Available online at www.sciencedirect.com
SCIENCE DIRECT®
Estuarine, Coastal and Shelf Science 67 (2006) 664–672
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Multigrain sedimentation/erosion model based on cross-shore equilibrium sediment distribution: Application to nourishment design

Fangjun Li*, Chris Dyt, Cedric Griffiths

Predictive Geoscience Group, CSIRO Petroleum, 26 Dick Perry Avenue, Technology Park, Kensington, WA 6151, Australia

Received 10 January 2006; accepted 11 January 2006
Available online 15 March 2006

Abstract

In the light of global warming and sea level rise there are many coastal beaches that suffer from erosion. Beach nourishment has become a common practice to maintain the sediment balance on a shore-face. In this paper, a three-dimensional numerical model for evaluating long-term impact of beach nourishment projects has been developed. The model addresses the longstanding complex issue of coastal morphology and sediment grain size distribution from an unconventional angle, which exploits the strong links between grain size distribution and the prevailing transport direction of each sediment constituent under 'average' wave and storm action. The present model predicts the redistribution of nourished sediment according to the subtle clues implied by equilibrium distribution curves and latest coastal wave transformation theories. After verification against recent field observations in Terschelling, The Netherlands, the model was used to predict long-term effects of different beach nourishment strategies. It was found that: (a) given the source sediment available in Terschelling the tactics of large volume and less frequent implementation are better than otherwise; and (b) from a pure engineering point of view, waterline nourishment outperforms offshore trough nourishment.

The model offers an additional tool for coastal engineers to evaluate the feasibility, effectiveness and the optimization of dumping locations for beach nourishment projects. It is also a useful tool for stratigraphic modelling of shallow-marine sedimentation in conjunction with sea level changes.

Keywords: sediment transport; beach nourishment; numerical model

1. Introduction

Beach replenishment is the most common solution for shore erosion, due to its environmental and economical benefit over traditional hard engineering measures. The location of the sediment dumping area and the composition of grain sizes are extremely important for the success and effectiveness of the whole replenishment project. This paper intends to address this issue based on both practical experience and contemporary coastal sediment transport theory.

Coastal morphological evolution has been investigated by two different approaches, the bottom-up and the top-down. Using the bottom-up approach, with the philosophy that if every detail is right then the whole picture would not be wrong, many sophisticated models for waves, currents, and sediment transport have been developed. Among them some models can couple almost all relevant processes acting in the coastal environment. For example, given a complete set of hydrodynamic conditions these models can predict with great confidence where sediment is deposited at any given time. However, the models do not tell us very much about the equilibrium state of the system. Consequently, many simple linear extrapolations of these short-term formulae and models have failed to predict shoreline evolution on longer timescales.

On the other hand, many people approach the issue from a spatially larger and temporally longer point of view, for instance, timescales of 10^2–10^6 years. Their data set extends from the characteristics of present day sediment to

* Corresponding author.
E-mail address: fangjun.li@csiro.au (F. Li).

0272-7714/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2006.01.006

historical/geological evidences. Very often the puzzle was solved in a top-down manner, e.g. reconstructing the processes from the present observations. In fact the processes that are most significant to short-term change may not be necessarily as significant to long-term evolution. Most of the hydraulics details have little long-term morphological meaning. The main challenge then lies in determining how relatively short-term processes (water motion, sediment motion and sediment balance) lead to observed longer term coastal behaviour and evolutionary sequences, which ultimately yield the preserved morphologies and stratigraphies. A number of successes have been made on identification of the processes from stratigraphic analyses (Masson et al., 2002; Hernández-Molina et al., 2003). A good example is the relationship between shallow-marine deposition and global sea level change (Vail et al., 1977).

The present model approaches the longstanding, complex, issue of coastal morphology and grain size distribution from a new angle. It starts from the study of characteristic aggregation of sediment at discrete locations across the cross-shore profiles. Pioneered by Guillen and Hoekstra (1996), the strong links between grain size distribution and the prevailing transport direction of each sediment constituent under 'average' wave and storm climate are revealed. Guillen and Hoekstra's original model is for two-dimensional profiles, which covers the area from the upper limit of storm waves to the edge of the outermost offshore bar. With the help of the latest field observations in Terschelling, The Netherlands the present work: (a) extends the model to three dimensions by introducing a wave transformation model; and (b) widens the simulation zone to the depth where the seabed sediment is only moved by the maximum storm waves.

