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Application of the stability index in artificial sand nourishment projects in Cuba

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Effective sand nourishment for beach regeneration requires selecting sediments from a borrow zone compatible with the native materials, ensuring their stability and longevity. In Cuba, most of its beaches are predominantly covered by biogenic-marine sediments, and assessing the suitability of borrow sand presents unique challenges. This article compares two methods for assessing sand suitability in Cuba, where biogenic-marine sediments predominate: the Stability Index (*Si*) method and the traditional approach proposed in the Shore Protection Manual, herein referred to as the Overfill Factor (*Ra*) method. The *Si* method assesses compatibility by comparing grain-size distributions without assuming log-normality, while the latter uses the statistical parameter to estimate overfill requirements. The purpose of this study was then to provide a first assessment on this topic by evaluating a method that possibly allows for better adjustment than traditional methods, with the case studies on the beaches in Cuba specifically covered by biogenic-marine sediments. Using real-life case studies of artificial sand nourishment projects on beaches in this geographic region with varied sedimentary characteristics, we determined the performance of both *Si* and *Ra* methods in classifying borrow materials. The results of this initial approach suggest that the *Si* method offers greater flexibility when evaluating borrow zones, providing more accurate results and the possibility of utilizing areas that would have been discarded by conventional methods. The possibility of more efficient use of natural and economic resources is also becoming evident. Furthermore, it indicates that the application of *Si* is feasible in subsequent artificial sand replenishment projects in Cuba and on similar beaches with biogenic-marine sediments in the Caribbean region. This study represents the first application of a specific methodology to be applied for evaluation of the suitability of sand for Cuban projects, with the aim of its introduction as an additional tool for future studies.

KEYWORDS

beach regeneration, artificial sand nourishment, sand suitability, stability index, critical ratio, borrow zones

1 Introduction

Artificial beach nourishment is a widely used strategy to combat erosion on sandy coasts, requiring sediments from an area commonly called a borrow zones, which must match or improve the stability of the native materials of the beach (National Research Council, 1995).

As stated in the *Coastal Engineering Manual* (EM 1110-2-1100 Part V, 2001), the particle size distribution of the borrow material can affect the cross-sectional shape of the nourished beach profile, the erosion rate of the fill material, and the beach's response to storms. Typically, borrow material does not exactly match the native beach material, which is why an analysis is required to assess the compatibility of the borrow zones material with that of the native beach from a functional perspective. A comparative analysis is also required to economically evaluate alternatives for a given project.

The first investigations into the compatibility of borrow material were carried out by Krumbein (1957); Krumbein and James (1965); Dean (1974), and James (1974; 1975), who addressed this issue through various comparative analysis techniques that utilized the sand-size distributions of the natural beach and borrow material at candidate sites. These approaches develop a factor or parameter that indicates the amount of fill material needed, obtaining a unit volume equal to that of the native sediments, taking into account the differences in the characteristics of the borrow sediment and those of the native beach. They assumed that the deposited material would be separated as a result of coastal processes and, given sufficient time, would approximate the original grain size distribution. The portion of borrow material that did not match the grain size distribution of the native sediment would be lost offshore, illogically losing the contribution of the coarser grains.

The method proposed by James (1975) is the most widespread and used internationally, since it was adopted by the *Shore Protection Manual* (US Army Corps of Engineers, 1975).

More recently, Pranzini (2002) and Pranzini et al. (2018), after delving into the research on this topic, pointed out a series of problems and limitations in the application of the aforementioned method and proposed an alternative.

According to Pranzini (2002), the adjustments made by James (1975) and Hobson (1977) to the original method, and the one proposed by Dean (1974), partially resolved the limitations and problems of evaluating borrow zones, but did not overcome issues related to the log-normal distribution and were based primarily on the use of sediment similar to the native material.

The alternative method proposed by Pranzini (2002) allowed the suitability of borrowed materials to be assessed without considering the log-normality of the sediment as an essential condition, nor was it intended to provide materials identical to the native ones. His proposal was based on the hypothesis that the stability of each grain size fraction introduced into the beach was inversely proportional to the value of that same fraction on the cumulative curve of the native sediments. This means that the stability of a grain coarser than the coarsest grain present on the

beach is equal to 1, and therefore can give a full contribution to the final volume. Conversely, the stability of a grain finer than the finest grain present on the beach will make a zero contribution.

This method has been extended and validated in beach nourishment designs and borrow zone evaluations mainly in Italy, Spain, and Israel (Pranzini et al., 2018, 2020; Bitan et al., 2020).

The phenomenon of erosion on Cuban beaches has been closely monitored since the 1970s, with the initial implementation of joint studies by the Institutes of Oceanology of the USSR and Cuba (Avello et al., 1973). Later, Juanes (1996), in his thesis for obtaining the degree of Doctor in Geographical Sciences, presented an inventory that summarizes the characteristics of 140 beaches in the archipelago, demonstrating that 86% of them are experiencing a continued retreat of their coastline and a general deterioration of their physical conditions. Specifically, for Varadero beach, this researcher demonstrated that it was maintaining a rate of coastline retreat of 1.2 m/year, with an annual loss of 50,000 m³ of sand. Subsequent research confirms this trend to a greater or lesser extent on different Cuban beaches (Tristá Barrera, 2002; García Hernández, 2005; Izquierdo, 2004).

Among the main causes of erosion in Cuba, a combination of natural causes associated with climate change and rising sea levels, as well as a lack of new natural sediment input, and causes originating from human intervention are cited. Among the latter, the most significant are the extraction of sand from the dunes and the island platform for the construction industry, the location of facilities on the dunes, damage to coastal vegetation, and inadequate construction of coastal defenses, port facilities, and tourist and sports marinas.

In response to this scenario, various actions have been implemented on Cuban beaches to control erosion, combining engineering interventions, adaptation measures, and regulatory approaches. Among these, Beach Nourishment has become the most widely used engineering technique. Therefore, deepening scientific knowledge is essential for the development of more efficient and sustainable projects that reduce the need for frequent interventions and optimize the use of available natural and financial resources. All existing methods for the design and stability assessment of beach nourishment projects are primarily based on studies conducted on beaches with terrigenous sediments. This has also been a concern for Cuban researchers, given that biogenic-marine sands predominate in this geographical region, showing significant differences in grain shape, weight, porosity, and density compared to terrigenous sediments. This issue is addressed in the work of Juanes (1996), and more notably in the studies by Tristá Barrera (2002) and García Hernández (2005), who propose adjustments to certain parameters in Dean's equilibrium profile model (1977) to better reflect the specific characteristics of biogenic sediments found on Cuban beaches.

This article approaches these issues and compares the theoretical foundations, applicability, and performance of different methods in the selection of borrow materials for beach nourishment in the Caribbean region, taking case studies of different projects carried out in Cuba. This is the first time that a

proposal different from that of the *Shore Protection Manual* [SPM84] is applied in this geographical environment, which will allow us to enrich the available work tools and evaluate their effectiveness for the first time in biogenic-marine sands, this being a first step in this line of research, which will allow the designs and analyses to be tailored to this environment.

2 Methods for assessing sand suitability

2.1 Overfill factor method R_a proposed in the shore protection manual

The first detailed method for assessing sand suitability in artificial sand nourishment projects and calculating an overfill factor to compensate for expected losses due to differences in particle size was proposed by [Krumbein and James \(1965\)](#). His method made it possible to determine the volumetric requirements of the borrow sand necessary to produce a granulometry identical to the native sand. These researchers assume that both native and borrow sediments have a log-normal distribution. A simple analytical formula—based on the “phi” means and classification values (in phi units) of both sediments—can be used to calculate the overfill factor. This method proved more effective than earlier approaches and, with modifications and expanded interpretive guidelines, was incorporated into the *Shore Protection Manual* [SPM73].

The procedure for calculating the overfill factor is described below. Following [Dean \(1974\)](#), the symbol K is adopted herein to denote the overfill factor. The size of the grain of sand is typically expressed in “phi” (ϕ) units ([Equation 1](#)),

$$\text{Size in units } \phi = -\log_2 (D) \quad (1)$$

where D is the sand diameter in millimeters. The sand size distributions, $f(\phi)$, is reasonably approximated by a relationship called “log-normal”,

$$f(\phi) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\phi-\mu)^2}{2\sigma^2}} \quad (2)$$

where μ and σ represent the mean and standard deviation of the particle size distribution of the sand in phi units. An example of approximations of the log-normal distribution is shown in [Figure 1](#), which represents the two-sand distributions and their log-normal approximations as straight lines on logarithmic probability paper ([Krumbein and James, 1965](#)).

This method requires that the retained portion of the borrow material have exactly the same distribution as the native material, leading to the definition of a Critical Ratio in phi ($R_{\phi\text{crit}}$), which represents the unit mass of introduced sand needed to produce a retained unit mass with a grain size (mm) exactly equal to that of the native sand. $R_{\phi\text{crit}}$ is estimated using the following ([Equation 3](#)),

$$R_{\phi\text{crit}} = \frac{\sigma_b}{\sigma_n} e^{\frac{\mu_n - \mu_b}{2(\sigma_n^2 - \sigma_b^2)}} \quad (3)$$

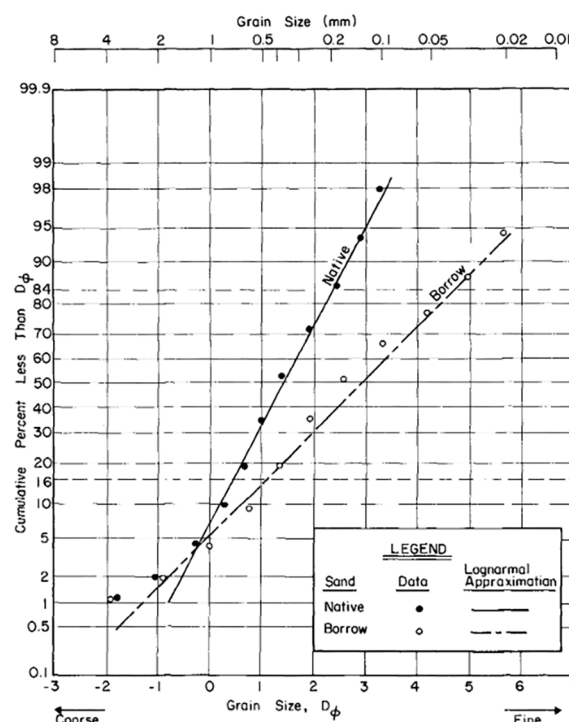


FIGURE 1

Approximations of the log-normal distribution of native and borrow sands for an Artificial Sand Nourishment project on Virginia beaches ([Krumbein and James, 1965](#)) (The figure is taken from [Dean \(1974\)](#)).

whenever $\sigma_b > \sigma_n$ (when $\sigma_b < \sigma_n$, $R_{\phi_{crit}}$ cannot be calculated).

