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RUN UP, REFLECTION AND STABILITY COEFFICIENTS FOR ORDERED CUBE SLOPES WITH ENERGY DISSIPATION

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ABSTRACT

The results of an experimental investigation, aimed at analyzing the water flow, stability of the components, and the reflection coefficient of a slope consisting of concrete cubes arranged in an organized manner, similar to a paving stone style, alongside larger blocks to enhance overall roughness, are presented. The experiment took place in the wave flume and basin at the University of Costa Rica, testing wave ranges typical of the Pacific coasts of Central America, characterized by long swell periods.

KEYWORDS: concrete cube breakwaters, run up maximum, reflection coefficients, stability parameter.

1 INTRODUCTION

The wave conditions along the Pacific coast of Costa Rica differ significantly from those in other parts of the world, primarily due to the generation fetch being around 10000 to 12000 km from the shoreline. This uniqueness results in the country receiving long-period waves with varying energy distribution daily. The conventional breakwater formulas, commonly applied to cater to wave conditions in European seas, may not directly meet the requirements for breakwater designs along the Costa Rican Pacific coast.

Practical tests were conducted with breakwaters featuring organized cubes resembling paving stones, known for their stability. However, these structures may exhibit high wave reflection and Run-Up values. To address these issues, larger blocks were incorporated into the slope to serve as energy dissipators, similar to those typically used for stabilizing hydraulic jumps.

2 EQUIPMENT AND TEST CONDITIONS

The run-up tests were conducted in the compact IMARES wave flume at the University of Costa Rica. This channel, measuring 11 m in length, 0.30 m in width, and 0.50 m in height, has the capability to generate both regular and irregular waves. The wave generator employed is of the vertical paddle type with horizontal displacement, specifically the VTI brand, featuring active wave absorption controlled by the AWASYS software from Aalborg University.

To measure the reflection coefficient at the base of the breakwater, four water level sensors were utilized, and data acquisition was made using the WaveLab software, also developed by Aalborg University.

Figure 1. Small flume of IMARES physical modeling laboratory

The stability tests were relocated to the wave tank (11 m * 22 m*1.40 m) because the failure level in the small flume was not reached. The generators in the tank have the same capacities as in the flume.

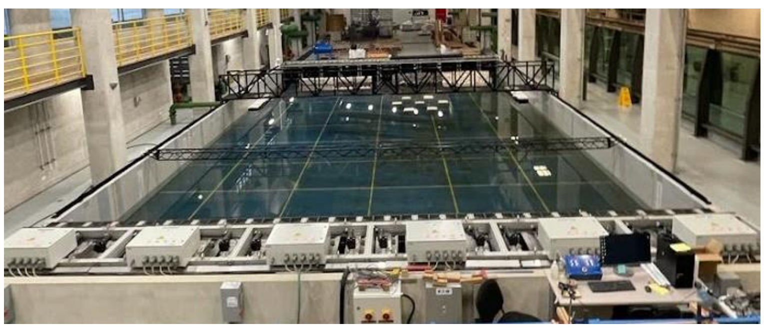

Figure 2. IMARES basin

All tests were performed at a 1:20 scale in regular wave condition, covering wave heights from 0.27 to 6.25 m and periods from 5 to 18s, typical wave design conditions of the Pacific of Costa Rica. This range of periods and wave heights, in addition to slope gradients from 1:1 to 1:2, covered Iribarren numbers from 2.8 to 27. The edge "a" of the cubes was 0.03m (0.60m prototype). The blocks for energy dissipation were of proportions a*a*1.5 (blue) and a*a*2.0a (red).

