APPROPRIATE LOCATIONS FOR GEOTEXTILE BAG REVETMENTS: AN ANALYSIS

Ana I. Antón[†]**; José M. De la Peña**[†]**; José L. Almazán**[‡]**; Antonio Lechuga**[†]

[†] **Centre for Harbors and Coastal Studies**
CEDEX
Madrid, 28026, Spain
ana.i.anton@cedex.es

‡ Universidad Politécnica
Madrid, 28040, Spain

LRH: Antón, De la Peña, Almazán and Lechuga
RRH: Coastal Environments

ABSTRACT: Pressure exerted by urban development, the increase in erosion on many coastal stretches, and the rise in sea level due to climate change over the last few decades have led governments to invest more in coastal protection. In turn, a reduction in costs and increases in ease of construction and rate of implementation have led to sand-filled geotextile elements, such as bags, tubes, and containers becoming an alternative or supplement to traditional coastal defence materials, such as rubble mounds, concrete, and so on. But not all coastal zones are appropriate for building sand-filled geotextile element structures as coastal defences. This article analyses zones appropriate for locating geotextile bag revetments to protect the coast from storm erosion and concludes that the least suitable zones are the surf zone (on an open coast and on a slightly protected coast) and also deep water (on an open coast), except if a suitable reinforcement is carried out when the demand make necessary this kind of defence.

ADDITIONAL INDEX WORDS: Geotextile bag revetments and coastal profile zones.

INTRODUCTION

Sand-filled geotextile elements are three-dimensional components made with sand-filled geotextile materials. There are basically three types of sand-filled geotextile elements: bags, tubes, and containers. These elements are used to build structures in coastal engineering, such as revetments or breakwaters, as an alternative to traditional materials. And as riverbank revetment stabilization, though the failure modes of such structures are not well understood. The purpose of this paper is to analyse coastal areas suitable for the location of revetments of sand-filled geotextile bag structures as coastal defences. Wave heights are defined according to coastal profile zones and types of coasts. Wave height limitations in geotextile bag revetment stability equations are calculated and appropriate geotextile bag revetment locations are analysed. Finally these appropriate locations are validated with examples of structures built in different countries.

The main work for improving knowledge on the performance of sand-filled geotextile bags was recently undertaken and has given the following results. Pilarczyk (1996) defined several coastal defence systems using geotextile elements. Wouters (1998) drew up a sand-filled geotextile bag revetment stability equation. Oumeraci *et al.* (2002, 2003) performed reduced and large-scale physical tests to draw up a submerged sand-filled geotextile bag breakwater and revetment stability equation. Mori (2009) and Mori *et al.* (2008) examined the application of the stability equation drawn up by Oumeraci *et al.* (2003) for submerged geotextile bag structures, whilst Dassanayake and Oumeraci (2013) drew up a new equation.

METHODS

Apart from its calculation or design, the type of geotextile structure chosen will depend on the load stresses to which the structure is subjected. The main load must be due to wave action. The marine climate of the zone where the structure is located must be previously known.

Locations of geotextile structures on the coast

Waves incident on a structure may be considered from two complementary standpoints. The first refers to the location of the structure with respect to the profile of a beach and, therefore, how its energy develops along the beach. The second is the type of coast where the structure is located and, therefore, the intensity of the waves incident on it. The location of the structure must be studied with respect to the profile zone of the beach and type of coast.

Beach profile

According to Weggel (1988), actions of waves incident on a structure along the profile of a beach vary in intensity. From this standpoint, he differentiates six zones in the profile of a beach, as the following figure shows. Each one is expressed by one specific equation.

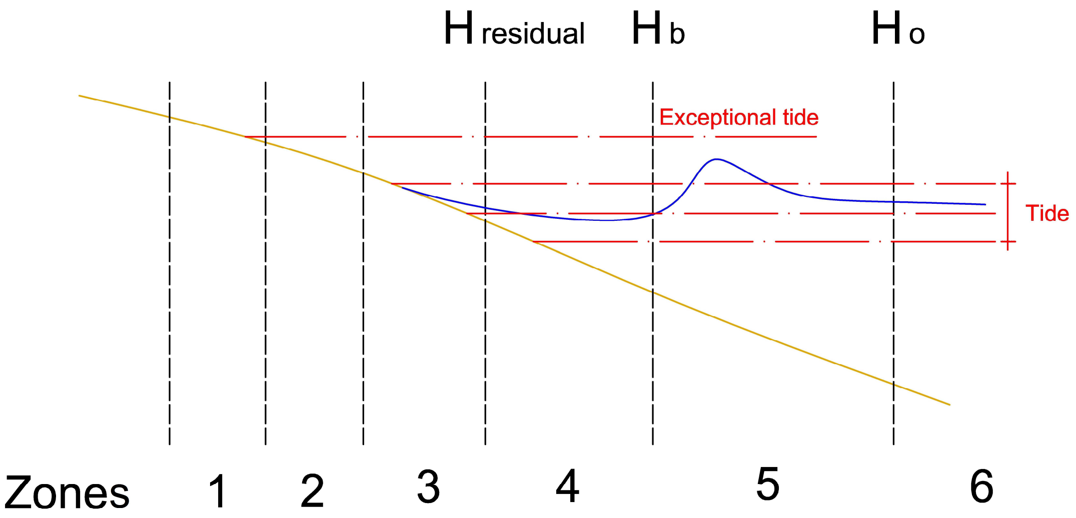


Figure 1: Detailed view of coastal profile zones, where: (1) - Dry beach, $H \approx 0$; (2) and (3) - Foreshore, $H \approx 0$; (4) - Beach face, $H=H_{residual}$; (5) - Breaker zone, $H=H_{breaker}$ and (6) - Deep water, $H=H_o$. Source: Weggel (1998)

These equations are derived from a dimensional analysis applied to structure and beach systems. There are four basic non-independent variables making up each of these equations in each zone. They are length (L), time (T), mass (M), and force (F), related through Newton's second law, together with variables making up each of these equations in each zone. These are Z_a, the semi-tidal range for the tide level; Z_s, the rise in sea level in a storm for a waves reach on the coast; R, the run-up, as the reference distance; D, the depth of water at the foot of the structure; $X_{w,}$ the distance between the shore line at half tide and the base of the structure; s, the slope of the beach; and for waves: H_o, high seas wave height, T, wave period, and H_i, local wave height.

