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CIVIL ENGINEERING

Measurement of jetty execution services - calculation of volumes and empty tailings

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ABSTRACT. The study presents results on the settlement characteristics of rock blocks used in the construction of coastal structures to protect and recover the coast. Bosman et al. (2014) studied the porosity of voids. Packaging density and the associated void porosity are important to coastal engineers for two main reasons. The first is that it affects hydraulic performance. The second is its relation to the acquisition of materials. The biggest question is to define the relation between the volume of the structure and the real value of the porosity, finally defining the relation between the volume of the structure and the weight of the blocks used. This article examines the porosity of voids, containment, and recovery structures on Icaraí beach in Municipality of Caucaia, State of Ceará. The commonly used density value for coastal work payments is 1.62 tons m^{-3}, based on international studies from 28 to 38 years ago. Recent bathymetric surveys at Municipality of Caucaia-CE confirm the actual density value as 1.43 tons m^{-3}.

keywords: Spie, breakwater, rocks, volumes, coastal engineering works.

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Introduction

This work presents the results of studies on the settlement characteristics of the rock blocks used in constructing the protection layer and body of coastal structures for recovering the coast.

Rock armor is a widely used construction material for coastal protection structures due to its strength, durability, flexibility, and cost-effectiveness. However, irregularities in its geometry can present engineering challenges by introducing variability and uncertainty into the final structure.

Bosman et al. (2014) examined void porosity, a crucial property influenced by irregular forms and sizes of rock armor.

Coastal engineers consider packing density and void porosity important for two main reasons: they impact hydraulic performance by dissipating energy in voids and altering wave reflections, instability, acceleration, and overtopping; and they relate to material acquisition.

In the design phase, it's important to estimate rock layer thickness, dimension cross-sections for contractors, and determine the total tonnage of rocks needed, which depends on void density. Studying packing relationships is important because uncertainties about voids and packing can pose risks for designers and contractors.

Factors affecting the porosity of rock fragments include particle size distribution, container wall effects, resistance effects, surface roughness, deposition history, and long-term durability.

Moreover, void porosity is a critical parameter for determining the quantities of rocks used in arm construction.

Porosity is affected by volume characteristics, such as flatness and rock shape, as well as by construction features like boundary definition, survey methods, placement techniques, and the influence of underlying layers. Additionally, intrinsic characteristics, including color, dimension, density, water absorption, and weathering resistance, also impact rock porosity.

The actual porosity value remains constant regardless of the boundary definition or the surveying methods employed, thereby representing porosity in an infinite, empty, and limitless structure. Consequently, the topographic method is tasked with defining the boundary of the rock structure.

The porosity of the imaginary void is an average value determined over the specified rock layer, based on the construction and measurement of the rock's structure.

The actual porosity of the void is defined during the calculation and tendering phase. The discrepancy between these two definitions accounts for the difference in the calculated and actual void porosity values.

The main challenge is defining the relationship between the structure's volume and the weight of the blocks used. Coastal defense structures are measured in cubic meters, while rock blocks are sold by weight in buckets.

This complicates calculations and payments but not the total weight of blocks, which is easily measured. For builders, a higher void index means fewer stones per cubic meter. For contractors, it's the opposite.

This study examines the porosity of voids and the structures for retention, recovery, and implantation at Icaraí Beach, Municipality of Caucaia, State of Ceará, as prepared by the National Institute for Waterway Research (Instituto Nacional de Pesquisas Hidrográficas, 2022).

The solution includes eleven curvilinear structures, totaling 420 meters, with a longitudinal spacing of 700 meters. Additionally, a 50-meter artificial beach drain, elevated over 4 meters, is recommended to withstand high water levels. The first > depicts a unitary section of the shoreline protection scheme, which will be implemented in four stages (Figure 1).

1st: three protection spies (5,6,7), already being built in the city of Icaraí.

2nd: four spies (1,2,3,4), with the implementation forecast for the end of second semester.