The *Shore Protection Manual* [SPM73], along with Dean (1974) and James (1974), describe certain limitations of the method; for example, it cannot be applied when the native material is more poorly graded than the borrow material. It also identifies unrealistic values when the borrow material is coarser than the native material.

Recognizing these limitations, independent Works by Dean (1974) and James (1974, 1975) led to proposals for alternative methods. For example, Dean (1974) proposed a refinement to the calculation of $R_{\phi_{crit}}$, and consequently an adjustment to the calculation of the overfill factor, K , which he shared two similar assumptions of the method of Krumbein and James (1965):

- Part of the distribution of the borrow material would be stable when placed on the beach.
- The particle size distribution of the native material could be used as a guide to determine the “stable part”.

It was assumed that, during and after fill placement, selective sorting processes would remove excess material across all grain size classes until only the stable portion remains. Additionally, it was assumed that only the minimum amount of selective loss necessary to produce a stable distribution would occur.

Dean’s approach aims to establish a more realistic equivalence between the native material and the retained fraction of the borrow material. This allows for the loss of fine fractions absent in the native material, while the coarser fraction of the introduced sand is deemed ‘stable’.

Stability is based on the equivalence of the mean diameter between the altered borrow material and the native sand, assuming the log normal distribution as described in Equation 2.

Thus, the overfill factor proposed by Dean could be calculated by numerically solving two equations:

$$\left(\frac{\mu_b - \mu_n}{\sigma_b} \right) = \frac{f(t)}{F(t)} \quad (4)$$

$$K = \frac{1}{F(t)} \quad (5)$$

where t is a dummy variable eliminated in the solution of the two equations, while $f(t)$ and $F(t)$ represent the Gaussian function and its integral (Equation 6), respectively,

$$f(t) = \left(\frac{1}{\sqrt{2\pi}} \right) \exp \left\{ -\frac{t^2}{2} \right\} \quad (6)$$

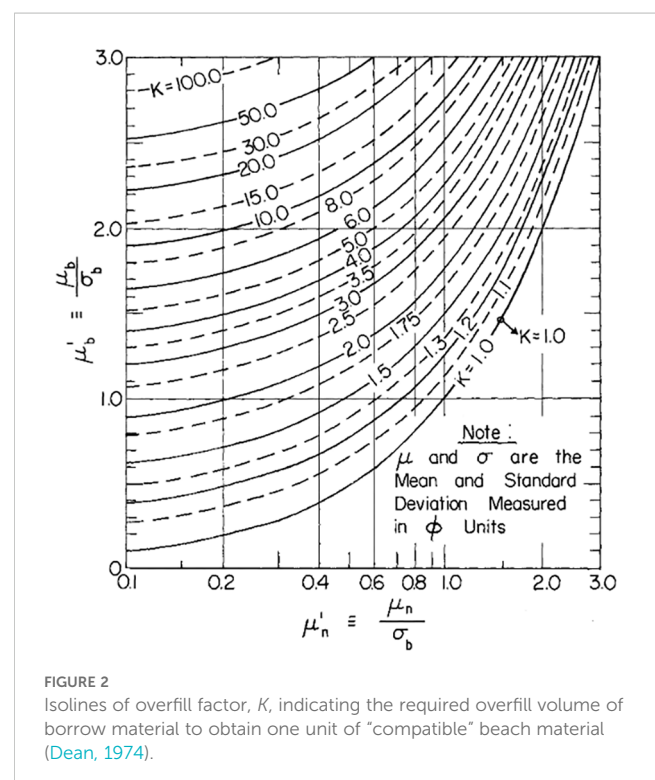
Given the difficulty in solving Equations 4 and 5 without the use of computers, something that in those years constituted a real practical obstacle, it was decided to give it a graphical approach.

Figure 2 represents the graph constructed by Dean (1974), which depicts the isolines of K (R_D) as a function of μ_b' and μ_n' , dimensionless parameters assumed to simplify the mathematical solution of the equations defining the relationship between the characteristics of native sand and borrow sand. A semilogarithmic graph was chosen for this representation of the isolines because it was found that each isoline is simply a vertically shifted form of any

of the others. For $\mu_b' > \mu_n'$ (i.e., the borrow material is coarser than the native material), 100% of the sediment is compatible according to the criterion used in this method, whereas in the opposite case, this graph provides a useful solution for determining compatibility.

James (1975) offered a new adjusted method for the calculation of the overfill factor, arriving at the following conclusions regarding the methods offered by Dean (1974) (Dean74) and James (1975) (James75):

- Both Krumbein and James (1965) and James (1975) coincided when the borrow material was coarser and better graded than the native material. In this case, they agreed in suggesting complete stability of the borrow material by providing fill factors equal to unity.
- A partial match occurred when the borrow material was finer and better graded than the native material. James75 did not offer quantitative guidance in these cases, recommending rejection of this material as unsuitable; however, Dean74 allowed for quantitative evaluation with low packing factors in some cases. In other cases, the numerical values obtained for the Dean74’s overfill factor were likely too high as to reject the material from consideration. When the borrow material had a mean ϕ fairly close to that of the native materials and also a similar grading value, Dean74 provided a useful quantitative estimate, whereas James75 did not.
- When borrowed material was less graded than native material, Dean74 always provided lower overfill factors than James75.



- d. In all quadrants there were reasonable arguments for interpreting the Dean74's overfill factor as a lower bound and the James75's overfill factor as an upper bound.

Based on these conclusions, it was determined necessary to find a compromise between the two methods, eliminating or minimizing the conceptual shortcomings they both presented. Thus, he proposed an adaptation of James75's to meet the need, proposing the Adjusted Overfill Factor R_a .

The approach to obtain R_a was similar to that of Dean (1974), in which only the finer size classes required modification, but it differed in that modification by selective sorting was assumed to lead to a stable distribution. In this case, the finer fraction had the shape of the native material distribution, and the coarser fraction that of the borrow material. Previously, Dean (1974) assumed that all material finer than a cutoff grain size was considered unstable.

Dean75 method to use the native mean phi to determine the cutoff grain size was complicated, as it did not allow for the removal of significant fine fractions from very poorly sorted borrow materials, whose phi values were similar to or bigger than those of the native materials. In the new approach by James (1975), grading modifications were assumed to be applied to all grain sizes finer than a "stable grain size" to produce a modified density of the borrow material proportional to that of the native material in this size range.

In the conceptual framework of the method previously proposed in SPM73, the choice of this stable grain size occurred quite naturally. Krumbain and James (1965) defined a "critical phi value" that represented the grain size for which the ratio of the stable distribution of the native to the borrow material was maximum, based on the assumption that no sorting losses occurred at this size. According to James (1975), an obvious adjustment was derived from the assumption that no sorting losses occurred for materials with sizes equal to or greater than this value.

The new approach by James (1975) thus provided overfill factors higher than those of Dean (1974) and lower than those of SPM73 in almost all applications. Exceptions occurred when the borrow material was better sorted, but only slightly coarser than the native material. Furthermore, the adjustment performed provided overfill factors greater than unity, unlike previous methods.

Like Dean74's method, the adjustment by James (1975) did not provide a simple mathematical formula for practical applications, so a graphical approach was also chosen.

In Figure 3, the isolines of R_a , commonly known as the Abacus of James (1975), were plotted in the range between 1.02 and 10, assuming that lower values, in quadrants 2 and 3, would assume $R_a = 1$, and therefore would be completely stable without the need for adjustments to the beach fill design. Values higher than the isolines plotted in quadrants 1 and 4 were considered completely unstable and indicated that the selected borrow zones should be discarded.

In the final conclusions of James (1975), it was argued that "... the use of overfill factors had limitations and had to be evaluated against other considerations, such as the method of management and construction and the contractor's payment basis ... they did not represent definitive solutions to the important problems involved in planning and designing artificial beach nourishment programs. They were the result of exploring the rational implications of some fairly simple concepts, and they were useful in part because they were straightforward and could be easily rejected when inappropriate. New and refined techniques would undoubtedly be developed as research on this topic progressed and experience with beach nourishment increased."

2.2 Stability index method S_i

Despite the limitations recognized by the authors offered the use of overfill factor, developed and finally refined by James (1975), the

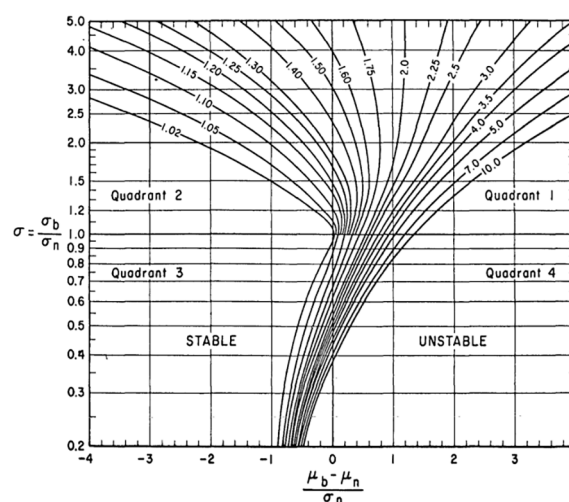


FIGURE 3
James (1975). Isolines of the adjusted overfill factor (R_a) versus the mean difference phi and the classification ratio phi.

