Experimental Study on Shoreline Erosion Using the EM2 Geomodel

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Abstract:

The Texas coastline is exposed to the dynamic zone of current convergence. Storm surge caused by hurricanes and tropical storms can remove large quantities of sand from the shoreline, resulting in eroding vast areas of land and destroying property. The study objective is to investigate the possible shoreline protection solutions. A schematic shoreline model using the Em2 Geomodel was developed to simulate erosion caused by Hurricane Ike (HDR Project No. 166742 report) with the average erosion rate as 60 ft /day, i.e. 2.5 inches every 5 minutes. A series of experiments were set up to reach 2.5 inch / 5 minutes with an equivalent shoreline slope 2% as the field geometry under the wave condition generated by manually pushing a wood block. Three common shoreline erosion control measures: lining the shoreline with rocks (A), with vegetation (B), and the implementation of jetties (C) were applied. The experiment results demonstrate that method (A) does not work as well as anticipated, while method (B) and (C) can reduce 50% of the erosion. A wave generator has been designed to control wave motion and an empirical total longshore sediment transport equation has been determined for the wave generator under different water depth, wave conditions, and slopes of the beach. Three erosion control measures have been tested under the same wave condition using wave generator, the results also indicate method (B) and (C) can reduce the erosion effectively, while the method (A) does not reduce the erosion.

Keywords: Texas coastline; Wave breaking; Longshore transport rate; EM2 Geomodel.

1. Introduction

Coastal erosion is caused by the action of waves and currents and reshapes the shoreline by transport the sediment from one place to another. With the sea level rise and storm frequency and severity increase, the erosion potential has been dramatic increased in recent years (Morton et al., 2004, Brown and McLachlan, 2002). The Texas coastline is exposed to the dynamic zone of current convergence, combined with predominately southeasterly winds. The coastal erosion rate in Texas is about 2.3 feet per year, some of the highest in the country reported by Texas General Land Office. Storm surge caused by hurricanes and tropical storms can temporarily remove large quantities of sand from the shoreline and deposited offshore resulting in eroding vast areas of land and destroying property. Hurricane Allen in 1980 caused a substantial amount of erosion to a section of the Highway 87 along the shoreline as shown in Figure 1. This part of the highway is about 20 miles long and is located between Sea Rim State Park and High Island, Texas. With the erosion rate about 5 feet per year (HDR Project No. 166742 report), it is the major problem for rebuilding the highway. Previous studies have conducted a field surveying and a series of laboratory tests including specific gravity, sieve analysis, liquid limit, plastic limit, hydrometer analysis and Emerson Aggregate Tests. The soil characterization was applied to assist in physical modeling of the beach profile response to storm surges. The objective of the study is to develop a small-scale coastal physical process model with 0.5 m coastal shoreline similar to the field in the closed area in Figure 1 using the Em2 Geomodel. The experiment is designed to simulate the beach profile response to wave and storm surges caused by hurricanes and tropical storms under different erosion control measures. The results provide fundamental idea to facilitate the restoration of Highway 87 between Sea Rim State Park and High Island.

