSIM[®] to better to carry out realistic numerical construction tests including re-location of armor units and placement of new units in the armor. The high precision DTM of the mound breakwater from a monitoring program is used here to create a numerical 3D model with rigid bodies (cubes, rocks, etc.). The software PLACSIM[®] is used later to carry out a series of alternative numerical construction tests for repairing the breakwater, to find feasible alternatives with optimum results. The goal is to find the best feasible procedure for breakwater reparation, using crawler cranes with realistic vertical velocities and error positioning, resulting in a structure similar to that considered in the physical tests to upgrade the breakwater. Fig. 3 shows the main screen to control the numerical placement simulator PLACSIM[®]; once the placement grid and order of placement are given, the simulator can place 30 to 40 units per minute (four-fold accelerated time) following the Newton's laws on rigid bodies (armor units).

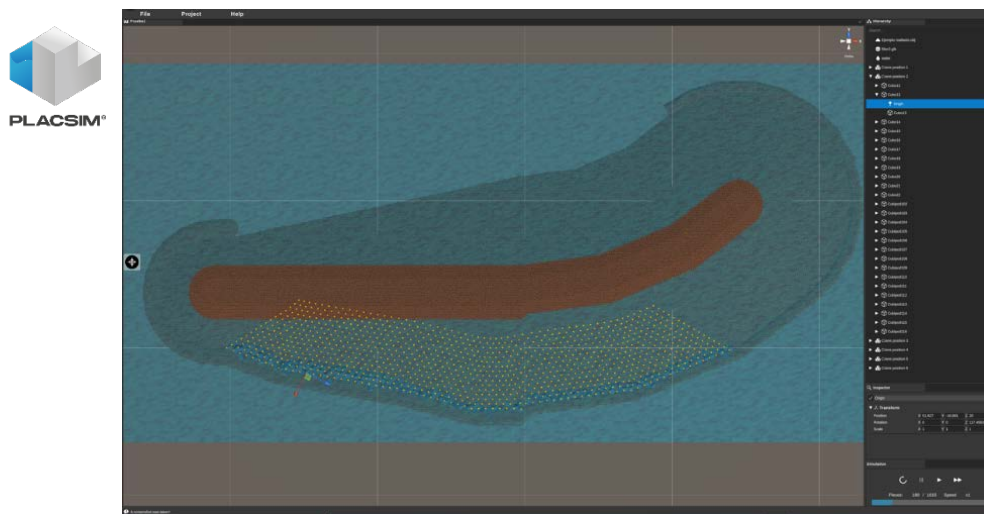


Figure 3. Main screen of PLACSIM[®].

The tested placement grid has each unit placement ordered in time according to the positions of crawler cranes, similar to prototype construction in which the crane operator knows the exact order and X-Y positioning of each armor unit to be placed. PLACSIM[®] generate a numerical model for the sea bottom, core and underlayers; once a grid and order of placement

is given to PLACSIM[®], it realistically placed all the armor units in the grid on the breakwater. The software allows to visualize the result from different points of view in order to assess the quality of the final result. If the result is not good (many lost units, etc.), a new placement grid or placement order can be defined for a new realistic placement test, learning from the poor results of the previous placement tests. This feed-back learning process can proceed until a feasible placement grid and order of placement generate an acceptable result.

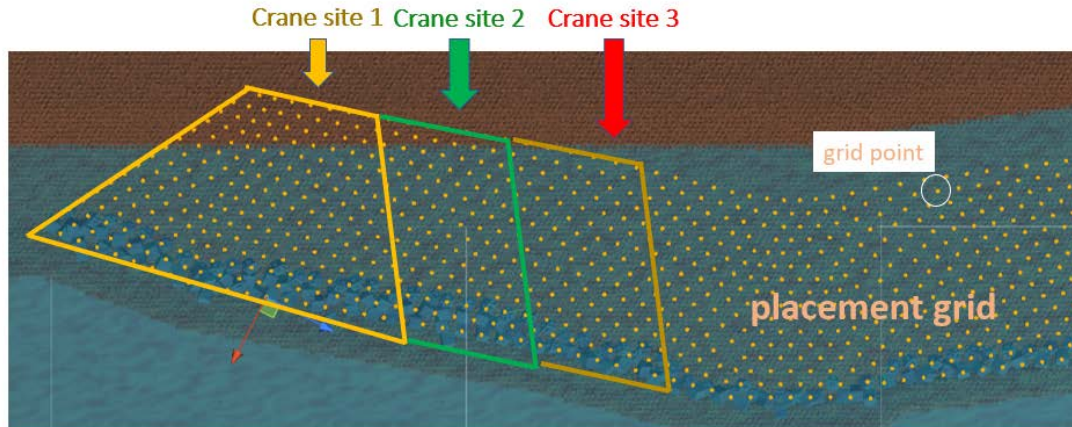


Figure 4. Placement sequences in PLACSIM[®].

