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A probabilistic approach to borrow sediment selection in beach nourishment projects

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ABSTRACT

A probabilistic approach is used to assess borrow material stability on artificially nourished beaches. A stability factor (**sf**) is attributed to each grainsize fraction of the native sediment based on its cumulative curve. Sum of these **sf**, weighted with the frequency of each grain size fraction of the borrow material, gives the Stability index (**Si**) with values between 1 (completely stable) and 0 (completely unstable).

Unlike other methodologies, the present one is not based on textural parameters requiring sediment log-normality. It considers the complete sediment distribution and computes stability for any borrow *vs* native material.

A detailed example of applying the method is provided and three other study cases are presented in which **Si** proved to be an effective parameter to address appropriate selection amongst different borrow sediments.

1. Introduction

Beach nourishment importance in shore protection projects is growing in parallel with environmental concern associated with traditional hard coastal engineering projects (Hanson et al., 2002) and with the value of tourist industry based on bathing activity. Development of large dredgers and high quarrying capabilities making deep continental shelf deposits (down to −130 m) available for big projects is an additional reason for beach nourishment expansion.

Compatibility of borrow sediment with native one is primarily based on grain size characteristics. Coastal Engineering Manual or CEM (USACE, 2002) gives this "general recommendation": *a nourishment project should use fill material with composite median grain diameter equal to that one of the native beach material.* Hence, borrow material grain size is an important aspect to be evaluated since it determines equilibrium beach profile, beach response to storms (Larson and Kraus, 1991), beach use and tourist attractiveness (Pranzini et al., 2011).

In beach nourishment projects, the eligibility of borrow material is frequently assessed by comparing its grain size distribution with that of the native sediment. Krumbein and James (1965) proposed an equation to calculate the volume of borrow material needed to obtain a unit volume of sediments with the same grainsize distribution of the native one (*Critical ratio*, $R_{\phi crit}$). They also provided an easy-to-use nomogram which is frequently used by professionals. Input data are Inman's textural parameters as Mean size (M_ϕ) and Sorting (σ_ϕ), and therefore it considers only D_{16} and D_{84} values. Moreover, its use implicitly requires a sediment log-normal distribution, a characteristic which is hardly observed in borrow materials extracted from recent alluvial deposits and in coastal sediments (e.g. Hobson, 1977). In addition, $R_{\phi crit}$ cannot be calculated when borrow sediment is better sorted than the native one. In this case, value 1 is assigned to $R_{\phi crit}$ when borrow sediments are larger and a generic "unsuitability" when they are finer. This prevents any further characterization of potentially suitable sediments. For instance, it is impossible to decide which of two or more available materials, maybe not very adequate but cheap, is the best to create a beach for a limited (seasonal) duration (e.g. for touristic purposes).

Later, taking into account that wave winnowing action is stronger on the finer sediment fractions than on the coarser ones, other researchers modified the previous equation and proposed a *Fill Factor* (**K**) (Dean, 1974) and an *Overfill Factor* (**R_A**) (James, 1975). On these occasions, nomograms for easy calculations were also available. The difference between the two is how fine and coarse fractions are considered. Overfill Factor calculation is now the most used system in beach nourishment projects.

A review of these methods to assess beach fill stability can be consulted in Stauble (2007), who also stated that fill compatibility is not well

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predicted by using the previous standard suitability methods and, in consequence, the use of the entire grain size distribution is needed.

According to this requirement, a method which satisfies such a need is presented herein. In addition, a) it doesn't require sediment log-normality, b) input data can derive from uneven sieving intervals, c) it can be applied to any borrow/native combination, d) its use is extremely easy. After being applied by several designers in nourishment projects in Italy and Spain, the method has proved to be robust enough and its use is proposed to the international community.

2. Methodology: stability index (Si) definition and computation

The working hypothesis is that the stability of each grain size fraction artificially introduced onto the beach is inversely proportional to that fraction's value in the cumulative distribution curve of beach native sediments (see Fig. 1). Following this rationale, the stability of a grain coarser than the coarsest grain present on the beach is equal to 1, and it will give a "full" contribution to the beach final volume after sediment winnowing by waves. On the opposite, the stability of a grain finer than the finest grain present on the beach is equal to 0, and it will give a "null" contribution to the final volume. Therefore, the method considers a *stability factor* (**sf**) of each grain size fraction **i** to be equal to the complement to 100 of the value that each grain size fraction has in the native sediment's cumulative curve (**cn_i**), divided by 100:

$$sf_i = (100 - cn_i)/100 \tag{1}$$

e.g. if the fractions 1 and 2 phi score 11.9% and 40.1% in the cumulative distribution curve (connecting lines in Fig. 1), new grains of those sizes deposited on the beach will give a contribution of 0.907 and 0.696 respectively to the final fill volume after wave winnowing.