Overfill factor Ra had been used in many beaches nourishment projects where artificial sand feeding was widely applied throughout the world, since it was proposed by the Shore Protection Manuals [SPM73, SPM75, and SPM84] (US Army Corps of Engineers, 1973, 1975, 1984), and due to its easy applicability and simplicity in calculations using graphics.

Therefore, there have been few researches and publications that addresses this topic until Pranzini (2002) proposed a new method, which has been successfully applied in projects carried out mainly in the Mediterranean Sea and Europe (Pranzini et al., 2018).

Among the limitations and problems identified in previous methods that this alternative method aims to solve are:

1. The old method only allows the estimation of the volume of borrow material required to obtain a final volume of sand with a granulometric distribution identical to the native sediments.
2. The need to hypothesize the log-normal distributions of native and borrow materials. The comparison is made using the respective values of Mean ($M\phi$) and Sorting ($\sigma\phi$) according to Inman (1952) formula. Native sediments frequently deviate from log-normality, especially composite sediments, which often present bi- or polymodal distributions, while log-normality does not occur in borrow materials that come from crushing or sieving coherent rocks, or when extracted from recent alluvial deposits. This logarithmic normality is more common in seafloor materials that do not constitute composite sediments.
3. This calculation does not yield accurate results with a ratio of $Ra = 1$ if the borrow material is better sorted than the native material. Consequently, a better graded, coarser borrow material is considered stable, regardless of its size. Different, coarser materials end up having the same Ra value and, therefore, the same suitability. The same is true

for finer materials, which will always be considered unsuitable, making it impossible to determine the most suitable among two or more low-cost materials that could be used for beach restoration.

This last limitation is clearly seen in the James (1975) Abacus itself (Figure 4). This abacus was the subject of particular analysis by Pranzini et al. (2024), during the “XVII Spanish Conference on Coastal and Port Engineering. Ibiza, May 8 and 9, 2024”, with the presentation entitled “The problems of James’s abacus and an alternative solution.”

According to these authors, there are two problematic areas within the abacus. The blue area in Figure 4, for instance, corresponds to borrow sands that are coarser and better-sorted than the native sands. These are simply considered “stable,” but the nomogram is unable to distinguish which of the different borrow sources is the most suitable. On the other hand, the red area in the same figure corresponds to well-sorted borrow sands of substantially similar size. In this area, the lines are so close together that small errors can lead to big differences volumetric in its use.

The proposed alternative method defines a Stability index S_i , based on the premise that a stable beach does not necessarily have to have a granulometric distribution identical to the original, therefore, it does not consider the log-normality as an essential condition. Furthermore, it proposes that an eroded beach most likely has coarser sand than the original due to the selective erosion it has undergone. Consequently, an environmental project should be to restore the beach to its original state.

It can also be added that the project to be carried out is for a beach that has been previously restored already. Therefore, its native granulometric distribution might have been modified, and the borrow zone used might not meet the suitability criteria proposed by James (1975).

The hypothesis of this new method is that the stability of each fraction introduced into the beach is inversely proportional to its

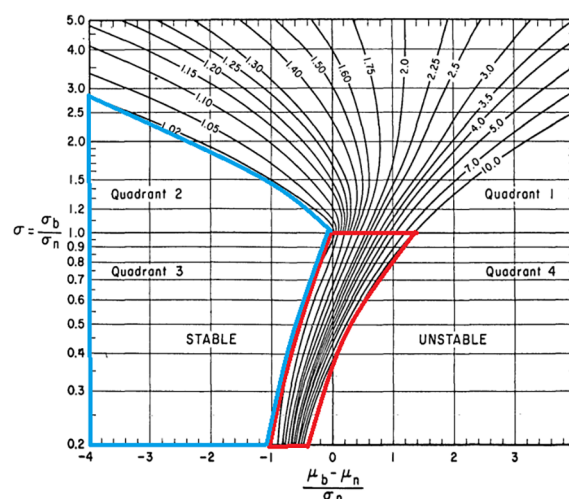


FIGURE 4
Problem area of James' Abacus (Pranzini et al., 2024).

stability in the native sand. This implies that the stability of a grain coarser than the coarsest present in the beach is equal to 1, thus completely contributing to the final volume. Conversely, a grain finer than the finest present in the beach is equal to 0, contributing nothing to the final volume. Therefore, the Stability Factor for each granulometric fraction (f_s) (Equation 7) is equal to the inverse of that same fraction “i” in the cumulative curve of the native sediment, divided by 100. (Figure 5).

$$(f_s)_i = \frac{100 - C_{ni}}{100} \quad (7)$$

where C_{ni} represents the cumulative percentage of the granulometric fraction “i” of the native sediment.

Multiplying “ f_s ” by the value of the representative fraction of the borrow sand grain size class yields its contribution to artificial beach nourishment. The sum of these values, divided by 100, represents the stability index Si (Equation 8), which always has a value between 0 and 1.

$$Si = (\sum q_{bi} \cdot f_{si}) / 100 \quad (8)$$

Here, $Si = 0$ means that all the grains of the borrow material are finer than the native grains. Conversely, if $Si = 1$, all grains are coarser than the coarsest grain present in the beach. Therefore, a fill material with $Si = 0.50$ will therefore have a particle size distribution identical to that of the beach.

The main advantage claimed for this method is that a Stability Index Si can be assigned to any type of material. This even includes materials for which previously proposed methods either do not allow evaluation or assign a generic Overfill Factor Ra value of 1. More specifically, by calculating the Stability Index Si , it becomes possible to evaluate borrow materials that would have been discarded with the calculations of Ra . However, due to their availability and low cost, these materials are feasible to use, thus enabling the creation of a suitability scale for alternative materials.

Only materials with Si values exactly at 0 or 1 would be impossible to classify within a finer scale, but in practice, it is unlikely to obtain such precise results.

To perform the calculations, a routine is created in an Excel spreadsheet, where the cumulative percentages of native and borrow sediment are entered, which then produce the f_s values. These f_s values are multiplied by the respective values in the other column. The sum of these results ultimately provides the Si values. An example of the spreadsheet used for this research is shown in Figure 6.

2.3 Data collection and analysis

As stated in the introduction, the objective of this research is to examine the different methods available for assessing the suitability of sand in beach regeneration projects where Artificial Sand Feeding is applied, comparing the performance of each of them by evaluating case studies in Cuba. This is the first time that a methodology other than the one proposed in the Shore Protection Manual [SPM84] is applied in the Caribbean’s biogenic-marine sand environment.

For this purpose, data will be taken from projects executed on the beaches of Varadero, Jardines del Rey (Cayo Coco and Guillermo), and Cayo Santa María – Las Brujas. As explained above, all sand suitability analyses for these projects were conducted using the James (1975).

Essentially, the same methodology, explained below, was followed for analyzing the granulometric characteristics of the native and borrow sands in these projects.

For native sands, sand samples were taken from selected profiles spaced 250 meters apart along the beach, with 28 samples collected per kilometer of shoreline for each project. The samples were collected to characterize each of the morphological element

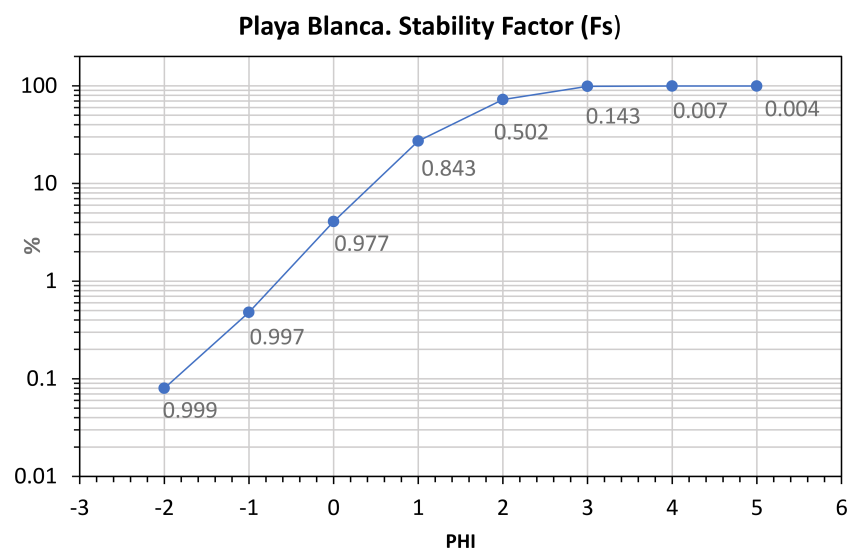


FIGURE 5
Cumulative curve and Stability Factor (Fs) calculated for Playa Blanca, Cayo Santa María, Cuba.

	A	B	C	D	E	F	G
1	Sand compatibility (Punta Hicacos 2012)						
2	Native Sand					Borrow Area (Mono 1)	
3	Phi	%	% Accumulated	(100 ac/100)	Fs	%	Is
4	-2.00	0.00	0.00	1.00	1.00	0.25	0.25
5	-1.00	0.12	0.12	1.00	1.00	1.48	1.48
6	0.00	0.38	0.50	1.00	1.00	5.60	5.58
7	1.00	6.98	7.48	0.93	0.96	20.70	19.87
8	2.00	66.81	74.29	0.26	0.59	38.63	22.84
9	3.00	24.66	98.95	0.01	0.13	25.71	3.44
10	4.00	0.73	99.68	0.00	0.01	7.38	0.05
11	5.00	0.00	99.68	0.00	0.00	0.25	0.00
12						100.000	0.535
13	M (μ)	0.31 mm				0.34 mm	
14		1.68 phi				1.55 phi	
15	σ	0.58				1.07	
16	General parameters of the project						
17	Beach length (m)					2400	
18	Average density (m³/m)					85	
19	Calaculated volume. Equilibrium beach profile for 20 m wide (m³)					165600	
20	Ra (James, 1975)					1.225	
21	Overfill volume (m³)					37260	
22	Total volume (VT+Ra)(m³)					202860	
23	Final project volume (m³)					203000	

FIGURE 6
Example of excel sheet created for the S_i calculation.

present in each profile (dune, post-beach, berm, fore-beach, inflection, valley, and submarine bar), as shown in Figure 7.