On the other hand, the following dimensionless variables were defined to determine the effect of structures on coastal processes in their vicinity: H_o/gT^2, the deep water wave steepness parameter; R/H_o, the relative run up on the beach/revetment system; d/H_o, the relative water depth at the base of the structure; Z_a/H_o, the relative half-tide range; Z_s/H_o, the relative storm surge elevation and X_w/gT^2, the dimensionless distance of the mean tide level shoreline from the revetment.

In zone 1, the structure is located outside the maximum reach of the maximum storm. This zone is described by the following equation:

$$\frac{X_w}{gT^2} > \frac{H_o}{gT^2}\frac{1}{s}\left(\frac{Z_a}{H_s}+\frac{Z_s}{H_o}+\frac{R}{H_o}\right) \qquad (1)$$

The profile zone of a beach located outside the maximum reach of the maximum storm corresponds to a dry beach. This part of the beach is defined as the profile zone of a beach between its land limit and the commencement of the beach front. Waves that can reach this zone are usually negligible (wave heights $H_1 \approx 0$) and only happen in extraordinary events. Wave actions that may therefore be expected on a geotextile structure sited in this zone are practically negligible and, additionally, have long return periods. Wave height is not the most relevant action to be taken into account.

In zone 2, the structure is located above the maximum sea elevation and below the maximum run-up. This zone is described by the following equation:

$$\frac{H_o}{gT^2}\frac{1}{s}\left(\frac{Z_a}{H_s}+\frac{Z_s}{H_o}\right) < \frac{X_w}{gT^2} < \frac{H_o}{gT^2}\frac{1}{s}\left(\frac{Z_a}{H_s}+\frac{Z_s}{H_o}+\frac{R}{H_o}\right) \qquad (2)$$

As indicated in CEM (1995), the profile zone of a beach located above the maximum sea elevation and below the maximum run-up corresponds to the foreshore, which is defined as the beach zone between the exterior part of the berm and the limit of the waves' descent at low tide. Waves in this profile zone are not directly incident. Only low-intensity wave heights are reached, originating from highly evolved residual waves, $H_2 \approx H_{residual} \approx 0$. Therefore, wave height may be considered practically negligible, with only a low-intensity incident current of water. Consequently, the wave actions are nil. Only the current of water due to the run-up's final development should be taken into consideration. Therefore it is not necessary to assess any consideration concerning geotextile bags with respect to applying the resistance equation due to waves, except for highly extraordinary events.

In zone 3, the structure is located above normal tides and below exceptional elevations. This zone is described by the following equation:

$$\frac{H_o}{gT^2}\frac{1}{s}\left(\frac{Z_a}{H_s}\right) < \frac{X_w}{gT^2} < \frac{H_o}{gT^2}\frac{1}{s}\left(\frac{Z_a}{H_s}+\frac{Z_s}{H_o}\right) \qquad (3)$$

Similarly, the profile zone of a beach located above normal tides and below exceptional elevations corresponds to the above defined foreshore zone. Waves can only be incident in zone 3 when exceptional tides or elevations occur, that is, with long return periods. Even so, waves cannot be considered as any more than residual and are incident with a flow of water pushed by a very low height run-up, $H_3 \approx H_{residual} \approx 0$. So, wave height cannot be considered in a formal sense but rather as a medium intensity current of rising and falling water.

In zone 4, the structure is located inside the tidal range with its base submerged during part of the tidal cycle. This zone is described by the following equations:

$$\frac{X_W}{gT^2} < \frac{H_o}{gT^2}\frac{1}{s}\left(\frac{Z_s}{H_o}\right) \text{ and } \frac{d}{H_0} < \frac{Z_a}{H_o} \qquad (4) \text{ and } (5)$$

The beach profile zone located inside the tidal range corresponds to what is called the beach face (CEM, 1995). Waves which may appear on a geotextile structure located in this zone correspond to residual waves, with medium intensity wave heights, an intermediate return period, and moderate crest lengths, $H_4 \approx H_{residual} << H_b$. Actions due to waves that might be incident on a geotextile structure located in this zone are medium in intensity.

In zone 5, the structure is located in the sea at low tide with its base always submerged. This zone is described by the following equation:

$$\frac{d}{H_0} < \frac{Z_a}{H_o} \qquad (6)$$

The profile zone of a beach located in the sea at low tide with its base always submerged corresponds to the breaker zone (CEM, 1995). A geotextile structure sited in this zone will be subjected to breaking wave action, with wave heights of a certain intensity constantly breaking in the $H_5 \approx H_b$ strip. The breaking waves and impact on the structure must be taken into account for its design. Wave actions to which a geotextile structure located in this zone is subjected are therefore of a certain intensity.

In zone 6, the structure has foundations located at a depth at which waves never normally break. This zone is described by the following equation:

$$\frac{H_o}{H_i}\frac{d}{H_0} - \frac{Z_a}{H_o} > 1.28 \qquad (7)$$

Finally, the profile zone of a beach where waves never break corresponds to the swash zone (CEM 1995). Wave action to which a geotextile structure is subjected in this zone of the beach profile is characterized as being due to developed waves, $H_6 = H_o$, with high-intensity wave heights and long return periods.

Table 1 shows the classification of load stresses to which a geotextile structure is subjected depending on the beach profile zone in which it is located.