3rd: four protection spies (8,9,10,11), with the implementation forecast for 2023.

4th: beach fattening along the entire stretch, with the implementation forecast for 2023/2024.

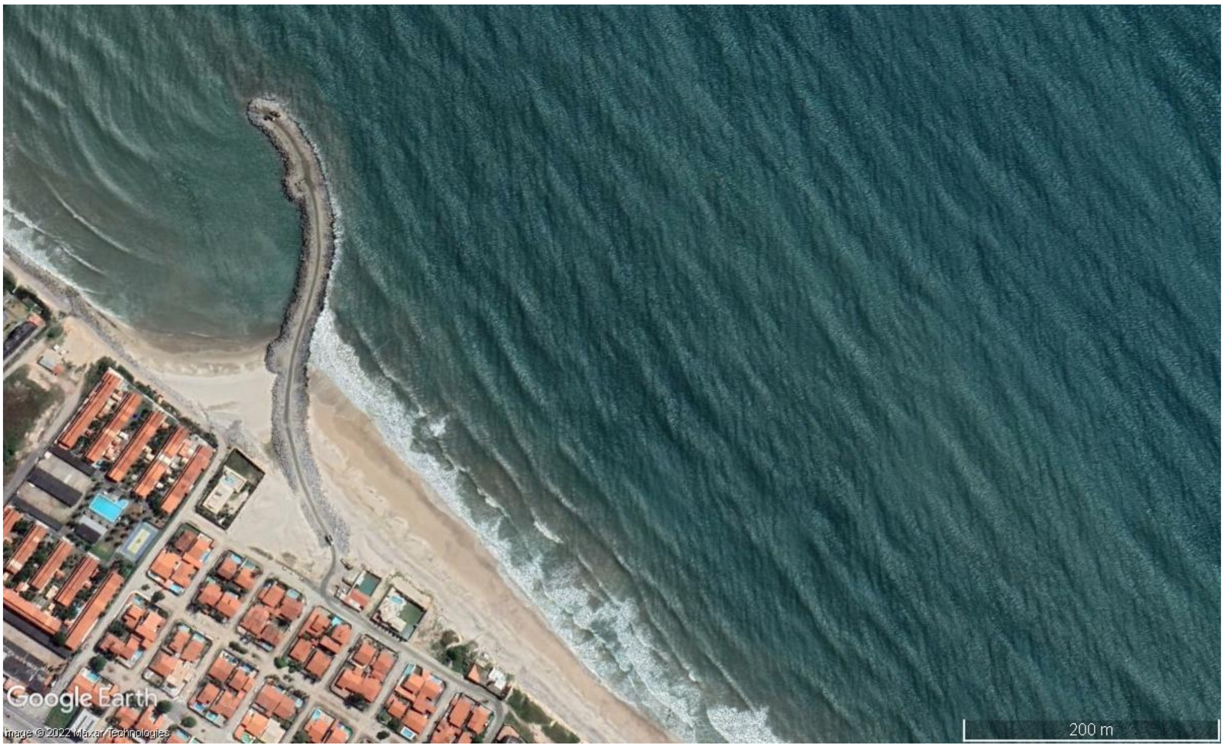

Figure 1. Satellite's photo of the 5th spie, in August 2022, at Icaraí, Municipality of Caucaia.
Source: Google Earth (https://earth.google.com).

This value is based on international studies conducted between 28 to 38 years ago. During this period, techniques, equipment, and assessment methods have significantly evolved, including inspection forms such as GPS differentials and laser distance meters. In this context, we reaffirm the reliability of bathymetric surveys and soundings for determining the actual density value of the Municipality of Caucaia structure, which is valued at 1.43 tons m^{-3}.

In conclusion, it is recommended that national control bodies, such as the Brazilian Association of Technical Standards (ABNT), conduct specific studies to define density values relating the weight of the supplied blocks to the volume of projected coastal structures, considering the granulometry of granitic rock blocks for supplier payments. ABNT organizes and standardizes documents applied across various areas, from academic settings to business procedures.