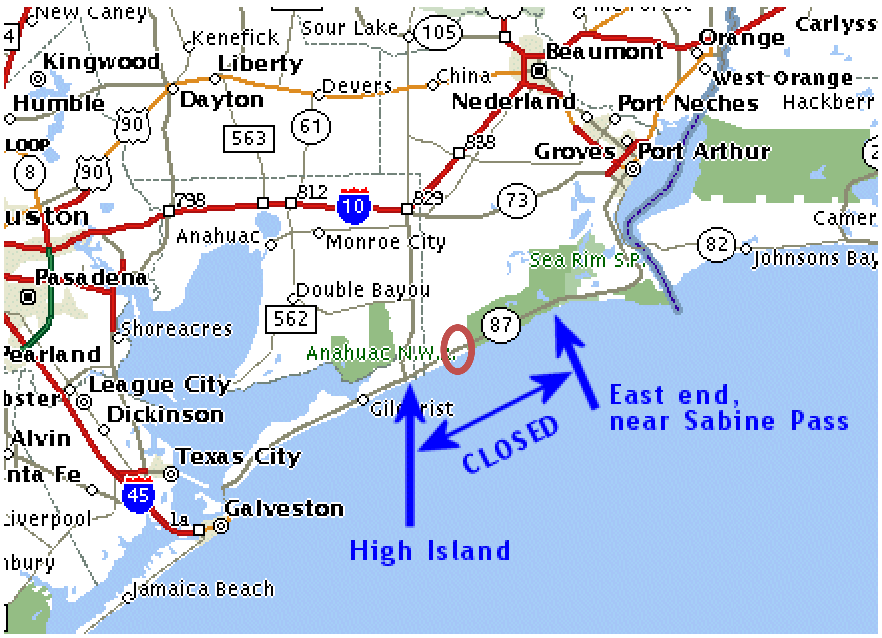

Figure 1: Map for Highway 87 restoration site.

It is known that wave is the primary cause of coastal erosion. Wave speed, the length of fetch and the length of time that the wind has been blowing are three factors to determine the wave energy. Such data can be found from the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service website. The hardness of sea-facing rock and the configuration of the seafloor can have an important influence on the rate of beach erosion (USGS, 2009). The previous study (Zaloom et al., 2003) showed that the thickness of surface sand layer ranges from 0 to 0.9 m (3 ft) depending on the location and its distance to the seawater. The surface sand was classified as poorly graded sand (SP) with mean grain size ranging from 0.17mm to 1.7 mm, which is a great highway subgrade material, as per AASHTO system. The field log and boring logs showed a layer of clayey sand and sandy clay ranges from 0 to 1.20 m (4 ft), following with a very soft to stiff clay deposit, which were classified as lean clay (CL). Some of the clay samples indicates there are layers of swelling, non-slaking and indispersive clay at depth about 1.8 m to 5.5 m (6 ft. to 18 ft) below the ground surface supported by dispersive clay layers. The action of wave/current can broke the indispersive clay layers into pieces.

Options to protect coastal erosion are soft and hard alternatives. The soft erosion control is used non-structural measures such as artificially replanting mangroves. Hard erosion solution, on the other hand, can control the erosion immediately to stable the shoreline. Implementing coastal protection structure is a complex task because of a lot of constraints and conflicts (Tamin et al., 2011). Revetment, sand-filled geocontainer and bamboo fencing are three hard structures used by Thailand and indicated reasonable results to prevent coastal erosion (Saengsupavanich, 2013). Therefore, wave characteristics, soils and structure of the soils, and erosion control measures are basic variables for design the experimental study.

2. Methodology

The physical modeling aspect was run to test proof-of-concept ideas regarding the role of wave action, shoreline slopes, there potential erosion control methods for reducing the erosion rate. Experiments were carried out in EM2 Geomodel to simulate the coastal erosion processes under different conditions. The EM2 Geomodel is a complex modeling system sharing many of the variables and behaviors of real world waterbodies. These variables can be precisely controlled, making it an especially powerful tool. The special media particle sizes are between 0.4 mm and 2.0 mm with a density of 1.6, about 60% the density of quartz sand, which demonstrates physical processes with impressive accuracy on compressed scales of space and time. Its range of colors allows for easy view of sediment transport processes. The EM2 with dimension of 0.83 × 1.96 × 0.13 m (33 × 77 × 5 inches) is capable of obtaining slopes up to 8% and can run as a closed-loop sediment and water recirculating flume with flows up to 250 ml/s.

2.1 S**chematic shoreline erosion model of Hurricane Ike**

A field survey has been conducted in the red circle range on Figure 1 before to design the physical model. A 1 to 10 dimensional scale physical model was designed to simulate the 5 m shoreline on field. The first step of the experiment was to test the erosion rate under the wave action similar to hurricane Ike using EM2 Geomodel. According to the HDR Project No. 166742 report: “beach and shoreline changes along the upper Texas coast: recovery from Hurricane Ike”, the average shoreline impact of Ike from Sabine Pass to High Island was 180 feet with peak erosion over 300 feet. The average erosion rate is about 60 ft / day, i.e., 2.5 in every 5 minutes. To character this wave action, a series of experiments were set up to reach the rate close to 2.5 inch every 5 minutes with an equivalent shoreline slope 2% to match the field geometry. The special media particle sizes is in the same range as the sand in the field. This set of experimental runs served as the base for the erosion control methods. The erosion rate was measured using rulers placed along the length of the shoreline.

