Dike and Adjustable Shutter for Strom Surge Coastal Protection in the Galveston Bay

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Abstract

Over the past 150 years, Galveston bay has had storm surges destroying the coastal regions. In this study various sizes of earth dikes, adjustable shutters and combined configurations against storm surges were investigated using the finite element method. Adjustable shutters are made of non-corroding piezoelectric materials buried in the ground and raised to various heights based on the storm surge. The storm surge wave heights and wave velocities were determined for various categories of simulated hurricanes Ike in the Galveston bay using ADCIRC and SMS software. The adjustable shutters and combined configurations performed well compared to the earth dikes. Also, simulated physical model studies performed in Europe on the durability of the earth dikes was reviewed. The performance of the earth dikes, adjustable shutters and combined configuration were compared based on the maximum stresses and deflections induced in the protection systems due to various sizes of storm surges.

Introduction

In Texas, Galveston bay has had the height number of hurricanes (http://hurricanes.egr.uh.edu). Galveston, Houston ship channel with the port of Houston are vital for the state of Texas and for the United State government. In fact, based on the Bay Area Houston Economic Partnership report, about 46 percent of the U.S. aviation fuel, 20 percent of the nation's gasoline supply and 40 percent of chemical-feed stocks are made in the Galveston Coast area. To prevent Galveston coast against a potential more devastating storm surge, different types of barriers are being proposed.

Hurricane Ike developed from a tropical wave west of Cape Verde on September 1st and strengthened to a peak intensity as a Category 4 hurricane, due to maximum wind speed (145 mph or 230 km/h). It happened over the open waters of the central Atlantic on September 4th. Several fluctuations in strength occurred before Ike made landfall on eastern Cuba on September 8th. The hurricane weakened prior to continuing into the Gulf of Mexico, and increased its intensity by the time of its final landfall on Galveston, Texas on September 13th. Ike continued to track across the United States and into Canada, causing considerable damage, before dissipating two days later.

A finite element model named Advanced Circulation (ADCIRC) for storm surge was developed for better estimation of hurricane storm surges (Luettich and Westerink, 2004). The advantage of utilizing ADCIRC is its ability to map intricate shoreline and the corresponding topography needed to resolve complex fluid dynamics (Desback et al, 2010). ADCIRC unstructured grid allows modeling complex coastal regions at fine spatial scale (Chu et al, 2010).

At present, there are only a handful of European countries that manage or have constructed large sea-resistant storm flood surge barriers. These countries include United Kingdom, Netherlands, Italy and Russia. Especially now when climate change and sea level rise are recognized facts that should be taken into account (Coastal Portal, 2010). Wave overtopping reduction has been the topic of many research projects throughout the years. Dikes (De Rouck, 2012), Storm walls (Van Doorslaer et al., 2010a), parapets (Van Doorslaer et al. 2010b), stilling wave basins (Geeraerts et al., 2006) and other constructions have been studied under certain geometrical and hydraulic boundary conditions.

Saffir–Simpson hurricane wind scale

Earlier versions of this scale (Simpson hurricane scale) incorporated central pressure and storm surge as components of the categories. The central pressure was used during the 1970s and 1980s as a proxy for the winds as accurate wind speed intensity measurement from aircraft reconnaissance were not routinely available for hurricanes until 1990

(Sheets, 1990). Storm surge was also quantified by category in the earliest published versions of the scale dating back to 1972 (National Hurricane Operations Plan, 1972). However, hurricane size (extent of hurricane-force winds), local bathymetry (depth of near-shore waters), topography, the hurricane's forward speed and angle to the coast also affect the surge that is produced (Jelesnianski, 1972, Irish and Ratcliff, 2008). For example, the very large Hurricane Ike (with hurricane force winds extending as much as 125 mi from the center) in 2008 made landfall in Texas as a Category 2 hurricane and had peak storm surge values of about 20 ft. In contrast, tiny Hurricane Charley (with hurricane force winds extending at most 25 mi from the center) struck Florida in 2004 as a Category 4 hurricane and produced a peak storm surge of only about 7 ft. These storm surge values were substantially outside of the ranges suggested in the original scale. Thus to help reduce public confusion about the impacts associated with the various hurricane categories as well as to provide a more scientifically defensible scale, the storm surge ranges, flooding impact and central pressure statements are being removed from the scale and only peak winds are employed in this revised version – the Saffir-Simpson Hurricane Wind Scale.

Saffir–Simpson hurricane wind scale (SSHWS), or the Saffir–Simpson hurricane scale (SSHS) is a 1 to 5 rating based on a hurricane's sustained wind speed. This scale estimates potential property damage. Hurricanes reaching Category 3 and higher are considered major hurricanes because of their potential for significant loss of life and damage. Category 1 and 2 storms are still dangerous, however, and require preventative measures. In the western North Pacific, the term "super typhoon" is used for tropical cyclones with sustained winds exceeding 150 mph (http://www.noaa.gov/). Beside five categories there are two more related categories including: tropical storm and tropical depression in which the wind speed is defined as 39-73 mph (34-63 knots or 63-118 km/h) and less than 38 mph (33 knots or 62 km/h), respectively. Table 1 shows five categories and types of damages due to hurricane winds.

Table 1. Saffir–Simpson hurricane wind scale

Category	Sustained Winds	Types of Damage	Description
1	74-95 mph 64-82 kt 119-153 km/h	Very dangerous winds will produce some damage:	Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph 83-95 kt 154-177 km/h	Extremely dangerous winds will cause extensive damage:	Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near total power loss is expected with outages that could last from several days to weeks.
3	111-129 mph 96-112 kt 178-208 km/h	Devastating damage will occur:	Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks
4	130-156 mph 113-136 kt 209-251 km/h	Catastrophic damage will occur:	Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	157 mph or higher 137 kt or higher 252 km/h or higher	Catastrophic damage will occur	A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

ADCIRC-SMS Model

SMS software is used to input the important parameters to the ADCIRC model. In 2011 to

2012 Vipulanandan and Guezo studied the storm surge analysis on Gulf of Mexico (Vipulanandan and Guezo, 2011-2013). In 2013, the Shutter Coastal Protection against Storm Surge Ike was modeled for Gulf of Mexico around Galveston Bay (Vipulanandan, Guezo, & Basirat, 2013). The coastline and bathymetry were imported from National Geographical Data Center (NGDC) to model the storm surge.

Gulf of Mexico Hurricanes

The Gulf of Mexico coast includes the coastal area from the Florida Keys to westward to Texas (Fig. 1). This coastal area has long been susceptible to strong hurricanes and the storm surge heights are shown in Fig. 1. Low-lying areas are especially vulnerable to damage from erosion, waves, and storm surge. Few of the selected hurricanes are as follows.