Table 1: Geotextile structure stresses according to the profile zone of the beach

Type of coast

The morphological structure of the coast and location of a structure with respect to the type of coast are essential for finding the stresses due to wave actions that a geotextile bag built coastal structure must withstand. In turn, stresses to which this type of structure is subjected will be different depending on the type of coast where it is located. As for any conventional coastal structure, waves have to be propagated from undefined depths to the point where the structure is located in order for the design wave height of a geotextile structure to be determined.

If the structure is at undefined depths, the design wave height will be ($H_{1/3}$) maximum. We shall call it H_o. If the structure is sited at intermediate depths, waves will have to be propagated from undefined depths to the point where the future structure will be located and the wave height reached, H_i, will be determined due to the refraction phenomenon. If, in addition, the point on the coast in question is protected from direct waves, propagation will have to occur in order for the design wave height affected by refraction and diffraction phenomena to be determined.

Depending on the degree of protection, the value of the height of a wave originating from undefined depths, H_0, will be amended. Thus we can class coasts as open, slightly protected, medially protected, protected, or heavily protected. To these types of coast must be added coasts such as enclosed rivers, estuaries, or bays where exterior waves penetrate a short stretch and local waves are more important. This type of coast is classed as included and shown in Figure 2.

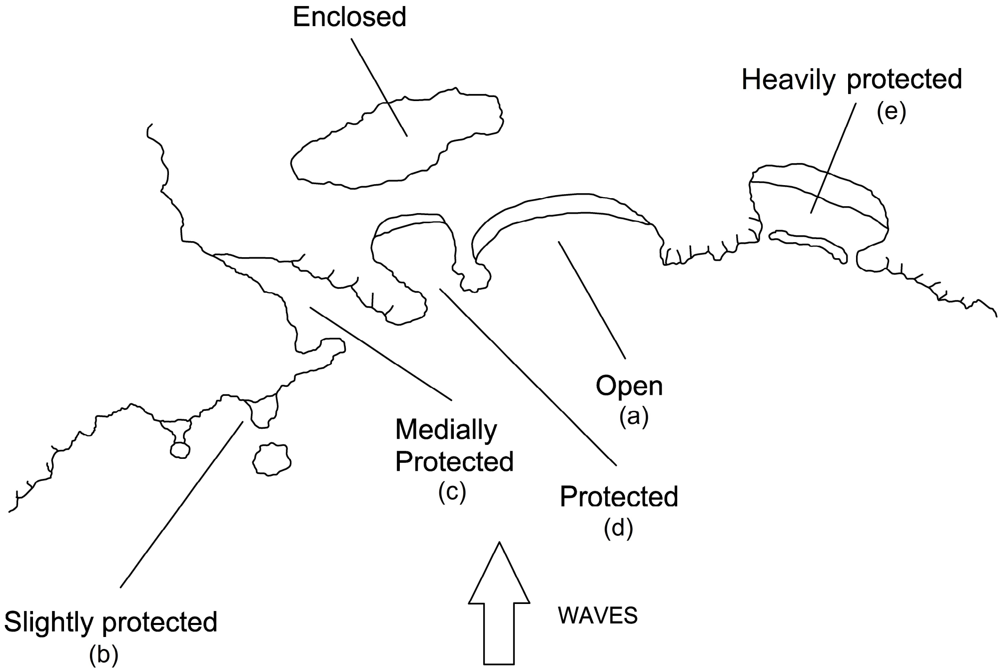


Figure 2: Potential schemes of coastal areas for placing geotextile bag structures. Examples include: (a) Open, where waves are directly impacting; (b) Slightly Protected, where intermittent waves are locally reduced, (c) Medially Protected, where waves are marginally reflected by obstacles; (d) Protected, where wave height intensity is significantly reduced; (e) Heavily Protected, where waves are highly diffracted.

An open coast is defined as a coast where waves are directly incident and no interfering obstacle is present. This type of coast appears geographically at cliffs, open beaches, capes, and reefs where there are no wave-modifying obstacles. The only phenomenon of wave modification is refraction. A slightly protected coast is where directly incident waves originating from deep water are partially or locally reduced. This happens when there is some obstacle in the sea creating a zone that mitigates wave action in its shelter and, therefore, a zone with less energy. So, even though the wave refraction phenomenon prevails, diffraction or some other wave-energy-reducing element can be observed. This type of coast appears on open sheltered coasts in the proximity of some obstacle or with nearby shallows. A medially protected coast is one where waves are reflected when they encounter obstacles in their propagation path and protection is partial.

To the substantial refraction phenomenon is added diffraction which increases in significance and intensity. This type of coast occurs in the partial shelter of islands, capes, and so on. A protected coast is one where wave intensity is significantly reduced by the presence of an obstacle and which is reached only by diffracted waves. This type of coast geographically occurs in bays with islands, peninsulas, and so on in front. A heavily protected coast is only reached by highly diffracted waves and wave heights are barely perceptible. This type of coast occurs with islands at the rear, inside bays and inlets in heavily protected sites, and so on. An enclosed coast is one where waves penetrating from the outside sea are few and local wind-formed waves prevail. This type of coast is associated with shallow coastal concavities and with adjacent, highly sedimentary active coasts. It occurs in lagoons, narrows, marshes, and fens.

When the purpose is to obtain a mere approximation or rough estimate in order to analyse whether a geotextile structure is suitable for a certain location, an approximate method may be used to obtain a value, with an overall approximation. The method consists of assigning an H_o = ($H_{1/3}$) maximum wave-height-reducing coefficient for an open coast to other types of coast, as shown in the following table. These coefficients were obtained from our own work experience for a generic study case or pre-design. For projects and more specific studies, they should be calculated from wave propagations.

Table 2: Wave-reducing coefficients according to the type of coast

RESULTS

One of the key points in designing a geotextile bag structure is to know the range of validity of significant wave heights. The method of determining the range of validity of significant wave heights consists of calculating bag equation stability limitations.

