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Predicting coastal morphological changes with empirical orthogonal function method

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Abstract

In order to improve the accuracy of prediction when using the empirical orthogonal function (EOF) method, this paper describes a novel approach for two-dimensional (2D) EOF analysis based on extrapolating both the spatial and temporal EOF components for long-term prediction of coastal morphological changes. The approach was investigated with data obtained from a process-based numerical model, COAST2D, which was applied to an idealized study site with a group of shore-parallel breakwaters. The progressive behavior of the spatial and temporal EOF components, related to bathymetric changes over a training period, was demonstrated, and EOF components were extrapolated with combined linear and exponential functions for long-term prediction. The extrapolated EOF components were then used to reconstruct bathymetric changes. The comparison of the reconstructed bathymetric changes with the modeled results from the COAST2D model illustrates that the presented approach can be effective for long-term prediction of coastal morphological changes, and extrapolating both the spatial and temporal EOF components yields better results than extrapolating only the temporal EOF component.

Keywords: EOF method; Coastal morphological change; Long-term prediction; Process-based numerical model; Shore-parallel breakwater

1. Introduction

Coastal defense structures represent an effective measure against coastal erosion. These structures include sea walls, breakwaters, groynes, or a combination of the above, in addition to soft engineering approaches, such as beach nourishment. All of these structures and approaches have advantages and disadvantages, and coastal engineers must study each case and propose the best solution for a particular site. However, the ways these structures affect the shoreline in the long term and their impacts on the adjacent coastal areas are not always clear.

In particular, shore-parallel breakwaters have proven to be an effective way to mitigate coastal erosion. However, the construction of coastal structures can sometimes produce unexpected problems, which may result in an increase of the maintenance cost along that stretch of coast or even generation of new erosion issues beyond the protected areas (Dolphin et al., 2012). Therefore, coastal dynamics should be fully studied during design of these structures.

In past decades, most of the experience regarding shore-parallel breakwaters has been gathered at locations with micro-tides, tidal ranges smaller than 2 m. In these places, design criteria drawn from field experience work accurately, and the effect of coastal defense structures can be assessed with confidence. However, for locations with meso- or macro-tides, field experience regarding shore-parallel breakwaters is limited, and classical design criteria may not always lead to high accuracy (Johnson et al., 2010).

There are different approaches to studying the shoreline evolution behind a group of shore-parallel breakwaters. Process-based numerical models have been widely used in recent decades. They are powerful tools for understanding the hydrodynamics in detail in the areas surrounding breakwaters, but they are less suitable for long-term simulation (De Vriend and

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Ribberink, 1996; Du et al., 2010; Roelvink and Reniers, 2011). Reasons include not only the high running cost of the process-based model for long-term simulation, but also the nonlinearity of coastal processes, causing accumulation of numerical and physical errors (Larson et al., 2003). Other models, such as the one-line model, may be more appropriate for long-term prediction, due to the reduced physical processes in the model. The one-line model is based on the continuity of alongshore sediment transport fluxes and ignores cross-shore sediment transport (Dean and Dalrymple, 2001). Wang and Reeve (2010) presented an application of the one-line model to shore-parallel breakwater schemes at Sea Palling (Norfolk, UK), and showed strong long-term prediction of shoreline changes. If the field data are abundant, data-driven methods such as the empirical orthogonal function (EOF) method can also be used to investigate, in a qualitative manner, the way the shoreline evolves under the wave and tidal conditions (Miller and Dean, 2007). However, as a non-physical process-based approach, the EOF method presents a number of limitations. For instance, the EOF method requires a data set consistently distributed in space and time, which is always impossible to obtain (Fairley et al., 2009). Also, the EOF method provides a means of discussing the behavior of the studied variable within the sampling period, but results cannot, in principle, be simply extrapolated beyond that period. In the work of Horrillo-Caraballo et al. (2014), extrapolation of temporal EOF components was conducted for prediction of shoreline changes beyond the training period, but with limited success. Alvarez and Pan (2014) found that, in order to reconstruct the morphological variables more accurately, both the spatial and temporal EOF components must be extrapolated.