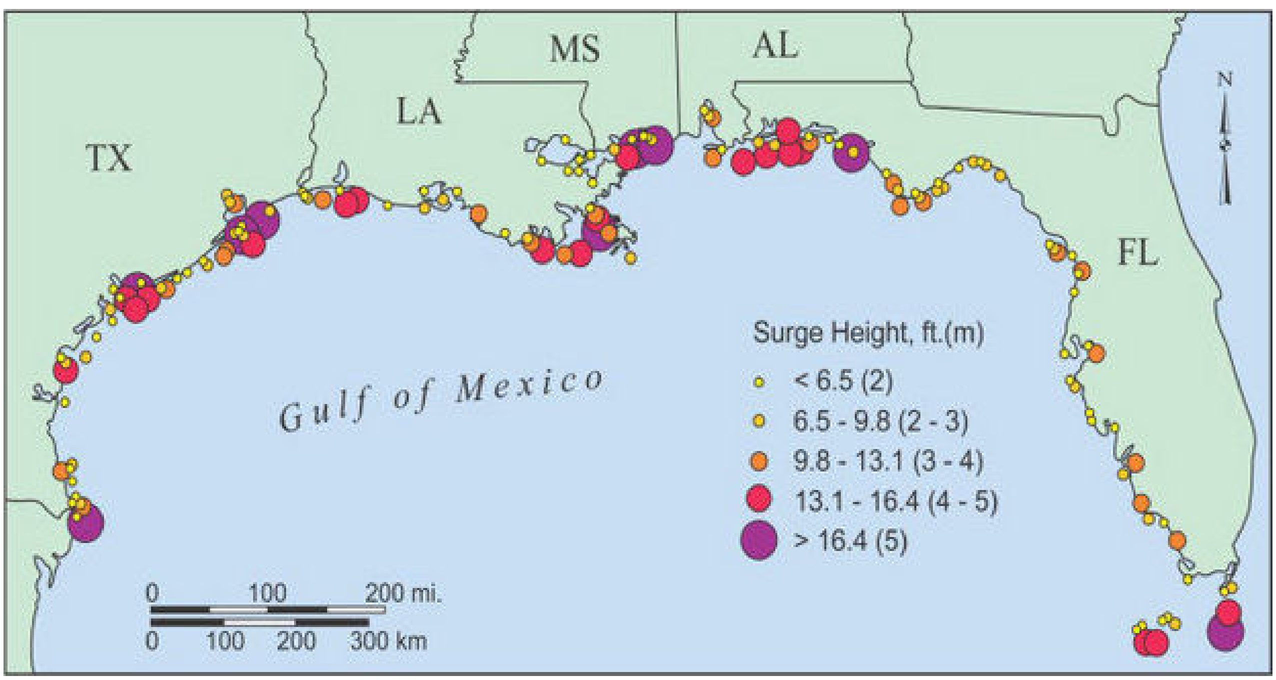

Figure 1. Peak height and location of storm surges along the Gulf Coast since 1880

The deadliest natural disaster in the United States happened in ***September 1900*** when a hurricane hit Galveston, TX. Based on the loss of lives and other distructions, Galveston

Island completed the first large-scale retrofit project in the United States by elevating the roads and buildings, and also building the Galveston seawall (Walden 1990). In 1961, category 5 Hurricane Carla caused extensive coasted erosion highlighting the need for proper protection for the coastal areas (Hayes 1967).

Hurricane Camille, a Category 5 hurricane, made landfall in Mississippi in August 1969 and caused "major destruction" in some areas near the beach because of waves and storm surge (Thom and Marshall 1971). High winds also caused damage farther inland.

The studies performed by Thom and Marshall (1971) after the hurricane led to building design criteria that resulted in the construction of new homes with improved resistance to higher wind forces.

In September 1979, ***Hurricane Frederic*** hit Alabama and caused widespread damage, including the destruction of many houses elevated to the BFE (Base Flood Elevation). After Hurricane Frederic, FEMA began to include wave heights in its determination of BFEs in coastal flood hazard areas (FEMA 1980).

Hurricane Charley made landfall in Florida in August 2004. Based on the extensive wind damage, the FEMA MAT concluded that buildings built to the 2001 Florida Building Code (FBC) generally performed well structurally (FEMA 2005a), but older buildings experienced damage because of old design and poor maintenance.

In September 2004, ***Hurricane Ivan*** made landfall in Alabama and Florida. Causing extensive damage that allowed heavy rains to infiltrate buildings and damage interiors. This damage highlighted weaknesses of older building and the need for developing new codes taking flooding into account (FEMA 2005b).

In August 2005, ***Hurricane Katrina,*** the worst hurricane in the United States (based on losses over $100 million) hit Louisiana and Mississippi. Flooding in New Orleans was worsened by levee failures, and floodwaters rose well above the first floor of elevated buildings. The long duration of the flooding added to the destruction (FEMA 2006). After Katrina, FEMA issued new flood maps for the area that built on the hazard knowledge gained in the 25+ years. These flood maps continue to aid in rebuilding stronger and safer Gulf Coast communities.

In September 2008, ***Hurricane Ike,*** considered the third worst hurricane in the United States (based on losses of $30 million) made landfall over Galveston, TX, and although wind speeds were below design levels, storm surge was more characteristic of a Category 4 hurricane. High waves and storm surge destroyed or substantially damaged over two-thirds of the buildings on Bolivar Peninsula (FEMA 2009).

European study

Dike, Levee, Seawall or Embankment

The process of wave overtopping on a dike, levee, seawall or embankment has been THE subject of a several research, resulting in e.g. equations for maximum velocities and flow depth of overtopping waves at the crest of a dike, see the new Overtopping Manual, 2007. The overall conclusion is that the hydraulic part of wave overtopping on a dike is well-defined.

In contrast, the erosive impact of wave overtopping on dikes, embankments or levees is not known well, mainly due to the fact that research on this topic cannot be performed on a small scale, as it is practically impossible to scale clay and grass down properly. Hence, in order to establish the resistance or strength of a dike for wave overtopping, field tests are required. For the simulation of overtopping, it is actually sufficient to reproduce the overtopping flow only. Thus, generation of true waves in a large scale facility, such as Delta flume (Netherlands) or GWK (Germany), is not required (Van Der Meer, 2008)

Basically, the following starting-points underlay the idea of the simulator, also described in Van der Meer et al., 2006:

Knowledge on wave breaking on slopes and generating overtopping discharges is sufficient; Knowledge on the pattern of overtopping waves, known as volumes, distributions, velocities and flow depth of overtopping water on the crest, is sufficient as well, except for some minor points; Only the overtopping part of the waves needs to be simulated, (Fig. 2). Tests can be performed in-situ on each specific dike

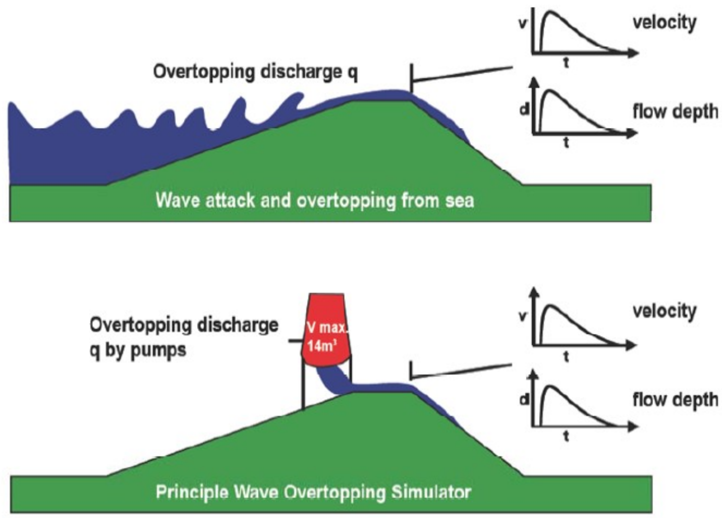

Figure 2. Principle of the wave overtopping simulator

The simulator was developed and designed early 2006 and constructed late 2006 within the ComCoast project (a European project between governments along the North Sea, see www.comcoast.org). At first a 1 m wide prototype was constructed and results of the calibration phase have been described by Van der Meer et al., 2006 and the full results on the wave overtopping simulator by Van der Meer, 2007.

