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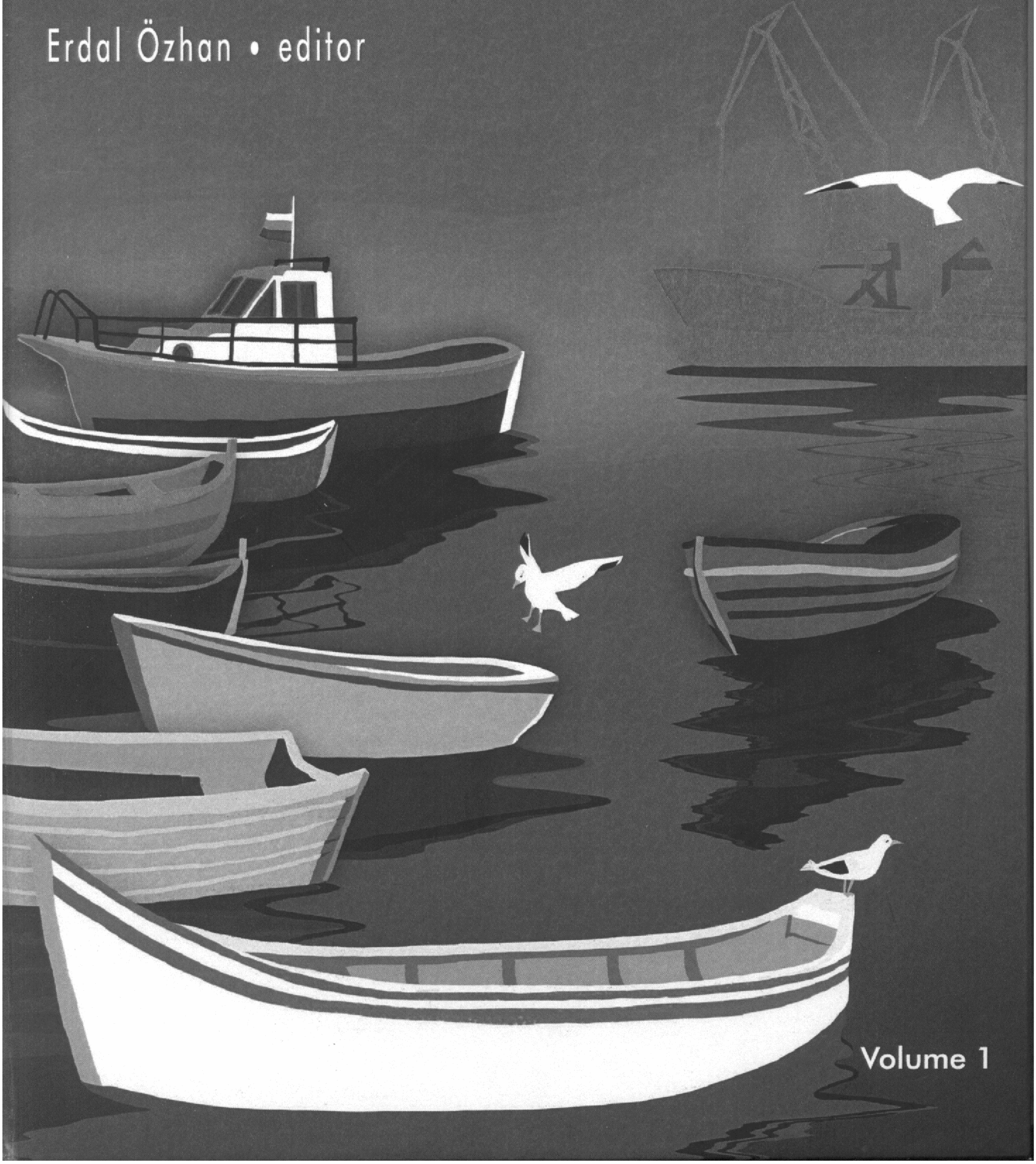
Erdal Özhan • editor



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Numerical Modelling of Shoreline Changes for Yevpatoria, Crimea

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Abstract

This paper describes numerical modelling of Yevpatoria (West coast of Crimean peninsula, the Black Sea) shoreline long term changes utilizing GENEralized SImulating Shoreline change model (GENESIS). The simulation process used the significant wave height and peak wave period obtained by means of the Simulating WAves Nearshore model (SWAN) for Yevpatoria region using JRA wind reanalysis of Japanese Meteorological Agency. The length of modelled sandy shoreline is about 2000 m. The GENESIS model calibration has been performed for period from 2006 to 2010. The long term changes of Yevpatoria shoreline were simulated for available coast protection structures.