Although some authors clearly indicate the wave height validity range, others do not and this may give rise to wrong use. This paper determines the range of validity for the significant wave height, H_s, in the other stability equations, where they have not been defined.

Variables taken into consideration in these stability equations are H_s, the significant wave height [m]; $\Delta = (\rho_s - \rho_w)/\rho_w$, the relative density of bags [–]; l_c, the maximum bag length [m]; D= $l_c \cdot \sin\alpha$, the width of bag layer [m]; α, the slope of structure [º]; and $\xi = \frac{\tan\alpha}{\left(\frac{H_S}{L_O}\right)^{1/2}}$, Iribarren number [–].

The width of bag layer is partly depending on the manner in which the geotextile bag elements are installed. There are two most common installation geometries, in a horizontal placement with approximately 50% overlap between adjacent geotextile bags and adjacent geotextile bags placed against each other on the slope. In this paper it is considered the first installation, however in the second one the width of bag layer is the width of the geotextile bag element.

Pilarczyk's equation (1996), which is valid for $\xi \leq 3$, is expressed as follows:

$$\frac{H_S}{\Delta D} = 2.5 \cdot cos\alpha \cdot \xi^{-1/2} \qquad (8)$$

As the author himself points out, the significant wave height for designing a sand-filled geotextile bag structure should be lower than 1.5 m without ever exceeding 2 m, in order to guarantee stability.

Wouters' equation (1998) for revetments is expressed as follows:

$$\frac{H_S}{\Delta D} = \frac{2.0}{\sqrt{\xi_O}} \qquad (9)$$

The maximum value that the significant wave height can reach while guaranteeing the stability of a geotextile bag revetment is determined by calculating the values of the variables in equation (9). Δ, maximum relative density of the geotextile bags equal to 1, considering that it varies between 0.9 and 1; ξ_O, minimum Iribarren number [–], as Figure 3 shows, equal to 1; α, maximum slope of the structure [°], since the most common values for the slopes of a beach are 1:2 or 1:3 and as the slope of the structure is the same as the beach where it is located, a structure with a 1:3 slope or, in other words, a structure with an 18.4° gradient, is taken into consideration; D, maximum bag layer width = $l_c \cdot \sin\alpha$ [m] (Recio and Oumeraci, 2008); and the maximum bag length is obtained from the expression (10), in which the greatest admissible volume of geotextile bags taken into consideration was 5 m^3.

$$V = \frac{l_c^3}{10} \qquad (10)$$

Therefore: $l_c = \sqrt[3]{10 \cdot V} = \sqrt[3]{10 \cdot 5}$ = 3.68 m, where the maximum bag layer width is D = 3.68·sin 18.4° = 1.16 m. Finally, the maximum significant wave height to which a revetment made of sand-filled geotextile bags may be subjected whilst guaranteeing the structure's stability is found by replacing the variables in (9) and is 2.32 m.

The minimum value that the significant wave height may reach whilst guaranteeing the stability of a revetment made of sand-filled geotextile bags is determined by defining the following values of the variables in the foregoing expression (9): Δ, the minimum relative geotextile bag density and is equal to 0.9; ξ_O, the maximum Iribarren number [–], as shown in Figure 3, and is equal to 11; α, the minimum slope of the structure [°] and is considered to be 18.4°; D, the minimum width of the bag layer and is equal to $l_c \cdot \sin\alpha$ [m] (Recio and Oumeraci, 2008). The least admissible volume is 0.05 m^3 (Lawson 2008), therefore: $l_c = \sqrt[3]{10 \cdot V} = \sqrt[3]{10 \cdot 0.05}$ = 0.79 m. And the minimum width of the bag layer is D = 0.79·sin 18.4° = 0.25 m.

Finally, by replacing the variables in (9), it is found that the minimum value of the significant wave height that bags can withstand is 0.13 m. The limit values of the significant wave height to which a sand-filled geotextile bag built revetment may be subjected, whilst guaranteeing its stability according to the Wouters equation (1998), lie between 0.13 and 2.32 m.

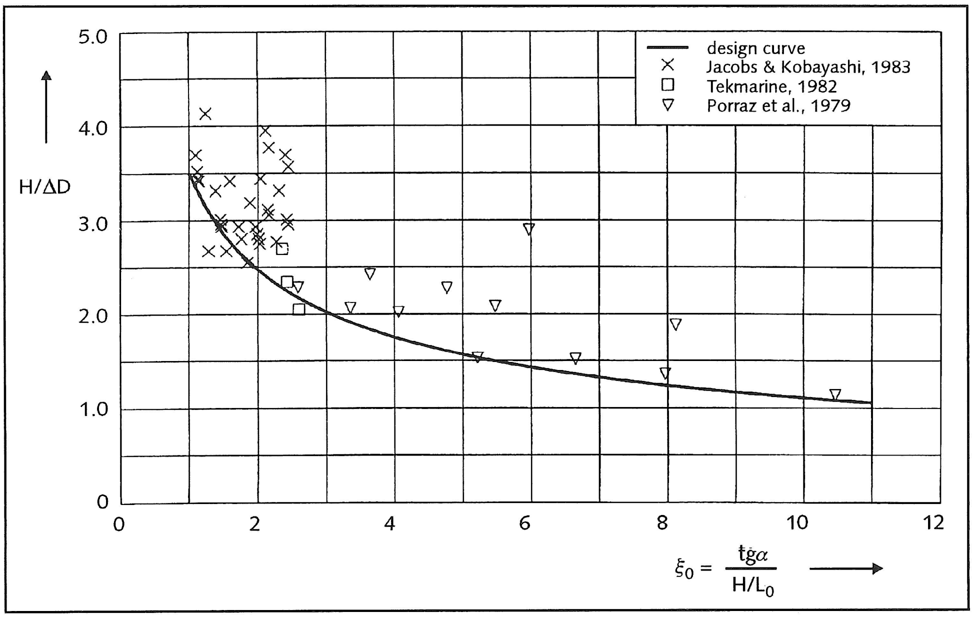


Figure 3: Design curve in which relates variables H/ΔD (Stability number) and ξ_O (Iribarren number) considering stability test results of three different authors (Jacobs

and Kobayashi, Tekmarine and Porraz et al.). Source: Pilarczyk (2000)

Oumeraci *et al.* (2002, 2003) differentiated the location of bags in the structure itself into two types in order to define the stability equation. On the one hand, they considered bags located on the slope of a revetment and, on the other, bags located at the top of a revetment.