The only failure mechanism described is erosion of the inner slope due to overtopping.

Hydrodynamic loads

Hydrodynamic loads are those load that result from water flowing against and around a rigid structural element or system.

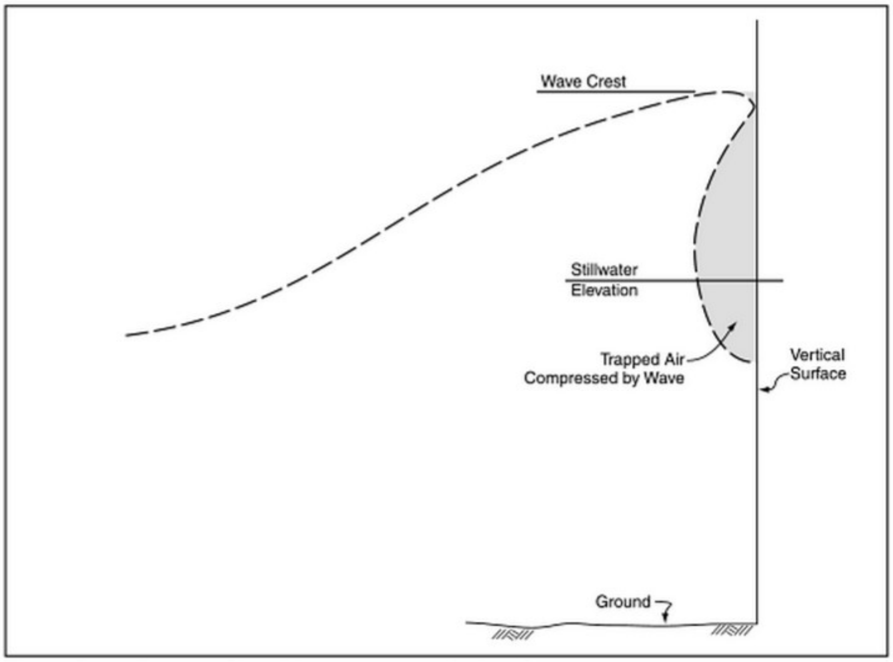

Figure 3. Impact of wave on a surface

The drag coefficient used in Eq. 1 is taken from the Shore Protection Manual, Volume 2 (USACE 1984). Additional guidance is provided in Section 5.4.3 of ASCE 7-10 and in FEMA 259, Engineering Principles and Practices for Retrofitting Flood prone Residential Buildings (FEMA 2001). The drag coefficient is a function of the shape of the object around which flow is directed. When an object is something other than a round, square, or rectangular pile, the coefficient is determined by one of the following ratios (Table 1):

1. The ratio of the width of the object (w) to the height of the object (h) if the object is completely immersed in water

2. The ratio of the width of the object (w) to the stillwater flood depth of the water (ds) if the object is not fully immersed (FEMA, 2011).

Table 2. Drag Coefficients for Ratios of Width to Depth (w/ds) and Width to Height (w/h)

Width-to-Depth Ratio (w/d_s or w/h)	**Drag Coefficient (Cd)**
1-12	1.25
13–20	1.3
21–32	1.4
33–40	1.5
41–80	1.75
81–120	1.8
>120	2.0

Hydrodynamic load equation is described as following (Sadraey & Müller, 2009):

$$F_{dyn} = \frac{1}{2} C_d \, \rho \, V^2 A$$

(1)

Where:

F_{dyn} = horizontal drag force acting at the stillwater mid-depth (half way between the stillwater elevation and the eroded ground surface)

C_d = drag coefficient (recommended values are 2.0 for square or rectangular piles and 1.2 for round piles; Table 2 shows the drag coefficient for other obstructions

ρ = mass density of fluid

V = velocity of water

A = surface area of obstruction normal to flow

Objective

Overall objective of this study was to compare the performance of dike to adjustable shutter during a storm surge. The specific objectives are as follows.

(1) Determine the storm surge height and velocity of categories1, 2 and 4 for Galveston bay.

(2) Determine the stresses and displacements in the dike and adjustable shutter and combined configurations.

Numerical Modeling

Hurricane Ike path way was used to simulate the storm surge in the Galveston bay. ADCIRC simulator and SMS software was used to perform analyses.

SMS software was used to perform ADCIRC analysis.

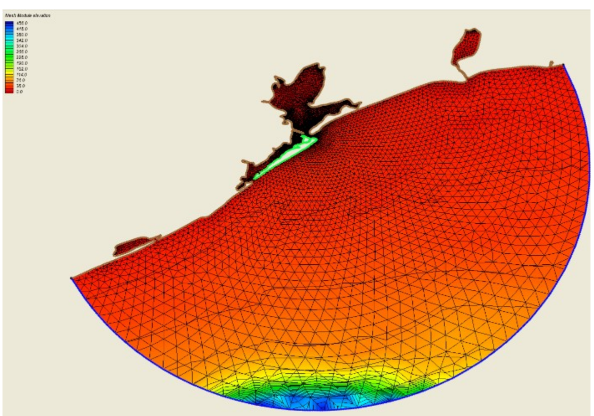

Figure 4. Storm Surge Ike applied on Gulf of Mexico around Galveston Bay

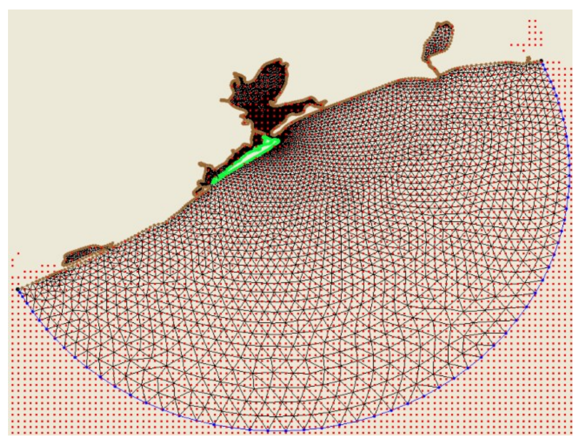

Figure 5. Shoreline, ocean, bathymetry and mesh generation

Hurricane categories 1, 2 and 4 simulating hurricane Ike was used to determine the storm surge and water depth averaged velocity (Fig.7 and 8). Category 1 has the wind speed of 76 mph, the category 2 which is the original speed of Ike storm surge with the highest speed of landfall wind 196 mph and the category 4 is selected with 140 mph of wind speed.