Introduction

Yevpatoria is a resort town located on the west coast of Crimea. Shallow coastal zone, shelving shore, lakes with therapeutic mud and wide sandy beaches have determined active development of children's health resort here in the twentieth century.

Wrong coastal management has led to sharp decline of recreational value of the resort:

- Shoreline recession (up to 30 meter at certain locations) (Goryachkin and Kharitonova, 2010);
  - Reduction of total beach area (by 100 000 m^2 from 1986 till 2009);
  - Disappearance of sand beaches in some areas;
- Sharp increase of proportion of limestone debris of varying degree of roundness in the composition of beach material.

Historical changes of Yevpatoria's shoreline are analysed in detail and main reasons of beach recession are shown in (Goryachkin and Dolotov, 2011). In our opinion hydraulic engineering has influenced the shoreline changeability the most. Concrete seawall 1.8 km long was built in the city center in 1968 – 1972, after that beach has completely disappeared in this area. Diffracting pier 200 meters long was then built at Karantinniy cape in 1979. Existing migration of sediments changed and vast sandbank was formed at the east side of the pier. Bypassing has been performed to keep constant depth of 5.4 meters since then. The material withdrawn from the bottom has been removed from Yevpatoria's coastal zone. The shoreline to the west of the sea port pier has started to retreat after that. Beaches of this area of the city are the most problematic now.

Local government have repeatedly initiated research to create and implement reconstruction projects for beaches recovery (Fomin and Ivanov, 2005; Goryachkin et al., 2013), but due to lack of funding, this issue is still not resolved.

The relevance of this work is motivated by the fact that there exists a project of dredging the port of Yevpatoria to the level of -7.2 m with a volume of excavation and sediment transfer of 300,000 m^3 to the west of the aforementioned pier. This knowledge of the characteristics of sediment movement in different situations and calculation of the most favourable location of coast protection structures has both practical and scientific significance.

GENESIS Numerical Model Overview

GENESIS numerical model was developed by Hanson (1987) to simulate long-term shoreline change at coastal engineering projects. The longshore extent of a typical modelled reach can be in the range of 1 to 100 km, and the time frame of a simulation can be in the range of 1 to 100 months. GENESIS modelling system simulates shoreline change produced by spatial and temporal differences in longshore sand transport. Shoreline movement such as produced by beach fills and river sediment discharges can also be represented. The main utility of the modelling system lies in simulating the response of the shoreline to structures sited in the nearshore. Shoreline change produced by cross-shore sediment transport as associated with storms and seasonal variations in wave climate cannot be simulated; such cross-shore processes are assumed to average out over a sufficiently long simulation interval or, in the case of a new project, be dominated by rapid changes in shoreline position from a nonequilibrium to an equilibrium configuration. The model is best suited to situations where there is a systematic trend of long-term change in shoreline position. The dominant cause of shoreline change in the model is spatial change in the longshore sand transport rate along the coast. Cross-shore transport effects such as storm induced erosion and cyclical movement of shoreline position as associated with seasonal variations in wave climate are assumed to cancel over a long simulation period. Cross-shore effects are implicitly included in the model if measured shoreline positions are used in verification of predictions. GENESIS is not applicable to calculating shoreline change in the following situations which involve beach change unrelated to coastal structures, boundary conditions, or spatial differences in wave-induced longshore sand transport: beach change inside inlets or in areas dominated by tidal flow; beach change produced by wind generated currents; storm-induced beach erosion in which cross-shore sediment transport processes are dominant; and scour at structures. Other limitations of the model that we would like to mention are: no wave reflection from structures; no tombolo development (shoreline cannot touch a detached breakwater); no direct provision for changing tide level; basic limitations of shoreline change modelling theory such as assumption that the profile erodes or accretes uniformly over the vertical height from the upper berm down to the depth of closure. The modelling system allows simulation of a wide variety of user-specified offshore wave inputs, initial beach configurations, beach fills, coastal structures such as groins, jetties, detached breakwaters, seawalls, compound structures such as T-shaped, Y-shaped, spur groins, bypassing of sand around and transmission through groins and jetties; diffraction at detached breakwaters, jetties, and groins; offshore input waves of arbitrary height, period, and direction; sand transport due to oblique wave incidence and longshore gradient in height; wave transmission at detached breakwaters.

