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Laboratory study and mathematical modeling of a novel marsh shoreline protection technology for sand collection

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ABSTRACT

Erosion along shorelines is a major cause in the conversion of shoreline wetlands to open water bodies. Conventional shoreline protection structures are expensive to construct and may impede environmental exchanges essential for connectivity and functionality. A novel marsh shoreline protection technology, the Wave Suppressor and Sediment Collection (WSSC) system, addresses these issues. Laboratory studies were conducted on three WSSC units to determine the governing parameters of sediment collection efficiency of this technology. The three units had varying open areas and pipe sizes which enabled those parameters to be directly compared. Two types of sands with median particle diameters (d_{50}) of 0.43 and 0.34 mm were used to evaluate the effects of particle size on the collection efficiency of the units. A new mathematical model was developed to predict the sediment collection efficiency using Van Rijn's equation for particle fall velocity, and Ribberink and Al-Salem's equation for sand concentration distribution in a water column. Results showed that the Unit 1, Unit 2 and Unit 3 are capable of collecting sand at 0.30, 0.21 and 0.21 (kg/h) for sand 1, and at 0.39, 0.29, 0.39 (kg/h) for sand 2 respectively. The mathematical model fit the experimental data well and from the model, mass accumulation coefficient (α) alpha was calculated. Mass accumulation coefficients (α) for sand 1 and sand 2 were- 0.94 and 0.97 for Unit 1, 0.63 and 0.70 for Unit 2 and 0.32 and 0.22 for Unit 3 respectively. A sensitivity study of the mathematical model was also performed to determine the governing factors behind the sand collection. The sensitivity study found that water depth, wave height and particle diameter affected the sand collection efficiency the most. The amount of open area on the units, frequency and wavelength were also found to have some effect on collection efficiency.

1. Introduction

Coastal land loss and the conversion of wetlands to open waters are major concerns for many coastal communities [1]. Large portion of marshes and wetlands are turning into open water bodies, especially in the state of Louisiana in the US [2]. Erosion along shorelines plays a major role in the conversion of shoreline wetlands to open waters. Porous breakwaters have earlier been studied as shoreline protection structures in coastal and ocean engineering [3]. Disconnected porous breakwaters have been widely used to protect shorelines from erosion and land loss [4]. Shoreline protection structures can be categorized as shore-parallel (breakwaters) and shore-normal (groins) structures [5]. By reducing the energy of waves, these structures promote sedimentation of littoral material in the protected area behind the structure [6].

Protecting wetland shorelines poses a unique challenge as the aquatic substrate is typically very soft, highly organic, and highly susceptible to erosion. In the marsh environments, many coastal structures are too heavy to be supported on the soft foundation materials. Constructing permanent structures near shorelines interferes with the physical and biological processes along the coast. In addition, hard breakwater structures are costlier than other alternatives that can be easily transported and installed in the site [7–11]. A viable alternative to conventional shoreline protection structures is needed to slow or possibly reverse the trend of coastal erosion. Latest discoveries in this field suggest the use of mild-type structures which partly transmits

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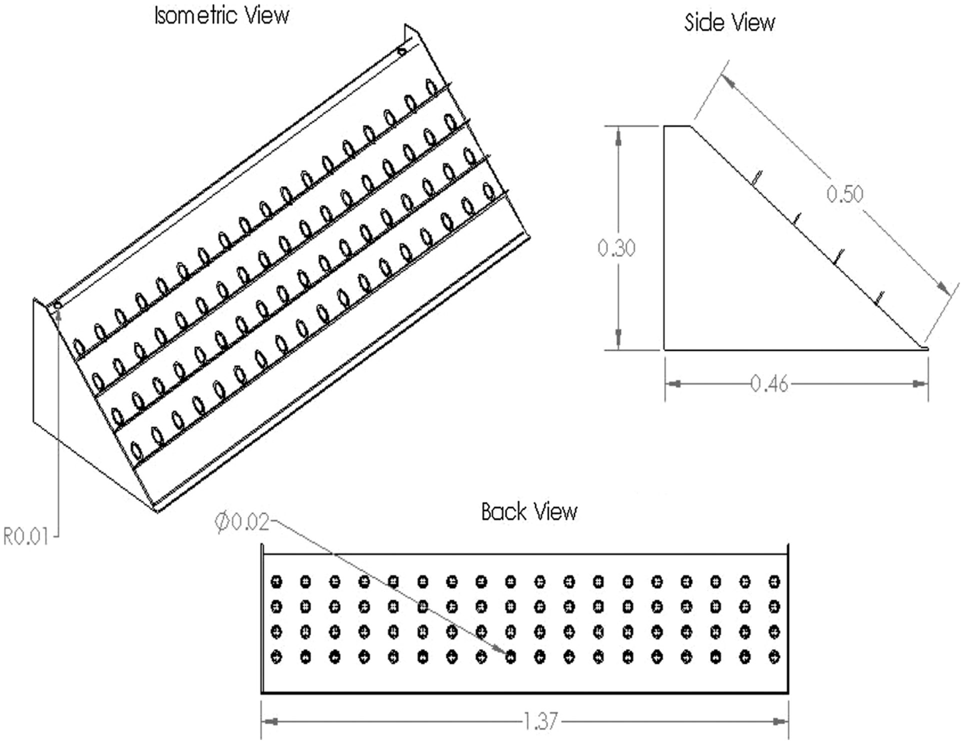