The equation of Oumeraci *et al.* (2002, 2003) for geotextile bags located on the slope of a revetment is expressed as:

$$\frac{H_S}{\Delta D} = \frac{2.8}{\sqrt{\xi_O}} \qquad (11)$$

The limit values of the significant wave height in the Oumeraci *et al.* equation (2002, 2003), which guarantee the stability of sand-filled geotextile bags placed on a revetment slope, are determined by the same procedure as described earlier. The limit values of the significant wave height to which sand-filled geotextile bags located on a revetment's slope may be subjected whilst guaranteeing the structure's stability according to the equation of Oumeraci *et al.* (2002, 2003) lie between 0.18 and 3.25 m.

The Oumeraci *et al.* (2002, 2003) equation for geotextile bags placed at the top of a revetment is expressed as follows:

$$\frac{H_S}{\Delta D} < 0.79 + 0.09 \cdot \frac{R_C}{H_S} \qquad (12)$$

According to the equation of Oumeraci *et al.* (2002, 2003), the significant wave height guaranteeing the stability of geotextile bags located at the top of the revetment slope will lie between 0 and 0.92 m.

The equation of Mori (2009) and Mori *et al.* (2008), for submerged structures of sand-filled geotextile bags, is formulated in the same way as equation (11). The maximum value that the significant wave height can reach whilst guaranteeing the stability of submerged sand-filled geotextile bag structures according to the equation of Mori (2009) and Mori *et al.* (2008) is determined by the same procedure as described earlier. The limit values of the significant wave height to which submerged sand-filled geotextile bag structures can be subjected whilst guaranteeing stability according to the equation of Mori (2009) and Mori *et al.* (2008) will be between 0.18 and 3.25 m.

It must be borne in mind that neither the structure's freeboard nor its height have been taken into account in applying this equation. These measurements are fundamental for finding the load stresses on such a structure. In addition, the valid wave height range is assumed to be that impacting on the structure, and therefore the height, H_o, which over-runs the structure and impacts on submerged structures, should be determined by the wave theory for design projects. However, we would prefer to err on the side of safety by taking the limitation of H_o' as H_o.

The new stability equation developed by Dassanayake and Oumeraci (2013) for submerged structures is as follows:

$$Ns\sqrt{\xi_0} = A\left(\frac{R_C}{H} \cdot \frac{1}{\xi_0}\right)^2 + B\left(\frac{R_C}{H} \cdot \frac{1}{\xi_0}\right) + C \qquad (13)$$

where A, B, and C are parameters obtained by empirical tests [–].

Table 3, below, shows the values of the A, B, and C parameters for the three cases taken into consideration in the tests performed for determining the new stability equation mentioned.

Table 3: Empirical parameters of the Oumeraci and Dassanayake equation (2013)

The geometric proportions of the geotextile bags employed in the reduced scale model, 10:5:1, are used to determine the significant wave height limitations of this new stability equation. Bearing in mind the maximum volume of 5 m^3 of currently made geotextile bags and knowing the length of the geotextile bags in the reduced scale model, that is, 0.14 m, we obtain the following:

The volume of a full geotextile bag in the model is $Vm = a \cdot 0.5a \cdot 0.1a = 0.05\ a^3$, and the volume of a current geotextile bag is $Vr = 5\ m^3$.

Considering $V_m = V_r \rightarrow 0.05\ a^3 = 5 \rightarrow a_r = 4.6$ m and the scale factor $\lambda = \frac{V_m}{V_r} = \frac{a_m}{a_r} = \frac{0.14}{4.6} = 0.03 \Rightarrow$ Scale: $E = \frac{1}{\lambda} = \frac{1}{0.03} \rightarrow E = 33$

Therefore, the significant wave height limit values for which a submerged sand-filled geotextile bag structure is stable will be as follows, for the new stability equation developed by Dassanayake and Oumeraci (2013): 1.65 ≤ Hs ≤ 7.92 for 80% filled non-woven bags, 1.32 ≤ Hs ≤ 3.63 for 100% filled non-woven bags, and 2.31 ≤ Hs ≤ 5.28 for 80% filled woven and non-woven bags. The range of validity of a significant wave height to which a submerged sand-filled geotextile bag structure can be subjected, whilst guaranteeing its stability according to this new equation, will be greatest for 80% filled non-woven bags: 1.65 m ≤ Hs ≤ 7.92 m.

DISCUSSION

Not all places on the coast prove suitable for the use of certain sand-filled geotextile bag structures. Therefore, considering the previously performed coastal zoning both along the longitudinal profile of a beach and the different types of coast, those coastal zones where revetments with sand-filled geotextile bags can be located and, consequently, the zones where they may be used are discussed in this section. Since wave intensity occurring in zones 1, 2, and 3 of the longitudinal profile of a beach is practically nil under normal conditions, no distinction is made between these zones and they are dealt with as if they formed a single zone.

Equations for designing this type of structure and its limitations in significant wave height are taken into consideration in determining suitable coastal sites for locating geotextile bag revetments. The range of limitations in significant wave height, from 1 m to almost 8 m, is very wide. So, it will be more advisable to use the formula of Dassanayake and Oumeraci (2013) than the formula of Pilarczyk (1996) for all the zones of the coastal profile. The latter can only be used when the significant wave height is less than 2 m.