The shoreline change numerical modelling system is using analytical shoreline change model, which is based on the following standard assumptions (Hanson and Kraus, 1989):

1. The beach profile shape is constant.
2. The shoreward and seaward limits of the profile are constant.
3. Sand is transported alongshore by the action of breaking waves.
4. The detailed structure of the nearshore circulation is ignored.
5. There is a long-term trend in shoreline evolution.

These basic assumptions define a flexible and economical shoreline change simulation model that has been found applicable to a wide range of coastal engineering situations.

Consider a right-handed Cartesian coordinate system in which the y-axis points offshore and the x-axis is oriented parallel to the coast. The Eq.(1) governing shoreline change is formulated by conservation of sand volume (Hanson and Kraus, 1989):

$$\frac{\partial y}{\partial t}+\frac{1}{\left(D_B+D_C\right)}\left(\frac{\partial Q}{\partial x}-q\right)=0, \tag{1}$$

where D_B is berm elevation, D_C is closure depth, both measured from the vertical datum, Q is longshore sand transport rate, q is a line source or sink of sand, which adds or removes a volume of sand per unit width of beach from either the shoreward side or from the offshore side at the rate.

The empirical predictive Eq.(2) for the longshore sand transport rate used in the model is:

$$Q=\left(H^2C_g\right)_b\left(a_1\sin 2\theta_{bs}-a_2\cos\theta_{bs}\frac{\partial H}{\partial x}\right)_b , \tag{2}$$

where H is wave height (m), C_g is wave group velocity given by linear wave theory (m/sec), b is subscript denoting wave breaking condition, Θ_{bs} is angle of breaking waves to the local shoreline.

The nondimensional parameters a_1 and a_2 are given by Eq.(3) and Eq.(4) respectively (Hanson, 1987):

$$a_1=\frac{K_1}{16\left(\rho_s/\rho-1\right)(1-p)\sqrt{1.416^5}} , \tag{3}$$

$$a_2=\frac{K_2}{8\left(\rho_s/\rho-1\right)(1-p)\tan\beta\sqrt{1.416^7}} , \tag{4}$$

where K_1 and K_2 are empirical coefficient, treated as a calibration parameters, ρ_s is density of sand (taken to be $2.65\cdot 10^3$ kg/m^3 for quartz sand), ρ is density of water ($1.03\cdot 10^3$ kg/m^3 for sea water), p is porosity of sand on the bed (taken to be 0.4), $\tan\beta$ is average bottom slope from the shoreline to the depth of active longshore sand transport.

The first term in Eq.(2) corresponds to the Coastal Engineering Research Center (CERC) formula described in the Shore Protection Manual (1984) and accounts for longshore sand transport produced by obliquely incident breaking waves. The second term in Eq.(2) is not part of the CERC formula and is used to describe the effect of another generating mechanism for longshore sand transport, the longshore gradient in breaking wave height $\partial H_b/\partial x$. The contribution arising from the longshore gradient in wave height is usually much smaller than that from oblique wave incidence in an open-coast situation. However, in the vicinity of structures, where diffraction produces a substantial change in breaking wave height over a considerable length of beach, inclusion of the second term provides an improved modeling result accounting for the diffraction current. The coefficients K_1 and K_2 are treated as calibration parameters in the model. Their values are determined by reproducing measured shoreline change and order of magnitude and direction of the longshore sand transport rate (Hanson and Kraus, 1989).

The major portion of alongshore sand movement takes place in the surf zone, the width of which depends on the incident waves, principally the breaking wave height.

The Eq.(1) for shoreline change is obtained based on assumption that the bottom profile maintains its shape moving parallel to itself only. To determine the location of breaking waves alongshore and to calculate the average nearshore bottom slope used in the longshore transport equation, a profile shape must be specified. For this purpose, the equilibrium profile shape deduced by Bruun (1954) and Dean (1977) is used. They demonstrated that the average profile shape for a wide variety of beaches can in general be represented by the simple Eq.(5):

$$D = Ay^{2/3}, \tag{5}$$

where D is the water depth, and A is an empirical scale parameter dependent on the beach grain size (Moore, 1982).