Finally, to obtain the type sample of the beach, a composite sample was obtained, weighting the weights per sieve in each profile using mathematical methods, obtaining a single value for each of them. This process, using each of the weighted type samples from each profile, was repeated to obtain the final value for the entire beach. In the case studies presented below, no substantial changes were found in the grain size of the type samples along the beaches, which would require a differentiation in the selection of the sand to be introduced.

In the case of the borrow zones, the sediments were characterized through sampling using a network of stations, which were distributed based on the size of the area to be sampled and the homogeneity of the sediment body, spaced 100 meters apart. At all stations, surface samples were taken. Additionally, in areas with lower sampling density—stations spaced 300 meters apart—subsurface sampling was carried out to verify the continuity of sediment characteristics along the lithological column (Figures 8, 9). The characterization and definition of these mineral resource blocks were accompanied by geophysical, geological, and bathymetric surveys.

The granulometric processing in the laboratory was carried out according to the methodology proposed by Petelin (1967) for the study and characterization of marine sediments. A Restsh AS 200 analytical sieve shaker was used, along with a set of sieves with mesh sizes of 0.062, 0.125, 0.25, 0.50, 1, 2, and 4 mm. Given the nature of

the samples, consisting entirely of sand, the dry sieving method was employed.

The sieve weight data were processed using Gradistat Version 9.0 software, developed by Simon Blott of the Current Environments Research Group and belonging to the Department of Geology at Royal Holloway University of London. From this, the mean particle diameter (M) in mm and ϕ units, the standard deviation (σ), kurtosis and skewness were obtained by the method of moments.

For sediment classification, the system proposed by Wentworth, aligning with the range of sieves used, was employed as outlined in the Shore Protection Manual [SPM84]. Using mathematical methods, and also using Gradistat Version 9.0 software, the composite or type sample was then obtained for both native and borrow sands.

3 Results with case studies

3.1 Generalities

Cuba, belonging to the Greater Antilles group, is an archipelago made up of a main island, which gives the country its general name, and four sub-archipelagos that surround it. More than 3,000 islands and cays have been counted, with more than 6,000 km of coastline. Due to its geographical location, Cuba divides the waters of the Caribbean Sea from those of the Gulf of Mexico and the Straits of Florida.

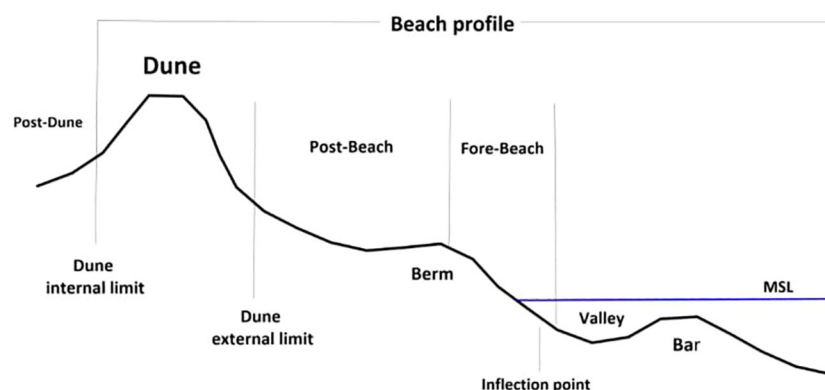


FIGURE 7
Morphological elements of the beach profile taken into consideration for sedimentological sampling.

Beaches, in particular, constitute an important natural resource for the country, not only for their use in tourism and the economic income they generate, but also for being an important line of defense against sea intrusion during extreme weather events and in combating the effects of climate change. Therefore, their preservation contributes to the protection of one of the country's most important natural resources, in addition to constituting an important action for environmental protection (Juanes, 1996).

However, although signs of erosion on Cuban beaches had been observed since the 1950s, references to this phenomenon first appeared in scientific work in the late 1960s, particularly regarding Varadero beach. This was initiated by Zenkovich and Ionin (1969), and

subsequent investigations into this issue have been continued by various researchers (Ionin et al., 1972; Pavlidis et al., 1977; Medvediev and Juanes, 1981; Medvediev, 1982; Suarez, 1976; Ramírez, 1989).

The search for solutions based on scientific advances led Cuban researchers and engineers to opt for Beach Nourishment as the preferred technique for beach restoration and maintenance, in combination with adaptation measures, management, planning, and updates to legislation. Thus, in 1987, the implementation of the first projects began at Varadero Beach, and the experience was later extended to other tourist regions of the country.

A key element in implementing this beach restoration strategy is the characteristics of the sediments. Many publications and

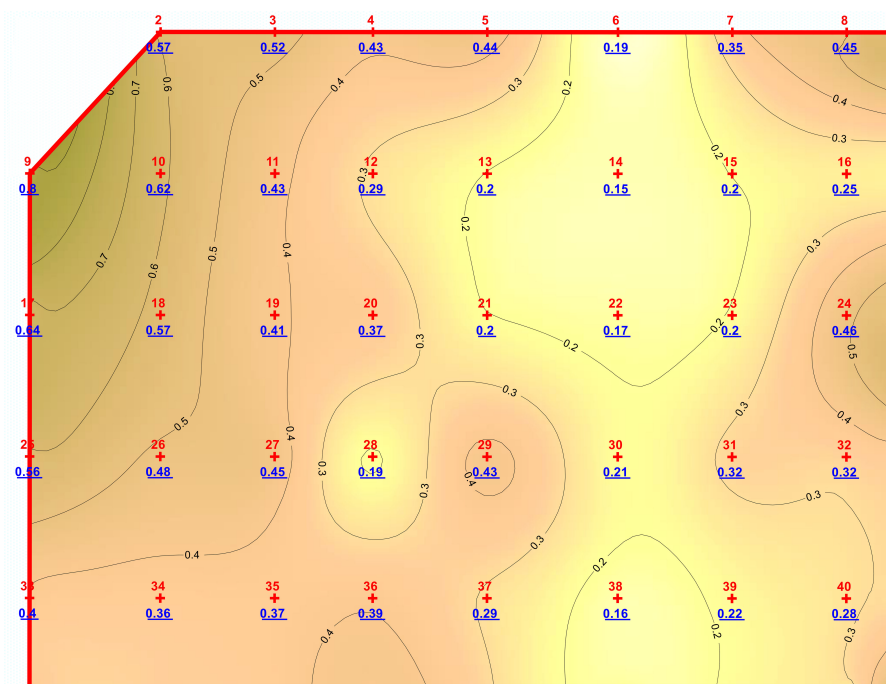
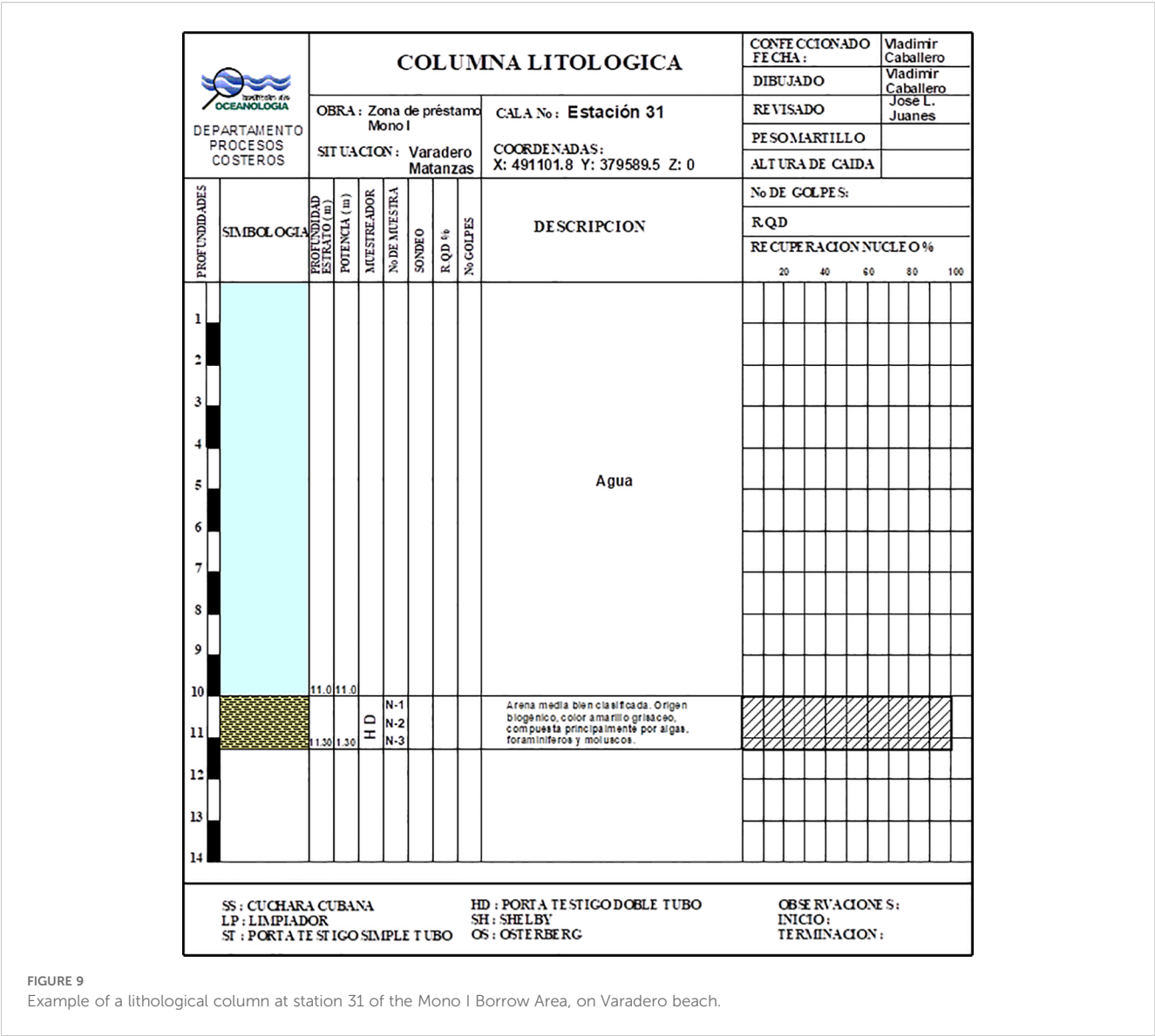


FIGURE 8
Example of a station network in the Mono I borrow area, on Varadero beach. In this case, the distribution of the particle size average (M) across the surface of the resource block is represented.



research projects on the topic have been conducted over the years, but the most comprehensive summary can be found in the monograph, “Geology of the Cuban platform” (Pavlidis et al., 1977). This work describes that terrigenous sand beaches are distributed locally and are often limited to river mouths, with their almost total absence observed in abrasive areas. However, an analysis of the contribution of biogenic remains demonstrates the primary role of these components in the platform sediments, except for the southeastern part of Batabanó, where oolite predominates.