Zones 1, 2, and 3 of the longitudinal profile of a beach

To ensure greater safety in relation to structure stability, only the top values of the range of significant wave height validity in the equations will be taken into consideration. This is due to the fact that the highest significant wave heights make structure stability precarious. In turn, the position of bags in the structure itself must be differentiated when the design is carried out using the Oumeraci *et al.* (2002, 2003) equation.

If a sand-filled geotextile bag revetment is located in zones 1, 2, or 3 of the profile of a beach corresponding to a dry beach and a foreshore, as defined earlier and, in turn, this beach belongs to an open type of coast, the structure may be designed with the equations defined, because wave heights do not exceed the limits of 2, 3.25, or 7.92 m, obtained earlier. Consequently, the structure may be located in these open coast zones.

Since the remaining types of coasts designated as slightly protected, medially protected, protected, heavily protected, and enclosed are more sheltered than an open type of coast, wave actions to which a sand-filled geotextile bag revetment located on these types of coast is subjected will be lower in intensity than wave actions to which the structure would be subjected on an open type of coast. Consequently, the significant wave height will be lower, mostly meeting the limitations indicated. This structure, located on these types of coast and in zones 1, 2, or 3 of the longitudinal profile of a beach, may be designed with the above-indicated equations.

Zone 4 of the longitudinal profile of a beach

If a sand-filled geotextile bag revetment is sited in zone 4 of a beach profile and belongs to an open coast type, waves to which it is subjected will be moderate in intensity and the wave height will be the residual type, as indicated earlier. Wave heights will not then exceed the limits established, namely 2, 3.25, or 7.92 m. This structure located in the said zone may be designed with the equations indicated earlier and may be sited in zone 4 of an open coast profile.

A structure located on the remaining types of coasts is subjected to wave action that is lower in intensity than the waves to which a structure sited on an open type of coast would be subjected as these are more sheltered coasts. When located on the remaining types of coasts, this structure could be designed with the equations indicated since the wave height values do not exceed the limitations required.

Zone 5 of the longitudinal profile of a beach

In zone 5 of the longitudinal profile of a beach corresponding to the breaker zone and belonging to an open coast type, the wave heights to which a sand-filled geotextile bag revetment structure will be subjected show a heavy discharge of energy and, consequently, wave heights may exceed some of the limits. This means that such equations cannot be used for designing this type of structure. As a result, its use in this zone is not recommendable.

If a sand-filled geotextile bag revetment is sited in zone 5 of the profile of a beach corresponding to the breaker zone belonging to a slightly protected and medially protected coast, the wave action to which this structure is subjected will be: $H_{cgeotextile} = H_O \cdot C_{profilereducer} \cdot C_{coastreducer}$.

As the geotextile structure is located in zone 5 of the coast profile of the breaker zone, a wave height coinciding with the breaker wave height (H_b) should be considered. When it is located on slightly and medially protected coasts, wave action will decrease by approximately 20 and 40%, respectively. Wave heights of 0.8 and 0.6 of this value should be used ($C_{coastreducer} = 0.8$ and 0.6).

The calculated wave heights for a sand-filled geotextile structure located in zone 5 of the beach profile belonging to slightly and medially protected coasts will therefore be $H_{cgeotextile} = H_b \cdot 0.8$ and $H_{cgeotextile} = H_b \cdot 0.6$, respectively.

Then, the breaker wave height would have to be guaranteed to be less than 2.5 or 4 m as indicated in order to design a sand-filled bag revetment located in zone 5 of the longitudinal profile of a beach belonging to the slightly protected type of coast using the Pilarczyk (1996), Wouters (1998), and Oumeraci *et al.* (2003) equations, and the breaker wave height would have to be guaranteed to be less than 9.9 m when using the Dassanayake and Oumeraci (2013) equation. Otherwise, its use in this zone is not recommended.

The wave breaker height would have to be guaranteed to be less than 3.3 or 5.3 m, as indicated, to be able to use the foregoing equations to design a sand-filled geotextile bag revetment located in zone 5 of the longitudinal profile of a beach belonging to a medially protected type of coast and the breaker wave height would have to be guaranteed to be less than 13.2 m when using the Dassanayake and Oumeraci (2013) equation. Otherwise, its use in this zone is not recommended.

In the event of designing a structure using the Oumeraci *et al.* (2003) equation, account must be taken of the position of the bags in the structure itself. The foregoing considerations would only be valid for bags located on the revetment's slope.

Then, in order to locate geotextile bags belonging to the crest or top of a revetment located in zone 5 of the longitudinal profile of a beach belonging to a slightly protected coast using the Oumeraci *et al.* (2003) equation, the breaker wave height would have to be guaranteed to be less than 1.25 m for a slightly protected coast or less than 1.67 m for a medially protected coast. Otherwise, its use is not recommended.

If a sand-filled geotextile bag revetment is located in zone 5 of the profile of a beach belonging to a protected, heavily protected, or enclosed coast, the wave action to which the structure is subjected will be residual. It is therefore within the range of validity of the wave height where the design equations of Pilarczyk (1996), Wouters (1998), and Oumeraci *et al.* (2003) may be applied for calculating its design and stability.

Zone 6 of the longitudinal profile of a beach

In the fully developed wave zone of the longitudinal profile of a beach belonging to an open type of coast, the wave heights to which a revetment type of structure is subjected are those evolving from the high seas, H_o, to intermediate depths, H'_o, and it cannot, therefore, be guaranteed that its value will be within the range of values in which design equations of geotextile bag revetments are applicable. Therefore, structures of this type cannot be designed in general in this zone of the profile and for this type of coast.

