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Beach nourishment alternative assessment to constrain cross-shore and longshore sediment transport

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ABSTRACT

A combined field and laboratory investigation was conducted to assess five options for creation of a recreational beach on a steep, armored shoreline on the eastern Black Sea coast. All designs incorporated a beach nourishment project placed between two existing, shore-normal, rubble-mound groins. Alternatives included the placement of a nearshore berm, longshore extensions added to the existing groins, and shore-parallel breakwaters. Several alternatives are reviewed for quantifying the performance of each design, including assessment of the change in shoreline position and project volume retained between the groins. Dimensionless benefits and benefit-cost ratios are quantified, and recommendations made on how to select the best outcome from a benefit-to-cost standpoint when options including hard structures are incorporated into a beach nourishment project design.

1. Introduction

The term beach nourishment came into general use at some point after construction of a project in 1922 at Coney Island, New York, USA [1]. Beach nourishment, sometimes referred to as artificial nourishment or renourishment, beach replenishment, or beach fill, involves the placement of large quantities of sand along or near a shoreline, typically in response to long-term shoreline recession. Project volumes are typically in the range of 10^4–10^6 m^3. A wide beach is at many sites essential for tourism and can help to reduce the potential for property damage caused by storms. Beach nourishment advances the shoreline seaward to reduce vulnerability to storms, enhances recreation, and in some cases provide habitat.

Beach nourishment is widely used for both coastal protection and recreational purposes. For example, the U.S. has more than 200 nourished areas and between the 1920s and 2000s placed about half a billion m^3 of sediments on its beaches [2]. Nourishment is the most popular shore reconstruction strategy in Europe; absent only in Slovenia, Bosnia Herzegovina, and Albania [3]. Hanson et al. [4] estimated that some 28 million m^3 of sediment was being used annually in Europe for nourishment. Cooke et al. [5] identified 130 beaches in Australia that were subject to nourishment projects between 2001 and 2011. They indicated that most Australian projects were small in scale but frequent compared to projects elsewhere.

Eastern Europe has seen fewer projects. Some beach nourishment projects have been completed on Black Sea shorelines; for example, Mamaia beach in Romania received 500,000 m^3 in 1989–1990 [6]. Zenkovich and Schwartz [7] report more than 2 million m^3 of sand placed on Georgian Black Sea beaches over a three-year period. In Turkey beach nourishment is not a common approach for shore protection. Some small projects of less than 5000 m^3 have been completed, but no large projects are described in the literature.

Many nourishment projects do not include the use of any structures to protect or constrain the new beach that results, yet many others do [8]. There are examples of nourishment projects employing shore-normal groins at one or both ends to inhibit the longshore movement of sand [9–11] or a shore-parallel sand berm or breakwater to help reduce wave energy incident on the project [12,13]. In some cases, this sand berm is placed using nourishment-quality sediment, in the hope that in addition to helping protect the project, it will help feed material to it over time. Regardless of other design details, project designers typically attempt to find nourishment sand that is similar to the native beach sand, in size, composition and color characteristics.

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Much of the Turkish Eastern Black Sea coast is devoid of recreation-quality beaches, and is protected by shore-parallel revetments and rubble mound groins that inhibit the longshore motion of sediment. Most of the numerous small harbors in the eastern region have been created artificially with rubble mound structures, and also inhibit longshore sediment transport. In some cases the harbors experience shoaling and then the need for disposal of the dredge spoil arises. This scenario raises the prospect of beach nourishment to provide recreational beaches where there are currently none, and provided the motivation for the study described here. There was a need for an appropriate design for a specific site, and an objective means of deciding which design was more suitable.

This paper considers a site near the eastern end of the Turkish Black Sea coast, with a steep beach backed by a rock revetment, between two existing shore-normal, rubble mound groins. Five design alternatives are considered and evaluated via laboratory experiments guided by field measurements that defined initial and forcing conditions. The design alternatives include one case with the addition of no new structures, one with additions to the existing structures, one with a submerged, stone breakwater, one with a shore-parallel, emergent, stone breakwater and one with a submerged, shore-parallel sand berm. The results are interpreted to define relative performance, and then their benefits and costs are considered to arrive to a recommended alternative. While the specific costs and benefits will vary from one site to another, the methodology presented can be applied at other sites, and the same approach used to investigate and compare design performance, costs, benefits, and benefit-to-cost ratio. Beach nourishment lifetime (or half-life) varies by design, which is reflected in benefit-to-cost ratios.