In a recently published study (Sánchez-Bellón et al., 2025) that utilized more advanced techniques, the textural, mineralogical, and chromatic characteristics of Cuban beach sediments were analyzed. This study, based on 91 beaches sampled throughout the archipelago, confirms the predominance of biogenic-marine sediments, mainly in the northwestern area and the keys. These are also the sites where Artificial Sand Replenishment works carried out to date are concentrated, due to their coincidence with the main tourist areas.

However, while research and project design have been greatly influenced by early international collaborations, local specialists have also drawn on other trends in the field. One of the main ones, as is the case in much of the world, was the results of the United States Army Corps of Engineers, whose experiences and guidelines are reflected in publications such as the Shore Protection Manual [SPM84], which do not provide specific treatment to the biogenic sediments predominant on the coasts of most Caribbean islands.

Recognizing this limitation, some specific research has been carried out to adapt methods, which base their results on terrigenous sands, to the particular conditions of Cuban sediments (Juanes, 1996; Tristán Barrera, 2002; García Hernández, 2005). More recently, in pursuit of this objective, the first Association Caribbean States (2024) was published within the framework of the Sandy Coasts project. This project was carried out by the Association of Caribbean States (ACS) with funding from the Korea International Cooperation Agency (KOICA). Despite these advances, there are still many areas to be researched in the

region with a view to tailoring solutions. In the specific case of sand stability, there is no known record of any studies having been conducted on the subject.

For this reason, the objective of this article was to provide a first approximation to this topic, comparing a method that, while not specifically developed for biogenic sediments, offers greater flexibility in its application, possibly allowing for better adjustments than with traditional methods.

3.2 Case study of the Punta Hicacos sector, Varadero

The first site selected for the study was Varadero Beach, in the province of Matanzas, approximately 140 km from Havana, on the northwestern coast of Cuba. (Figure 10).

Varadero is the country's most iconic beach and one of the most famous in the Caribbean region due to the quality and beauty of its natural surroundings. However, erosion problems along its coastline have been evident since the late 1950s.

Since 1987, 15 artificial sand nourishment campaigns have been carried out in different sections of this 20-km-long beach, returning a volume of just over 4 million cubic meters to the coastal system. For this purpose, two borrow zones, commonly known as Mono I and Mono II, have been used. These zones differ slightly in their granulometric characteristics and sediment selection. For the present analysis, two of these campaigns were used, both carried out in the 4-km-long section known as Punta Hicacos, at the eastern end of the beach. These two campaigns were selected because both were carried out using different borrow zones for the same beach sector, allowing a comparative analysis of both. Additionally, the available data are more complete and reliable since, unlike previous campaigns, the same sampling and field data processing criteria

were applied. The first of these artificial sand nourishment campaigns was carried out between 2003 and 2004, marking the first beach restoration action in this area. A total of 456,687 m³ of sand were supplied from the Mono II borrow pit (Caballero et al., 2004). The second of these campaigns was carried out in 2012, as a maintenance of the original project, this time 272,140 m³ of sand were supplied along 2.2 km, but, for this new campaign, the borrow zones used was Mono I (Caballero and Izquierdo, 2012). (Figure 11).

Sedimentological sampling and subsequent laboratory analysis for the characterization of the beach sediments and borrow zones were carried out following the methodology explained in section 2 and the results of the granulometric and distribution characteristics of the type sample are presented in Table 1.

The overfill factor R_a obtained for the campaign carried out in 2003–2004 is 1, which means no adjustments to the design volume are needed due to differences in granulometric characteristics. In contrast, for the year 2012, an overfill factor R_a of 1.225 was obtained, implying an addition of 22.5% (37,260 m³) to the original volume. However, when applying the stability index S_i to both campaigns, the sand is classified as stable. The 2012 campaign is closer to the 0.5 threshold in the calculation of S_i , which indicates that the beach will maintain an erosion rate similar to that observed up to that point; in other words, no greater stability of the fill is expected compared to its predecessor from 2003–2004. However, the R_a value requires increasing the fill by 22.5% over the original design, which will have implications for the project cost and environmental impacts, but without solving the problem of achieving greater fill stability (Table 2).

This is an interesting point to consider in future campaigns, and calculating S_i is very useful for this. When the objective is to increase beach stability, another borrow zones should be selected. If previous results have been satisfactory, a reliable indicator will be



FIGURE 10
Location of Varadero beach.



FIGURE 11
Punta Hicacos Project Sector and location of the Mono I and Mono II borrow zones.

Figures 12 and 13 show the degree of overlap between the granulometric distributions, which is very well described by the results obtained with the application of the Stability Index.

3.3 Case study of Jardines del Rey (Coco and Guillermo Cays)

The tourist destination known as Jardines del Rey is made up of a group of islands or cays that form part of the Sabana-Camagüey

TABLE 1 Granulometry distribution of the typical samples of native and borrow sand in each of the Artificial Sand Nourishment campaigns.

Sample distribution		Campaign 2003 - 2004		Campaign 2012	
		Beach	Mono II	Beach	Mono I
Percentage retained by sieves (mm)	4	2.37	1.20	0.00	0.25
	2	3.35	5.29	0.12	1.48
	1	13.58	27.06	0.38	5.53
	0.50	38.04	45.10	6.98	20.6
	0.25	35.90	18.14	66.81	38.53
	0.125	5.98	2.45	24.66	25.61
	0.062	0.07	0.14	0.73	7.38
	Background	0.00	0.00	0.00	0.25
Average in mm (M)		0.29	0.39	0.31	0.34
Mean in phi (M)		1.81	1.36	1.68	1.55
Sorting in phi (σ)		1.12	1.02	0.58	1.07

TABLE 2 Comparison of sand suitability assessment results James (1975)– Pranzini (2002) in the projects executed in the Punta Hicacos sector, Varadero, Cuba.

Campaign	James (1975)		Pranzini (2002)	
	Ra	Lost volumen to be compensated	Si	Suitability
2003 - 2004	1	0 m ³	0.624	Stable
2012	1.225	37,260 m ³	0.535	Stable

archipelago in the central-eastern part of the northern coast of Cuba (Figure 14). Known for its lush nature and beautiful beaches, the latter have not escaped the effects of erosion, necessitating artificial sand nourishment projects in four sections of the sandy coast between 2016 and 2017.

For the execution of these projects, three borrow zones were defined (La Jaula, Felipe and Felipe 1, the latter being a limited area within its namesake), based on their proximity to each beach and the granulometric characteristics of the sand. Table 3 shows each of the beaches to be regenerated, the borrow zone used, and the volume of input, while Tables 4 and 5 show the granulometric comparison of the standard samples.

As shown in Tables 4 and 5, the relationship between the granulometric characteristics of the native and borrow sands in all the beaches complies with the recommendation that the introduced material be slightly coarser than the original, with the smallest range observed at Las Coloradas beach. Similarly to the previous case, the stability evaluation was carried out using the method proposed by James (1975), with this analysis being repeated through the calculation of the Stability Index *Si* proposed by Pranzini (2002). The results are presented in Table 6. As expected, the overfill factor *Ra* is found to be 1 or very close to 1 for El Paso, Larga, and Flamenco beaches, although the latter two indicate the need to provide an additional volume of 2,675 m³ and 12,000 m³, respectively, to the design. However, when calculating the Stability Index *Si*, high stability values are obtained. It is

noteworthy that Flamenco, where a greater increase in fill is recommended, has the highest *Si* of all. This result highlights the inconsistencies pointed out by James (1975) regarding the calculation method of *Ra*, which were addressed by Pranzini (2002, 2018) in his new proposal. Pranzini's method places greater emphasis on the sample distribution and the contribution of each granulometric fraction to stability, independently of the selection coefficient (σ) and the log-normality of the distribution.

As expected, Las Coloradas has the highest *Ra*, recommending an increase of 20% (50,000 m³) to the design volume. Meanwhile, the *Si* value is below the 0.5 threshold that defines sands as identical, so a higher erosion rate in the fill is expected compared to what was occurring on the beach before artificial nourishment. This is an important factor for planning future maintenance campaigns and for identifying the need to locate a new borrow zone that allows for greater stability. For a better understanding of the compatibility of the sands and the degree of overlap between them, Figures 15–18 are presented.