Methodology

The Brazilian Association of Technical Standards defines topographic surveying as using angular and distance measurements with appropriate instruments to establish ground support points and determine topographic coordinates. Detail points are used for planimetric representation at a specific scale and altimetric representation through level curves or quoted points.

A topographic survey measures the location, shapes, arrangements, and features of natural and artificial resources on land. It collects data on terrain contour and elevation to calculate volumes needed by engineers, architects, and the government. Topographic surveys cover various mapping products, whether terrestrial, aerial, or underground. In our study, a total station was used to determine the total volume of its spies.

Total stations were initially developed in the 1980s by Hewlett-Packard (Binker and Minnick 1995). These instruments electronically detect horizontal and vertical angles and combine with an Electronic Distance Measurement (EDM) system to generate the X-Y-Z coordinates of a point relative to the instrument's coordinates. The angle readings can be "1, with a precision of 0.5". Digital readings eliminate uncertainty related to real readings, data, and micrometer interpolation. The electronic system mitigates angular errors commonly associated with conventional theodolites. Additionally, electronic instruments are equipped with a double-axis compensator that corrects for horizontal and vertical angle deviations caused by plumb line variations. With the inclusion of a data collector, the total station can directly interface with microprocessors and software. The capability to measure and record data using a single device has significantly transformed topographic surveying.

In the practical stage, we used the following types of equipment:

Nikon brand total station (DTM-332, class 2), with aluminum tripod and calibration certificate (because this equipment needs to be calibrated to continue observing the same precision); Two telescope poles with circular bubble level, with reflective circular prisms; Steel tape, unknown brand, 10 meters of length.

Steel pins and red synthetic paint for the materialization and signaling of the basic and topographic support stations.

In offices, computers, AutoCAD software to design the shoreline and verify all the carapace and the constructive structure (Figure 2).

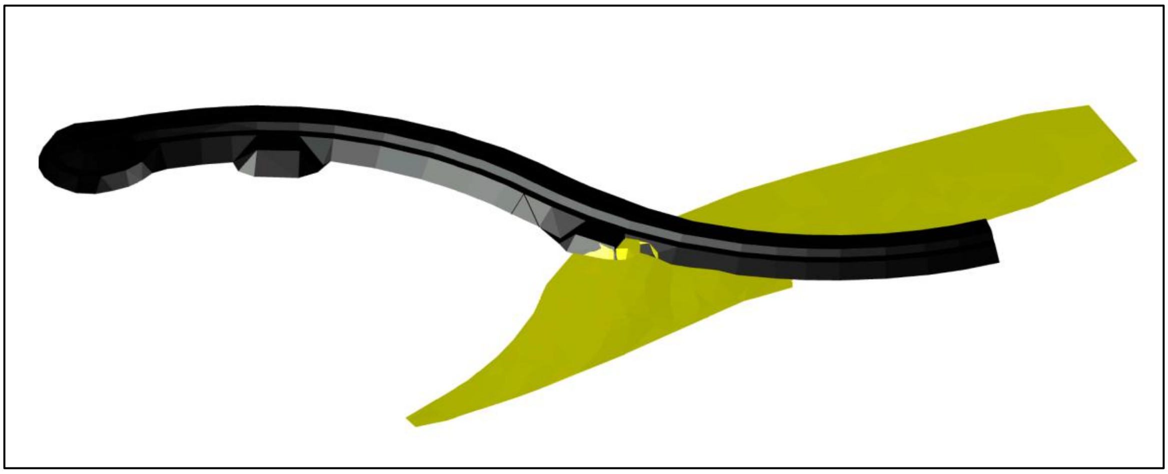

Figure 2. Diagram shorelines block 5, Icaraí, Municipality of Caucaia.

