Scope of Work
Evaluation of Concrete Pile Foundations During Hurricane Michael

Proposal to the Florida Department of Business and Professional Regulation
Florida Building Commission (FBC) Hurricane Research Advisory Committee (HRAC)

Taylor Engineering Research Institute (TERI) and the School of Engineering (SoE)
University of North Florida

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1. Introduction

After Hurricane Michael ravaged Mexico Beach and surrounding areas in October of 2018, a team from the Federal Emergency Management Agency (FEMA) documented the damage. The resultant Mitigation Assessment Team (MAT) report identified several places where concrete piles failed [1]. In particular, the MAT observed several instances where scour and erosion exceeded the ability of the pile/column foundations to remain vertical. Instances were also observed where lateral loads and bending moments exceeded the material properties of the foundation piles/columns, causing them to crack and break. Examples are shown below in Figure 1:

Figure 1. Examples of failed concrete piles during Hurricane Michael (adapted from FEMA [1]). Note that the pile closest to the shoreline (pile boxed in red) did not fail.

The left image in Figure 1 shows broken columns that appeared to fail near the location of a concrete slab. The right image of Figure 1 shows lateral cracks (i.e., stress fractures) on the gulf-fronting pile that was possibly attributed to surge or wave action. As pointed out by FEMA [2], concrete piles should not be failing in these manners. Further complicating matters, embedment depths for piles that failed these ways were often unknown. FEMA [2] recommended analysis to determine what caused these failures and how these failures could be prevented in the future. As FEMA [1] pointed out, several failure mechanisms are possible including slab undermining, insufficient number and size of grade beams, erosion and scour, insufficient material strength, inadequate embedment depth, inadequate spacing and size, inadequate connections, wind loads, water loads, and alterations. The overall goal of the research proposed herein is to determine which of these failure mechanisms or combinations thereof led to the structural failures associated with Figure 1 and to develop preliminary mitigation measures to help prevent these sorts of failures from occurring in the future.

2. Relevance to Florida Building Code [3, 4]

Building [3]

- Chapter 16: Structural Design, Section 1612: Flood Loads, 1612.4: Design and Construction
- Chapter 16: Structural Design, Section 1609: Wind Loads, 1609.1.1: Determination of Wind Loads
- Chapter 18: Soils and Foundations, Section 1810: Deep Foundations, 1810.3.1.4: Driven Piles
- Chapter 18: Soils and Foundations, Section 1810: Deep Foundations, 1810.3.3.2 Allowable Lateral Load

Residential [4]

- Chapter 4: Foundations, R407.3 Structural Requirements

3. Research Tasks

Task 1 – Information Gathering and Field Visit

Task Objective: The goal of Task 1 is to collect necessary data for an in-depth foundation system analysis.

Research Approach: Task 1 will consist of data collection associated with the structural foundation failures detailed in FEMA [1]. Since the failed foundations were mostly from residential buildings, obtaining detailed construction drawings will be difficult if not impossible. However, significant information may exist that is accessible. First, a thorough historical image search using Google Earth [5] will be conducted to better understand the structures whose concrete piles failed during Hurricane Michael in terms of their dimension, locations relative to the waterline, and locations of other structural elements near the piles (i.e., slabs, grade beams, etc.). Once this image search is completed, county building officials in Bay County will be contacted to see if any construction drawings are on file from permits that may have been issued. Next, investigators will contact FEMA to determine if any of these structures had elevation certificates and/or letters of map revision (LOMR) that may have been used to reduce flood insurance premiums. A preliminary search using Google Earth [5] showed that much of this foundation debris may still present along Mexico Beach (debris was still present in October of 2020 which was the date of the latest available photos). This will be verified in conversations with Bay County officials. If some debris is still present along Mexico Beach, a field visit will be conducted where investigators will take detailed measurements of this debris – particularly foundation column dimensions, rebar diameters, pile spacing, and approximate scour depths relative to the structures.

Task 2 – Determine Maximum Environmental Load Conditions

Task Objective: The goal of Task 2 is to determine the maximum load conditions that likely led to the concrete foundation failures.