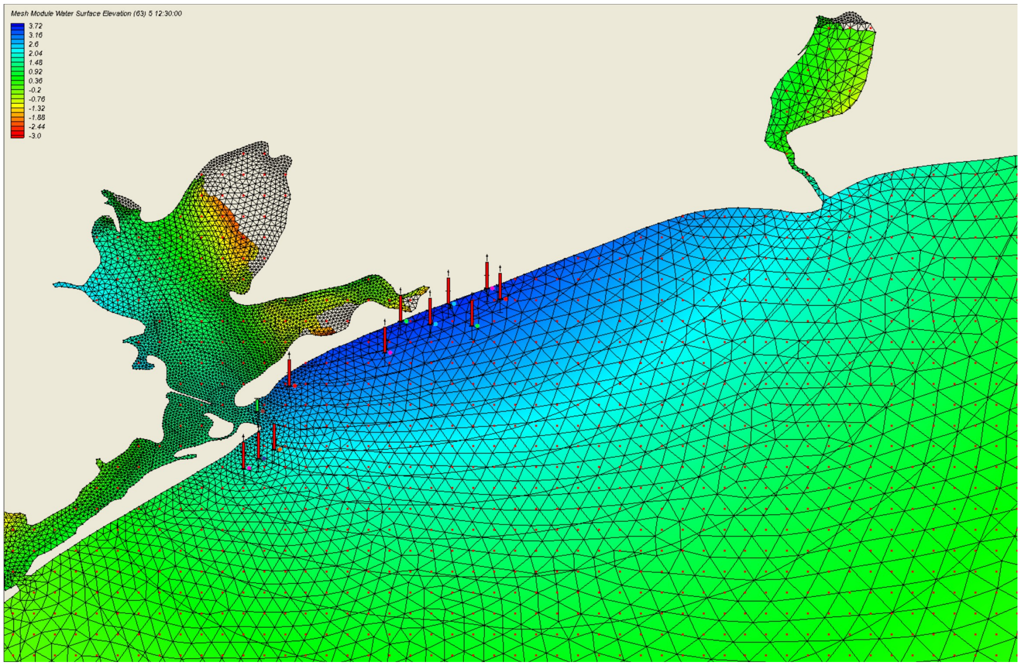

Figure 6. Different stations in observation the results

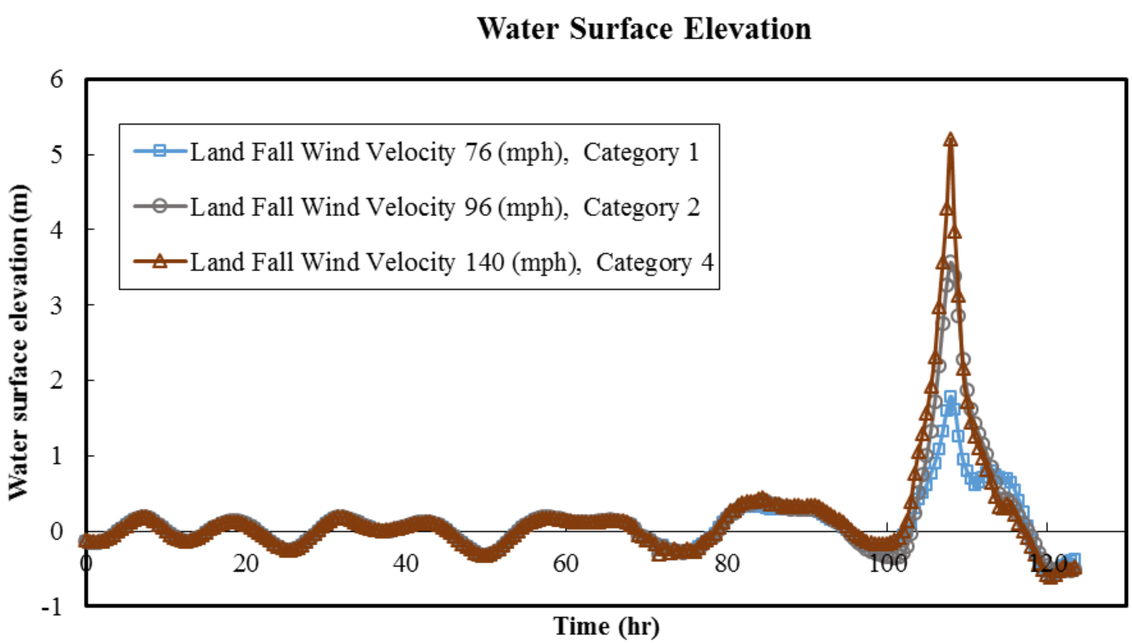

Figure 7. Water surface elevation versus time

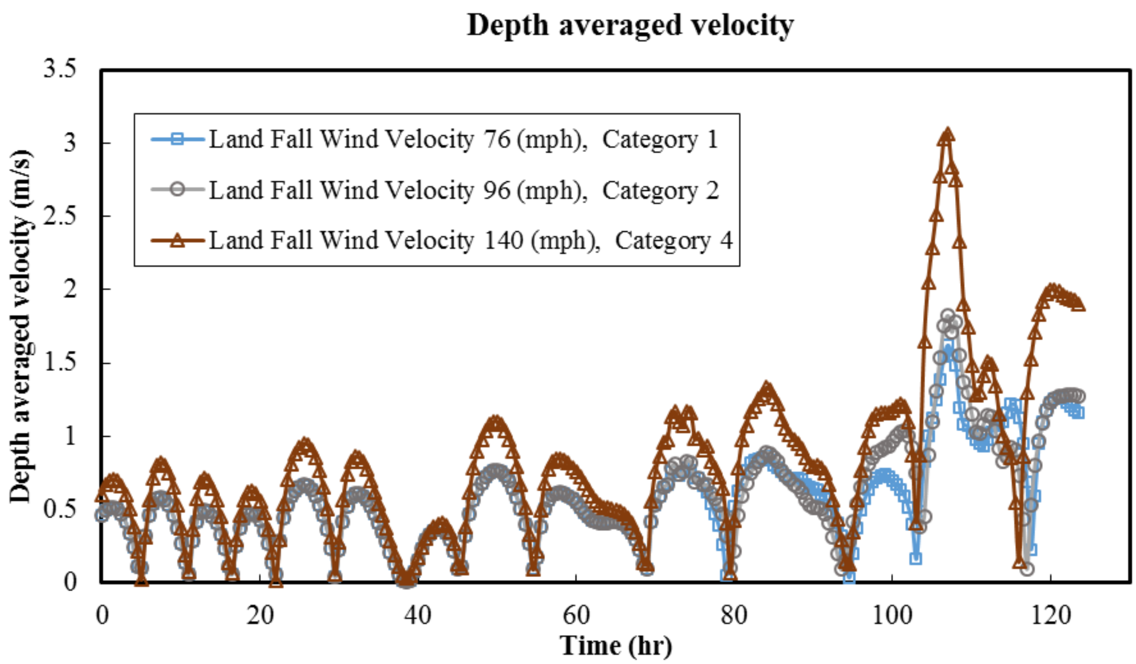

Figure 8. Depth average velocity versus time

For category 1 hurricane the storm surge elevation and depth average velocity were 1.8 m and 1.68 respectively. For category 2 hurricane the storm surge elevation and depth average velocity were 3.56 m and 2.66 respectively. For category 4 hurricane the storm surge elevation and depth average velocity were 5.2 m and 3.12 respectively. The results of ADCIRC analysis used to find hydrodynamic pressure. The hydrodynamic pressure from category 1, 2 and 4 are 1500, 3500 and 5000 pa. The shutter barrier, dike and the combination of them were modeled to see the effect of the storm surges in ABAQUS software.