The procedure for each series of experiments is as follows:

1. An equivalent shoreline 2% was set using the mixed special media.
2. The desired wave motion is obtained using a 4 inch × 1 inch × 6 inch board and manually moving it up and down for 5 minutes.
3. The erosion was videotaped and the shoreline change measured at the end of each trial.
4. Video was used to visually monitor and document the experiments, with special attention paid to erosion near the boundaries.

5. After all data have been collected for a given prevention method, the EM2 Geomodel was cleared and a new prevention method was then added.

The first series tests were for the beach erosion with no prevention techniques. These simulate normal erosion during the Hurricane Ike. The second series test involved the placing of rocks onto the simulated coast. The rocks were placed in a straight line on the right side of the coast, while they were placed in a staggered formation on the left side of the coast (Figure 5). The third series test involved the placing of simulated vegetation throughout the coastline (Figure 6). There was no particular pattern used for this experiment, but it simulated whether or not vegetation can keep the sand from eroding away by acting as a holder for the sand. The implementation of jetties were tested at the end.

2.2 Wave generator development

In order to quality the wave character, a wave generator (Figure 2) has been designed for EM2 Geomodel and the setup procedure are documented as:

1. Adjust the tray to minimal allowable percent slope by moving the support legs to the farthest ends of the tray without impacting stability.
2. Measure and record the slope of the tray.
3. Place Wave Generator in EM2 River Model at the low end of the tray.
4. Place clamps under the lip of the tray and tighten wing nuts only until snug. Please do not over-tightening to avoid damaging the lip of the tray.
5. Connect motor to motor driver.
    a. Black → A+
    b. Green → A-
    c. Red → B+
    d. Blue → B-
6. Connect Motor Driver to Motor Controller to ensure both Controller and Driver are connected to 12V – 2A power supply.
7. Remove aluminum handle from tray plug by removing the screws with an Allen-key.
8. Insert plug until it contacts the upper plate of the wave generator.
9. Shape the sand in the tray to a uniform slope within the tray.
    a. Leave roughly 6 inches gap between the sand and wave generator.
    b. 2% ~ 6% slope relative to tray can be modeled.
    c. Add percent slope of tray to relative slope to count the initial slope of the beach.
10. Fill tray with approximately 20 gals (DO NOT EXCEED 27 gals) of water.
11. Turn on the power supply for the Motor Controller and Diver.
12. Adjust Hertz on the Motor Controller.
    a. Motor Controller increases or decreases RPMs
    b. NEVER EXCEED A READOUT OF 600 ON THE MOTOR CONTROLLER
13. Press the PLAY button on the Motor Controller
    a. If the motor is NOT turning in a counterclockwise rotation press the FORWARD/BACKWARD button.
    b. Counterclockwise rotation produces smoother operation and less motor stress.