If a sand-filled geotextile bag revetment is planned to be located in zone 6 of the profile of a beach belonging to a slightly protected or medially protected coast, the wave action to which this structure would be subjected would be: $H_{cgeotextile} = H_O \cdot C_{profile\ reducer} \cdot C_{coast\ reducer} \cdot$

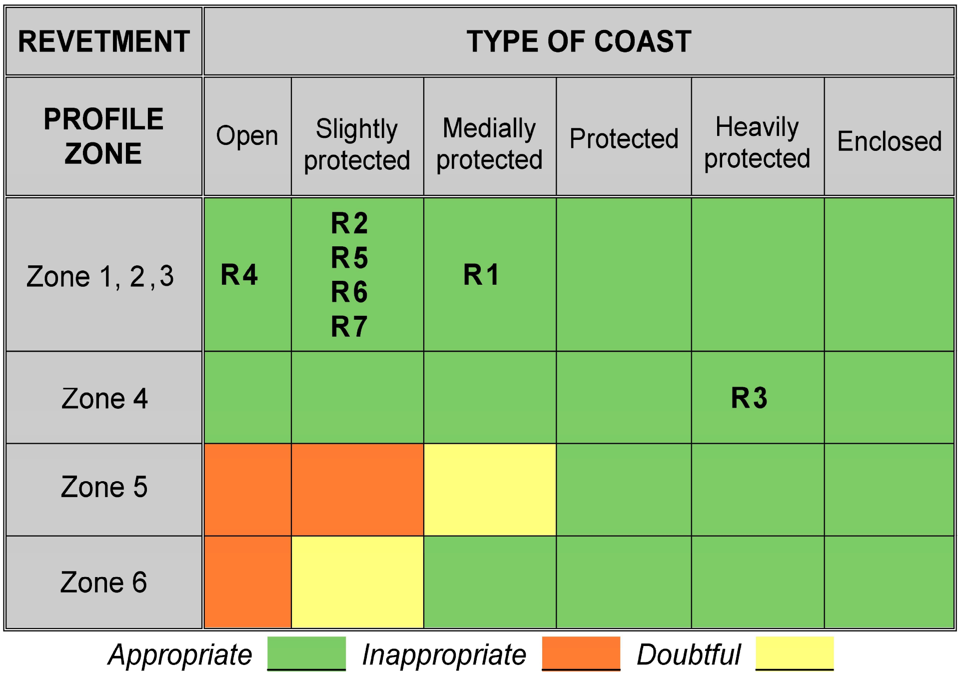
Considering the same procedure as for zone 5, for a sand-filled geotextile bag revetment located in zone 6 of the profile of a beach belonging to a slightly protected type of coast, a more detailed analysis would have to be performed to determine whether the wave height to which the said revetment would be subjected would be higher than 2.5, 4, or 9.9 m. Should the maritime climate in the zone give higher wave heights, it would not be appropriate to use the foregoing equations. It would not be advisable to design a sand-filled geotextile bag revetment located in zone 6 of the profile of a beach belonging to a slightly protected coast with the equations indicated.

For a medially protected coast, the height of the waves to which a sand-filled geotextile bag revetment would be subjected would be less than 3.3, 5.3, or 13.2 m, in cases of heavy storms. The equations of the aforementioned authors would thus be valid and it could be sited in that zone on that type of coast.

If a sand-filled geotextile bag revetment is sited in zone 6 of the profile of a beach belonging to a protected, heavily protected, or enclosed beach, the waves incident on the structure will be similar to high sea waves (H_o), with wave heights under normal conditions of less than 5, 10, or 20 m when taking Pilarczyks (1996) and Wouters (1998) equations into account and less than 8, 16, and 32 m when taking the Oumeraci *et al.* (2002, 2003) equation and the Dassanayake and Oumeraci (2013) equation into consideration. It may therefore be sited on this type of coast and in that zone.

In summary, Figure 4 shows different zones of the longitudinal beach profile (vertical) and different types of coasts (horizontal). Suitable, doubtful, and unsuitable locations are given for carrying out the design using equations relating to the stability of a sand-filled geotextile bag revetment and, therefore, for its location.

Having determined the significant wave height limit values in the equations of stability design for geotextile bag revetments and their suitable locations, they are finally validated with the behaviour of seven examples built in different countries. The revetments and their main properties considered are located on the following beaches (countries) and, as Figure 4 shows, all of these revetments are located in appropriate locations.



REVETMENT	**TYPE OF COAST**					
PROFILE ZONE	Open	Slightly protected	Medially protected	Protected	Heavily protected	Enclosed
Zone 1, 2,3	🟩 **R4**	🟩 **R2** **R5** **R6** **R7**	🟩 **R1**	🟩	🟩	🟩
Zone 4	🟩	🟩	🟩	🟩	🟩 **R3**	🟩
Zone 5	🟧	🟧	🟨	🟩	🟩	🟩
Zone 6	🟧	🟨	🟩	🟩	🟩	🟩

Appropriate 🟩 *Inappropriate* 🟧 *Doubtful* 🟨

Figure 4: Summary of coastal sites for placing geotextile bag revetments by comparing the significant wave height of the site with the limits obtained from the equations previously indicated. In the inappropriate sites, significant wave height is usually bigger than those limits. Therefore, geotextile bag revetments cannot be designed. In doubtful sites, significant wave height could be bigger than the known limits, so it should be necessary to investigate more. R1, R2, R3, R4, R5, R6 and R7 are seven examples of geotextile bag revetments.