Dike Adjustable Shutter, and Shutter Anchored in Dike

Three cases are defined as case 1 dike, case 2 shutter and case 3 shutter anchored in dike. In case 1, the shutter has the width of 1 m. the shutter base has the dimension of 3 meter in flood side and has the dimension of 2 meter in coast side. The thickness of the base in 60 cm. and the height of the shutter is 5 meter. In case 2, the dike has the height of 5 meter the slope of 1:3 in each side and the top width of 7 meter on top.

In the static analysis (frequency of loading is zero), the mesh generated with element type of hexahedral, C3D20R, 20 node quadratic brick element while in dynamic analysis frequency of loading is 10 Hz), element type was C3D8, an 8 node linear brick element. Material used for shutter is steel and plastic (piezoelectric) with elastic perfect plastic behavior with E = 200 GPa and ν = 0.3 and yield stress of 250 MPa (for steel) and E = 80 GPa and ν = 0.45 and yield stress of 80 MPa (for plastic, piezoelectric). The dike is made up of hard clay with behavior of linear elastic, E = 70 MPa, ν = 0.4 and strength of 300 kPa. Fig. 9- 14 are shown the mesh generation for case 1 dike, case 2a and 2b adjustable shutter with steel and plastic material, respectively, and case 3a, 3b and 3c steel shutter anchored on top of dike, plastic shutter anchored inside dike and plastic shutter anchored on top of dike, respectively.

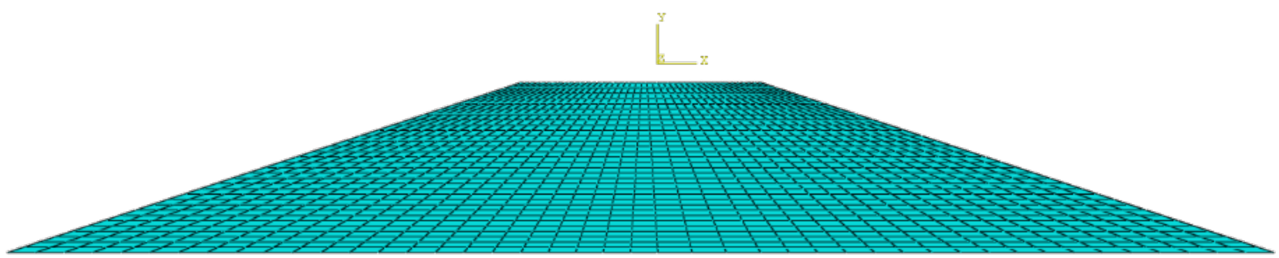

Figure 9: Case 1, Dike

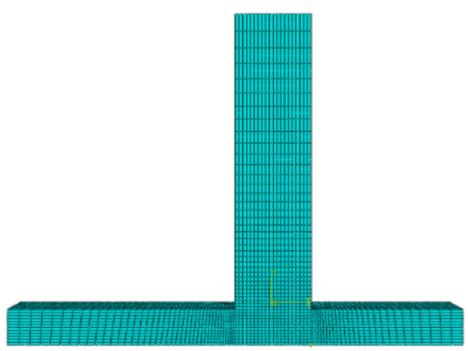

Figure 10: Case 2a, Steel Shutter

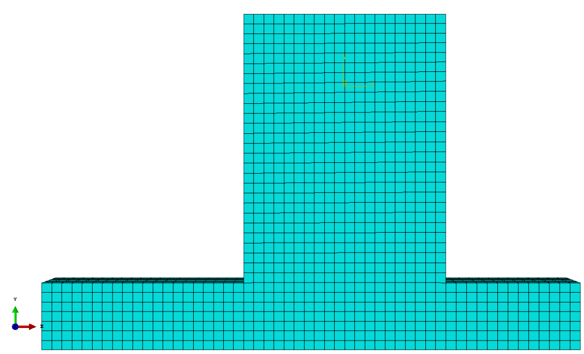

Figure 11: Case 2b, Plastic Shutter

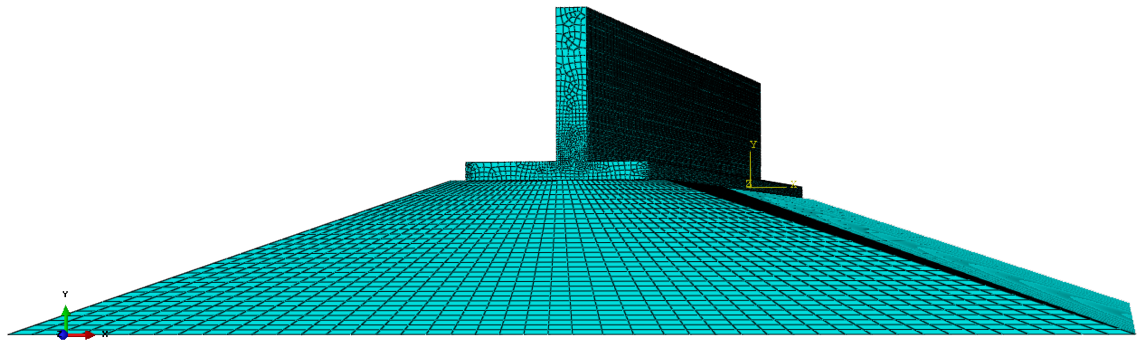

Figure 12: Case 3a, Steel Shutter on Top of Dike

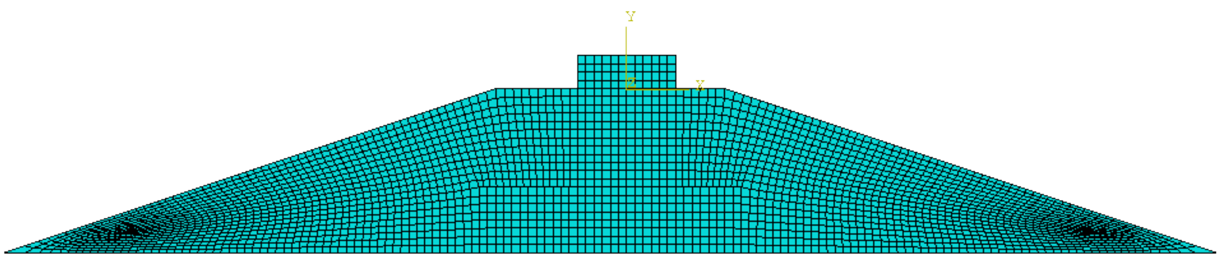

Figure 13: Case 3b, Plastic Shutter Anchored inside the dike

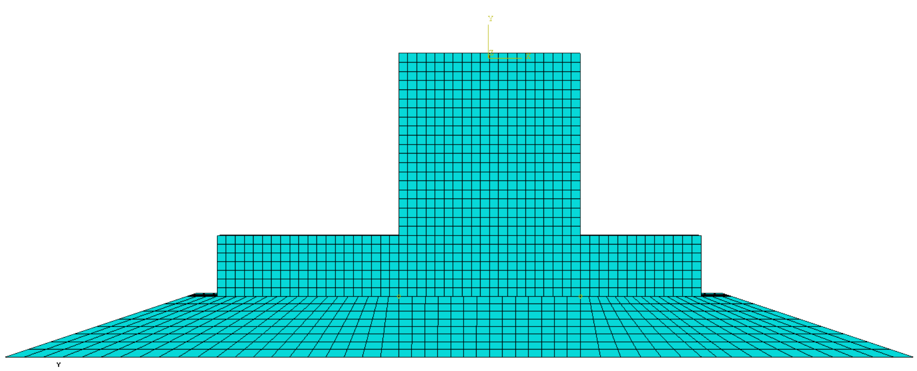

Figure 14: Case 3c, Plastic Shutter Anchored on Top of the dike

Von misses stress observed from the static analysis (Fig. 15 -22). The von misses stresses are shown in Fig. 15 - 22 for case 1, dike, case 2, shutter and case 3, combined configuration, respectively.

