Project Summary

Prediction of Hydrodynamic Vulnerability of Coastal Bridges to Extreme Storm Surges

Grant Dates: 9/1/2013 – 8/31/2016 (Extended to 8/31/2018)

NSF Award Number: CMMI # 1334551

Grant Amount: $300,000

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November 30, 2018

Acknowledgment

We acknowledge the contribution of Ke Qu, Yalong Cai, Wenbin Dong, and others in computation, analysis, and documentation of this project. This project is sponsored by Natural Science Foundation (award number CMMI # 1313877). The PIs are grateful to the project managers Drs. Kishor Mehta and Y. Grace Hsuan for their valuable input during this project.

Contents

Abstract

In correspondence to consequences of change in climate and hurricane patterns, this research investigates impact of ocean surges and waves on coastal bridges and the resulting vulnerability of them to extreme surges and waves during storms and tsunamis. Computer modeling study is made on wave impingement at coastal bridges to understand relevant physical phenomena, and analysis is presented on mitigation measures. Modeling systems are developed for high fidelity simulation of surge and waves at bridges. Hindcast modeling has been made for storm surges and waves in the metro NYC region during the Hurricane Sandy, and, on this basis, potential extreme surge and wave events in this region are predicted in conditions of sea level rise and different hurricane patterns in the future, together with analysis on vulnerability of coastal bridges to scour and hydrodynamic load. The results of this project shed light in understanding of involved physical processes and phenomena, and they present new modeling capacity for their prediction. It is anticipated that the results of this project will be beneficial to development of future coastal bridges and resilient coastlines.

Key works

Ocean surge and wave, hydrodynamic impact, vulnerability, coastal bridges, computer models, SIFOM-FVCOM, and SIFUM-FVCOM

1. Objective

This research aims at (i) investigation of the phenomenon of hydrodynamic impacts on bridges during extreme storm surge events, (ii) assessment of the vulnerability of bridges along coastlines of the metro NYC regions during such events. The problems of study involve multi-scale and multi-physics processes, and they include evolution of storm surges in the open sea at scales as large as O(100) km, propagation of the surges to shorelines, and transfer of surge forces to bridge components at scales as small as less than O(1) m. The two objectives of the proposed research are achieved via efforts as follows:

- Simulation of hydrodynamics of surge and wave impinging on coastal bridges
- Prediction of extreme storm surges at bridges in conditions of sea level rise and different hurricanes
- Investigation of dynamic response and vulnerability assessment of bridges to the hydrodynamic impacts

The research is carried out by computer modeling and analysis of the results.

This project also trains students at different levels in relevant aspects including data analysis, multidisciplinary research, mathematical and computer modeling.

2. Background and Motivation

Global warming and climate change are reshaping and affecting our environments in numerous ways. One of their most significant consequences is the rise in sea level due to melting of polar glaciers and arctic ice. Global sea level has been rising at an alarming rate of 0.18 cm/yr during the period of 1961-2003 and this rate has been observed to accelerate to 0.3 cm/yr during the period of 1993-2003 (Solomon et al. 2007). The median range of global sea level rise over next 100 years is projected to be in the range of 0.2-0.6 m, and this rise could be as high as 0.8 to 2 m by 2100 under unfavorable glaciological conditions (Pfeffer et al. 2008). According to a recent study by Yin et al. (2009), global warming is expected to cause the sea level to rise twice as fast along Northeastern U.S. coastline as compared to the global average rate. This rate is expected to be particularly high along New York and New Jersey shores (Stanley 2004).

It has been observed from recorded data that the pattern of hurricanes has been changing, although the contribution of global warming and climate change is still a subject of research. Data indicate that hurricanes have been becoming stronger and more frequent, and the number of category IV and V storms has greatly increased over past 35 years along with the ocean temperature (Gabriel et al. 2008). Occurrence of Hurricanes Irene and Sandy in 2011 and 2012, respectively, indicate the effect of climate pattern change in the Northeast USA. In particular, as a general emerging changing pattern, precipitation has been increasing in high latitude regions (Northern Hemisphere). During the last century, annual areal averaged precipitation increased from 7 to 12% in the Northern Hemisphere. The Northeast region is projected to see 20 to 30% increase in winter precipitation (Dore 2005).