Therefore, each grain size fraction of the borrow material will give the overall stability a contribution equal to its frequency (**fb_i**) multiplied for its own stability factor (**sf_i**). The sum of all these values, scaled dividing by 100, allows us to obtain the Stability index (Si):

$$\mathbf{Si} = \Sigma(fb_i \cdot sf_i) / 100 \tag{2}$$

which ranges between 0 and 1 and where, obviously, $\Sigma fb_i = 100$. In an extreme scenario (**Si** = 0) all the grains of the nourishing material are finer than the smallest grain present on the beach. On the opposite (**Si** = 1) all the grains are coarser than the coarsest native grain. A borrow material whose grain size distribution is identical to the one of the beach sediments, will have a **Si** = 0.500. This formulation is valid for infinitesimal intervals. Having discrete sieving intervals (frequently 1/2phi), each **fb_i** value refers to the lowest dimensional limit of the i-th class of the native sediment, which makes it unlikely to attribute the cn_i value to all the grains belonging to the same fraction of borrow material. A more correct estimation can be obtained adopting a value which is intermediate between that of the i class and that of the i-1 class:

$$\mathbf{sf_i} = [100- (cn_i + cn_{i-1})/2]/100 \tag{3}$$

Thus, the final formula, substituting (3) into (2) becomes as follows:

$$\mathbf{Si} = \Sigma\, fb_i \cdot [100 - (cn_i + cn_{i-1})/2]/100 \tag{4}$$

This method allows the attribution of a Stability index (**Si**) to any kind of material, even to those for whom the previous methods were not applicable.

It is important to highlight that neither the here proposed method nor the previously described ones were calibrated on actual nourishment works, but are based on theoretical calculations.

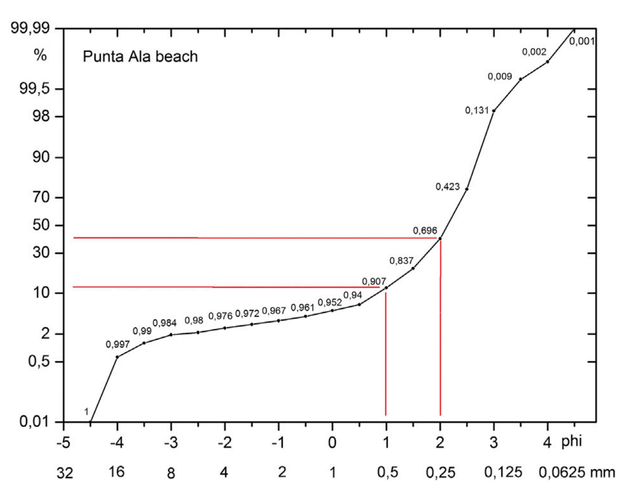

Fig. 1. Cumulative curve of native sand on a log-probability plot and stability factors (sf) computed according to Eq (4) for Punta Ala beach.

3. Example and study cases

A complete example of the use of the method is included for the case of Punta Ala beach (Italy). Moreover, three other study cases with different characteristics from Italy and Spain (Fig. 2) are hereafter mentioned.

3.1. Punta Ala beach nourishment

Punta Ala beach is a 7-km-long barrier whose southern 3 km are severely eroding, thus menacing a prosperous tourist industry. Native sediment at Punta Ala beach is a medium ($M_\Phi = 1.93$) and well sorted ($\sigma_\Phi = 0.68$) sand, with a modal class at 2.5 phi (Table 1). Three borrow sites were available for its nourishment: two offshore deposits (Alma and Hidalgo) and a small beach formed on the lee side of a Marina.

In relation to the native sediment:

- Alma sediment is a bit finer ($M_\Phi = 2.18$) and better sorted ($\sigma_\Phi = 0.40$), but it has the same modal class;
- Hidalgo sediment is more similar to the native one and consists of medium and well sorted sand ($M_\Phi = 1.92$; $\sigma_\Phi = 0.47$) with the same modal class too;
- Marina sediment is coarser ($M_\Phi = 1.64$) and less sorted ($\sigma_\Phi = 0.57$), with the modal class at 2.0phi (Table 1).