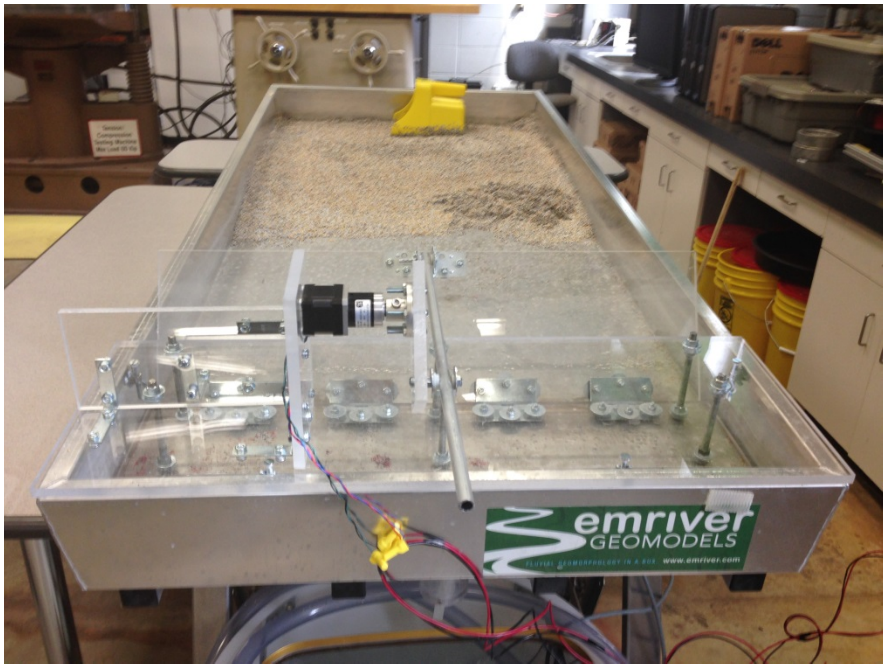

Figure 2: Wave Generator.

2.3 Empirical total longshore sediment transport equation for EM2 Geomodel

The widely utilized CERC formula (SPM 1984) for estimating the potential longshore sand transport rate is based on the assumption that the total longshore sediment transport is proportional to the longshore component of energy flux in the surf zone as in equation (1):

$$Q_{lst} = \frac{\rho K \sqrt{g/\gamma_b}}{16(\rho_s - \rho)(1-a)} H_{s,b}^{2.5} \sin(2\theta_b) \qquad (1)$$

$Where: Q_{lst} = Longshore\ Transport\ Rate\ \left(\frac{volume}{time}\right)$

$K = empirical\ coefficient$

$\rho = denisty\ of\ water\ (\frac{1000kg}{m^3})$

$\rho_s = density\ of\ sand\ (\frac{1550kg}{m^3})$

$a = porosity\ of\ sand\ (\cong 0.4)$

$\gamma_b = breaker\ index\ \left(= {H_{s,b}}/{h_b}\right)$

$H_{s,b} = significant\ wave\ height\ at\ breaking$

$h_b = calm\ water\ depth\ at\ location\ of\ wave\ break$

$\theta_b = angle\ of\ wave\ at\ breaking.$

Based on the wave information reported by US Army Corps of Engineers, the typical wave in the study area has average wave height 2.7 meter, wave period 9 second and wave angle 180 degree. The wave speed can be estimated as 4.28 m/s (Schenck, 1975). The experiment for total longshore sediment transport using EM2 has been conducted with the wave generator. Each trial was run for an hour at a Motor Controller reading of 408 with the wave speed 0.2 m/s, wave height 2 cm, and wave period 3 seconds. The geometrical scale is 1: 65 between the model and prototypal. The wave height at break (H_b) and water depth (h_b) are recorded. The absolute initial percent slope (S_0) was compared to the average absolute resultant slope (S_{AVG}) of the sand. A series of the width and length along shoreline are measured from the point of the wave break to the further reach of the wave on the sand after the water drained. The resultant slope was calculated using average the depth divided by averaged length. Trials which produced excessive non-uniform morphology were discarded. The area of the change (Q_{lst}) was calculated as a triangular shape resulting in a transportation rate for 1 inch width of the tray. With the measurement, we combined $K = k\sin(2\theta_b)$ in equation (1) to investigate the relationship between K to the other variables. The K-Value (Table 1) for each trial was solved by using Excel Solver and plotted against the initial percent slope (refer to the level plane) in Figure 3. The calculated K is function of the beach slopes. The more interesting is the K in the experiments is a function of the initial slope. Therefore, the empirical total longshore sediment transport equation for EM2 Geomodel:

$$Q_{lst} = \frac{\rho K}{16(\rho_s - \rho)(1-a)} H_{s,b}^{2.5} 45.847 {S_0}^{2.4513} \quad (2)$$

Please note, longshore transport rate also change with the time and equation (2) only estimates the transport rate at one hour.

