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On the design of beach nourishment projects using static equilibrium concepts: Application to the Spanish coast

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ABSTRACT

The concept of equilibrium plan form and equilibrium profile has been widely used as an engineering tool in order to design beach nourishment projects. The scope of this paper is to further explore this "equilibrium beach" concept in crenulated bays, as a long-term tool for beach nourishment projects. The proposed methodology is based on González and Medina (2001) and combines the static equilibrium plan and profile for long-term analysis. This methodology includes a modified equilibrium plan form, which is able to define the orientation of the local wave front in the diffracting point, and also to locate the downcoast starting point of the static equilibrium beach from which the parabolic plan form of Hsu and Evans (1989) is valid. This methodology permits the application of any equilibrium profile formulation. An example of the application of this methodology and long-term formulations to the design of the Spanish nourishment project of Poniente Beach (Gijón) is presented. Ten years after its construction, the beach has still got a static equilibrium and remains pretty close to the predicted equilibrium beach in plan and profile.
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1. Introduction

Beach nourishment is a viable engineering alternative for shore protection and is the most important technique for beach restoration. The traditional engineering response to coastal erosion has been to prevent coastal erosion by employing coastal structures such as seawalls, groins, or detached breakwaters. However, some cases show adverse environmental effects in the near and far field of these structures. Nowadays, coastal engineers are interested in developing a "soft engineering" dynamic approach, such as adding littoral material or modifying vegetation. An increasingly important option is the integration of this with "supporting structures" when necessary. From both the economical and technical point of view beach nourishment has significantly increased in the last 15 years. Its application is suitable for some, but not all, locations where erosion is occurring, particularly those with high rates of erosion. Sometimes the solutions require the use of "hard" static structures built of rock, steel or concrete. However, beach nourishment is a valid alternative for providing natural shore protection and recreational opportunities, restoring dry beach area that has been lost to erosion or defending the hinterland from flooding.

The determination of the stability and evolution of a fill for a beach nourishment project require the use of an important set of formulations and numerical tools, which have been establish based on the different spatial and temporal scale of the processes. The different dynamics affecting a beach are presented in spatial scales ranging from centimetres (turbulence) to tens of kilometres (tides). In time scales they range from seconds (waves) to decades (the rising of the mean sea level). As a response to these dynamics, the beach morphology also changes within all of these scales: centimetres–kilometres, and seconds–decades. Despite the calculation power of computers, it is inadequate and almost impossible to calculate the changes that take place on a greater scale, by integrating the smaller scale processes. This is due to the lack of a unified sediment transport theory that retains the influence of all of these effects which are produced on different spatial and temporal scales. This lack of a unified theory makes it necessary to analyze all the processes occurring on different scales (time or space) with different tools or formulations. Therefore, the scale of interest in each particular problem must be known and the adequate formulation to said scale must be employed. The different dynamics and morphological responses of the beaches are usually classified as: micro-scale, meso-scale and macro-scale according to the spatial dimension and to short-term, middle-term and long-term timeframes.

In a beach nourishment project the scales of interest are the meso-scale (tens of hundreds of metres), macro-scale (kilometres) and long-term (years), given that they define the fill evolution throughout the useful life. The elements of smaller scales (for example, the erosion produced by a storm) are only relevant if their effects last throughout time or space in units close to those of interest (for example, weeks to months) or if their effect provokes the functional breakdown of the work (for example, the waves overtopping the

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dunes and flooding the back part of the beach). Following GIOC (2003), the functionality and stability of any solution alternative in a beach nourishment project should be designed on a long-term scale and afterwards, the functionality and stability should be verified on the middle- and short-term scales (under seasonal and extreme storm events).

The objective of long-term analysis is to determine which will be the final shape of the beach and/or the temporal evolution of said shape on a scale of years in order to assure that the beach functionality continues throughout its useful life. The two most widely used models for the analysis of beaches at this long-term timeframes are those based on the diffusion equation (Hanson and Kraus, 1989; Hanson et al., 2003) and those based on equilibrium hypothesis (Capobianco et al., 2002; Kraus, 2001). For the latter, the beach stability and the equilibrium plan and profile are analyzed based on a modal wave climate and their associated current system. This analysis does not include other sea oscillations (e.g., infragravity waves, edge waves, etc.).

The aim of this paper is to further explore this "equilibrium beach" concept in crenulate-shaped bays as a long-term tool for beach nourishment projects. The paper is organized as follows: first, a brief review of design elements based on equilibrium formulations is presented. Next, a beach nourishment methodology combining equilibrium plan and profile for long-term analyzes is presented. Finally, the methodology is applied to a real case on the Spanish coast.