A severe consequence of sea-level rise and change in the hurricane pattern is a significant increase in the risk of catastrophic storm surges along coastlines. Storm surges are expected to apply dynamics forces on coastal bridges. A majority of bridges have been designed without considering the dynamic forces during storm surges and there is a substantial knowledge gap on the understanding of dynamic force being applied on structures during storm surges. In addition, although important coastal bridges are usually well maintained, their performance during extreme surges, which could be similar to those encountered during Hurricane Katrina and Sandy, has not been systematically investigated.

The scientific communities and governments are becoming increasingly aware of the risk of lifeline infrastructures to coastal surges. For instance, the Executive Committee of the Transportation Research Board (TRB) has investigated potential impacts of climate change on U.S. transportation infrastructures (TRB 2008). It identifies “rising sea levels coupled with storm surges and land subsidence” as one of weather extremes that could affect safety and serviceability of transportation infrastructures, and recommends “adopting strategic, risk-based approaches to decision making” and “Reevaluate design standards” to address effects of climate changes on transportation infrastructures. In response to these predictions, NYC Mayor

Michael Bloomberg released the Vision 2020: New York City Comprehensive Waterfront Plan in March 2011, which emphasizes building climate resiliency and calls upon both the public and private sectors to address vulnerabilities of facilities, including bridges, along the coast (NYC DCP, 2011).

3. Research and Result

During this project, investigations have been made towards its objectives, and, the main results are summarized using the abstracts of the published papers as follows. Some results were produced by the work that was started before but finished during this project.

3.1 Wave impact on bridges

<u>Hydrodynamic effects of solitary waves impinging on a bridge deck with air vents</u> (Qu, et al. 2017)

Air vents in bridge decks are considered one potential measure for mitigating risk of damage to coastal bridges caused by extreme storm surge because they may reduce hydrodynamic uplift loads significantly. This paper presents a systematic, two-dimensional, numerical study on physical phenomena and hydrodynamic loads involved during the impact of solitary waves on a bridge deck with vents. The effects of the opening size of vents and other prominent factors, including submergence of the deck, wave height, water depth, and number of girders, on hydrodynamic loads were investigated through the numerical study. It was found that, when the deck was submerged initially, the vertical loads on the bridge deck achieved their maximum values at a certain opening size of vents, and their magnitudes could be significantly higher than on a deck without vents. Formulas as functions of these factors were developed based on the computational results to estimate efficiency of air vents to reduce hydrodynamic loads on bridge decks.

Numerical investigation of connection forces of a coastal bridge deck impacted by solitary waves (Cai, et al., 2018)

In this work, a numerical wave-loading model using the dynamic-mesh updating technique is combined with a nonlinear finite-element (FE) model to investigate the behavior of costal bridge superstructures under solitary waves. The numerical model has been tested by comparing it with laboratory experiments performed at Oregon State University. It is proven that the proposed model is reliable for predicting the bridge–wave interaction. Full-scale numerical experiments are then conducted to discuss the effect of vertical flexibility on connection forces. In this study, a typical value of horizontal restraint has been assigned to each bridge deck, and the vertical flexibility is introduced by allowing the bridge deck to rotate about the onshore side. The results show that a higher extent of deck rotation movement is accompanied with larger horizontal resultant forces. Also, the pattern of vertical resultant is significantly influenced, whereas the peak value does not change much. Moreover, the general characteristics of the relationship between the vertical resultant force and the overturning moment are discussed in detail for a vertically fixed deck, and they are represented by interaction diagrams. The direction of the overturning moment is distinguished. The significance of a negative overturning moment is revealed. At the end of the paper, an empirical model for predicting the interaction diagrams is proposed and tested.

Numerical investigation of hydrodynamic load on bridge deck under joint action of solitary wave and current (Qu, et al. 2018)

During the past few decades, there have been many instances of significant damage to coastal infrastructure, especially bridges, due to ocean waves generated by hurricanes and tsunamis. Since ocean waves and currents co-exist and twist with each other in natural marine environments and their interaction may result in more severe damaging waves, taking both of them and their interaction into account is important in better understanding of damage processes of coastal bridges. This paper conducts a numerical investigation on hydrodynamic load on a bridge deck due to joint action of solitary waves and currents. Effects of prominent factors including current velocity, submersion depth, wave height, and water depth have been studied. Efficiency of air vents in reducing the hydrodynamic load has also been discussed. The numerical investigation indicates that, in a linearly pattern, a current in the wave direction leads to a higher maximum of the hydrodynamic force in the horizontal direction, and a current in the opposite direction results in a lower maximum. However, the behaviors of other characteristics of the force, including the maximum of its vertical component and the minimums of its horizontal and vertical components, become complicated and highly nonlinear because of water overtopping on the deck. In addition, a current can play a pronounced role, either positive or negative, in efficiency of air vents in reducing the hydrodynamic load. It is anticipated that the findings in this paper will enhance our understanding on mechanism of bridge damage by waves and may also be useful in design of future coastal bridges.