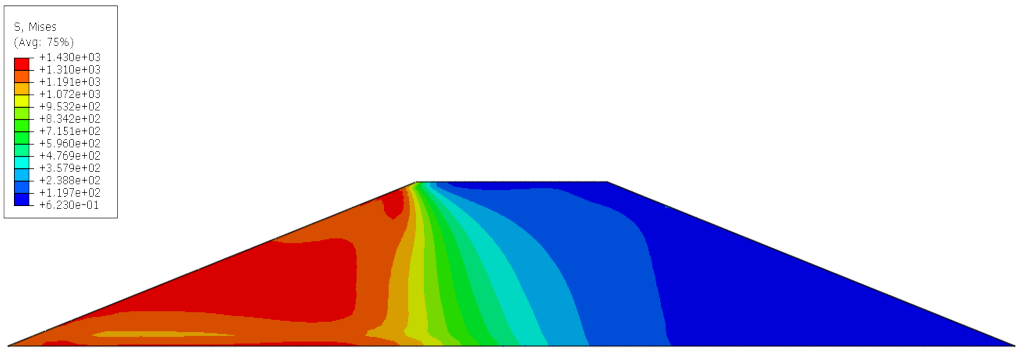

Figure 15: Case 1, Dike

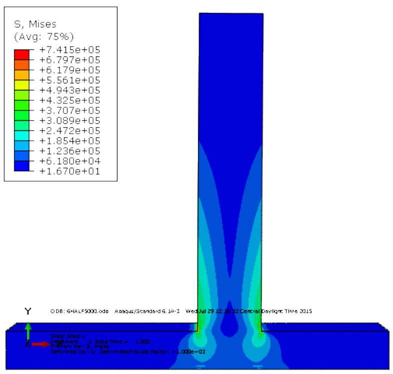

Figure 16: Case 2a, Steel Shutter

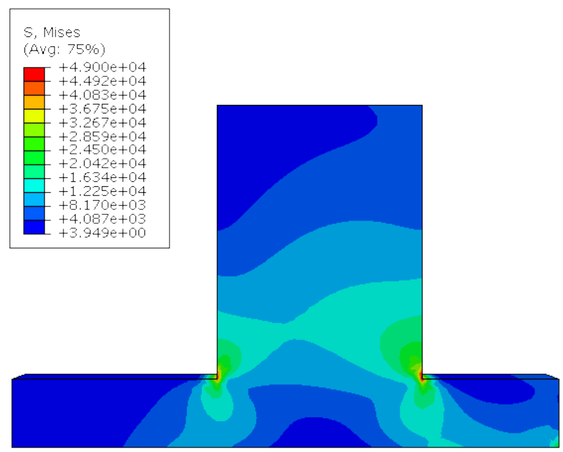

Figure 17: Case 2a, Plastic Shutter

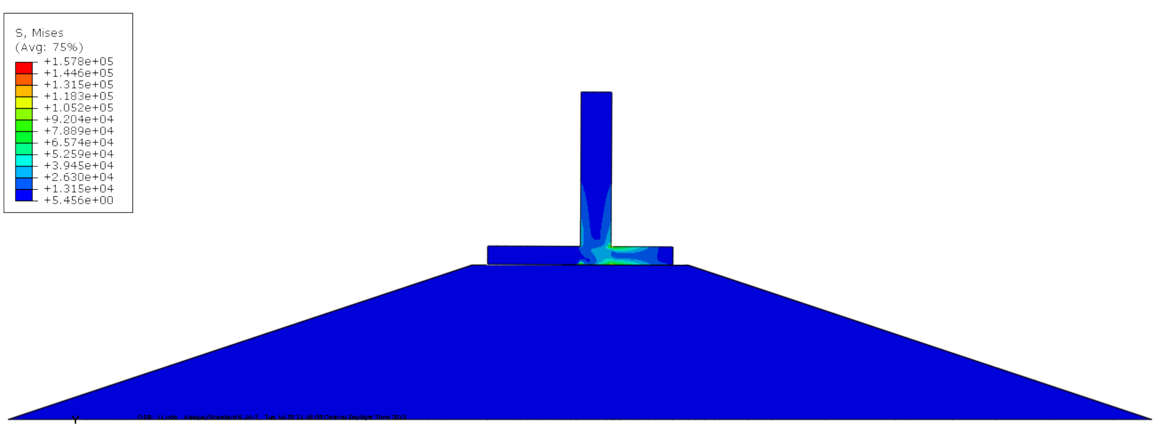

Figure 18: Case 2a, Steel Shutter on Top of Dike

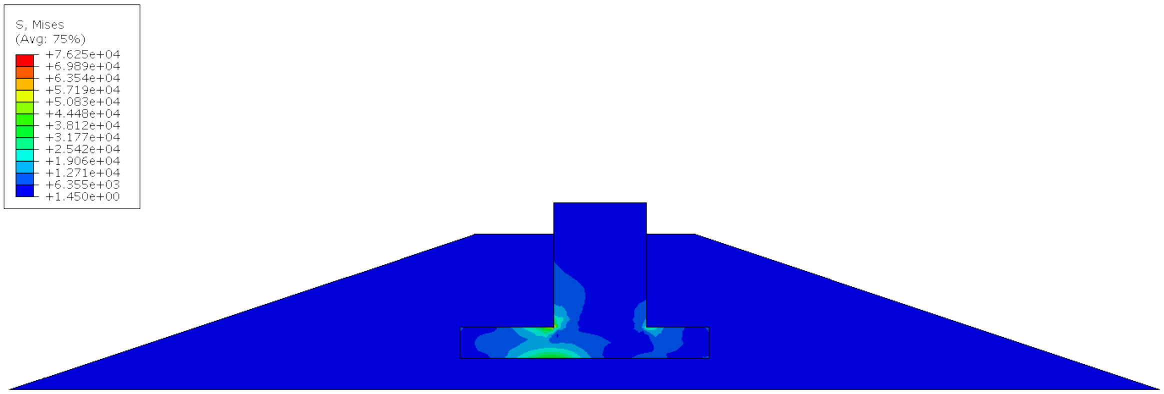

Figure 19: Case 3b, Plastic Shutter Anchored inside the dike

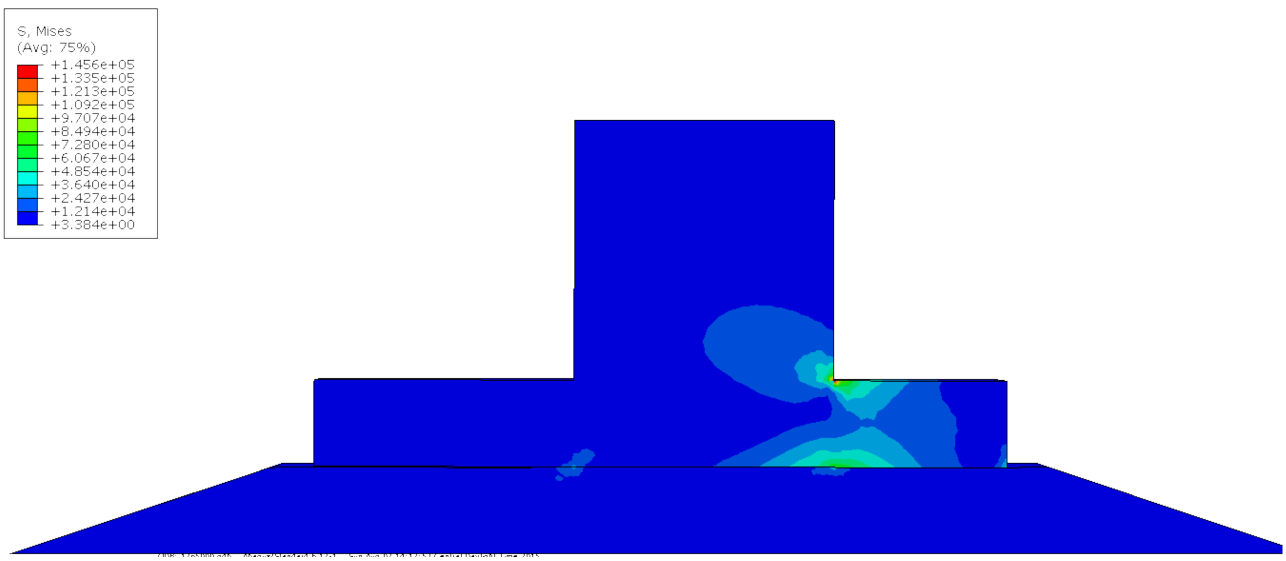

Figure 20: Case 3c, Plastic Shutter Anchored on Top of the dike

For static analysis (frequency of loading is zero) in all the cases the top of the structure has the highest displacement. The normalized highest displacements for all