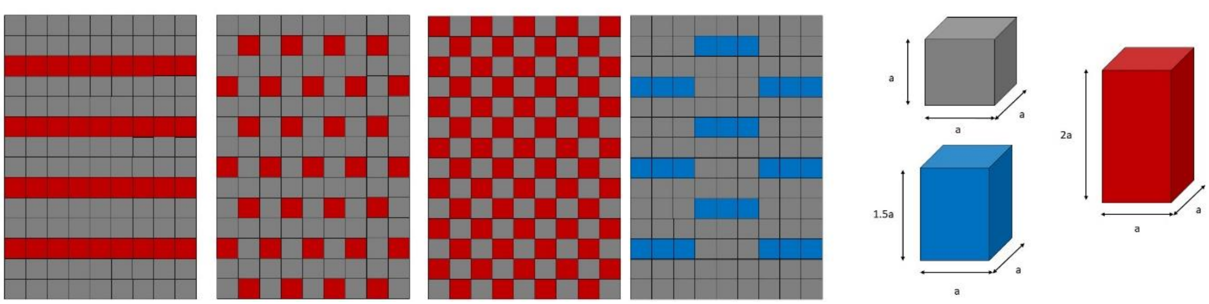

Figure 3. Block slope configurations “wall”, “chess horse”, “chess” and “row of three”

Figure 1 shows the different block configurations used, all repeated for the 1.5a and 2.0a cases. Additionally, for comparison purposes, tests were performed with a "smooth" configuration (no energy dissipation blocks) and a typical two-layer configuration of randomly placed cubes.

3 RESULTS AND DISCUSSION

3.1 Wave Run-Up

The approach employed by Losada and Giménez Curto (1979) for studying Run-Up involves analyses with Iribarren numbers less than eight in a random cube configuration. However, given the distinctive wave conditions of the Costa Rican Pacific, it has been observed that values exceeding this threshold are present. As depicted in Figure 4, the experimental data indicates that the maximum Ru/H values fall within the Iribarren number range of 9 to 14. The curve proposed by the Losada method, illustrated by the blue line, is applicable to only 58% of the total obtained values. The data that best fit the curve were obtained from tests with a slope of 1:2, represented by green square points, where 94.7% of the values fall below the curve. Regarding the results for slopes of 1:1.5, represented by orange triangular points, 63.2% of the points are above the curve, and for slopes of 1:1, 57.9% (blue circular points).

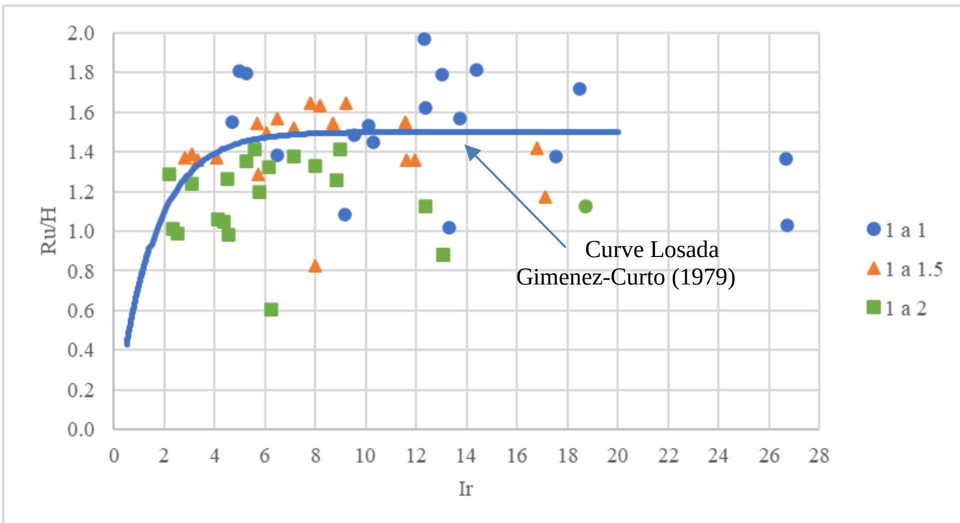

Figure 4. Experimental data and Losada Gimenez-Curto curve for Ru/H vrs Ir for random cubes configuration

In the experiments with ordered cube configurations, it is observed that an increase of water flow obstruction results in a lower Run-Up. Figure 5 a) illustrates the waves colliding with the blocks of the "Chess horse" configurations, where there is a separation in the flow and obstruction of the same. Similarly, in Figure 5 b) displays the "wall" configuration, where there is a direct collision of the flow with the taller pieces that obstruct its passage.

a) Fluid separation in chess horse configuration with cubes 1.5a height for slope 1:1.5

b) Fluid separation in wall configuration with cubes 1.5a height for slope 1:1.5

Figure 5. Impact of wave flow into the structure for attenuation of the Run-Up

The performance of the slopes was evaluated by comparing the Ru/H values against the Iribarren number, with each obtained value plotted in Figure 6, illustrating the results for the row 3 configuration. These values offer a clear view of the performance of the slopes when compared to the experimental results obtained for the smooth configuration (without flow obstructions) and the experimental double-layer random configuration.

