Benchmarking of Hydrodynamic Models for Development of a Coupled Storm Surge Hazard-Infrastructure Modeling Method to improve Inundation Forecasting

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Abstract

Fragility-based models currently used in coastal risk assessment frameworks are limited in their capability to reliability predict the failure of flood defense systems which often involves spatially and temporally complex processes. Such models frequently neglect temporal correlations and cause-effect relationships between the various failure mechanisms that may arise under extreme flow conditions like storm surge. Furthermore, current models neglect impacts of the performance of flood defense geo-structures on the storm surge response. These problems are compounded by the lack of understanding of how neglecting time-evolution and structural information affects decision makers' ability to make judgments on surge risk and infrastructure investment. Our work intends to couple state-of-the-art surge flow models with time-dependent, multi-dimensional fragility models for flood defense systems and implement adaptive meshing capabilities to supplement this coupled model. The resultant coupled surge-fragility model will therefore respond to changing conditions of flood protection systems as they develop through time. We plan development for human-in-the-loop experimentation intended for validating and testing the impact of our model and its improved flood forecasting on real-time decision-making. The primary intention of this proposal is to facilitate efforts for benchmarking our hydrodynamic models to provide supplement information for a subsequent submission of a larger proposal wherein we will couple our flow models and fragility models.

1 Introduction

Flood embankments known as levees, floodwalls, dikes, digues or sheet piles are vital structures for defending against flooding threats and hurricane storm surge. Failure mechanisms in cases such as Pin Oak and Elm Point levees in the Midwest, Sacramento-San Joaquin River Delta in California, Herbert Hoover Dike in Florida and New Orleans in Louisiana have provided geotechnical and hydraulic engineers with broad case studies. All of these disasters have shown the importance of improving the US levee structures (200,000 miles) to modern geotechnical standards with minimum costs in both normal and flood conditions.

By performing collaborative research among geotechnical engineers, hydro-dynamical researchers and economists, the broad standards will be more efficient, effective and practical. The process of levee management is a sequence of first identifying hydro-dynamical loading precisely, then assessing the response of the levee, and finally creating plans to control the risk and to mitigate it to as low as possible. All of these sequential tasks are interconnected.

Various failure mechanisms are possible for flood control, and every type of levee structure behaves differently under storm surge loading. In fact, the factors that affect levee performance vary from site to site. To have a broad and effective assessment of the overall reliability of a levee, it is key to have a thorough understanding of all main potential failure mechanisms. Overall, three potential main failure mechanisms may develop in different types of floods: geotechnical failure, i.e. internal erosion or piping, wherein water flows through the levee structure or underlying soil layers; hydraulic failure, i.e. overtopping, wherein water flows over the top of the levee structure; and structural failure, i.e. sliding, wherein the levee structure displaces along an underlying soil layer. Due to the complex behavior of soils and water, capturing geotechnical and hydraulic failures requires knowledge about multi-physics interactions and complex hydrodynamic modeling of flow. Overtopping is the only mechanism reliably resolved by current hydrodynamic models, which we intend to improve upon.

2 Hydro-dynamical Analysis

Our model for coastal and inland flooding by hurricane storm surge is based on the solution of the shallow water equations (SWE), partial differential equations derived from the well-known Navier-Stokes equations, which describe the general motion of fluids and are themselves derived from Newton's physical laws of conservation of mass and momentum. Many flow processes may be modeled by the SWE, and the equations are particularly suited for modeling of wave propagation, such as propagation of hurricane storm surge or tsunamis (Dawson C. a., 2008), (Park, 2007). We generally must solve the SWE over long periods of time and on large, geometrically complex spaces, in order to model these phenomena. To do so accurately and efficiently, we must use large-scale computational models (Dawson C. a., 2008).

Our numerical algorithm for solving the SWE is a variant on the finite element method, a numerical method commonly used in engineering disciplines, known as the discontinuous Galerkin method (DG). The DG method lend itself to significant scalability for large-scale parallel computing. The method also offers other advantages such as, high accuracy, fast convergence rates, simple implementation of mesh and polynomial refinement (techniques for tuning the accuracy of solutions), local mass conservation properties, and the ability to accurately resolve discontinuous wave phenomena (such as shock-waves or tidal bores) (Kubatko, Bunya, Dawson, Westerink, & Mirabito, 2009).

One of the first test cases we intend to study is the southern Louisiana coastline under the conditions of hurricane Katrina, due to the extreme nature of this event as well as its thorough documentation and investigation by the Interagency Performance Evaluation Taskforce (IPET) (IPET, 2008) (IPET, 2007a). We will apply IPETs data to simulate the conditions of the storm for our own model. IPET also investigated the performance of levees and floodwalls under these storm conditions. They identify, study and record the mechanisms and characteristics of the failures which occurred on some of these infrastructure both from scale model centrifuge experiments and observations in the field (IPET, 2007b). We will use these results to verify the results of our own model.