Research Approach: A preliminary analysis using Google Earth [5] showed that the photographs presented by FEMA [1] and reproduced in Figure 1 were likely taken from 1100 FL-30 in Mexico Beach as shown below in Figure 2:

Figure 2. Google Earth [5] image showing 1100 FL-30 in Mexico Beach from October 2020

To assist with orientation, the pile boxed in red in Figure 1 is believed to correspond to the pile boxed in red in Figure 2. An image of this same location is also available from June of 2015 and is shown below in Figure 3. In addition, data from FEMA [1] appeared to indicate that the peak surge elevation in this location was approximately 19 feet above mean sea-level (MSL). Elevation data from Google Earth [5] indicated that this structure was built approximately 12 feet above MSL. Thus, it would appear that 7 feet of water flooded the structure – likely filling the carport beneath the house and possibly flooding part of the house's first floor. This approximate elevation is noted in Figure 3.

Taken together, these preliminary data suggest that the failure mechanism shown in Figures 1 and 2 was due to a combination of wind load, surge/wave loading, and load amplification due to air/water/structure interaction. The wind would have imparted significant lateral loads on roughly the top half of the structure directly. Similarly, the surge and associated wave action would have imparted forces upon the structure's piles directly. In addition to this, some air would have been trapped between the carport and the structure's first floor. This trapped air pocket may have amplified wave loading in a manner similar to the mechanism that caused several bridge collapses during hurricanes. These bridges include several high-profile structures like the Escambia Bay Bridge after Hurricane Ivan in 2004, several Gulf Coast bridges after Hurricane Katrina, and most recently, the Pensacola Bay Bridge after Hurricane Sally in 2020. The trapped air under a structure like this tends to cause a high-frequency oscillatory force upward and laterally that may be as high or higher than water forces alone.

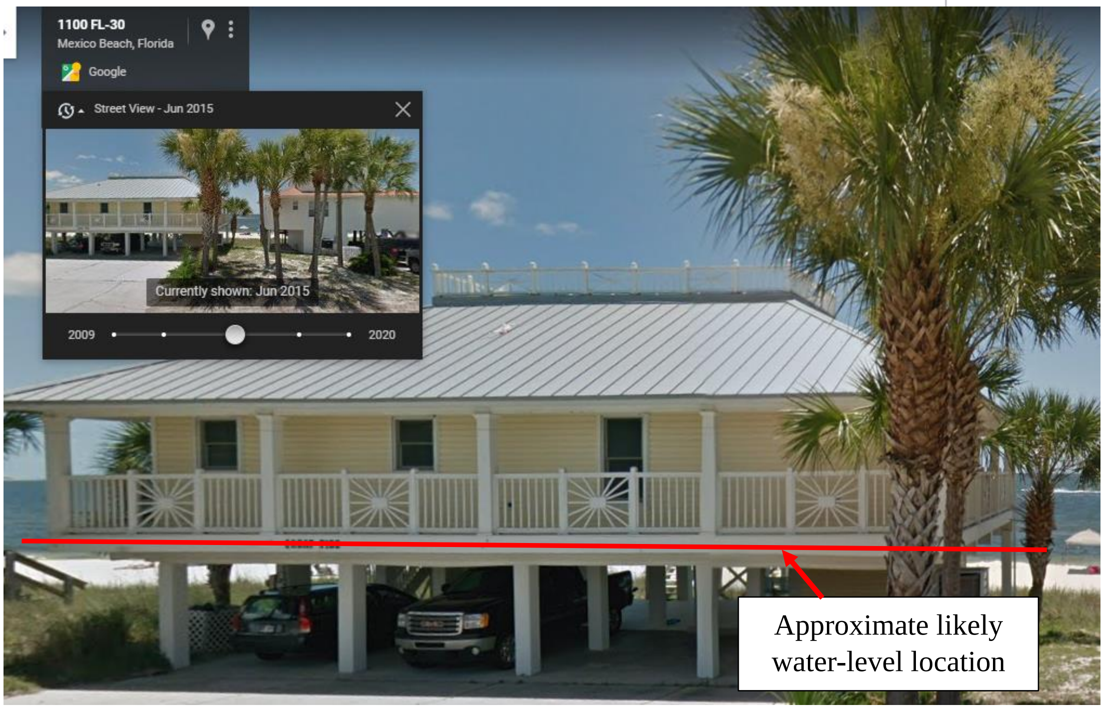

Figure 3. Google Earth [5] image showing 1100 FL-30 in Mexico Beach from June 2015