3.2 Model development for high-fidelity simulation of surge and wave at bridges

<u>An overset grid method for integration of fully 3D fluid dynamics and geophysics fluid dynamics models to simulate multiphysics coastal ocean flows</u> (Tang, et al. 2014)

It is now becoming important to develop our capabilities to simulate coastal ocean flows involved with distinct physical phenomena occurring at a vast range of spatial and temporal scales. This paper presents a hybrid modeling system for such simulation. The system consists of a fully three dimensional (3D) fluid dynamics model and a geophysical fluid dynamics model, which couple with each other in two-way and march in time simultaneously. Particularly, in the hybrid system, the solver for incompressible flow on overset meshes (SIFOM) resolves fully 3D small-scale local flow phenomena, while the unstructured grid finite volume coastal ocean model (FVCOM) captures large-scale background flows. The integration of the two models is realized via domain decomposition implemented with an overset grid method. Numerical experiments on performance of the system in resolving flow patterns and solution convergence rate show that the SIFOM-FVCOM system works as intended, and its solutions compare reasonably with data obtained with measurements and other computational approaches. Its unparalleled capabilities to predict multiphysics and multiscale phenomena with high-fidelity are demonstrated by three typical applications that are beyond the reach of other currently existing models. It is anticipated that the SIFOM-FVCOM system will serve as a new platform to study many emerging coastal ocean problems.

Domain decomposition for a hybrid fully 3D fluid dynamics and geophysical fluid dynamics modeling system: A numerical experiment on a transient sill flow (Tang, et al., 2016)

A modeling system is presented for prediction of multiscale and multiphysics coastal ocean processes, and a numerical experiment is made to evaluate its performance. The system is a hybrid of a fully three dimensional fluid dynamics (F3DFD) model and a geophysical fluid dynamics (GFD) model. In particular, it integrates the Solver for Incompressible Flow on Overset Meshes (SIFOM) and the Finite Volume Coastal Ocean Model (FVCOM) using a domain decomposition method implemented with Chimera grids. In the hybrid SIFOM–FVCOM system, SIFOM is employed to capture small-scale local phenomena, and FVCOM is used to simulate large-scale background coastal flows. Simulation of a transient sill flow demonstrates that, while its performance is promising, the hybrid SIFOM–FVCOM system encounters difficulties in correctly resolving the flow at current front where there is strong unsteadiness and thus it needs further improvement.

Evaluation of SIFOM-FVCOM system for high-fidelity simulation of small-scale coastal ocean flows (Qu, et al., 2016)

This paper evaluates the SIFOM-FVCOM system recently developed by the authors to simulate multiphysics coastal ocean flow phenomena, especially those at small scales. First, its formulation for buoyancy is examined with regard to solution accuracy and computational efficiency. Then, the system is used to track particles in circulations in the Jamaica Bay, demonstrating that large-scale patterns of trajectories of fluid particles are sensitive to small-scales flows from which they are released. Finally, a simulation is presented to illustrate the SIFOM-FVCOM system's capability, which is beyond the reach of other existing models, to directly and simultaneously model large-scale storm surges as well as small-scale flow structures around bridge piers within the Hudson River during the Hurricane Sandy.

Integration of fully 3D fluid dynamics and geophysical fluid dynamics models for multiphysics coastal ocean flows: Simulation of local complex free-surface phenomena (Qu, et al. 2018)