On Jumeirah Beach (Dubai, United Arab Emirates), the revetment named R1 is built with geotextile bags weighing 2 T on the slope of the revetment and with geotextile bags weighing 5 T at the toe. As it is located in zone 3 of the beach profile

($H_o \cong 0$) and on a medially protected coast ($H_d = H_o \cdot Cr = 0 \cdot 0.6 = 0$ m), R1 is located in a suitable zone and can be designed with all equations including Pilarczyk’s (1996), which is the most restrictive. On Stockton Beach (New South Wales, Australia) the revetment named R2 is built with geotextile bags weighing 2 T. It is located in zone 3 of the beach profile ($H_o \cong 0$) on a slightly protected coast ($H_d = H_o \cdot Cr = 0 \cdot 0.8 = 0$ m), so it is located in a suitable zone and can be designed with all of the equations. On the beach located at the mouth of the river Maroochy (Queensland, Australia), the revetment named R3 is built with geotextile bags weighing 2 T. Located in zone 4 of the beach profile ($H_o \cong H_{residual}$) on a heavily protected coast ($H_d = H_o \cdot Cr = H_{residual} \cdot 0.2$), R3 is located in a suitable zone and can be designed with all the equations. On Kelso Beach (KwaZulu-Natal, South Africa), the revetment named R4 is built with geotextile bags of 2.3 × 2.0 × 0.6 m volume. Located in zone 4 of the beach profile ($H_o \cong 0$) on an open coast ($H_d = H_o \cdot Cr = 0 \cdot 1 = 0$ m), R4 is located in a suitable zone and can be designed with all the equations. On Amanzimtoti Beach (KwaZulu-Natal, South Africa), the revetment named R5 is built with geotextile bags of 2.3 × 2.0 × 0.6 m volume. Located in zone 3 of the beach profile ($H_o \cong 0$) on a slightly protected coast ($H_d = H_o \cdot Cr = 0 \cdot 0.8 = 0$ m), R5 is in a suitable zone and can be designed with all equations. On North Beach (East Cape’s Jeffrey Bay, South Africa), the revetment named R6 is built with geotextile bags of 2.3 × 2.0 × 0.6 m volume. Located in zone 3 of the beach profile ($H_o \cong 0$) on a slightly protected coast ($H_d = H_o \cdot Cr = 0 \cdot 0.8 = 0$ m), R6 is in a suitable zone and can be designed with all the equations. On Kelly Beach (Port Alfred, South Africa), the revetment named R7 is built with geotextile bags of 2.3 × 2.0 × 0.6 m volume. Located in zone 3 of the beach profile ($H_o \cong 0$) on an open coast ($H_d = H_o \cdot Cr = 0 \cdot 1 = 0$ m), R7 lies in a suitable zone and can be designed with all the equations.

CONCLUSIONS

Structures built with geotextile components or elements arise due to a need to build emergency structures to prevent the collapse of coastal buildings that are in danger due to storm erosion. Their main characteristics are the quick rate at which they can be built, their low cost due to the use of materials from the zone, and low maintenance.

Not all places on the coast are suitable for the use of sand-filled geotextile bag revetment structures. The most appropriate zones for designing and, as a consequence, using sand-filled geotextile bag revetments are usually the dry beach and very shallow water zones without reaching wave breaker depths except on heavily protected coasts. Inappropriate zones for designing and locating sand-filled geotextile bag revetments are profile zones 5 and 6 on open coasts and profile zone 5 on slightly protected coasts, except if a suitable reinforcement is carried out when the demand make necessary this kind of defence. And doubtful zones for designing and locating sand-filled geotextile bag revetments are profile zone 5 on medially protected coasts and profile zone 6 on slightly protected coasts.

When designing a sand-filled geotextile bag revetment, the limitations of wave height in stability equations and appropriate areas of the coast should be taken into account since not all equations are suitable for designing these structures in all zones. The most restrictive equation is (8) (Pilarczyk, 1996), because it can be used when the significant wave height is $Hs < 2$ m. However, equation (13) (Dassanayake and Oumeraci, 2013) is less restrictive because it can be used when the significant wave height is $Hs < 7.92$ m, and, therefore, in a greater number of locations on the coast.

ACKNOWLEDGEMENTS

The first named author is grateful for the participation of members of the Ports and Coasts Study Centre, CEDEX, Madrid (Spain), without whom it would not have been possible to draw up this paper.

LITERATURE CITED

Akter, A.; Crapper, M.; Pender, G.; Wright, G., and Wong, W. S., 2012. Modelling the failure modes in geobag revetments. *Water Science & Technology*. 65(3), 418–425.

Coastal Engineering Research Center, 1995. *Engineering and Design. Design of beach fills*. Department of the Army. U.S. Army Corps of Engineers (EM 1110-2-3301), 112p.

Dassanayake, D.T. and Oumeraci, H., 2013. Hydraulic stability formulae and nomograms for coastal structures made of geotextile sand containers. *Proceedings of the 7th International Conference on Asian and Pacific Coasts* (Bali, Indonesia), pp. 24–26.

Lawson, R., 2008. Geotextile containment for hydraulic and environmental engineering. *Geosynthetics International*, 15(6), 384-427.

Mori, E., 2009. Coastal structures made of geotextile elements filled with sand: field and experimental research. University of Firenze, Italia, Ph.D. dissertation, 250 p.

Mori, E.; Aminti, P. L., and D'Eliso, C., 2008. Field experiment on a groin system built with sand bags. *International Conference on Coastal Engineering* (Hamburg), pp. 219–231.

Oumeraci, H.; Hinz, M.; Bleck, M., and Kortenhaus, A., 2003. Sand-filled geotextile containers for shore protection. *Proceedings of the 6th International Conference on Coastal and Port Engineering in Developing Countries* (Colombo, Sri Lanka, COPEDEC), pp. 88–94.

Pilarczyk, K. W., 1996. Geotextile systems in coastal engineering – An overview. *Proceedings of the 25th Conference on Coastal Engineering* (Orlando, Florida, ASCE*)*, pp. 2114–2127.

Pilarczyk, K. W., 2000. *Geosynthetics and geosystems in hydraulic and coastal engineering.* A.A. Balkema, 913 p.

Weggel, J., 1988. Seawalls: the need for research, dimensional considerations and suggested classification*. Journal of Coastal Research*, Special Issue No.4, pp. 29–39.

Wouters, J., 1998. *Open Taludbekledingen; stabiliteit van geosystems (Stability of Geosystems)*, Delft Hydraulics, *Report No. H-1930, Annex 7 (in Dutch).*