The volume of transported rock blocks is measured using Federal Police road scales, which shows the truck's fee amount and net weight. The project adhered to all guidelines, using four types of rocks: Jetty core (0.3 ton), Intermediary (0.3 to 0.5 tons), Post body (1 to 3 tons), and Carapace (3 to 5 tons).

Two methodological approaches were used to link the cubic meters of built structure to the block's weight. During this study, the material offered as a sample determined the weight proportion (in tons) relative to the transport bucket volume (in cubic meters) in the Jetty Adequacy Study. This was done with 'Edcon, Comércio e Construções' and 'Assist, Consultores Associados'.

In the methodology, the weight transported in each bucket was noted and compared to the size of the buckets (width, length, and height), and the measure of the height of the rock in relation to the bottom of the bucket. The buckets utilized were as follows: measurements: 2,3m of width, 5,3 m of length, and 1,4 m of height, with an 18 cubic meters volume.

After completing the jetty, the weight of the blocks was calculated using invoices from the rock purchases for jetty 5 and compared with the final measured volume.

Results and discussion

Volume of the structure:

Skimmers' structures help control coastal erosion and ensure safe port access by absorbing, refracting, diffracting, and reflecting wave energy (Reeve et al., 2018). Positioned perpendicular to waves, they reduce wave height, aiding ship anchorage and erosion control. Various breakwaters, made from different materials, vary in permeability and ability to reduce wave energy, significantly impacting coastal dynamics and morphodynamics.

The traditional structure of a skimmer consists of a small rock core covered with large (heavy) stones or concrete elements.

This outer layer is called reinforcement, being formed by rocky blocks, large enough to resist the action of waves and the inner layer by small blocks, enough to avoid the removal of fine native material in the middle. The traditional skimmer has some advantages: The failure of the armor layer is not sudden and when it occurs, it gradually evolves.

Also, allows high energy dissipation due to its slope and transmission through the porosity of the rock blocks. It can be used for various types of soil and features easy maintenance and construction, small wave reflection and minimal overtopping than vertical structures (Figure 3).

A traditional skimmer consists of a small rock core covered with large (heavy) stones or concrete, known as reinforcement. The outer layer resists wave action, while the inner layer prevents finer material from being washed away. The advantages include gradual failure of the armor layer, high energy dissipation, suitability for various soils, easy maintenance, construction, reduced wave reflection, and minimal overtopping compared to vertical structures (Figure 3).

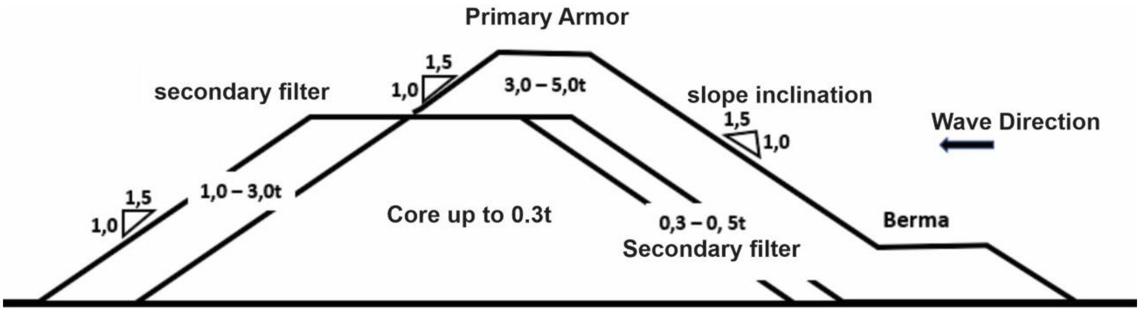

Figure 3. cross section of the Icaraí beach skimmers, with indication of the natural elements and weight of the blocks.

Normally each skimmer layer should be designed to prevent the finest materials from being washed away by the top layer. The outer layers are designed to withstand anticipated wave action. The choice of building materials primarily depends on their availability. Additionally, constraints may arise from the strength of the sea floor; if there is sand present, a filter is typically required. After designing a skimmer, its cost must be carefully evaluated to determine the most sustainable solution.