Table 1: Experiment Results for K value per 1 inch shoreline

Trial	H_b (in)	h_b (in)	γ_b	S_0	Q_{lst} (in^3/hr/in)	K
1	0.750	0.800	0.938	8.26%	5.47	0.097
2	0.813	0.800	1.016	11.40%	13.58	0.206
3	0.787	1.500	0.525	8.35%	8.85	0.105
4	0.669	1.000	0.669	9.83%	8.99	0.180
5	0.945	1.281	0.737	7.81%	9.77	0.087

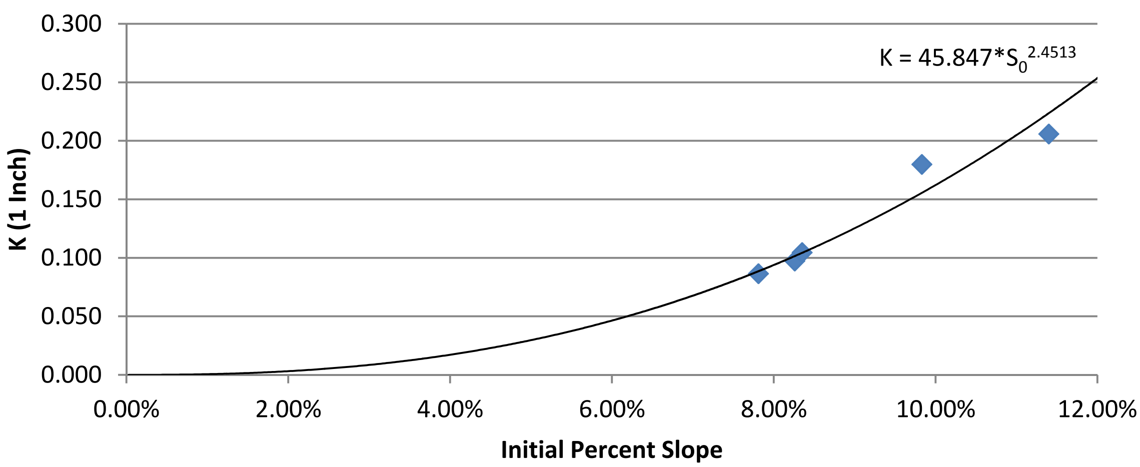

Figure 3: Fitted K for Sedimentation Rate along shoreline.

3. **Results**

3.1 Results for Schematic shoreline erosion model

The shoreline changes before and after the erosion are shown in Figure 4 (no control), Figure 5 (rock prevention), Figure 6 (vegetation prevention), and Figure 7 (jetty prevention). Figure 5 showed the rocks did not prevent much erosion, and actually made the erosion worse than it was in the first experiment. The straight line of rocks was able to hold back more erosion than the staggered. The reason is the straight line rocks acted more as a barrier to prevent the water from passing through it, while the staggered rocks allowed the water to pass around each rock and further erodes soil. Figure 6 indicated that using vegetation works far better than rocks as an erosion prevention method. As opposed to the rocks, which displaced a large amount of sand, the plants used the sand to hold itself in place and the branches of the vegetation acted as a barrier to make the vegetation a better alternative. Figure 7 showed that rocks were stacked from on the shore out into the water in order to break the wave before it hit the shore. Out of all experiments, it was proved to be the most effective. Instead of trying to prevent erosion at the shore, the jetty disrupts waves, decreasing their amount impact at the shore. The erosion at the jetty had ⅓ to ½ the amount of erosion as with no erosion prevention methods. On the other hand, the edges had the same amount of erosion as with the original experiment, about 3 inches. It means more jetties is required along the shoreline.