the cases compared with each other for different storm surge elevation from different storm surge categories (Fig. 21). Also, the von misses stress is normalized with the strength of structure's material and compared in all cases with different storm surge elevation (Fig. 22) and wind speed (Fig. 23).

For dynamic analysis (frequency of loading is 10 Hz), the normalized von misses stress versus storm surge elevation is shown in Fig. 24.

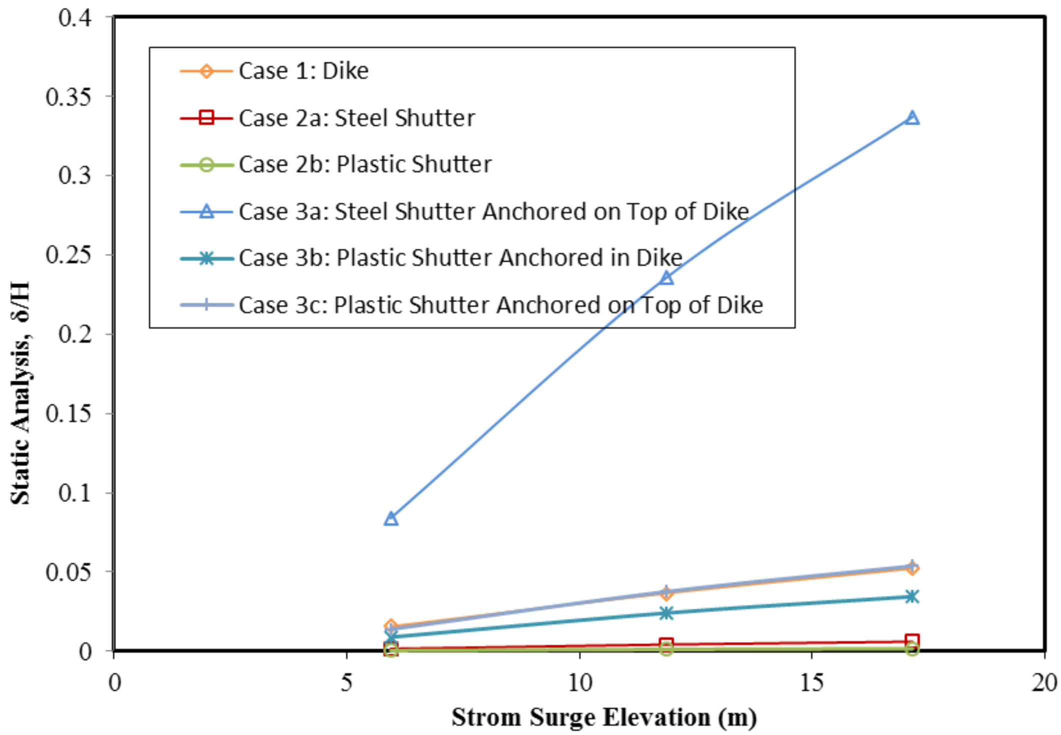

Figure 21: Normalized displacement from Static analysis versus storm surge elevation

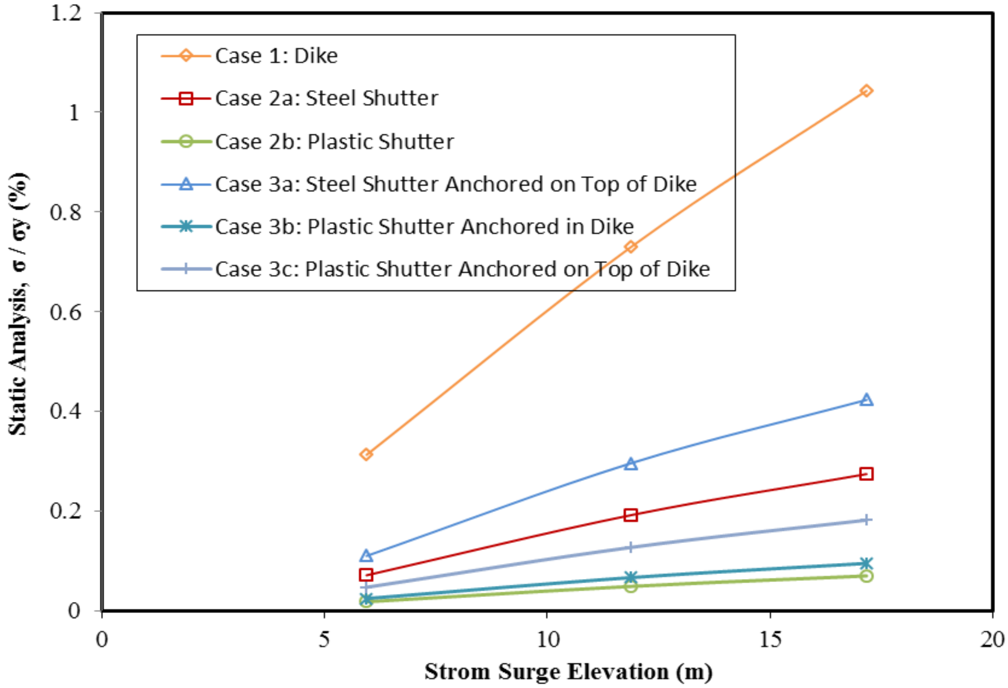

Figure 22: Normalized von misses from Static analysis versus storm surge elevation