Adequate simulation of a storm on the scale of hurricane Katrina requires the resolution of a large-scale spatial domain containing the Gulf of Mexico, Caribbean Sea, and a large portion of the northwestern Atlantic Ocean, so that we may accurately capture all of the salient features of the physics of the storm-sea interaction. We also require the accurate resolution of small-scale features such as inlets, rivers and channels in order to adequately model flow behavior in coastal floodplains. Hydrodynamic modeling on such a large and complex domain demands a significant degree of computational resources, both in terms of system memory and processing power. We have yet to undergo any testing with such a large-scale problem, since we currently do not have the computational resources at our disposal to do so. However, other researchers using high performance machines and similar techniques as our own on the same problem, or similarly scaled problems, have well documented the computational demands of those systems, giving us a perspective from which to anticipate the computational demands of our own systems before running any simulations (Kubatko, Bunya, Dawson, Westerink, & Mirabito, 2009), (Kerr, et al., 2013) , (Dietrich, et al., 2012), (Tanaka, Bunya, Westerink, Dawson, & Luettich, 2011), (Dietrich, et al., 2011), (Bunya, et al., 2010).

In lieu of the resources to perform large-scale simulations, we ran our model on several smaller test cases in order to test its capabilities in terms of interaction with internal barriers. For example, we have results from running our hydrodynamic model on a relatively small coastal domain, with an open-ocean boundary at one end and a channel inlet at the other, shown in Figure 3. The channel inlet is bounded by floodwalls, which appear as internal barriers in our domain (shown in white).

For this problem a tidal bore roughly 2.5 feet in elevation with a velocity of at most 3.5 feet per second in magnitude enters at time t = 0s from the open-ocean boundary, flowing towards the channel inlet. Figure 4 shows snapshots of this flow condition at various instances during the simulation. At time t = 8500s (Figure 5), near the end of this simulation, we can note a small amount of overtopping at the bend of the northern channel boundary, located near the center of the image, with pool depth of roughly 2 feet on the landward side of the floodwall.

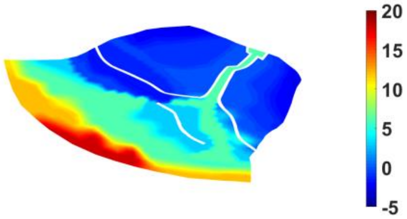

Figure 3: Domain boundaries and topography for our test case with internal barrier interaction. Colors correspond to bathymetric depth, i.e. depth of topography below sea level. Note that negative depths correspond to elevations above sea level. All depths are expressed in feet. External and internal boundaries (floodwalls) appear in white.

(a) (b)

(c) (d)

Figure 4: Snapshots of surface elevations in test case flow domain at different points in time during a tidal bore event. Colors correspond to elevation of either water or topography (whichever is larger) measured in feet. The black lines show the triangular unstructured mesh upon which our computations are performed. Elevations shown are actually average values for each element.

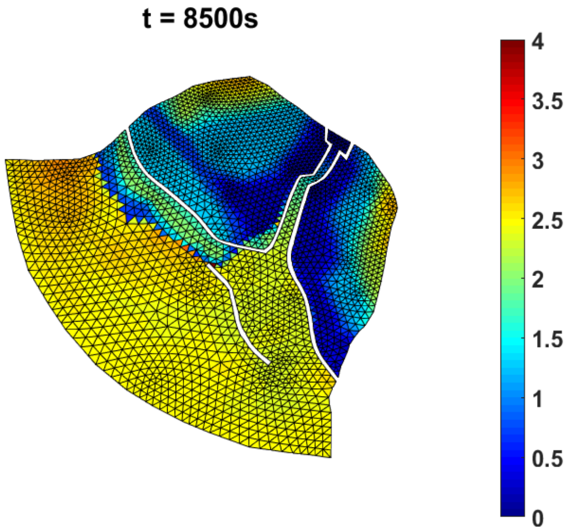

Figure 5: Snapshot of surface elevations in test case flow domain at time t = 8500s during a tidal bore event.

Though we have no exact measurements for this test case to which we may compare our computation results, the results of this test are useful in showing that our model is capable of resolving the physics of flow interaction with solid boundaries in a seemingly realistic manner. In other words, we observe no spurious numerical oscillations in our results, and the flow behaves as one might intuitively anticipate in the field under these conditions based on one's theoretical knowledge and/or practical experience of flow behavior.

3 Conclusion

We propose to use the requested resources primarily for benchmarking the performance of our storm surge model and for verifying the model as we continue to make developments. The benchmarking results we obtain will supplement a larger proposal wherein we intend to interface our hydrodynamic model with a geotechnical model. The results of the current project will provide initial evaluation of the efficiency and scalability of our codes on OSC hardware, so that we may more fully gauge the resource requirements of our coupled hydrodynamic-geotechnical model.

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