The Hudson formula (1953, 1959) calculates the minimum size of rockfill needed for stable structures like skimmers against storm waves. It was based on model tests with regular waves in rock structures without a permeable core. The formula relates the average weight of the reinforcement to wave height and structural parameters. For further details, see the Shore Protection Manual, volume 2 (Department of The Army, US Army Corps of Engineers., 1984).

The Instituto Nacional de Pesquisas Hidroviárias [INPH] of the Ministry of Infrastructure prepared the initial beach recovery project for Caucaia, Ceará. It detailed the volumes of granite rock blocks by weight class for skimmer 5 sections (Table 1).

To minimize accident risks during stone placement by transport buckets, two swivels spaced 150 meters apart were designed for the 420-meter-long spigot. The volume is calculated from the jetty's plans but does not account for erosion at the base or deepening rocks, as the [INPH] project does not include rock filters or geotextiles necessary for sandy soils, like canvas.

Table 1. total volume of granite blocks according to weight class. Source: [INPH], 2022.

Weight Class	Volume (m^3)
Até 0,3t	34.543,25
0,3 a 0,5t	8.195,25
1,0 a 3,0t	7.088,00
3,0 a 5,0t	17.721,50
Total	67.548,00

After the operation, the rockfill is elevated to confirm whether the slope of the structure adheres to the project specifications (1.5:1) or 330 meters, and to determine if the rock blocks have shifted further than anticipated, thereby increasing the volume of rocks. Bathymetric and topographic surveys of area number 5 were conducted to present the actual volume. Densification was assessed through underwater soundings, with the average areas of densification on the sea floor being considered, averaging a measurement of 0.40 meters. All procedures were supervised by the Municipality of Caucaia, and the final measurements are as follows:

– Beach jetty body total volume: 80.274,32 m^2.
– Increase in the volume of the lateral carapace: 1.109,241 m^3.
– Volume of density difference: 4.193,82 m^3.

Total volume: 1st, 2nd and 3rd lifting, respectively:

80.274,43 + 1.109,24 + 4.193,82 = 85.577,49 m^3.

The final volume: 85.577,49 m^3. In comparison to the initial project, it increased from 72.548 m^3 (17,95%), 10,64% corresponds to the execution volume, 1,52% corresponds to the volume of the lateral carapace and 5,78% corresponds to the densification.

Void's porosity of the structure

In the methodology, voids were calculated using bucket volume. Forty-one samples were taken for core-type material and 78 (seventy-eight) for material above one ton. Granulometries were simplified into two groups based on quarry block classes. Spreadsheet models recorded delivery dates, invoice numbers, and the three dimensions of the bucket, with depth varying by rock block height, and total weight in tons from purchase invoices. From these values, freight volume in cubic meters and density (mass/volume) in tons per cubic meter were calculated.

For granite blocks weighing up to 1 ton, which corresponds to the material applied to the core of the structure, the height of the load had an average depth of 1.5 ± 0.07 meters, the mass 25.20 ± 1.51 tons, and the volume 18.97 ± 0.94 cubic meters. Considering these values and the corresponding calculations, the load density was 1.33 ± 0.09 tons per cubic meter, using for the rocks the density informed by the quarry and equal to 2.67 t m^{-3}. Thus, we will have the Sterile and Empty ratio = 0.505, that is, a percentage of 51% (Figure 4)

Date	Jetty	Type	Invoice Nº	Length (m)	Width (m)	Depth (m)	Weight (t)	Volume (m^3)	Proportion (t/m^3)
04/07/2022	6	0 à 1t	262959	5,5	2,3	1,55	25,97	19,6075	1,324493
08/07/2023	6	0 à 1t	400950	5,5	2,3	1,4	23,68	17,71	1,337098
08/07/2023	6	0 à 1t	400954	5,5	2,3	1,39	20,84	17,5835	1,185202
08/07/2023	6	0 à 1t	400956	5,5	2,3	1,45	23,21	18,3425	1,265367
08/07/2023	6	0 à 1t	400963	5,5	2,3	1,38	25,03	17,457	1,433809
12/07/2022	6	0 à 1t	401415	5,5	2,3	1,45	24,54	18,3425	1,337877
12/07/2022	6	0 à 1t	401422	5,5	2,3	1,5	21,48	18,975	1,132016

Figure 4. Spreadsheet template used for calculating core-type material.