The average nearshore slope for the equilibrium profile defined by Eq.(5) is calculated as the average value of the integral of the slope $\partial D/\partial y$ from 0 to y_{LT}, resulting in Eq.(6):

$$\tan\beta = A(y_{LT})^{-1/3}, \tag{6}$$

where y_{LT} is the width of the littoral zone, extending seaward to the depth D_{LT} is maximum depth of longshore transport (Hanson and Kraus, 1989).

From Eq.(5) one can obtain Eq.(7) for the average slope:

$$\tan\beta = \left(\frac{A^3}{D_{LT}}\right)^{1/2} \tag{7}$$

Hallermeier (1983) has offered an empirical Eq.(8) to estimate D_{LT}:

$$D_{LT} = 2.28 \cdot h_E - 68.5\frac{h_E^2}{gT_E^2}, \tag{8}$$

where h_E is the height of the highest one-tenth waves, T_E is corresponding wave period, and g is the acceleration due to gravity.

Calibration of GENESIS Model Coefficients

The process of shoreline changes simulation with GENESIS must be started with model parameters calibration for the area of interest. Measurements of samples taken at the site show, that value of sand particles effective grain size diameter ($d50$, mm) varies from 0.1 to 0.45 (0.33 was used in simulations), average berm height from mean water level – 1.2 m. The simulation process uses the significant wave height and peak wave period which were obtained by means of the SWAN model (Booij et al., 1999) for Yevpatoria region using JRA wind reanalysis of Japanese Meteorological Agency. This data was then used to calculate depth of closure to be 5 m according to Eq.(8) and calibrate GENESIS model longshore sand transport coefficients K_1 and K_2 by matching Yevpatoria's shoreline change for period from 2006 to 2010 (Fig. 1). The values obtained for K_1 and K_2 are 0.005 and 0.0002 respectively. We assume these numbers to low saturation of longshore sand flow. Visual observations by divers of deficit of sand deposits on the sea bottom in the littoral zone support this assumption.

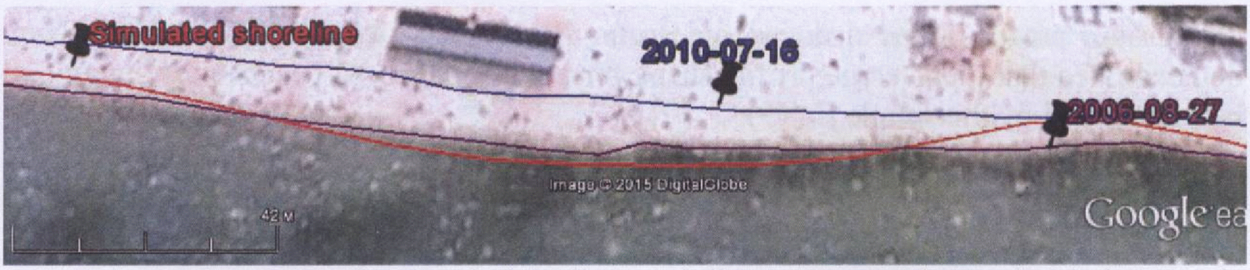

Fig. 1: A part of the simulated shoreline: red line corresponds to simulation result; blue corresponds to reference shoreline for July 16th, 2010; magenta corresponds to initial shoreline for August 27th, 2006.

Modeling of possible coast protection structures

We have identified two areas important for recreation businesses where the shoreline has retreated the most. Effects of coast protection structures such as groins and detached breakwaters have been modeled for the same time period to find a solution for beach recession in the areas of interest.

First simulated structure configuration is comprised of two groins located on the borders of one of selected areas. Results show that calculated shoreline builds up at eastern groin and erodes at western groin much further than actual shoreline for 2010 (Fig. 2). Hence groins can not be chosen as an appropriate coast protection solution.

The second protection structure configuration consists of submerged detached breakwaters. This is modeled by setting detached breakwater transmission coefficients to 0.3. Five detached breakwaters are located in the western area of interest (Fig. 3) and four in the western area (Fig. 4)

Simulation results show that sand is being accumulated in the area protected by detached breakwaters if they are placed about 2-6 meters away from original shoreline for the western area of interest, and 5-15 meters – for the eastern area.