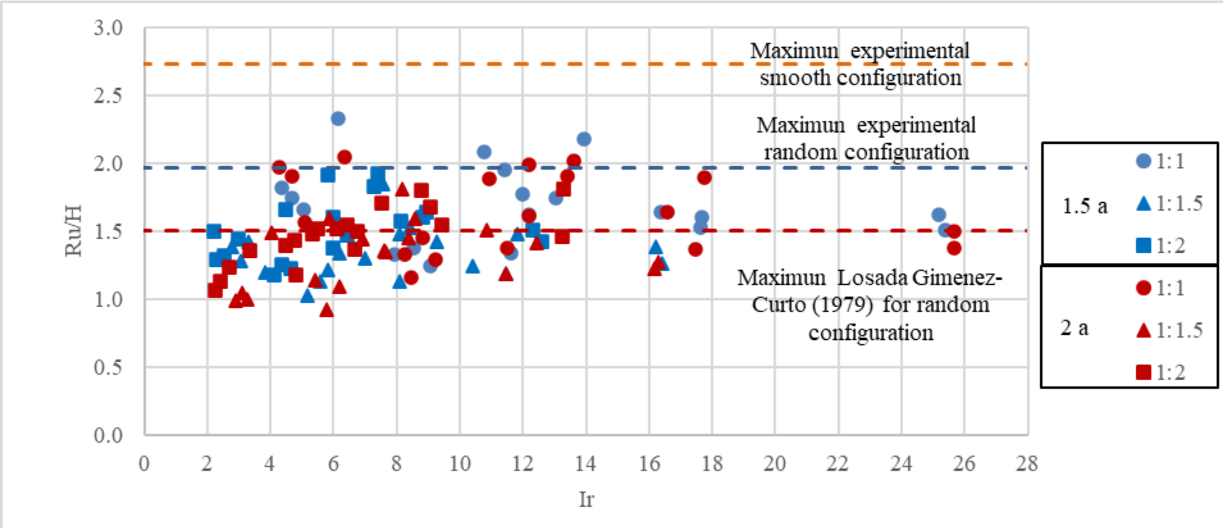

Figure 6. Results of Ru/H vs Iribarren number (Ir) for the “row 3” configuration

With all the values obtained for the different configurations, thresholds at the 95% confidence level were established as shown in Table 1. It is observed that the best performance was achieved with 'chess', followed by 'row 3,' then 'wall', and finally 'Chess horse'.

Table 1. 95% thresholds range for experimental Run Up

Configuration	Ru/H (a)	Ru/H (1.5 a)	Ru/H (2 a)
Smooth	2.5	-	-
Random	1.9	-	-
Wall	-	2.2	2.4
Chess Horse	-	2.3	2.4
Row	-	2.0	2.1
Chess	-	2.1	1.9

3.2 Reflection coefficient

The reflection coefficient varies among different configurations. Experiments conducted with various slopes revealed that the smooth configuration yielded the highest reflection, whereas the random configuration exhibited the least reflection, resembling the extremes for all arrangements. Figure 7 displays the graph obtained from tests conducted with a 1:1 slope.