It is striking, in the case of Las Coloradas beach, that the *Ra* value is very similar to that obtained for the 2012 campaign at Punta Hicacos, Varadero; however, the *Si* value is totally different, although not very far from each other. This result confirms the importance that Pranzini (2002) attributes to the contribution of each granulometric fraction, allowing a more accurate suitability analysis to be carried out without the need to hypothesize the log-normality of the sediment distribution, while allowing the

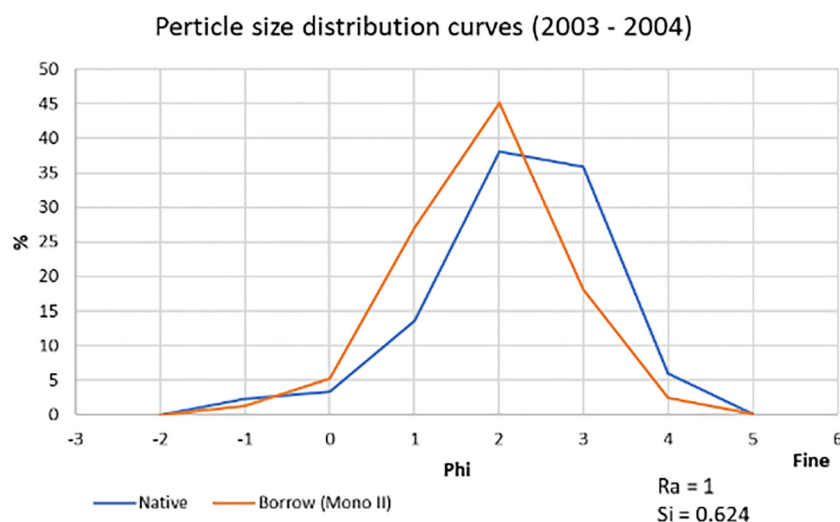


FIGURE 12
Overlapping of particle size distributions in the 2003–2004 campaign.

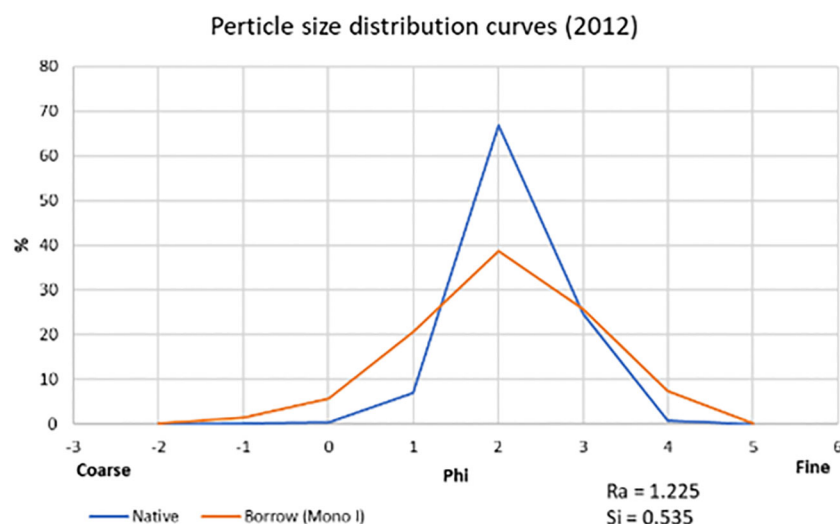


FIGURE 13
Overlapping of particle size distributions in the 2012 campaign.

evaluation and differentiation of materials that classical methods discard or classify within the same range.

3.4 Case study of Cayo Santa María

Cayo Santa María is located to the west of the Sabana-Camagüey Archipelago, in the province of Villa Clara, in the north of the island of Cuba (Figure 19). This small island, also home to attractive beaches and extensive areas of natural beauty, has recently seen the development of a new sun-and-sand tourist destination. However, as is the trend for Cuban beaches and the Caribbean in general, the effects of erosion have become evident in

recent years, necessitating intervention with engineering measures, especially artificial sand nourishment, which, together with proper coastal management and urbanization, guarantees its quality.

During 2016, the necessary studies and work were carried out for the development of projects executed in 2017 across three beach sectors, using the same borrow zones known as Borracho, because of its proximity to the homonymous cay. Table 7 summarizes the main parameters of the projects, and Table 8 presents a comparison of the granulometric characteristics of the sands.

According to the results shown in Table 8, the relationship between the granulometric characteristics of the native and borrow sands in all the beaches complies with the recommendation that the introduced material be slightly coarser than the original, with Perla

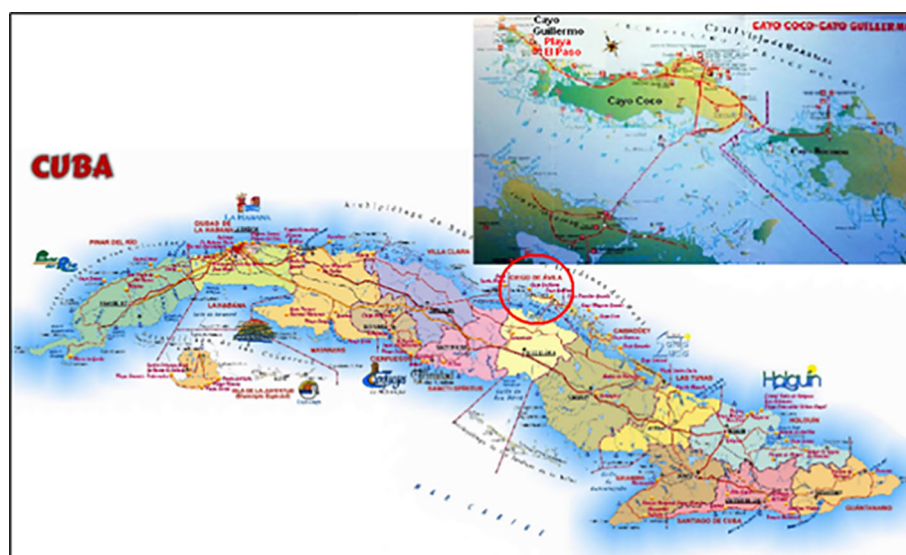


FIGURE 14
Location of Coco and Guillermo keys in Jardines del Rey.

TABLE 3 Projects executed in Jardines del Rey (Cayos Coco and Guillermo) between 2016 and 2017 (Izquierdo et al., 2014).

Beach	Location	Length (m)	Volume (m ³)	Borrow Zone
El Paso	William	3,500	378,000	Felipe
Flamenco	Coco	2,500	267,500	Jaula
Larga	Coco	2,500	252,000	Jaula
Coloradas	Coco	2,500	300,000	Felipe 1

TABLE 4 Granulometry distribution of typical samples of native and borrow sand on the beaches of El Paso (Cayo Guillermo) and Flamenco (Cayo Coco).

Sample distribution		El Paso Beach		Flamenco Beach	
		Beach	Felipe	Beach	Jaula
Percentage retained by sieves (mm)	4	0.10	0.72	0.00	0.71
	2	1.30	2.64	0.30	2.08
	1	4.70	10.60	1.90	11.42
	0.50	18.50	33.47	9.10	27.14
	0.25	28.60	29.16	34.60	28.74
	0.125	42.20	16.15	53.7	24.70
	0.062	4.30	4.39	0.10	2.99
	Background	0.00	2.41	0.00	1.86
Average in mm (M)		0.31	0.44	0.27	0.41
Mean in phi (M)		1.69	1.17	1.90	1.27
Selection in phi (σ)		1.03	1.24	0.76	1.23

Blanca showing the smallest difference. As in previous cases, the stability evaluation was carried out using the method proposed by James (1975), and this analysis was repeated using the Stability Index *Si* calculation proposed by Pranzini (2002). The results are presented

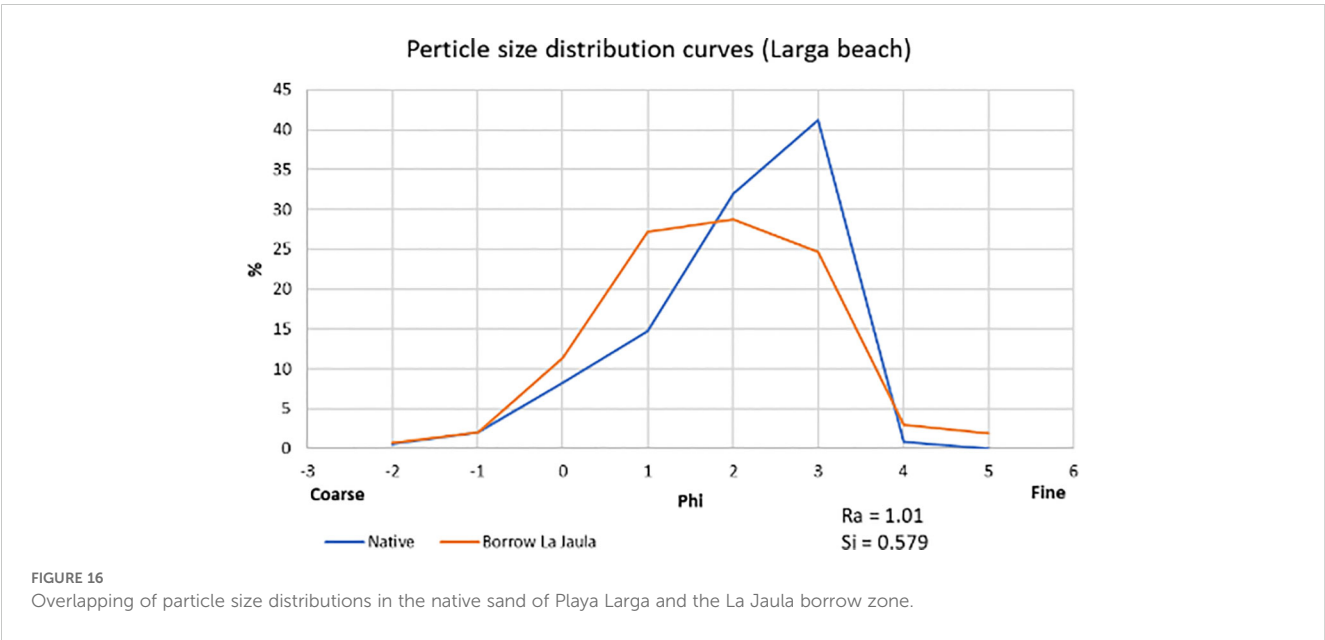
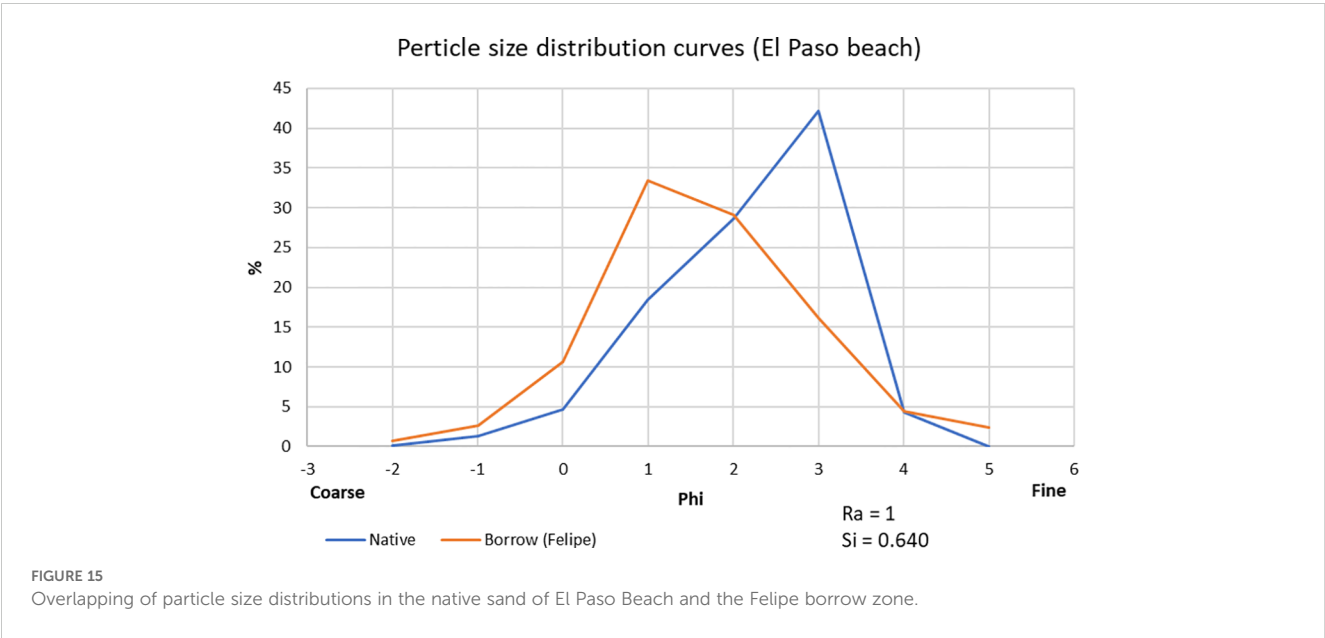
in Table 9. In the case of these beaches, the calculation of the Overfill factor *Ra* is never equal to 1, despite all of them fulfilling the condition of providing coarser sand than the native ones. Particularly striking are the beaches of Piedra Movida and Las Coloradas, which, despite the