PLACSIM[®] uses the Newton's laws on rigid bodies (armor units) controlling the X-Y horizontal positioning of each unit with some error positioning (waves, wind, etc.) and lowering velocity (crane operator); however, the software is very efficient and it can accelerate the real time for a faster placement (more than 40 units/minute). This numerical simulator is two orders of magnitude faster than realistic physical placement tests and three orders of magnitude faster than prototype placement. This video-game efficiency allows for multiple analysis of placement grids to optimize the construction process and to assess the feasibility of a given construction procedure. This software is especially adequate to design feasible placement grids to repair damaged breakwaters because no reliable rule of placement is available for damaged breakwaters.

Figure 5 shows a view of the 3D numerical model during the process of placement of new cube units in a damaged cube-armor layer; The Newton's laws are applied to rigid bodies considering the vertical velocity and positioning error of the crawler crane used to repair the breakwater, similar to Muñoz-Palao et al. (2024). The quality and feasibility of the repair process depends on the repair placement grid, positioning errors of crawler crane and vertical velocity of units before contact. The numerical 3D model with rigid cubes and rocks derived from the high precision DTM of the mound breakwater is modified by the numerical repair process using the model; in Fig. 5, the underlayer and damaged armor (white cubes) are taken from the laser scanner of a small-scale breakwater model in a wave flume, repeated along the trunk in the numerical 3D model.

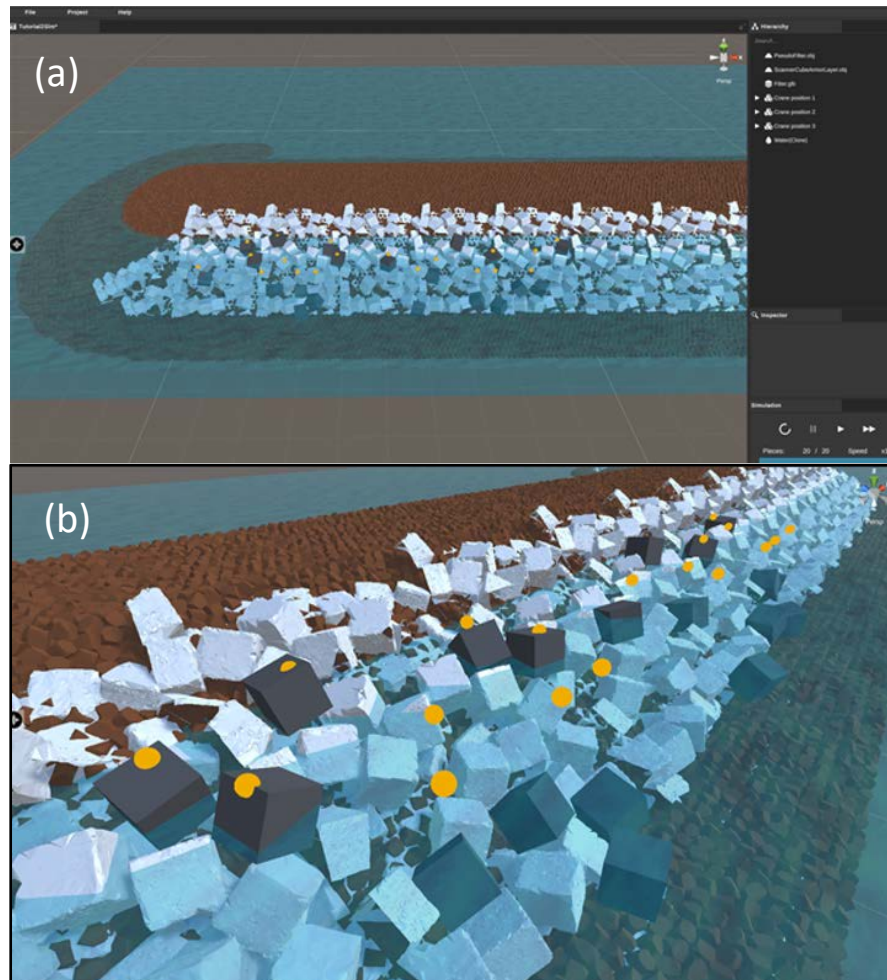


Figure 5. Placement of cube units to repair a damaged armor: (a) general view and (b) detail.