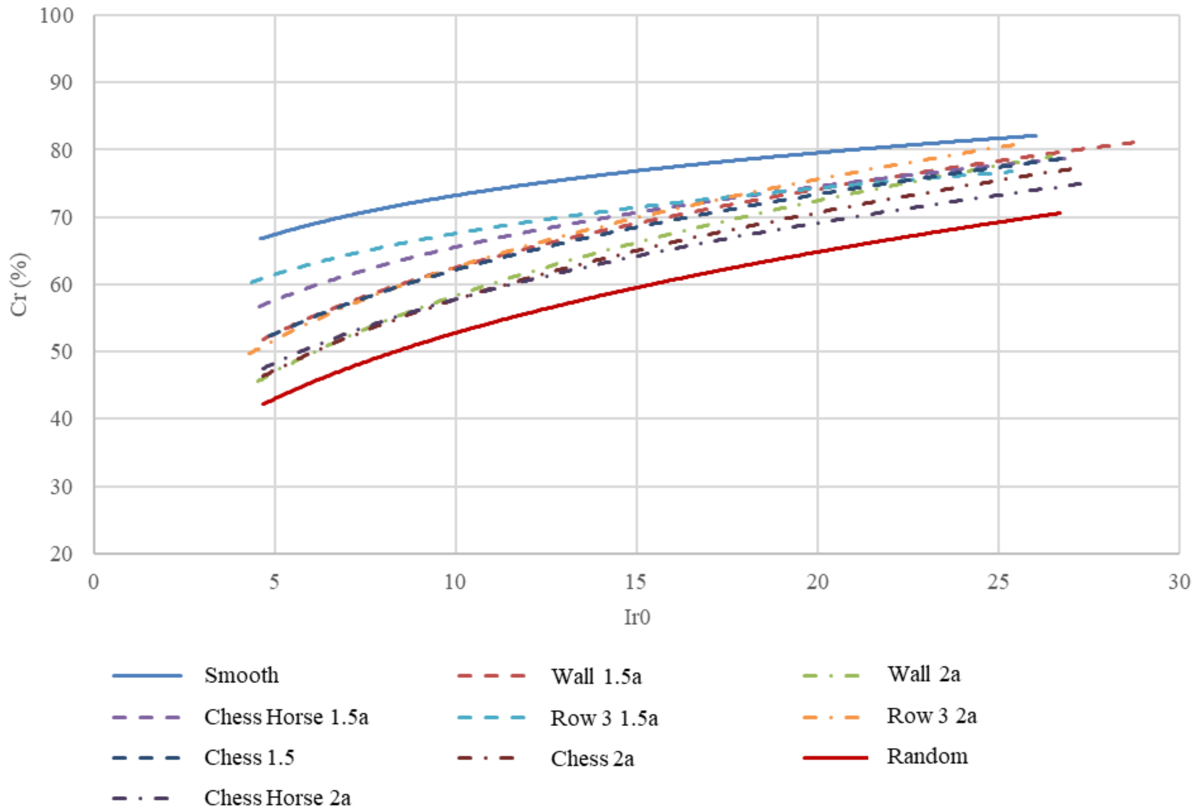

Figure 7. Results of Reflection coefficients vrs Ir for slope 1:1 with different configuration test

The configurations that exhibited lower reflection were those with double height, especially ‘chess horse’, ‘chess’, ‘Row 3’, and ‘wall’.

3.3 Stability

Stability was assessed only for the 'Chess horse' and 'Row 3' configurations, chosen based on the quantity of material utilized in constructing the armor. A count of the cubes necessary for each armor was conducted, and the volume of concrete was estimated. It was noted that there was a reduction in the material used, ranging from 12% to 37%, compared to the conventional random double-layer armor, as seen in Table 2.

Table 2. Percentage of amount of material volume used in the armor for each configuration in related with Random doble layer.

Configuration	Cubes a (%)	Cubes 1.5a (%)	Cubes 2a (%)
Random	100.0	-	-
Smooth	58.8	-	-
Chess	-	73.5	88.2
Wall	-	68.6	78.4
Row 3	-	63.2	67.5
Horse	-	66.8	74.8

Similar to the Run-Up analysis, the stability parameter Ψ of Losada and Giménez-Curto (1979) for random double-layer armor was evaluated under typical Costa Rican wave conditions. Figure 8 compares actual experimental data and Losada’s results. It is evident that there is increased instability in the armor for the 1:2 slope compared to what the formulation predicts; the experimental values are represented by grey square-shaped points on the graph. Concerning the 1:1.5 slope, the Losada’s curve aligns well with the experimental results, as evidenced by the orange triangular-shaped experimental points being close to the respective slope curve. Finally, for the 1:1 slope, there is not a curve to compare. Nevertheless, the expected trend of achieving better stability is obtained.

