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Laboratory study of a novel marsh shoreline protection structure: Wave reduction, silt-clay soil collection, and mathematical modeling

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ABSTRACT

Shoreline erosion along open water bodies and waterways is a major cause in the conversion of wetlands and uplands to open water habitat. Conventional shoreline protective structures are expensive to construct in these environments, and may impede environmental exchanges essential for connectivity and functionality. The structure, Wave Suppression and Sediment Collection (WSSC) System that contains multiple Wave Robber™ units, is an alternative for shoreline protection that maintains environmental connectivity. The primary goals of this study are to evaluate the wave reduction and sediment collection performance of the unit as well as optimize its design. This study showed that the unit reduces 84 to 90% of the wave energy while collecting and retaining fine-grained sediment. A mathematical model fits the sediment collection data reasonably well with average correlation coefficients of about 0.87. Modeling results show that the sediment collection efficiency of the unit for fine-grained sediment is about 14%. Total area of flow through the unit was determined to be more important than the area distributed among the number and size of pipes. The sensitivity study shows that wave height and initial concentration are the most important factors effecting sediment collection.
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1. Introduction

Natural and induced waves cause land loss along edges of wetlands, watercourses, and shorelines. The resulting conversion of wetlands and uplands to open water habitat in coastal areas is an issue of major international and national significance. This conversion has many interrelated sources, but shoreline erosion along open water bodies (bays and estuaries) and waterways (bayous, rivers, canals, and navigation channels) is one of the major causes. Numerous structures have been proposed and used to reduce shoreline erosion, but most are very expensive and restrict the flow of water into shallow-water areas.

The latest shoreline protection designs are mild-type structures (Makris and Memos, 2007) where waves are partly transmitted through or above these permeable structures. The waves are moderately dissipated by breaking on the coarse slopes and/or by turbulent abrasion within those structures (Dickson et al., 1995). There are extensive examples of permeable structures such as porous breakwaters and shoreline protection devices. A porous structure allows waves to broadcast through it by means of energy dissipation (Huang and Chao, 1992). Pilarczyk (2003) showed that mild-type structure's purpose is to reduce the hydraulic loading to a desired level that maintains the dynamic equilibrium of the shoreline.

Mild-type structures lessen wave energy that arrives at the coast, and improve sediment deposition at the shoreline caused by locally induced wave diffraction and near shore movement behind the structure (Turner, 2006). McCormick (1993) identified the need for a predictive method for determining the effectiveness of different structures on shoreline recession. Without a reliable method of predicting shoreline-response, an incorrectly designed or placed shoreline protection device for the wave and site conditions can result in the configuration of an unnecessary tombolo or eroding down drift. Sediment transport after a mild-type structure is affected by many causes, including sediment supply, sediment properties, wave characteristics, coastal region topography, and breakwater configurations (Ming and Chiew, 2000). Further, conventional shoreline protective structures (e.g., terraces, sediment fences, breakwaters, and rip-rap) are expensive to construct in these environments, and may impede environmental exchanges that are essential for connectivity and functionality.

A need exists for structural measures that reduce shoreline and water bottom erosion as well as promote increased sedimentation so that impacts to coastal shorelines are controlled. Pierce Industries, LLC, of Cut Off, LA, invented a structure called modular shoreline protection/sediment retention system (Wave Robber™) as an alternative to conventional measures. This device is patent pending with the

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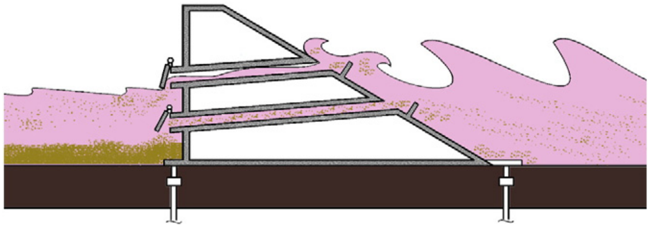

Fig. 1. Wave Robber™ mechanism in wave reduction and sediment collection.

International Patent Publication number of W02011/044556a. Fig. 1. shows the sediment collection and wave energy suppression mechanisms of the structure. The pipe openings within the unit provide a path for the water and sediment to travel. As the wave hits the device, a majority of the wave is reflected, while the remaining energy forces water through the pipes. A check valve prevents backflow through the pipe. Suspended sediments trapped behind the unit tend to settle in the more shallow water when provided sufficient retention time. Trapped water is allowed to return to the water body over weirs spaced occasionally between units.

Pre-fabricated, self-contained, floatable modular construction of the units allows for easy delivery and installation, even in remote shallow-water environments, as well as potential removal and re-use. One way the structure reduces or eliminates the need for heavy equipment, which can destroy natural habitat in shallow water, is the hollow cavity, which is used to help stabilize and reduce the weight, inside the structure, which enables the device to be filled with water. Along with the water, an engineered anchoring system can be installed to ensure stability. The units within the structure are joined together with an occasional weir to allow trapped water to return, maintaining ecological and hydrologic connectivity, while capturing suspended sediment from tidal wave action, serving as shoreline protection along navigation channels and canals, and being used in lieu of earthen dikes for sediment retention. These features make this system unique. If proven successful, this device could work with or replace breakwaters and jetties in many different soil conditions. Fig. 2. shows the marsh protection structure with units and weir.