With the same methodology for granite blocks measuring between 1 and 5 tons, the cargo had an average depth of 1.84 ± 0.09 meters, a mass of 24.07 ± 2.01 tons, and a volume of 23.28 ± 1.26 cubic meters. Thus, the load density was 1.3 ± 0.08 tons per cubic meter, using the density equal to 2.67 t/m^3, we will have the Sterile/Vacuum ratio = 0.61, producing a Percentage of 61 %.

Using the same methodology for granite blocks weighing between 1 and 5 tons, the cargo exhibited an average depth of 1.84 ± 0.09 meters, a mass of 24.07 ± 2.01 tons, and a volume of 23.28 ± 1.26 cubic meters.

Consequently, the load density was calculated to be 1.3 ± 0.08 tons per cubic meter. Utilizing a density value of 2.67 t m^{-3}, the Sterile/Vacuum ratio was determined to be 0.61, resulting in a percentage of 61% (Figure 5).

Date	Jetty	Type	Invoice Nº	Length (m)	Width (m)	Depth (m)	Weight (t)	Volume (m^3)	Proportion (t/m^3)
01/07/2022	6	0 à 5t	262743	5,5	2,3	1,95	21,05	24,6675	0,85335
01/07/2022	6	0 à 5t	262740	5,5	2,3	1,65	23,60	20,8725	1,130674
01/07/2022	6	0 à 5t	262744	5,5	2,3	1,85	21,09	23,4025	0,901186
04/07/2022	6	0 à 5t	263024	5,5	2,3	1,80	25,45	22,7700	1,117699
04/07/2022	6	0 à 5t	263026	5,5	2,3	1,90	25,31	24,0350	1,053048
04/07/2022	6	0 à 5t	263039	5,5	2,3	1,90	24,51	24,0350	1,019763
04/07/2022	6	0 à 5t	233301	5,5	2,3	1,95	23,13	24,6675	0,937671

Figure 5. spreadsheet template used for calculating void's carapace materials.

The calculation results show that densification varies according to the block's size, (higher on blocks that measure until 1 ton and 1,33 ± 0,09 t m^{-3} than on 1,03 ± 0,08 t m^{-3}). One of the first conclusions of this study shows the necessity of different conversion rates for each rock granulometry.

The construction of a structure estimated in a project of 100 m^3, using the first ratio (stones < 1.0 t) would require 132 tons, considering the price of the stone placed in the work with R$ 45.00 reais, only due to the difference, the builder would lose R$ 13.5 reais m^{-3}. Although it can be considered a low amount, the payout difference would be 1,116,786.25, which is a lot.

The porosity of voids is crucial for determining rock amounts in coastal protection structures. The shell layer thickness depends on the layer thickness coefficient (kt), which corrects for the actual thickness being less than twice the rock's nominal diameter (Lathan et al., 2002). Field tests on numerous rock constructions determine this thickness. Any boundary differences will affect the layer thickness and void porosity, necessitating two definitions for porosity due to design sensitivity.

Imaginary void porosity is the average value over a rock layer, defined after construction and measurement. Actual porosity is defined during calculation and bidding. The difference between these definitions causes discrepancies in porosity values. Table 2 compares three standard orientations to clarify the uncertainty in void porosity for irregular and rounded reinforcement.