This study attempted to refine and improve the extrapolation method proposed by Alvarez and Pan (2014), in order to improve the accuracy of prediction using the EOF method. A process-based numerical model, COAST2D, was first run for a certain period of time to produce the full morphological evolution within the computational domain (Pan et al., 2005; Du et al., 2010). EOF analysis was performed for several periods of time with a regular time increment within the sampling period. Spatial EOF components were extrapolated by fitting both linear and exponential functions. Temporal EOF components were also extrapolated. The extrapolated EOF components were then used to reconstruct bathymetric changes. The reconstructed bathymetric changes were compared with the modeled results from the COAST2D model to check the accuracy.

2. EOF method

The EOF method can be used to calculate a set of orthogonal functions (eigenvectors), representing both the spatial and temporal components, which can be used to reconstruct the original data set at any point during the studied period. Each component represents a percentage of the total variation of a given variable (Larson et al., 2003). The set of functions obtained is sorted, so the first couple of functions, including the spatial and temporal components, represents the most significant part of the variation of the variable. The EOF method also guarantees that the number of functions is lower than that in other methods. It can provide the spatial and temporal patterns of variation. These features make the EOF method a simple and objective method for analyzing shoreline evolution.

While a detailed description of the method can be found in Jollife (2002), and an example of EOF analysis of coastal morphological changes can be found in Muñoz-Perez et al. (2001), a brief description is provided here. Let $\boldsymbol{F}$ be an $n \times m$ matrix containing the data of n points along a shoreline during m surveys. Each point represents the position of a given variable. The EOF method requires two series of functions, $X(n,i)$ and $T(m,i)$, to describe the spatial and temporal components of the variable, respectively:

$$d(x=n,t=m)=\sum X(n,i)T(m,i) \tag{1}$$

where $d(x=n,t=m)$ is the variable value at point n and time of m surveys, and i represents the number of components/functions considered. To obtain $X(n,i)$ and $T(m,i)$ for component i, the eigenvalue and vector problem in Eq. (2) have to be solved:

$$\begin{cases}(\boldsymbol{A}-\lambda\boldsymbol{I})X=0 & \boldsymbol{A}=\boldsymbol{F}\boldsymbol{F}^{\mathrm{T}}\\(\boldsymbol{B}-\lambda\boldsymbol{I})T=0 & \boldsymbol{B}=\boldsymbol{F}^{\mathrm{T}}\boldsymbol{F}\end{cases} \tag{2}$$

where λ represents the eigenvalue for the system, and $\boldsymbol{I}$ is the identity matrix. Therefore, by applying the EOF method to prediction of shoreline changes, for instance, it is possible to reproduce the shoreline behavior within the surveyed period using a reduced number of orthogonal functions. However, in order to obtain satisfactory results of long-term prediction of coastal morphological changes using the EOF method, a certain quantity and high quality of field data are required to obtain the functions $X(n,i)$ and $T(m,i)$ at the desired spatial and temporal resolutions. This, however, may not be always available. As an example, Fairley et al. (2009) applied the EOF method to a shore-parallel breakwater scheme at Sea Palling to gain insights into coastal morphological changes at the site using shoreline positions measured with an Argos (video imaging) system. Results showed that the first two couples of the spatial and temporal EOF components only represent 59% and 16% of the total variation of the coastal morphological changes, respectively. When there are insufficient field data available for the coastal scheme to be built, it is difficult to perform EOF analysis, and results will be inaccurate. Therefore, in this study, a process-based numerical model was run in a well-controlled environment to generate sufficient and accurate data for EOF analysis, through which long-term prediction of bathymetric changes could be achieved.

3. COAST2D model

The COAST2D model is a two-dimensional (2D) depth-averaged hydrodynamic and morphodynamic model, which has been well validated during its development and refinement (Pan et al., 2005; Du et al., 2010). The model consists of a number of fully interactive modules, mainly the following: a