As a result of this complex multi-fluid loading mechanism, it is unlikely that a first-level component-by-component forcing analysis would be an accurate representation of actual lateral forcing conditions during Hurricane Michael. Nonetheless, as a "first-cut," such an analysis will be performed using results from Task 1. Both the approximate original beach profile and several subsequent scour depths will be investigated during this stage of research. ASCE [6] will be used compute wind loads while linear wave assumptions following Dean and Dalrymple [7] will be used to compute wave loads on the piles and any inundated portions of the structure.

Once the first-level analysis is completed, a computational fluid dynamics (CFD) model of a structure similar to the structure shown in Figure 3 will be conducted using Siemens' Simcenter STAR-CCM+ [8] and results from Task 1. Several approximated scour depths including situations where the subgrade below the ground-level slab has been eroded will be investigated to determine scour depth effect on lateral forcing. It is likely that k-epsilon Reynolds Averaged Navier Stokes modeling will be used throughout because the proposed PI has found that such models describe the "wave loading on bridge" problem well and this "wave loading on a residential structure" problem is similar [9, 10]. A Eulerian volume of fluid (VOF) approach will be used to segregate air from water and to impart both wind and wave forces on the structure. A Richardson extrapolation analysis will be performed to verify that this model has been properly resolved both in terms of its mesh geometry and its implicit timestep. Results from this CFD analysis will yield forcing on a structure like the structure shown in Figure 3 as a function of time.

Results from first-level analysis will be compared with CFD results. If these two sets of data significantly differ, recommendations will be provided about how to modify the Florida Building Code to ensure that coastal wind/surge/wave loads are accurately represented.

Task 3 – Determine Structural Response to Environmental Loading

Task Objective: The goal of Task 3 is to determine how piles that failed during Hurricane Michael respond to environmental loading data computed in Task 2.

Research Approach. Task 3 will utilize the results from Task 2 to determine how a structure like the structure shown in Figure 3 would have responded to wind, wave, and trapped air loading. Like Task 2, two levels of analysis will be performed. First, ACI [11] will be used to compute the piles' capacities and these values will be compared with results from both the first-level and CFD analyses from Task 2. Next, a finite element analysis (FEA) model of the same structure used during Task 2 will be prepared using ANSYS [12]. The soil-structure interaction (SSI) will be modeled simultaneously using GEO5 [13]. Loads will be applied to the models using maximum data from both the first-level and CFD analyses. The soil's response to the loading from Task 2 will be modeled to estimate the lateral bearing capacity and lateral deformation (i.e., pile distortion) using Brom's [14] and Vesic [15] analytical solutions for soil modulus, respectively. Any lateral movement exceeding the serviceability limit at the ground surface will be geometrically remodeled and analyzed to assess the development of critical shear stresses and probable structural failure mechanisms in the piles.

If FEA results show that that structure failed during either of these analyses, then we believe the "why did these structures fail" question has been answered. If results show that the structure does not fail, then CFD assumptions associated with Task 2 will be reinvestigated. During Task 2, several assumptions would have been made in terms of the water elevation relative to the structure, maximum wave height, maximum wavelengths, scour conditions, embedment depth, and maximum wind speeds. Even a small change of some of these variables – particularly the water elevation relative to the structure, the amount/location of scour, and pile embedment depth – could significantly affect results. As such, if the first series of assumptions do not lead to failure, the assumptions will be modified, the CFD analysis will be repeated, and the results will be used as inputs for structural and FEA computations. This process will be repeated iteratively until computational structural failure is observed that approximately matches observations described in FEMA [1] and observed during Task 1.