2. Site description and study approach

The site considered lies within the Turkish province of Rize at the southeastern limit of the Black Sea (Fig. 1). Most of the shoreline was covered by a highway constructed between 1997 and 2007 which was then protected by rubble mound revetments and shore-normal rubble mound groins. Approximately 5% of the coast of the 80 km long province is now composed of beaches. Small harbors, nearly all of them man-made, are found nearly every two km, on average. With the construction of the highway, most of the previously existing beaches were destroyed. In large part to provide recreational opportunities, the Rize Municipality supported an effort to artificially create a beach in the Alipasa coastal region, located 6 km west of the Rize city center. The study described here was motivated by the need for beaches for recreation, with a specific focus on how best to nourish to obtain and retain a small pocket beach between two existing shore-normal, rubble-mound groins, for public recreational use.

A combined field and laboratory approach was chosen to investigate five different design alternatives. The aim of the field component of the study was to define the bathymetry and structural geometry of the candidate site, and the sediment characteristics and their spatial variability. The laboratory study allowed consideration of different structural alternatives under controlled forcing. The aim was not to exactly simulate conditions at the candidate site, or response, but to obtain suitable results to guide selection of the best design alternative and the relative merits of the alternatives.

A numerical modeling approach could have been invoked with the same goals, but this option brings with it other problems. For example, in this study, a coupled wave-hydrodynamics-sediment transport-bathymetric change model would likely be utilized. Multiple wave transformation processes are present here: shoaling, refraction, diffraction, and breaking. Errors in the description of the wave field would propagate into the hydrodynamic model, and then to the sediment transport. The sediment transport occurs via both bedload and suspended load, and in both cases, the quantity of interest is typically the net difference between large positive and large negative quantities. Other errors can be introduced via improper definition or description of (time-dependent) bed friction and turbulence, and through the discretization and solution schemes employed, which lead to approximate solution of the governing equations, which are themselves approximations of the real physical processes. A physical model introduces scaling effects that cause the model results to differ from the full-scale prototype scenario, but eliminates some of these other problems. Considering all of these issues, a physical modeling approach was chosen here.

2.1. *Field data collection*

The plan view of the site as it existed at the inception of the study is shown in Fig. 2. All of the structures shown are of rubble mound construction. The structures to the west form a small fishing harbor and the others were placed to inhibit longshore sediment transport and protect the highway.

A bathymetric survey was conducted that specifically targeted the vicinity of the two groins that would bound the proposed recreational beach. The net transport direction is from west to east in this region, as evidenced by sediment deposition on the west sides of the shore-normal coastal structures, and supported by wave hindcast results [14,15]. For this reason, the survey was extended further to the west than east, relative to the area of interest. It was desired to include any potential impacts of the western fishing harbor on waves and sediment transport. The entire beach, from the top of the revetment fronting the highway (altitude approximately 4 m) to a depth of 9 m, was surveyed, using a combination of boat-based and terrestrial surveying techniques. The choice of maximum survey depth was guided by previous repeated survey work done in the area over a two-year period, which suggested that the depth of closure in the area is 7 m [16].

A Topcon HiPer V real-time kinematic Global Positioning system was deployed on a small boat for positioning during the field survey (Table 1 shows equipment used and measurement uncertainty). A reference station was established near the western fishery harbor to provide position corrections, with elevation tied to Turkey's National Vertical Control Network (TUDKA).

Onshore portions of the beach profiles from the top of the revetment (elevation 4 m) down to sea level (elevation zero) were surveyed using a GPS antenna deployed on a survey pole. Areas from the shoreline (elevation zero) down to depths of ∼1.5 m could not be readily surveyed due to the presence of revetment stones. A 3.2 m long boat with acoustic depth sounder was used to survey between the 1.5 m and 9 m depth contours. A sound velocity profiler was used to record variations in speed of sound over the water column, which were found to be negligible. An averaged sound velocity value was used during the post processing of depth sounder data. A bar check was also done to validate the reported depths before the measurements. The survey was done in a half day in calm conditions.

The bathymetric survey track followed shore-normal transects at 15 m longshore intervals, with simultaneous depth and position data collected. A couple of shore-parallel crossing lines were surveyed to fill in gaps.

The range of mean water level fluctuations is small in the Black Sea. Alpar et al. [17] reported that the difference between the highest and lowest monthly mean sea levels is 19 cm, and Volkov and Landerer [18] reported that the time series of seasonal sea level anomalies averaged over the Black Sea is ±20 cm. Defant [19] noted that the tidal amplitudes are very small (3–9 cm) in the Black Sea,