Figure 4: Before and after shoreline change without Erosion Preventatives

Figure 5: Before and after Using Rocks as Erosion Preventatives

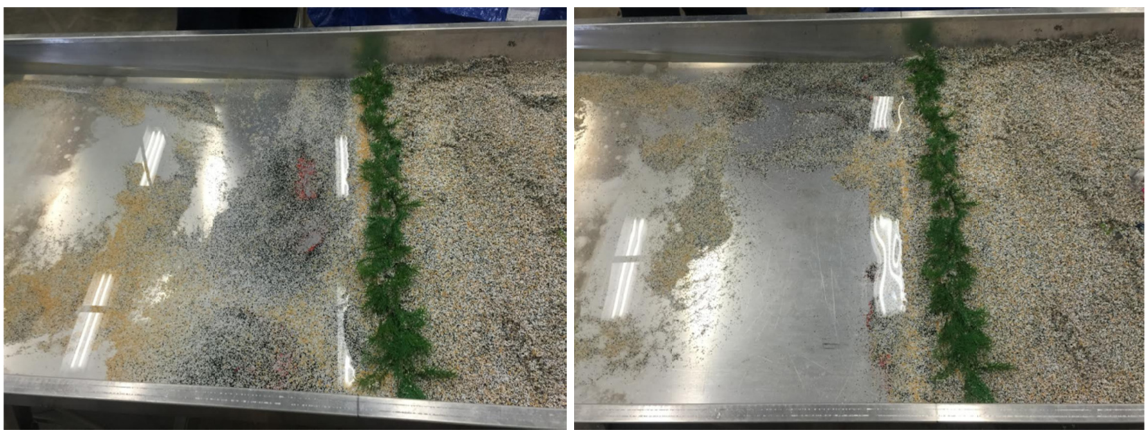

Figure 6: Before and after using Vegetation as Erosion Preventative

Figure 7: Before and After Test Using a Jetty as an Erosion Preventative

Table 2 Results from Experiments Run with and without Erosion Prevention Methods

Series	Erosion Length (inch) in 5 minutes				
	No control	Straight rock	Staggered rock	vegetation	jetty
1	2.75	3.00	3.125	1.375	1.10
2	2.5	2.88	2.98	1.50	0.80
3	2.78	2.6	2.75	1.10	1.20
4	2.81	2.75	2.90	1.20	1.23
5	2.63	3.10	3.15	1.30	1.50
Average	2.70	2.98	2.87	1.30	1.17

Table 2 shows results from the experiments without the control and with four different controls. The erosion length refers to the average length from the start of the shoreline to the shoreline after the experiment. It demonstrates using rocks to prevent erosion didn't work as well as anticipated, staggering the rocks working worse than having them in a straight line. However, the vegetation and the jetty are proved to be incredibly effective because both of which drastically decreased erosion. The most plausible to use would be placing jetties every few hundred feet from each other. Jetties not only eliminate the need for plant life on the beach, it also provides a practical use as a fishing spot for tourists.

3.2 Results for shoreline erosion model using wave generator

The experiments to compare the erosion control methods have been conducted with the wave generate using Motor Controller reading of 398. The wave period is averaged as 3.12 seconds. A series of the width and length along shoreline are measured to make sure every run has the same of beach slope. After half an hour, a series of the width and length from the point of the wave break to the further reach of the wave on the sand have been measured. The total volume of the sand were calculated by summing the measured small cubic volume. Trials which produced excessive non-uniform morphology were discarded. With 10.78% of the initial slope, $H_b = 0.55$ inch and h_b=1.35 inch and K estimated in equation (2), the total half hour erosion rate per unit width without erosion prevention is 3.8 in ^{3}, which is about 10% higher than the measurement (3.4 in ^{3}). The erosion rate per unit width in half hour for the shoreline with rocks, vegetation, and jetties are 3.74 in ^{3}, 3.06 in ^{3} and 2.23 in ^{3}, respectively. The results for rocks and jetties are similar with the schematic model, however, the vegetation in this setup is not as good as the schematic model. The reason is the location for planting the vegetation is too close to the shoreline. The ongoing experiments are for different ordination of the shoreline and the different soils.

4. Conclusion

The study demonstrates two sets of the experiments using Em2 Geomodel to investigate the possible shoreline protection solutions. A wave generator has been designed to control wave motion and an empirical total longshore sediment transport equation has been determined for the wave generator under different water depth, wave conditions, and slopes of the beach. A schematic shoreline model and shoreline erosion model using wave generator were developed to simulate erosion. Three common shoreline erosion control measures, lining the shoreline with rocks (A), with vegetation (B), and the implementation of jetties (C) were applied. Both setup experiment results demonstrate that method (A) does not work as well as anticipated, while method (B) and (C) can control the erosion. However, the method (B) in the shoreline transport model does not show the significant improvement due to the location of the vegetation.

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