TABLE 5 Granulometry distribution of the typical samples of native and borrow sand on Larga (Cayo Coco) and Coloradas (Cayo Coco) beaches.

Sample distribution		Larga Beach		Coloradas Beach	
		Beach	Jaula	Beach	Felipe 1
Percentage retained by sieves (mm)	4	0.60	0.72	1.20	0.79
	2	2.00	2.64	5.10	2.73
	1	8.20	10.60	18.50	11.41
	0.50	14.70	33.47	29.20	38.18
	0.25	32.00	29.16	24.70	31.20
	0.125	41.20	16.15	19.40	11.36
	0.062	0.80	4.39	1.60	2.03
	Background	0.00	2.41	0.00	1.87
Average in mm (M)		0.33	0.41	0.49	0.53
Mean in phi (M)		1.55	1.27	0.89	0.91
Selection in phi (σ)		1.06	1.23	1.19	1.106

TABLE 6 Comparison of sand suitability assessment results James (1975) – Pranzini (2002) in the projects carried out in Jardines del Rey, Cuba.

Beach	James (1975)		Pranzini (2002)	
	Ra	Lost volume to be compensated	Si	Suitability
El Paso	1	0	0.64	Stable
Larga	1.01	2,675 m ³	0.58	Stable
Flamenco	1.05	12,000 m ³	0.67	Stable
Las Coloradas	1.2	50,000 m ³	0.48	Unstable



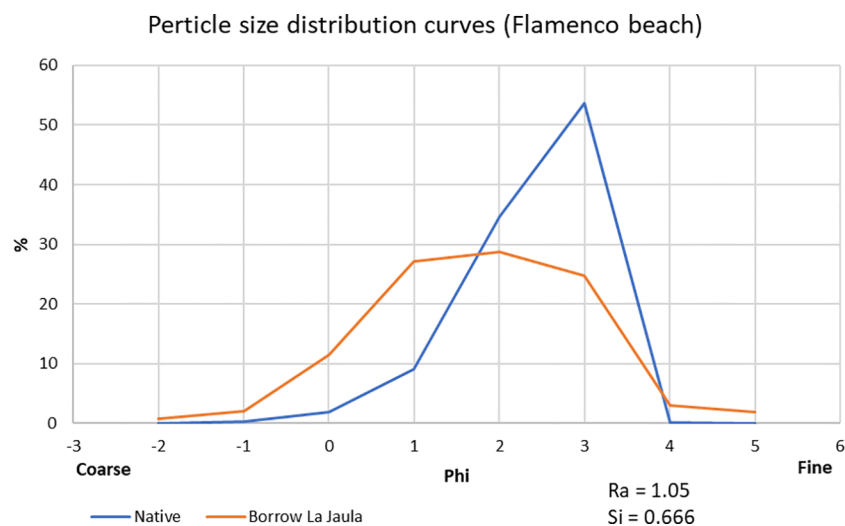


FIGURE 17

Overlapping of the granulometric distributions in the native sand of Playa Flamenco and La Jaula borrow zone.

great difference in sand granulometry, obtain values different from 1, the second of them even being very close to the R_a value of Perla Blanca, which is much closer to that of the borrow zone. These results demonstrate the importance given by the method of James (1975) to the selection coefficient and the log-normality of the sample type, where there are marked differences.

However, when applying the Stability Index Si , it is precisely Piedra Movida and Las Coloradas that obtain the highest stability value, as expected, which would have avoided the incorporation of 5% and 13% respectively of additional sand volumes only in these two beaches and, in their entirety, 9.8% (38,900 m³). Figures 20–22 show the overlap of native and borrow sands, and it can be seen graphically how Si can describe more accurately the compatibility of

the sands, since the contribution of the coarsest fractions in Piedra Movida and Las Coloradas is clearly observed.

4 Discussion and conclusion

This article focuses on the calculation of stability based on the grain size difference between native and borrowed sediments, an essential part of beach nourishment projects, which generally receives little attention and the most commonly used methods date back to the 1970s and are often applied inadequately. The final morphology of the beach, its stability, and its dynamic equilibrium depend on various coastal processes, and wave action undoubtedly

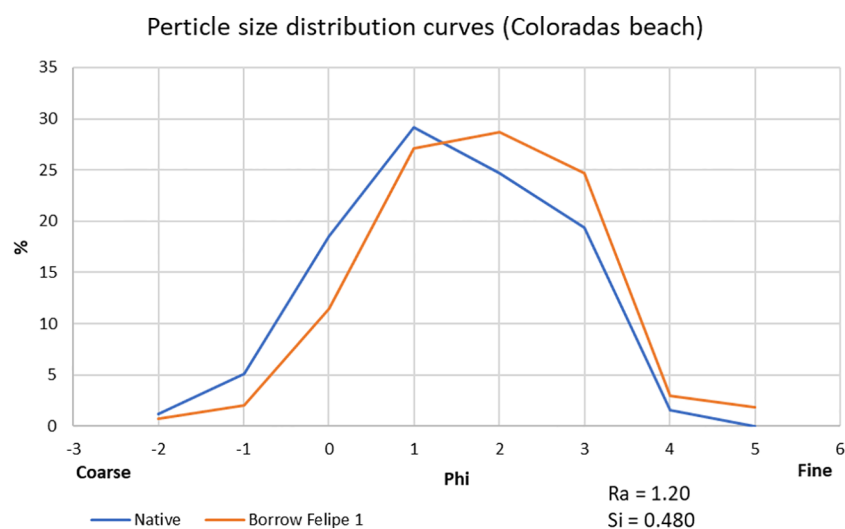


FIGURE 18

Overlapping of particle size distributions in the native sand of Las Coloradas beach and the Felipe 1 borrow zone.

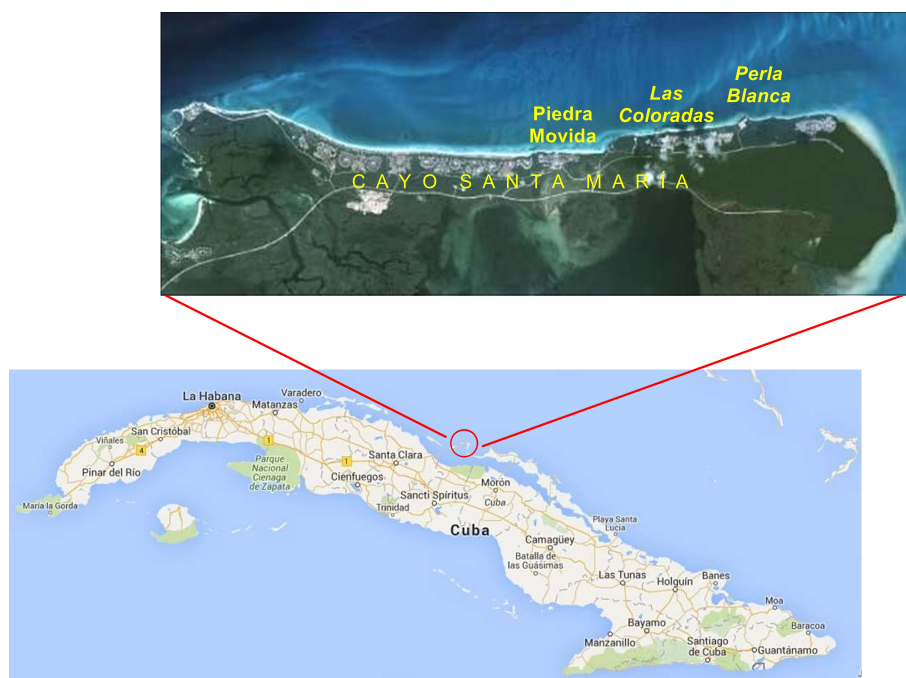


FIGURE 19
Location of Cayo Santa María.

plays a leading role. However, it is not the aim of the article to analyze these complex processes, which are, indeed, studied in more depth in other research efforts or during the design phase of the projects.