Table 2. existing guidelines for typical properties constructed with randomly placed irregular, rounded armor rocks. Kt- layer thickness coefficient; Nv - void porosity (%).

Rock Shape	SPM (1994)	British Standards Institution [BSI] (1984)	Balkema et al. (1991)
Equivalent e irregular			
k_t	1,15	0,75-0,85	0,75-1,20
Nv: %	40	37-39	38-40
Rounded			
k_t	1,02	0,73	0,8-1,20
Nv: %	38	35	35-37

Using international standards based on all full-scale structures reviewed by various coastal works construction manuals, the following static values provide an indication of the average void porosity value, and its variability based on different coastal structures (average level of voids = 39%). The relationship between weight and volume of material depends on the relationship between density of rock and the volume of voids:

- Weight X Volume = Density of rock. 1 - (void's volume).
- Weight X Volume = 2.67 t m^{-3}. 0.61 = 0.62 t m^{-3}.

If we consider an average value of international standards, the material's weight of 1 m^3 volume execution uses 1.62 tons of rocks.

With the data obtained from the average of the invoices (NF's), referring to the purchase of rocks for the execution of number 5, the quantification of the weight (tons) used for its construction was obtained. It is important to emphasize that for this study, only two classes of rocks were considered, as shown in Table 2. In core-size stones, a total of 71,048.19 tons were recorded, and of larger blocks, 51,370.72 tons, making a total volume of 122,418.91 tons, as shown in Table 3.

Table 3. Table of purchase of rocks for the execution of post 05, values in tons.

Spie 05	Core (até 1 t)	Body and Carapace (> 1 a 5 t)
Measurement 05	8.703,41	5.373,81
Measurement 06	30.082,01	12.004,18
Measurement 07	28.472,54	28.742,47
Measurement 08	3.790,23	5.250,26
Total	71.048,19	51.370,72

If we divide the total mass of rocks by the total volume of the structure, we have the total density of the structure = 1.43 t m^{-3}. Considering the density, we can calculate the percentage of rock equals 53.56%, by subtracting the percentage of waste and voids = 46.44%. This result is interesting because it is lower than the average of traditional values used (1.62 t m^{-3}), but higher than the average achieved by the tests of volumes transported by trucks (1.18 t m^{-3}), Table 4.

Table 4. Calculation to define the density of the structure and the percentage of steril and empty.

Calculations	t m^{-3}
Rock Density (a):	2,67
Structure Density (b):	1,43
Difference (c): = a - b	1,24
Sterile and Voids = c/a	0,464
Percentage of Rocks:	53,56%
Percentage of Sterile and voids:	46,44%

Conclusion

The climate change projected by the IPCC 2022 (Castellanos, et al., 2022), will convert the risks in some regions, since Brazil is considered a highly vulnerable country and already heavily impacted by climate change. With the impacts of climate change, sea level rise, coastal erosion, ocean acidification, coral bleaching, and severity of droughts may be perceived, bringing some consequences such as: problems in water supply, fall in agricultural production, increase in food insecurity, and health problems.

In this sense, in response to the erosion scenario, different types of intervention should be increased for the production and recovery of the affected areas. An increase in interventions with the use of skimmers, jetty's, and hydraulic embankments is expected on the coast of the State of Ceará.

The value of 1.62 tons m^{-3} used for payment for services for the execution of coastal work is based on studies carried out internationally, between 28 and 38 years ago. Even though the evaluation techniques have changed in this period due to the implementation of GPS, laser distance meters, we reaffirm the robustness of the baltimetric surveys and soundings to define the real value of the density of the Municipality of Caucaia structure in the amount of 1.43 tons m^{-3}.

As a conclusion, we can suggest that national control bodies such as the Brazilian Association of Technical Norms (ABNT), which is responsible for organizing documents and norms, which are applied in different areas, start specific studies to define density values relating the weight of the blocks supplied with the volume of the projected coastal structures, considering the granulometry of the granitic rock blocks, for payment to suppliers.

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