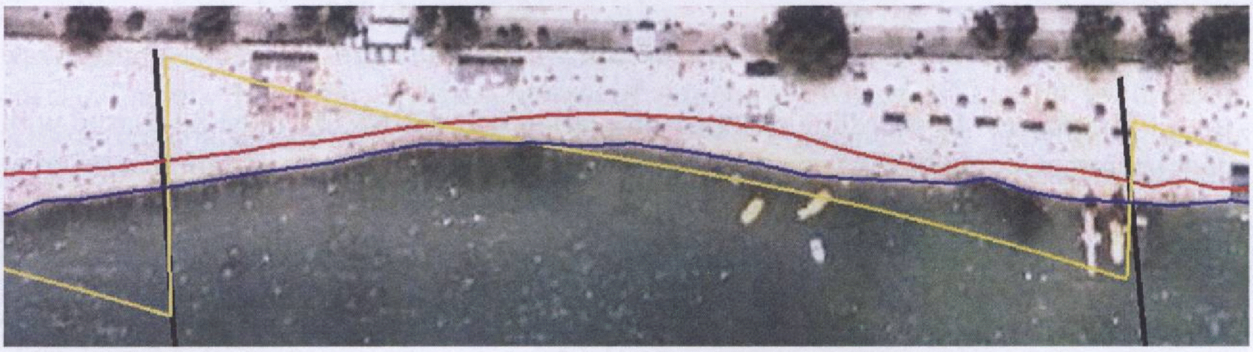

Fig. 2: Simulation of shoreline change with groins as possible coast protection structures for selected areas: yellow line corresponds to calculated shoreline; red corresponds to reference shoreline for July 16th, 2010; blue corresponds to initial shoreline for August 27th, 2006, black lines represent groins.

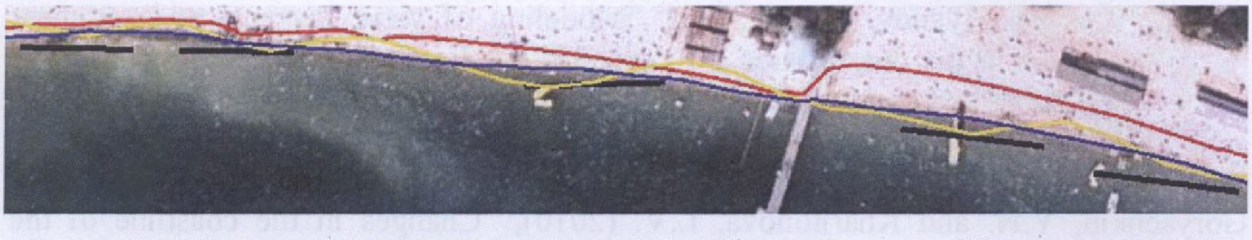

Fig. 3: Simulation of shoreline change with breakwaters as possible coast protection structures for western area: yellow line corresponds to calculated shoreline; red corresponds to reference shoreline for July 16th, 2010; blue corresponds to initial shoreline for August 27th, 2006, black lines represent detached breakwaters.

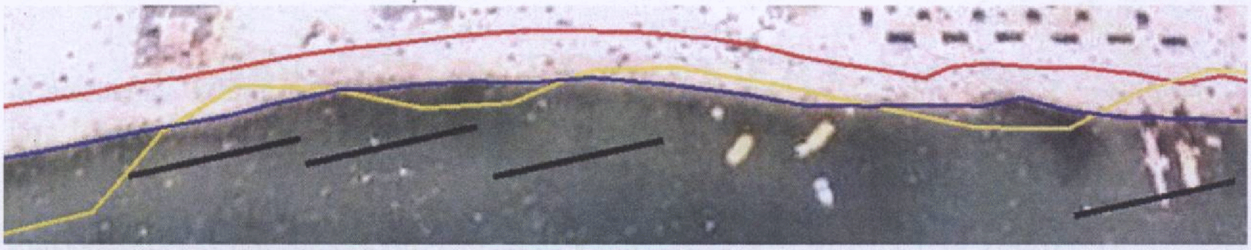

Fig. 4: Simulation of shoreline change with breakwaters as possible coast protection structures for eastern area: yellow line corresponds to calculated shoreline; red corresponds to reference shoreline for July 16th, 2010; blue corresponds to initial shoreline for August 27th, 2006, black lines represent detached breakwaters.

Conclusion

Simulation of shoreline change shows that detached breakwaters are appropriate coast protection structures for two areas of Yevpatoria's shoreline most important for recreation businesses. Sand accumulation is being observed in the areas of interest. Since some of detached breakwaters are located right next to the original shoreline (2-6 meters) beach fills can be performed behind them.

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