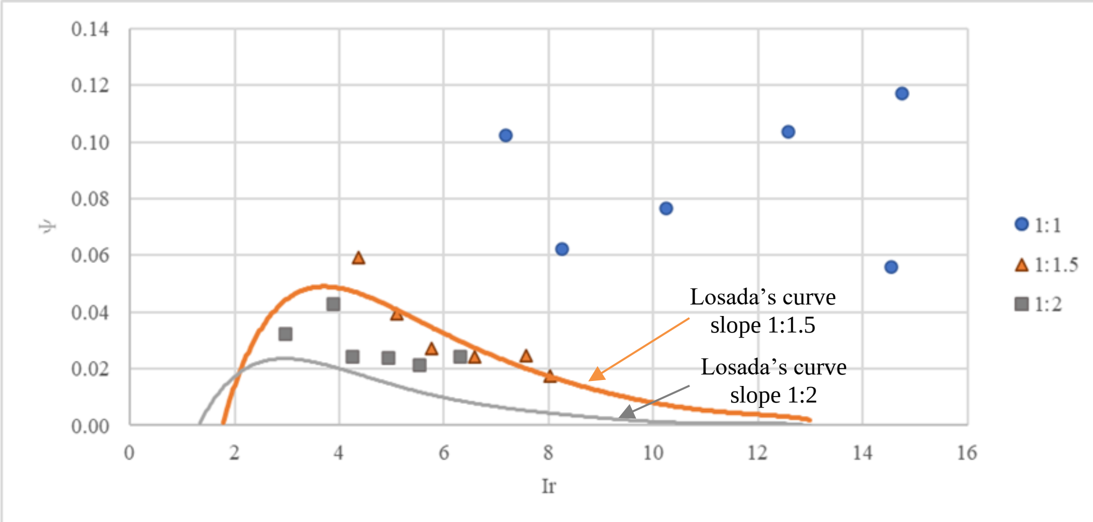

Figure 8. Stability curves and experimental data with Costa Ricans Pacifics waves conditions

The construction of breakwater armors with random cubes becomes straightforward, as there is no need to carefully place them in a specific manner. For this reason, the contact and support between continuous pieces are minimal, and the weight of the cubes becomes more crucial for stability. Conversely, when using configurations where the cubes are arranged, the contact between the faces of neighboring elements is greater, increasing friction between the blocks and making their displacement more challenging.

The improvement in stability with the ordered configurations can be observed in Figure 9, which depicts the graph obtained from tests conducted for Row 3. In this graph, blue points represent cubes with a height of 1.5a, while red points represent cubes with a height of 2a, both for different slopes. The experimental stability coefficient values in all cases are lower than those theoretically established by the curve with a slope of 1:1.5 for cubes with a random configuration. Additionally, it is noticeable that the height of the cubes also influences stability In the 1:1 slope, there is a 56.5% improvement when using the taller cubes (2a) compared to the ones with lesser height (1.5a). Regarding the slopes of 1:1.5 and 1:2, the same behavior is observed with improvements of 19.9% and 56.4%, respectively, when employing the cubes of 2a instead of those of 1.5a.