2. Equilibrium curve based coastal sediment transport model

In the present model, sediment non-uniformity is generally treated by considering a number of discrete grain classes with representative grain sizes and densities of the solid matter. In principle the bed composition is described by the fractional contribution of each grain class f_{ks} to the volume of solid.

$$f_{ks} = \frac{\mathrm{vol}_{ks}}{\sum_{ks=1}^{n} \mathrm{vol}_{ks}} \tag{1}$$

where f_{ks} is the fraction of the ks(th) grain class by volume; vol_{ks} (m^3) is the volume of sediment of the ks(th) grain fraction; $\sum_{ks=1}^{n} \mathrm{vol}_{ks}$ (m^3) is the total volume of sediment. The sum of all fractions is unity.

The model is designed for wave-dominated shallow-marine sedimentation and beach erosion. The simulation area is divided into square cells. Vertically, each cell contains layered sediment deposits. Each cell's top layer could be 'active'. The active layer forms the reservoir of sediments from which grains can be actively entrained and transported. The thickness of active layer d_{act} is related to the energy level of wave climate. The active layer is assumed to be well mixed by the transport process, so that the grain fractions within the active layer have no vertical structure. Since the active layer interacts with the transport process itself, it can have horizontal and temporal variations. Below the active layer there is the underlying layer. Its sediment composition may vary in all spatial directions, but cannot change directly in time because it is not directly subject to movement. Material can be exchanged between the active layer and the underlying layer through their interface. This exchange is due to time variations of the active layer interface level during deposition or erosion.

At surface, the coastal area is divided into three zones, active zone 1#, active zone 2# and non-active zone, defined in Fig. 1. Active zone 1# includes the entire surf zone for both fair weather and storm weather. It starts from the upper limit of average storm waves effect and ends at the outside edge of the outermost offshore bar. Active zone 2# extends from the offshore boundary of active zone 1# to the maximum distance of sediment dispersion. The remaining area is defined as the non-active zone.

Active zone 1# is characterized by intense turbulence activities and strong sediment exchange in both vertical and horizontal directions. Erosion and deposition oscillate quickly as a result of wave actions. Following Guillen and Hoekstra (1996, 1997), the present model assumes that for each grain size fraction, the cross-shore equilibrium of sediment distribution curve is a steady and characteristic curve. It is independent of the availability of each grain size fraction, and it is only affected by hydrodynamic conditions. The shape of the equilibrium distribution curves depends on the hydrodynamic processes acting in the region. These curves reflect the general time-averaged equilibrium energy dissipation in active zone 1#. The differential behaviour of grain size fractions reveals the selective transport and diffusion processes taking place in active zone 1#.

Compared with active zone 1#, active zone 2# is a weak sediment transport zone, where the rate of sediment transport is small and created by very low frequency extreme weather conditions. The Terschelling field study shows an inverse, onshore fining trend of sediment grain size distribution (see Fig. 2).

For a given simulation area the present multigrain model starts from a wave transformation model (Li et al., 2003), by solving the parabolic version of the mild slope equation. The wave transformation model calculates the representative maximum storm wave propagation over the simulated offshore region to define the wave-breaking line. The offshore boundary of active zone 1# is assumed to be a constant distance outside

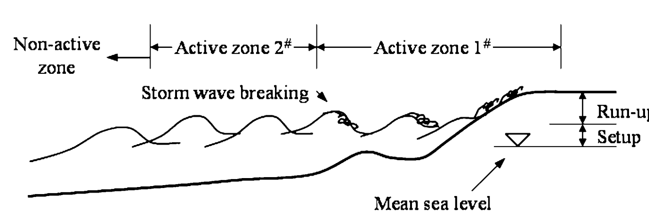

Fig. 1. Definition sketch of coastal zones.