The application of the Stability Index S_i and its comparison with the calculation of the Overfill Factor R_a , in projects carried out on Cuban beaches, confirms the conclusions of Pranzini (2002) that it offers greater flexibility when evaluating borrow zones with different characteristics, opening up the range of possibilities.

More realistic and adjusted analysis were obtained, by offering the possibility of not hypothesizing the log-normality of the sediments and giving greater weight to the granulometric distribution in each of its fractions.

In cases like in (Table 6) Las Coloradas beach sand suitability assessment resulted unstable. Practically, on these cases, the use of the Stability Index S_i is preferable because it doesn't overestimate stability like the Overfill Factor R_a might, though it doesn't improve it either. We recommend identifying an alternative borrow zone or proceed with the nourishment acknowledging that erosion rates may increase.

The possibility of optimizing the use of sand as a mineral resource therefore, directly implies a reduction in environmental impacts and a better use of economic resources, thus contributing to greater efficiency in solutions, bringing them closer to more sustainable and environmentally friendly coastal management practices.

In this sense, the analysis carried out demonstrates that the application of this method contributes to the saving of thousands of cubic meters of sand. Therefore, its inclusion as a working tool and adaptation to the specific conditions of the Caribbean will decisively contribute to achieving the objective of applying sustainable management and engineering measures, something crucial for a region that depends largely on its natural attractions, especially its beaches and coral reefs.

Although further research is needed, this initial approach indicates that its use is feasible in subsequent artificial sand replenishment projects in Cuba and on similar beaches in the Caribbean region with marine-biogenic sands.

The results presented demonstrate inconsistencies in the value of the Overfill Factor R_a , even in samples with a high degree of log-normality, as only the textural characteristics of the sediments are

TABLE 7 Projects executed in the Santa María Keys in 2017 (Peña et al., 2016).

Beach	Location	Length (m)	Volume (m ³)	Borrow Zone
Piedra Moviada	Sta. María	1,200	113,400	Borracho
Las Coloradas	Sta. María	2,000	226,000	Borracho
Perla Blanca	Sta. María	500	57,500	Borracho

TABLE 8 Granulometric characteristics of the sample type from the projects executed in 2017 on the Santa María and Las Brujas keys (Peña et al., 2016).

Sample distribution		Beaches			Borrow Zone
		Piedra Movida	Las Coloradas	Perla Blanca	Borracho
Percentage retained by sieves (mm)	4	0.00	0.00	0.80	0.50
	2	0.03	0.19	0.40	1.80
	1	0.48	0.71	3.60	8.90
	0.50	6.55	5.41	23.18	22.10
	0.25	28.29	45.53	45.14	35.30
	0.125	59.78	47.21	26.53	24.10
	0.062	4.46	0.59	0.68	6.10
	Background	0.00	0.00	0.00	1.20
Average in mm (M)		0.23	0.27	0.36	0.38
Mean in phi (M)		2.11	1.91	1.46	1.41
Selection in phi (σ)		0.70	0.65	0.85	1.18

TABLE 9 Comparison of sand suitability assessment results James (1975) – Pranzini (2002) in the projects carried out in Cayo Santa María, Cuba.

Beach	James (1975)		Pranzini (2002)	
	Ra	Lost volume to be compensated	Si	Suitability
Piedra Movida	1.05	5,400	0.688	Stable
Las Coloradas	1.13	26,000	0.635	Stable
Perla Blanca	1.15	7,500	0.508	Stable

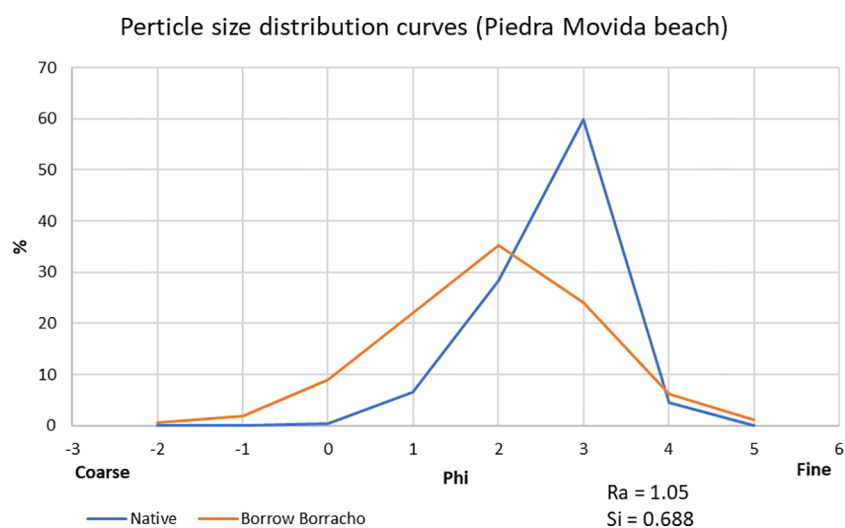


FIGURE 20

Overlapping of particle size distributions in the native sand of Piedra Movida beach and the Borracho borrow zone.

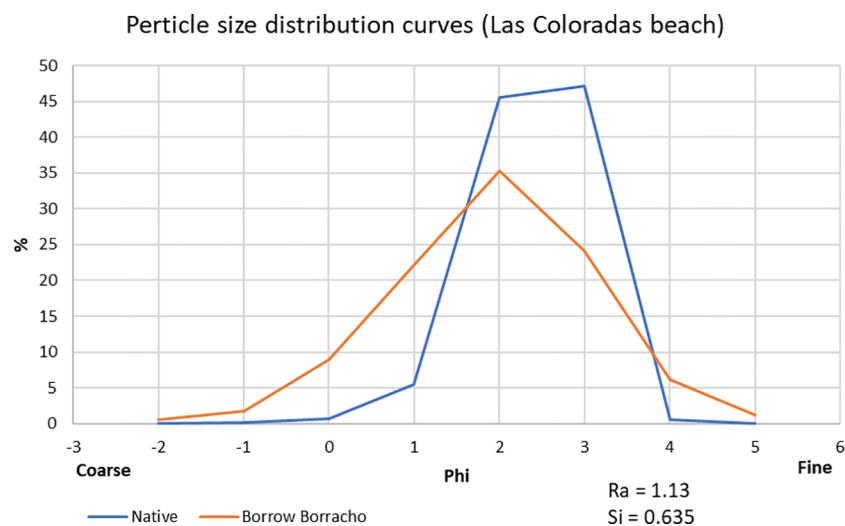


FIGURE 21

Overlapping of the granulometric distributions in the native sand of Las Coloradas beach (Cayo Santa María) and the Borracho borrow zone.

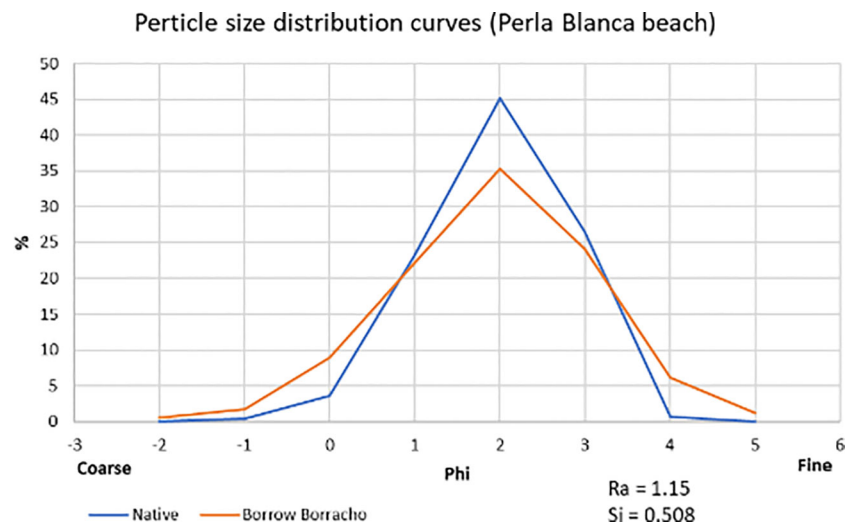


FIGURE 22

Overlapping of particle size distributions in the native sand of Piedra Movida beach and the Borracho borrow zone.

considered and not the specific weight of each fraction in its contribution to stability. This can lead, in some cases, to overestimation of dredging volumes. Therefore, we propose the introduction of the Stability Index Si method in new projects.

In this sense, establishing long-term monitoring programs on the beaches benefiting from this method is an essential tool for confirming its effectiveness. Likewise, the analysis of existing data from past monitoring will provide important results for the final validation of the method.

Its use and subsequent analysis of results on beaches with different sedimentological and morphodynamic characteristics will be an important step in its widespread use. Cuba and the Caribbean boast a wide variety of coastal environments and sandy

shores, making it feasible to conduct these studies by incorporating new beach observation and monitoring techniques (drone photogrammetry, tracking cameras, etc.), which, until now, have been used to a limited extent in the region.

The Si method, unlike the Ra method, allows for a clear scale to be established when there are several possible borrow zones to be used, facilitating decision-making and establishing priorities, not only based on the quality and compatibility of the sediments, but also from the practical perspective of execution and available budget. This will improve the precision of the studies and the information available in the database of the Cuban National Office of Mineral Resources, allowing this experience to be generalized to other countries in the region. It also constitutes an important input

to be taken into account for the Update of the [Association Caribbean States \(2024\)](#).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

AA: Conceptualization, Investigation, Writing – original draft, Data curation. YC: Supervision, Writing – review & editing. JD: Funding acquisition, Writing – review & editing. VC: Writing – original draft, Investigation, Conceptualization, Visualization, Data curation.

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