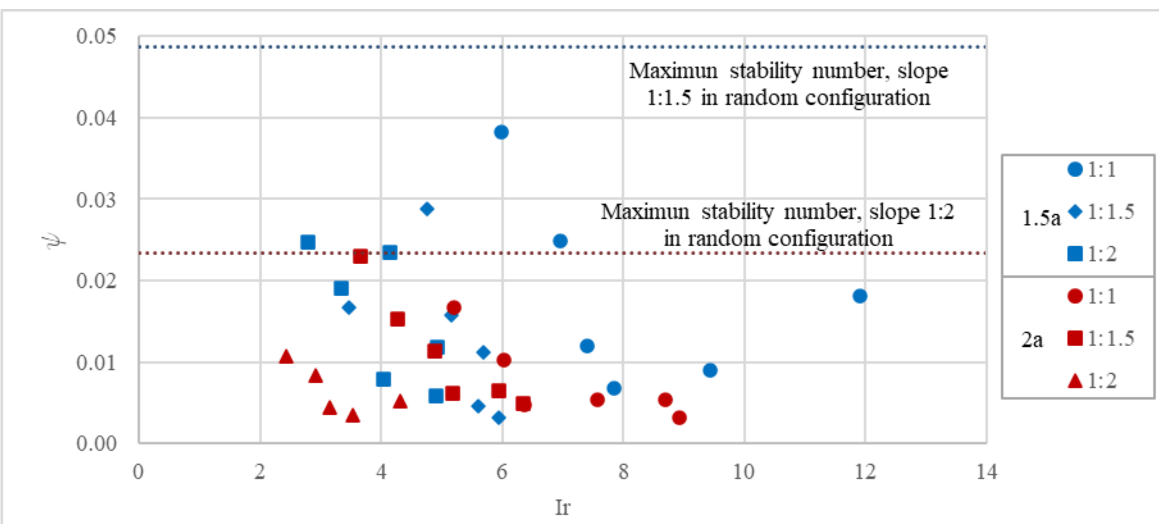

Figure 9. Results of the stability test for the configuration Row 3 with different slops and cube height

In the 'Chess horse' configuration, there is also an improvement in stability compared to Row 3, as shown in Figure 10. There is also an enhancement when using larger cubes, with improvements of 49.7% and 18.3% in the 1:1 and 1:2 slopes, respectively. However, in the 1:1.5 slope, there was a decrease of 5.1%. Nevertheless, only 8.3% of the obtained data exceeds the theoretical maximum for the 1:2 slope.

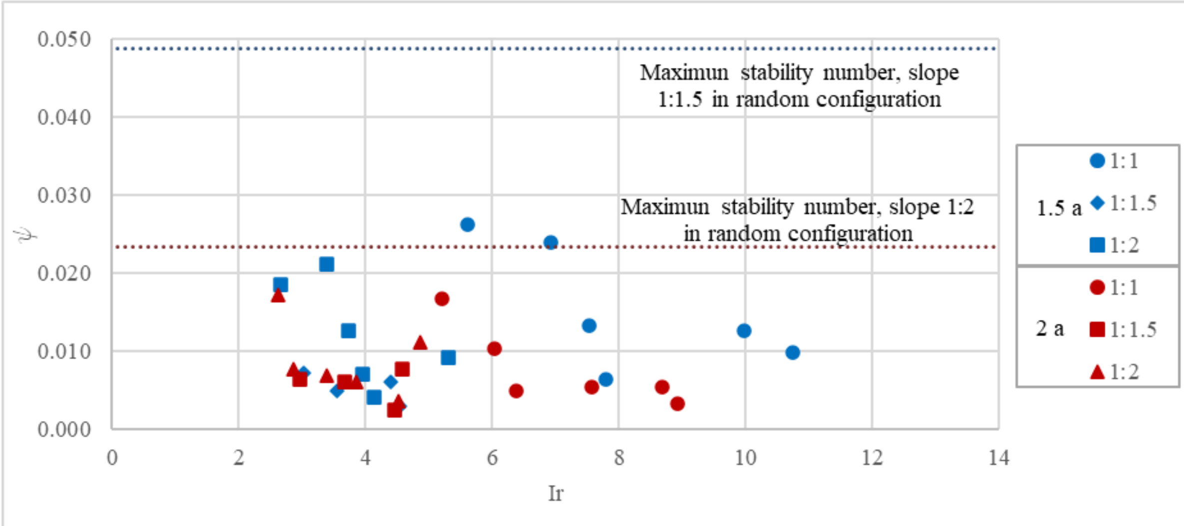

Figure 10. Results of the stability test for the configuration 'Chess horse' with different slops and cube height

In these two ordered configurations, there is an improvement of up to 70% in stability numbers compared to the random double-layer configuration. Furthermore, among the configurations used, when double-height cubes are employed in the armor, it is less prone to failures. This is attributed to the increased weight and a higher normal force on the faces of neighboring cubes, enhancing friction, thereby making it more difficult for the cubes to displace from their placement position.