Firstly, Overfill factor (**R_A**) was determined on the nomogram for the three potential borrow sediments (Fig. 3, Table 1). Furthermore, the Stability index (**Si**) was also calculated (Table 1). Details of the computation method and grain size distributions at Punta Ala (native beach, with related sf_i values in Fig. 1) and the three potential borrow sands are shown in Table 2.

Although a quantitative comparison between the values obtained through the two methods it's not possible, a qualitative comparison can be performed.

Alma borrow sand is considered unsuitable with both methods, having **R_A** = 6 and a **Si** lower than 0.50. In case of being used, most of the fill would shift offshore.

However, both Hidalgo and Marina sediments could allow an effective beach nourishment, the latter being more stable than the former. The final choice anyway can be linked to management reasons and not only to strictly stability ones. If nourishment is carried out to maintain the beach in order to protect the backing structures, then Marina coarser sediment will be more suitable because it will produce a more stable and wider dry beach, but characterised by a steeper foreshore if compared to the pre-existing one. In this sense beachgoers could dislike such increase in grain size and beach slope and would prefer a milder slope close to the original one – *i.e.* the one that can be obtained with Hidalgo sands. That is, **Si** value is preferred to be larger than 0.50 but, if the characteristics of the beach are to be maintained, that value cannot be exceeded too much.

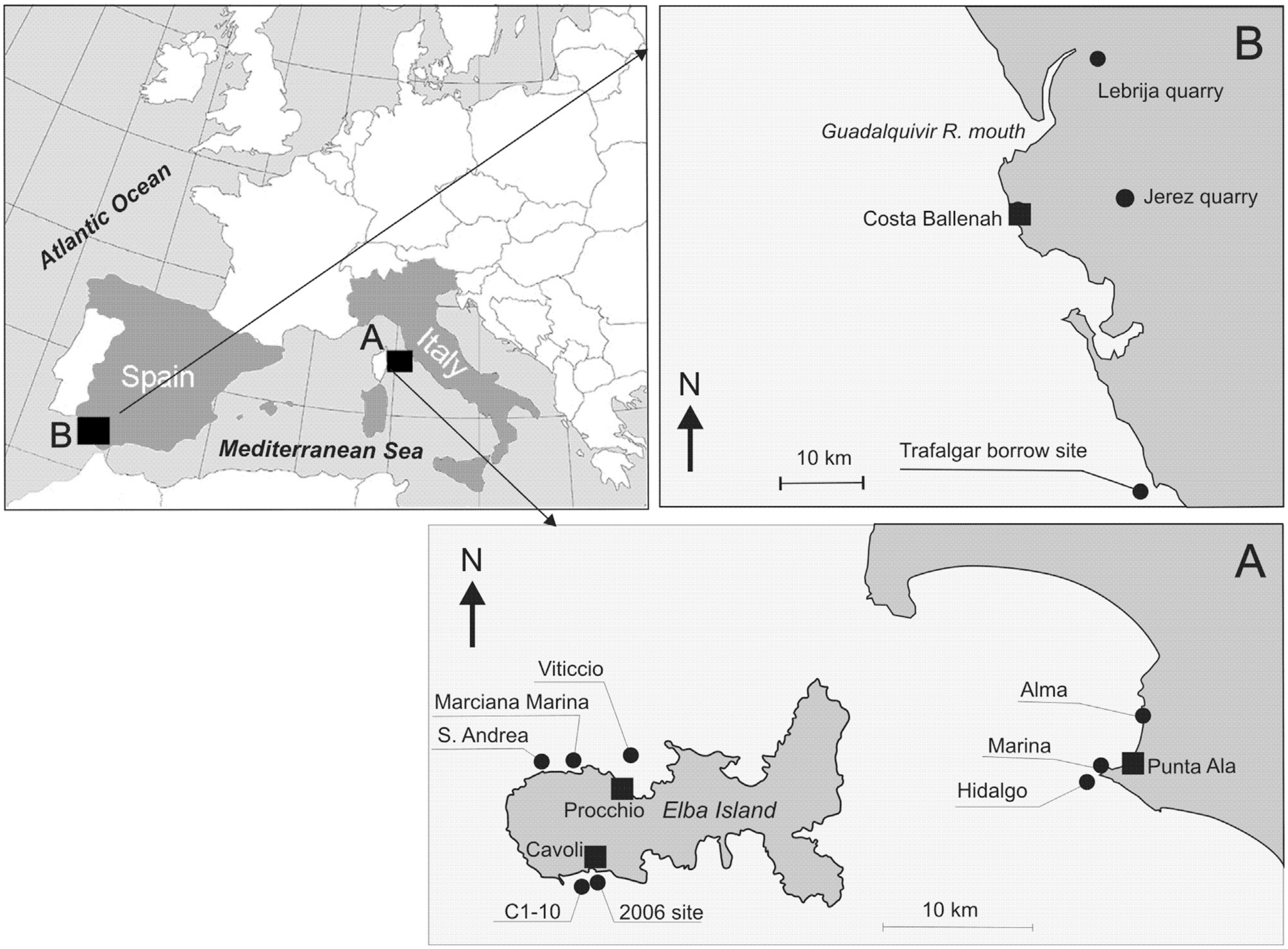

Fig. 2. Location map of three nourished beaches (squares) and the borrow areas (black dots) in Italy (A) and Costa Ballena in the south of Spain (B).