The initial test showed the system has extraordinary potential for increasing sedimentation and reducing erosion in open water areas or along shorelines. Extensive additional tests are necessary to support its implementation. The primary goals of this study were to quantify the structure's performance in terms of wave height reduction and sediment collection. One important aspect is to optimize the number and diameter of pipes that allow for optimum wave height reduction and sediment collection. In this study, two units with different pipe numbers and diameters were selected. The two units have relatively the same area of pipe openings allowing for direct comparison of the performance of the two designs. The laboratory testing was used to support mathematical analyses of these devices. Mathematical modeling was used to determine the most sensitive variables governing sediment collection.

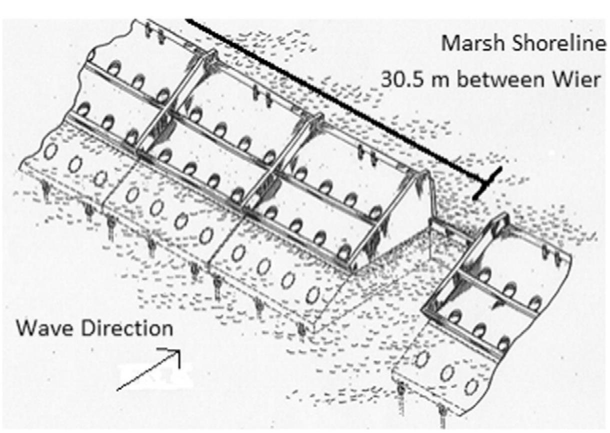

Fig. 2. The marsh protection structure with weirs (Pierce Industries, LLC).

2. Experiment and equipment setup

2.1. Wave tank and device setup

All laboratory tests were conducted in a 3.81 m long, 1.83 m wide, and 0.508 m deep wave tank with a smooth floor. Fig. 3. shows the wave tank setup and details the test unit and wave sensor locations, all dimensions are in SI units. A sealed 0.15 m wide, 0.15 m tall weir was used behind a 0.305 m tall sheet pile on the side of the unit (only used during sediment experiments) angled toward the unit to deflect any waves away from the weir. This kept the sediment transfer over the weir to a minimum. The laboratory units were sealed with Plumbers' Putty™ to prevent water and sediment from infiltrating between the unit and the wave tank's floor. This step was taken to insure that the reduced wave energy, and sediment collected behind the unit is transferred through the pipes of the unit. The back of the units were placed 0.60 m away from the back of the wave tank.

Two different laboratory-scale units used for the experiments are shown in Figs. 4 and 5. The laboratory-scale units have a different diameter and number of pipes, but with similar cross-sectional pipe area of 0.02 m^2; Unit 1 contains 72, 1.91 cm diameter pipes while the Unit 2 contains 10, 5.08 cm diameter pipes. All pipes are on a 1° slope from the front to the back of the unit.

Wave heights were measured using the Sea Gauge Wave and Tide Recorder (SBE 26plus, Sea-Bird Electronics, Inc.). The Sea Gauge Wave and Tide Recorder measured the wave pressure above the sensor, which was then converted to wave height using $H_{rms} \cong 2\sqrt{2var\{\gamma\}}$. Soil used in the sediment collection study is an organic silty-clay material from Cut Off, Louisiana with a specific gravity of 2.68; liquid limit of 47.53; and a plasticity index of 1.95, which is classified as A-7-5 by ASSHTO and OH by USCS (Das, 2009).

2.2. Wave reduction

Wave height reduction experiments were conducted using three different water depths [0.15, 0.19, and 0.23 m]. Experiments at each water depth were conducted twice for the two different units. Each experiment was operated continuously for 90 min. The wave and tide recorder measured wave properties of the area front of the unit for the first 45 min, and was then moved behind the unit for the last 45 min. Experiments for each of the three different water depths were completed before changing the unit. The same sequence was then repeated for the second unit. Wave heights in front and behind the unit were compared to calculate the wave reduction.

2.3. Validation of velocity

Velocity measurements were taken using an Acoustic Doppler Velocimeter (SonTek). This ADV takes 3-D velocity measurements at a sample volume 10 cm in front of the sensor. Experimental procedure used was similar to that described by other authors (Das et al., 2015; Precht and Hauttel, 2004). The sensor was installed above the wave tank on an adjustable wooden and metal stand, allowing for stability and reliable placement. Sample times up to 7 min were used in this experiment at a sampling frequency of 25 Hz. Velocity measurements were taken at a water depth of 19.1 cm. Sampling location was located in the center of the tank, 177.8 cm from the paddle, which was very close to the unit. The velocities were measured at two heights (7.6, and 11.4 cm), corresponding to the heights of the two rows of pipes of the unit. Three velocity tests were run at each height. After data acquisition, data were filtered for correlation of over 70% and Sound to Noise Ratio (SNR) over 15. Mean velocity at each height was then determined.

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