3.4 Practical example

To summarize the results, a practical example is provided, taking into account potential conditions of waves in the Costa Rican Pacific. Utilizing the IMARES database, we consider a wave height of 3.5 m, corresponding to a 25-year return period, and a typical period of 16 s for designing a one-layer breakwater. Using the Losada method, the estimated Run-up is 5.24 m, calculated as follows:

$$L_0 = 1.56(16)^2 = 399.36\,m$$
$$\rightarrow I_{r_{1:2}} = \frac{2}{\sqrt{\frac{3.5}{399.36}}} = 5.34.$$

Then,

$$A_u = 1.50 \qquad\qquad B_u = -0.67$$

$$R_{u\,1:2} = 3.5 \times [1.50 \times (1 - e^{-0.67\times 5.34})] = 5.24\text{ m}.$$

Using the thresholds found for random doble-layer armor the Run Up is calculated as is shown:

$$R_u/H = 1.97 \rightarrow R_u = 1.97 \times H$$
$$R_u = 1.97 \times 3.5 = 6.90\text{ m}.$$

There's a difference of 1.66 m between both methods.

In the table 3 is shown the estimated Run-Up for the configurations Chess horse and Row 3 use for the design height of the breakwater. The weight of the cubes was taken of Losada formula:

$$W = \Psi\,\gamma_w H^3 R \qquad (1)$$

The stability number (Ψ) used to compare the new configurations and the typical doble-layer was take from the maximum value obtain from the experimental data and the curve of the slope 1:2 of Losada's method, respectively, the R parameter correspond a relative density of the material used, in this time concrete.

Table 3. Parameter of Run Up estimate with experimental thresholds at 95%, weight and dimension elements, for armor configurations: doble layer, Row 3 and chess horse.

Configuration	R_u (m)	Weight (kg)	Cube dimension a (m)
Chess horse 2a	8.40	555	0.60
Row 3 2a	7.35	725	0.70
Doble layer cube armor	6.90	995	0.75

Taking in consideration the increases of the stability in the new propose configurations a it can be used a higher slope like 1:1. In the table 4 it is shown the diference between the typical doble-layer random cube and this proposusal configuration. It was caluted a 10 m long seccion of breakwater.

Table 4. Quanty of material required to build a 10 m long breakwater of a typical doble-layer armor with slope 1:2 and the new configurations of chess horse and row 3 with slope 1:1 and the reduction of material of this configurations.

Configuration	Random doble-layer armor slope 1:2	Chess horse 2a slope 1:1	Reduction of material between chess horse and doble layer (%)	Row 3 2a slope 1:1	Reduction of material between row 3 and doble layer (%)
Cubes "2 a" coverture (%)	0	26.5	0	25	0
Cubes "a" coverture (%)	100	73.5	26.5	75	25.0
Armor superficial area (m^2)	244	175	28.1	161	34.1
Amont of cubes	762	466	38.9	357	53.2
Concrete volume (m^3)	569	210	63.0	179	68.4
Cross section area of the sub-armor (m^2)	223	183	17.9	155	30.5
Total volume of material (m^3)	22300	18300	17.9	15500	30.5

4 CONCLUSIONS

The stability of the breakwater elements is enhanced by arranging the cubes in an orderly manner, as opposed to the traditional random double-layer placement.With the new configurations, there is a reduction in the required concrete quantity ranging from 12% to 24%, depending on the chosen configuration. Currently, the use of a double layer of cubes increases the material amount and results in lower stability compared to orderly arrangements. For better efficiency in functional design, the configuration resembling "Row 3" is recommended, as it outperforms random cube configurations in the Ru/H ratio.The configuration with the highest stability in testing was the 'Chess horse', showing good performance in Ru/H with only a 15.8% deviation from the established threshold for random order. Randomly arranged cube breakwaters exhibit lower resistance than orderly ones. However, in the event of damage to a random armor, another cube may eventually fall into the damaged area. In contrast, orderly cubes experience a sudden brittle failure that exposes the sub-armor. One advantage of using cubes in the breakwater armor with configurations like 'Chess horse' and 'Row 3' is the potential to reduce the amount of material in both the armor, sub-armor, and the breakwater core. By increasing the stability of cubes in these configurations compared to random placement, steeper slopes can be employed, reducing the cross-sectional area of the structure. Additionally, another benefit of using less material is related to the transport and handling of pieces on-site. Smaller cubes allow the use of machinery with lower power and size, making it more economical in terms of fuel consumption. Moreover, if the construction site is not close to the project, the costs associated with transporting smaller pieces are lower.

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