Fig. 1. Dimensions of Unit 1 (1.91 cm Diameter Pipes).

wave through or above them and have better economic and ecological impact [12]. They attenuate the wave energy by locally induced wave diffraction near the coast and provide sediment accumulation behind the structure [13]. Once the waves break on the slopes of the structures the energy is dissipated by turbulent abrasion on the structures [14].

Among different non-rock alternatives, the Wave Suppressor and Sediment Collection (WSSC) system, with an International Patent Publication Number of EP 2486192 B1, works considerably well in Louisiana's wetlands. The wetlands and marshes of Louisiana are low-energy zones with negligible tidal variations. However, because of the shortage of upstream sediment supply from the Mississippi River [15], the one-way loss of loose sediment from the wetlands is causing erosion and land-loss. The WSSC system was invented to tackle this problem and it consists of multiple, self-contained WSSC units attached to one another [16]. The purpose of the WSSC system is to reduce wave action along shorelines, navigation channels, and canals while retaining sediment behind the units. The units are made of High-Density Polyethylene (HDPE) with Manning's coefficients ranging from 0.009 to 0.015 and are hollow, making transport over water easier than that of rock jetties. Once in place, WSSC units can be filled with water or other materials to rest them firmly on the marsh floor where they are anchored in place. McCoy et al. [16] provided a more detailed description of the working principles of the technology with figures. In general, as waves hit the units, much of the wave energy is reflected and the remaining energy carries the water and suspended particles to the back of the units. The pipes integrated into the WSSC units are sloped and check valves are present at the back end of the pipes to prevent back-flow [16].

A major issue faced while designing coastal structures is accurately forecasting the structure's performance [17]. Formulating models and performing field investigations of nearshore sediment transport induced by waves and the accurate prediction of morphological beach response has become more sophisticated in the past few years [18,19]. Many variables affect the wave energy reduction and sediment transport; i.e. breakwater characteristics, sediment contribution, wave properties, and sediment characteristics [20]. Porosity and flow resistance largely affect sediment transport through breakwaters [21]. Shoreline response to a coastal structure must be predicted correctly to avoid undesired erosion in surrounding areas [17]. Accurate models are necessary for the planning and design of coastal structures to avoid undesired negative impacts [22].

Previous study performed on the WSSC technology by McCoy et al. [16] have provided a basic understanding of the units' functionality. The mathematical model developed in the previous study for the silt-clay transport was found to be inapplicable for sand transport. The model developed by McCoy et al. [16] used a constant sediment concentration for silt-clay in the water column. For sand collection study, the concentration is a function of water depth. In addition, McCoy et al. [16] assumed the horizontal flow velocity as a constant in the water column which was a limitation of that model. Hence there was a need to develop a new model to accurately predict sand transport.

The objectives of the sand collection study are to- (a) determine if the units can collect sand, (b) determine the rates at which the units collect sand, (c) compare the sand collection among three units, and (d) determine the efficiency comparison among units based on their geometries. To gain a better understanding of the effect of particle size on the sand collection, it was decided that multiple particle sizes should be tested using each unit. With these results, a new sand collection model could be developed to better predict sand collection by the WSSC units. The sensitivity study was carried out to determine the governing factors behind the sand collection so that the unit designs can be optimized for maximum efficiency.

2. Experiment setup

2.1. WSSC units

Three units were evaluated in the sand collection experiment. Two of these units have approximately equal open area, allowing this parameter to be directly compared. Figs. 1–3 show the three different lab scale models used during the experiments. The main differences between Unit 1, 2 and 3 are the number of pipes connecting the front