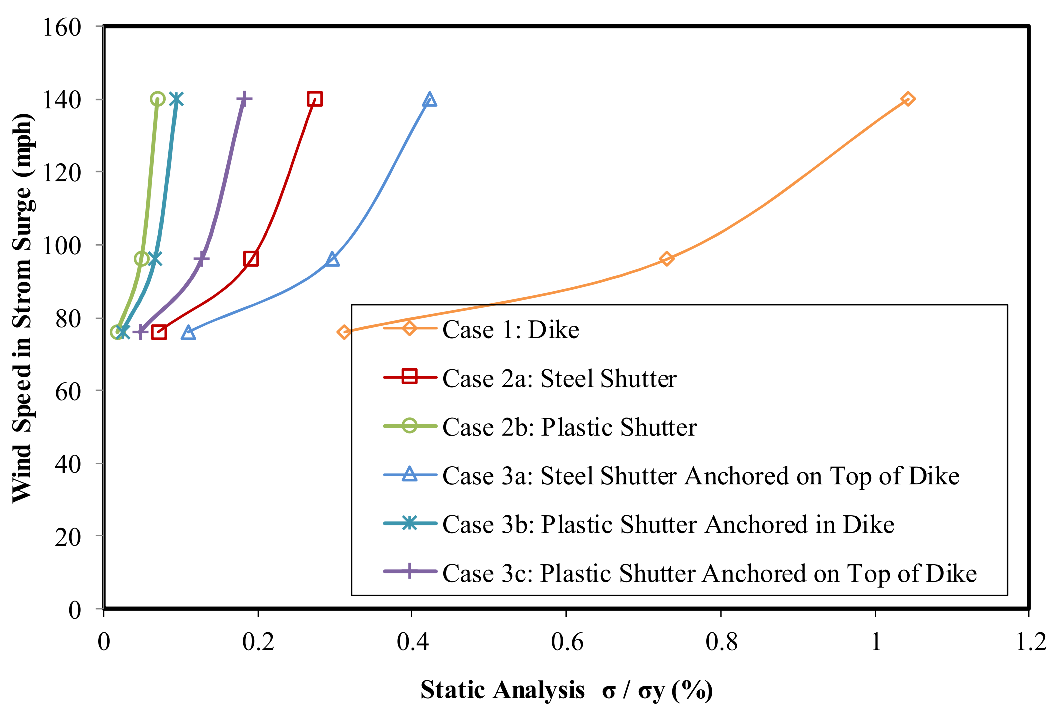

Figure 23: Wind speed versus normalized von misses stress for static analysis

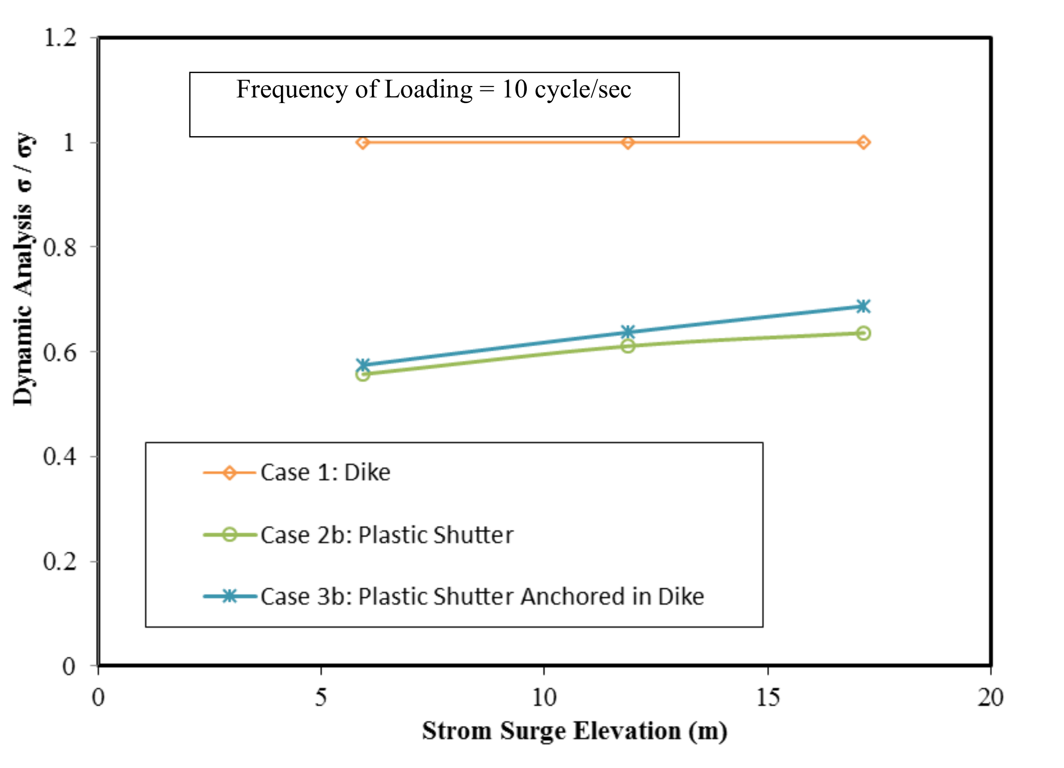

Figure 24: Normalized von misses from dynamic analysis versus storm surge elevation

Conclusion

Three wind speeds were selected to be applied on Gulf of Mexico to evaluate the water surface elevation and water depth average velocity. Wind speed of 76, 96 and 140 mph were selected to apply on the Gulf of Mexico which are categorized to 1, 2 and 4, respectively, according to the Saffir–Simpson hurricane wind scale.

Storm surge elevation from category 1 increased by 60 % to category 2, while increase to category 4 increased the water depth by 90% compared to category 1 water depth. Average velocity increased from category 1 to 2 by 99% and increased to category 4 about 190%.

Based on the static analyses (frequency of loading is zero), following conclusion can advanced

(1) For the dike, the soil reached to yield stress in 30 % in the static analysis of the

section close to the toe. The maximum deflection were 0.00216, 0.006 and 0.03 mm for category 1, 2 and 4, respectively. The dike volume was almost 10 times of the adjustable shutter.

(2) For the adjustable shutter the non-corrosive plastic material reached yield stress less than 5 % of the section close to toe.

(3) For the combined configuration the plastic shuttle inside the dike had the lowest stress whereas the steel shutter on top of dike had the higher stress.

Based on the dynamic analyses (frequency of loading is 10 Hz), following conclusion can advanced

(1) The wave induced stresses were about 100 times higher than the static load.

(2) For the dike, the soil reached to yield stress 50 % in dynamic analysis.

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