A modeling system is presented for simulation of multiphysics coastal ocean flows at scales from O (1) m to O (1,000) km, especially for high-fidelity simulation of local, complicated, free-surface phenomena. The system integrates the Solver for Incompressible Flow on Unstructured Mesh (SIFUM) and the Finite Volume Coastal Ocean Model (FVCOM) on the basis of a domain decomposition approach. In this system, the former is built on the Navier-Stokes equations and simulates small-scale, fully three-dimensional phenomena in local flows, whereas the latter is based on the geophysical fluid dynamics equations and describes large-scale, background ocean currents. The integrated SIFUM-FVCOM system is developed from a previous system consisting of a structured-grid model and an unstructured-grid model (Tang, et al., J. Comput. Phys. 273, 2014), and it combines two unstructured-grid models and has capability of dealing with free-surface phenomena and resolving complex geometries in local flows. In the new system, SIFUM and FVCOM are coupled in two-way via Schwarz iteration, and they march in time together as a single system. The SIFUM-FVCOM system performs as intended with regard to capturing physical phenomena (e.g., generation of dam-break wave and slashing of water at structure), converging with grid spacing, and permitting seamless transition of solutions for far- and near-fields. In addition, its prediction of benchmark flow problems matches well with analytical, computational, and experimental data. The system is able to simultaneously and directly simulate many multiscale, multiphysics real-world phenomena that could not be handled before. Such capability is illustrated by its application to coastal flooding and the resulting impact on a coastal bridge and a beachfront house.

3.3 Vulnerability of coastal bridges to extreme surges

Resiliency planning: Prioritizing the vulnerability of coastal bridges to flooding and scour (Shields, 2016)

Bridge owners are faced with the daunting task of maintaining or replacing aging infrastructure over the next century. Added to this challenge are climate change projections such as rising sea levels. A major concern to bridge owners is the need to strengthen the resiliency of their bridges while utilizing a limited amount of financial resources. This paper will offer a methodology for prioritizing the vulnerability to flooding and scour for a state department of transportation's bridge inventory. Through the use of geographic information system (GIS) software, data is mined from the National Bridge Inventory (NBI) - making this methodology applicable to any state agency in the country. The New York City metropolitan region will be presented as a case study.

<u>Vulnerability of coastal bridges to extreme storm surge in metro NYC region</u> (Qu, 2017)

For the purpose to evaluate vulnerability of offshore and ashore infrastructure in the metro New York region, a hindcast of storm surges and waves during the superstorm Hurricane Sandy 2012 is made, and its results match the measurement data. Then, a numerical investigation of storm surges and waves has been made considering sea-level rise and change in hurricane routes. On this basis, an analysis on vulnerability of coastal infrastructure is made with regard to extreme surges and waves, scours, hydrodynamic loads at bridges in the region.

4. Education

Three PhD students (Ke Qu, Yalong Cai, and Wenbin Dong, at CCNY) and a few undergraduate students, including those from underrepresented groups (e.g., Jarren Sanderson, Jonathan Akujobi, at City Tech College of New York) have been involved in activities of this research. A presentation by the students is as follows: Sanderson, J. and Akujobi, J. “Prioritizing the Vulnerability of Coastal Bridges to Flooding and Scour, ” CUNY Undergraduate Research Scholars Program Poster Presentation, John Jay College, July 2016.

5. Products

This project generates the following products:

A. Totally 6 journal papers, one PhD thesis, 2 proceeding papers, and 16 presentations have been generated, as follows:

Journal papers (6): Cai, et al. 2018; Qu, el al. 2018b; Qu, et la. 2017a; Qu, et al. 2018a; Qu, et al. 2016**;** Shields 2016a**;** Tang, et al. 2014

PhD thesis (1): Qu, (2017)

Proceedings (2): Qu, et al., 2017b**;** Tang, et al., 2016

Presentations (16): Qu, and Tang, 2014; Shields, 2016b**;** Shields, 2016c; Shields, 2018**;** Tang, 2016**;** Tang, 2017**;** Tang, et al., 2018c**;** Tang and Qu 2014**;** Tang and Qu 2015; Tang, et al. 2014; Tang, et al., 2015a; Tang, et al. 2015b; Tang, et al., 2018a; Tang, et al. 2018b**;** Tang, et al. 2013; Tang and Zou 2016

B. Two preliminary computer modeling systems SIFOM-FVCOM (Tang et al., 2014), and SIFUM-FVCOM (Qu, et al., 2018b)

C . A web page about this project is made at http://tang.ccny.cuny.edu/surge_wave_impact_bridge.html

6. Concluding Remarks

The project has progressed as planned, and it lasted a longer than expected. In many components, the research performed over expectation in several fronts, such as modeling study of wave impact on bridge deck, model development (i.e., SIFOM-FVCOM, SIFUM-FVCOM). Due to level of difficulty and limit of timeframe, study of fracture modeling, which is a small component in the proposal, could not be performed. In addition, it is expected that more analysis will be made on vulnerability of bridges in metro NYC region stemming from this project.

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