2. Design elements: Orthogonality hypothesis and equilibrium formulations

The hydrodynamic and sedimentary processes that take place in a beach are three-dimensional. However, for engineering applications, the present limitations of tools, formulations and understanding of these processes make it impossible to analyze them in a fully three-dimensional way. Hence, an additional work hypothesis in the study of beach stability is introduced, and it regards the orthogonality of the longitudinal and transversal movements of a beach under wind–wave actions. According to the orthogonality hypothesis, any beach movement can be analyzed by studying independently the longitudinal and transversal movements of the beach. The orthogonality hypothesis allows the analysis of beach stability by studying separately the beach cross-shore (transversal axis) and the beach longshore (longitudinal axis) dimensions (De Vriend et al., 1993). The orthogonality hypothesis is close enough to reality, especially in open beaches with extreme morphodynamic states (dissipative or reflective). In beaches with intermediate morphodynamic states there is a notable plan-profile interaction, for which the separate analysis of the cross-shore and the longshore must be carried out carefully, taking into account the morphodynamic states.

The equilibrium hypothesis postulates that if the action of the acting dynamics is maintained indefinitely, the beach shape will reach a constant final position, which can be denominated "equilibrium beach". Thus, associated to this beach state the along- and across-shore, the gradients of the wind waves, their mean quantities and related mean sediment transport are negligible. In reality, it is not necessary for the action to be maintained indefinitely, but rather for the shape response to be faster than the scale of interest. Concerning the beach profile, it is assumed that the modifications are produced in reduced space scales O(100 m) and temporal scales considered to be instantaneous (days to months) in a long-term study, which implies that the profile always reaches equilibrium. In the case of plan shape, the final equilibrium shape can be analyzed in longer temporal and space scales (years and O(km)) compared with the profile, although this makes sense only in beaches in static or dynamic equilibrium where there is no loss of net material.

Thus, the determination of the stability and evolution of a fill for a beach nourishment project in a long-term scale will be based on the concept of "equilibrium beach", which combines the equilibrium plan form and the equilibrium profile, as is shown in Fig. 1. Some equilibrium plan and profile formulations are discussed in the next section.

2.1. Equilibrium plan form in crenulated-shaped bays

A great number of static equilibrium-shape models and formulations have been proposed, such as the spiral logarithm by Yasso (1965), Vichetpan (1969), Silvester (1970) and others. Hsu and Evans (1989) showed that the logarithmic spiral does not follow the complete periphery of the equilibrium bay, proposing a parabolic relationship.

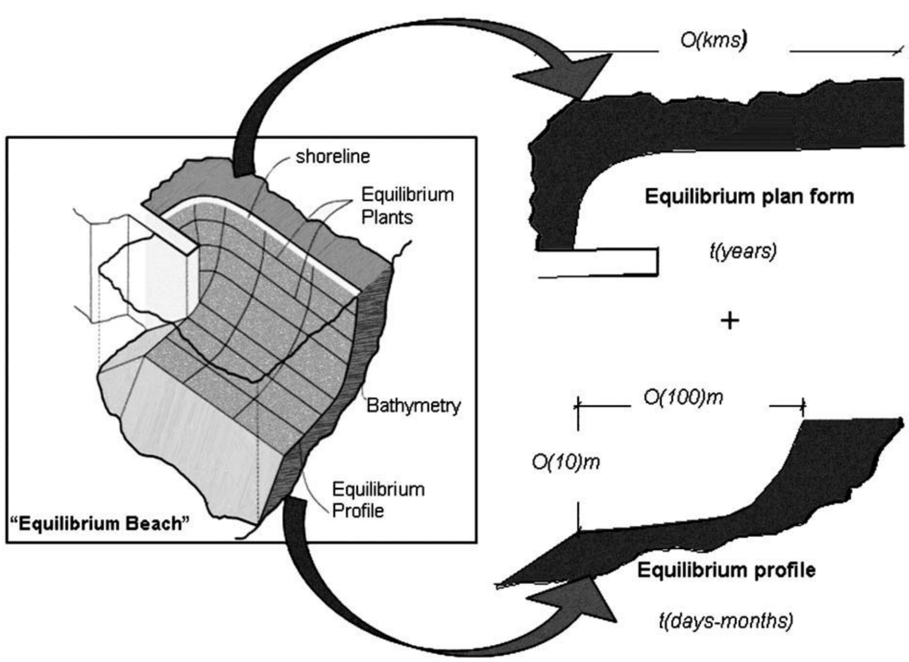

Fig. 1. Sketch of an "equilibrium beach" (equilibrium plan + equilibrium profile). Orthogonality of the longitudinal and transversal movements of a beach.

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