Table 1
Statistical parameters (Inman, 1952), Overfill factor (R_A) and Stability index (Si) for the considered sediments in Punta Ala nourishment.

	$M_{ø}$ (phi)	$\sigma_{ø}$ (phi)	Mode (phi)	Overfill Factor R_A	Si
Punta Ala (native)	1.93	0.68	2.5		
Alma (borrow)	2.18	0.40	2.5	6.0	0.44
Marina (borrow)	1.64	0.57	2.0	<1.02	0.67
Hidalgo (borrow)	1.92	0.47	2.5	1.40	0.58

Experience gained in several projects suggests not to overpass 0.60.

3.2. *Three other study cases*

The use of the Stability index proved to be effective in selecting borrow materials at three other beach nourishments with different aspects to be considered. Unfortunately, the limited length of this short communication prevents us from including all the details.

Firstly, the pocket beach of Procchio (Northern Elba Island, Fig. 2A) which constitutes the first case in which **Si** was applied in a mixed sand and gravel beach. $R_{\phi crit}$ is poorly reliable for this kind of beaches because it considers only specific parameters as D_{16} and D_{84}. Otherwise, **Si** is especially suitable because its computation based on the whole grain size distribution.

Secondly, Cavoli bay is located on the south-western side of Elba Island (Fig. 2A) and exposed to high energy waves approaching from south. It hosts a small, 415 m long, eroding pocket beach. After the failure of the first beach nourishment in 2006, application of **Si** methodology to new borrow sites permitted to discard a stable sediment but that gave rise to a steeper profile, unsuitable for child, elderly and disable people.

Finally, the Overfill Factor and the Stability index were used to assess the suitability of different sand sources when designing the nourishment of Costa Ballena beach (SW of Spain, Fig. 2B). Two quarries close to the beach (Lebrija and Jerez) and one submerged shoal (Trafalgar) were considered as borrow sites (Fig. 2B). The Overfill Factor calculation gave rise to two problems: firstly, a great variability of the index with small variations in M_{Φ} and σ_{Φ} in the central area of the James' figure (where native and borrow values are very similar). Secondly, all samples in the third quadrant are equally classified, providing no criteria to differentiate among them. In this case, comparison of **Si** values allowed to realize that there was no appreciable difference between Jerez and Trafalgar sediments and therefore only economic or logistic criteria were applied to decide the use of one or another site.

4. Conclusions

The Stability index (**Si**) is based on the hypothesis that the stability of each grain size fraction artificially introduced onto the beach is inversely proportional to that fraction's value in the cumulative distribution curve of the beach native sediments. **Si**, like James' Overfill factor, allows to define which borrow material is the most suitable for the nourishment of a specific beach. However, unlike the James' methodology based on textural parameters, **Si** method can be used independently from sediment log-normality hypotheses. In addition, input data can derive from irregular or non-homogeneous sieving intervals. **Si** can be computed for any native/borrow sediment size distribution and can assist in choosing the