Preliminarily, simple analysis of Figure 2 and Figure 3 gives some clues as to the likely failure mode. It would appear from these figures that after scour, the ground-level slab acted as fixity point for the piles and incorrectly provided some level of lateral restraint. Repeated extreme loading appears to have caused the piles to fail at this point of fixity.

Task 4 – Develop and Test Mitigation Measures

Task Objective: The goal of Task 4 is to evaluate mitigation measures that could prevent concrete foundation failures in the future.

Research Approach: Once failure criteria have been established during Task 2 and Task 3, the final step of the research proposed here will be to evaluate techniques that could prevent these sorts of structural failures from occurring in the future. Several alternatives will be explored including adding lateral bracing to a structure's piles in the cross-shore direction, ground improvement, adding more piles to a structure, slightly raising the structural elevation, increasing embedment depth, and "venting" the structure to allow trapped air to escape from the structure's underside.

For each mitigation scenario, both Task 2 and Task 3 will be repeated to determine the environmental loading associated with the new structural shape and the structural response to these loads. Results will be presented as either "successful" or "unsuccessful," and mitigation options will be characterized in terms of their applicability for retrofitting existing structures or for building new structures. In addition, recommendations will be provided about how to modify the Florida Building Code's requirements for lateral resistance to coastal environmental loading.

4. Staffing

PI: Raphael Crowley, Ph.D., P.E. The proposed PI is an expert in coastal environmental forcing and scour. He has over 15 years of research experience in both coastal scour and wave/surge loading on coastal superstructures.

Co-PI: Ryan Shamet, Ph.D., E.I. The proposed Co-PI is an expert in geotechnical analysis, including soil response to structural and environmental loading. Dr. Shamet specializes in subsurface characterization and soil strength assessment in Florida. He will assist in the constitutive modeling, soil-structure interaction computations, and modeling of the soil conditions at Mexico Beach.

Graduate Student: to be determined. If this project is funded, one graduate student will work half-time (i.e., 20 hours/week) on this project. His or her graduation will be partially dependent upon successful completion of this research project.

5. Project Budget

The budget for this project will be as follows:

Faculty support	$25,793
Graduate student support	$31,845
Fringe	$1,973
Field visit to Mexico Beach	$1,478
F&A @ 25% Rate	$15,272
Total	$76,361

6. Deliverables

Interim Report and Presentation. Six months after the project's start-date, a detailed report will be prepared and sent to the FBC/HRAC for review. Details associated with the various analyses will be presented including applicable equations, model mesh conditions, and calculation results. This report will serve as a progress update that details the current state of research, preliminary results, and descriptions of any issues that may have been encountered. This report will be presented to the FBC/HRAC via an accompanying presentation at a regularly scheduled FBC/HRAC meeting.

Final Report and Presentation. One year after the project's start-date, a final report will be submitted to the FBC/HRAC for review. Included in this report will be an introduction, detailed methodology including applicable equations and design conditions, results, discussion/analysis, mitigation recommendations, and a list of conclusions. Like the interim report, a presentation to FBC/HRAC at a regularly scheduled meeting will accompany the written report.

7. References

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[9] Matemu, C., Crowley, R., and Resio, D., 2020, "Development of a one-way coupled diffraction/trapped air model for predicting wave loading on bridges under water wave attack," Journal of Fluids and Structures, 97.

[10] Crowley, R., Robeck, C., and Dompe, P., 2018, "A three-dimensional computational analysis of bridges subjected to monochromatic wave attack," Journal of Fluids and Structures, 79, pp. 76-93.

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[14] Broms, Bengt. B., 1964, "Lateral Resistance of Piles is Cohesionless Soils," Journal of Soil Mechanics and Foundations, vol. 90 SM3.

[15] Vesic, A.S., 1977, "Design of Pile Foundations," National Cooperative highway research program synthesis 42, Transportation Research Board.