The yellow points in Fig. 5 indicates the placement grid points. The units to be placed are activated in a given order; when a unit moves downward with a prescribed velocity (simulating crane placement) it is affected by the multiple collisions with neighboring units already placed and may cause or not movements of the placed units. If the result is not acceptable (units not placed where they should be placed), the placement grid can be changed until a feasible placement grid to repair that specific damaged armor is obtained. The robustness of a given solution (placement grid and order of placement) can be analyzed by increasing the positioning error or the lowering velocity of the armor units simulating worse environmental conditions during construction. The software PLACSIM[®] can be used with uneven sea bottoms for new breakwaters and also to upgrade old breakwaters.

Fig 6 shows the placement of many cube units in the trunk section of a new breakwater using BPE. Although PLACSIM[®] simulates correctly this typical case, the main advantage is not to find solutions for the simple cases but solutions for the most complex ones (repair, roundheads, uneven sea bottom, different unit sizes, etc.) in which general rules for placement grid design are not applicable.

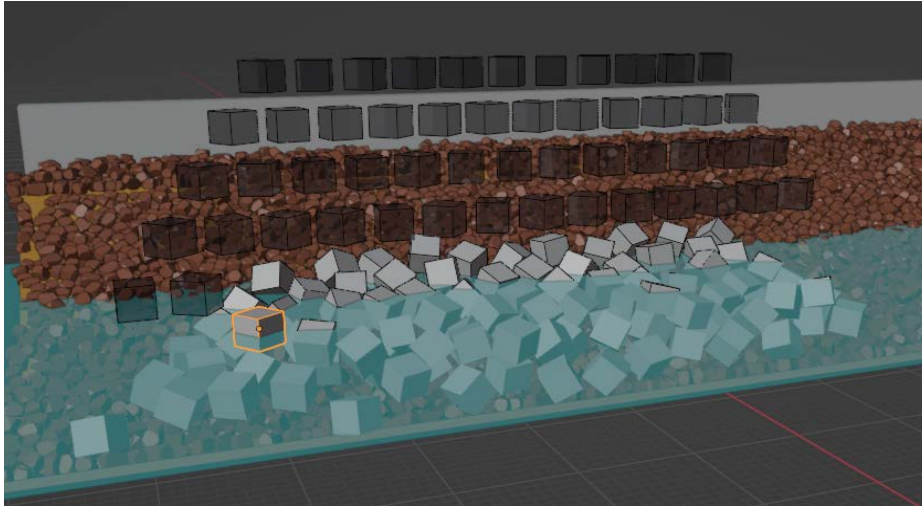


Figure 6. Placement of cube units in the truck of a new breakwater using BPE.

CONCLUSIONS

The construction of hundreds of new breakwaters in the next decades, and the rehabilitation many old breakwaters are favored by a sustained long-term growing of the marine trade and the world shipping fleet. In this paper, a new proprietary software named PLACSIM[®] is described as a numerical tool to optimize the construction procedures of new breakwaters as well as upgrading and rehabilitation of damaged breakwaters. The new software PLACSIM[®] is similar to that used by Molines et al. (2021) and Muñoz-Palao et al. (2024) based on physic game engines and the open-source software Blender and BPE to solve the Newton's laws on the rigid body dynamics, calibrated with physical tests results. PLACSIM[®] used software PhysX instead of BPE and a realistic 3D description of the mound breakwater on an uneven sea bottom. The new software uses the Newton's laws (PhysX) on rigid bodies (armor units) with coefficients (collision margin, friction, bounciness, damping, etc.) calibrated with physical tests. Armor units (Cube, Cubipods, rocks, etc.) may have complex geometries, and the effect of wind and waves during construction at prototype scale can be considered in the simulator by introducing X-Y horizontal positioning errors. The lowering velocity of armor units during placement is controlled to mimic the crane operation.

The numerical simulator PLACSIM[®] is designed for repair works and rehabilitation of old breakwaters as well as to optimize the construction procedure of new breakwaters. Feasible grids for special areas (roundheads, repair, uneven bottoms, etc.) are not easy to find and unfeasible grids may lead to heavy economic loses during construction. Cost saving, safe and reliable construction procedures and better knowledge of the final result are the main advantages of using PLACSIM[®] to prevent the use of unfeasible placement grids. 3D realistic numerical placement tests carried out using the new software can be used for feasibility analysis of breakwater construction in different environmental and handling conditions. This numerical simulator for armor unit placement is three order of magnitude faster than prototype placement.

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