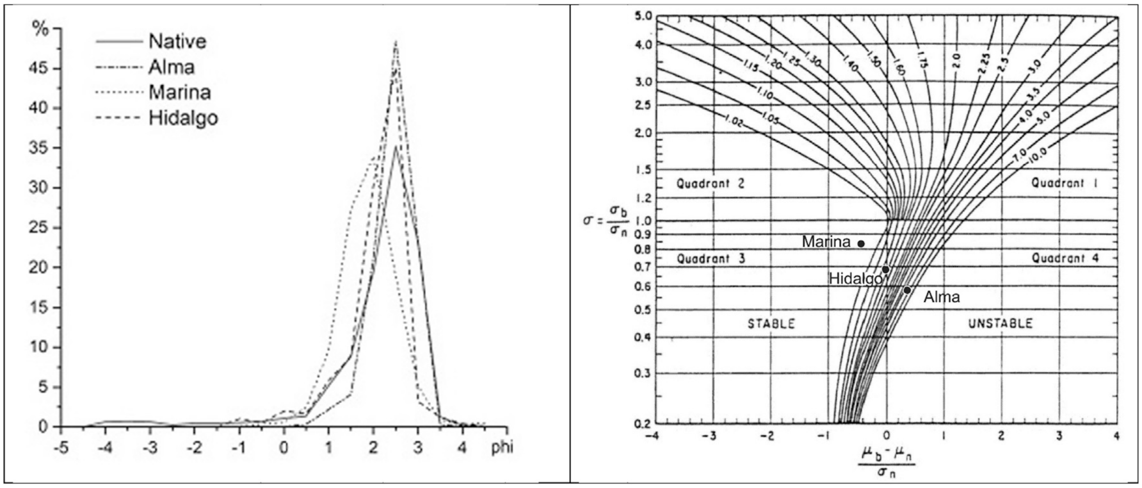

Fig. 3. Grainsize distribution for native and three potential borrow sites for nourishment at Punta Ala beach (left), and the nomogram to estimate the Overfill Factor (R_A) values (right).

Table 2
Spreadsheet to compute the Stability index (Si) for three different borrow materials to be used at Punta Ala beach.

Phi size	Weight %	Native			Alma		Marina		Hidalgo
		Cumulative Weight cn_i	sf_i [a]	fb_i	$fb_i{\cdot}sf_i$	fb_i	$fb_i{\cdot}sf_i$	fb_i	$fb_i{\cdot}sf_i$
−6	0,00	0,00	1000	0,00	0,00	0,000	0,00	0.00	0.00
−5,5	0,00	0,00	1000	0,00	0,00	0,000	0,00	0.00	0.00
−5	0,00	0,00	1000	0,00	0,00	0,000	0,00	0.00	0.00
−4,5	0,00	0,00	1000	0,00	0,00	0,000	0,00	0.00	0.00
−4	0,64	0,64	0,997	0,00	0,00	0,000	0,00	0.00	0.00
−3,5	0,67	1,31	0,990	0,00	0,00	0,000	0,00	0.00	0.00
−3	0,62	1,92	0,984	0,00	0,00	0,000	0,00	0.00	0.00
−2,5	0,23	2,15	0,980	0,00	0,00	0,000	0,00	0.00	0.00
−2	0,46	2,61	0,976	0,00	0,00	0,000	0,00	0.00	0.00
−1,5	0,46	3,07	0,972	0,00	0,00	0,023	0,02	0.00	0.00
−1	0,51	3,58	0,967	0,01	0,01	0,091	0,09	1.00	0.97
−0,5	0,68	4,26	0,961	0,01	0,01	0,328	0,32	0.50	0.48
0	1,09	5,35	0,952	0,05	0,05	0,575	0,55	2.00	1.90
0,5	1,35	6,70	0,940	0,32	0,30	2,459	2,31	1.63	1.53
1	5,18	11,89	0,907	2,17	1,97	9,562	8,67	5.79	5.25
1,5	8,87	20,76	0,837	4,12	3,44	27,203	22,76	8.85	7.41
2	19,34	40,09	0,696	20,99	14,60	33,987	23,65	30.22	21.03
2,5	35,24	75,33	0,423	48,75	20,61	18,964	8,02	45.13	19.08
3	23,14	98,47	0,131	23,16	3,03	5160	0,68	3.18	0.42
3,5	1,24	99,71	0,009	0,29	0,00	0,858	0,01	1.20	0.01
4	0,19	99,90	0,002	0,09	0,00	0,297	0,00	0.40	0.00
4,5	0,10	100,00	0,001	0,04	0,00	0,493	0,00	0.10	0.00
Si $= \Sigma(fb_i \cdot sf_i)/100$					0,44		0,67		0,58

[a] $sf_i = [100- (cn_i + cn_{i-1})/2]/100$ Equation (3).

best sand considering not only fill stability but also tourist purposes.

Use of **Si** has proved to be effective in selecting borrow materials in the four studied cases. Different aspects were considered: bimodality in native size sand, very small differences in native and borrow sediments, and quarries versus sea bottom as borrow sites.

Another advantage of the **Si** method is the ability of discriminating among borrow materials with the same Overfill Factor (e.g. $R_A = 1$). *Id est*, when Overfill Factor only proposes a “stable” statement but does not permit classification of different borrow sources.

In future nourishments, detailed monitoring programs should be carried out to establish a relationship between **Si** and fill stability (and even to predict fill longevity), as could be done for the other considered methods.

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