Education for Improving Resiliency of Coastal Infrastructure:

Multi-hazard Capacity Building to Mitigate Risks in Vulnerable Communities in Puerto Rico

(CRC- Year 1-6)

Ismael Pagán Trinidad-PI, Professor and Director; Carla López del Puerto, Co-PI, Professor, Raúl E. Zapata López, Co-PI, Professor and Associate Director

Department of Civil Engineering and Surveying, University of Puerto Rico at Mayagüez

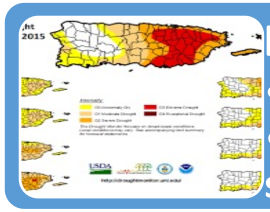
Students (Program, Area) and Posters

Juan Rodríguez (PhD Candidate, Structures); **Yesenia Franqui** (ME, Contruction), **Alexander Molano** (MS, Transportation), **Ivelisse Ramos** (PhD candidate, Transportation**); Neslon Cordero** (ME, Environmental); Undergraduates Course Team (**Ian Feliciano, Brandon Soldevila, Daleen Torres, Marilyn Torres, Gerardo Trossi**); **Jorge Romeu** (MS, Structures)

Additional Material: Faculty Project Videos; Webinar Videos; Activity List; CRC Presentations; more

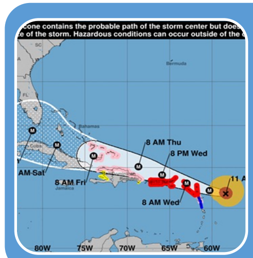
HSOAC-RAND (Ismael Pagán-Trinidad, Carla Lopez del Puerto, Ricardo López,, Francisco Maldonado, Alberto Figueroa, Raúl Zapata-López, José Guevara, José Cedeño, Ivelisse Ramos); Resilient Design Course (Ali Saffar); USARMY ERDC- SOUTHERN COMMAND Resilient Design; EPA Radon Sampling in PR; Transportation T2 Center (Benjamín Colucci); More

Project's Timeline vs. Recent Extreme Events in Puerto Rico (Costs = $139B)



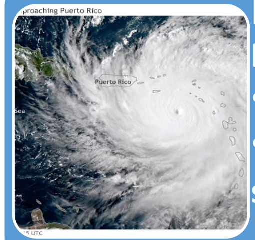
Extreme Drought (2014-2016)

- Third driest period in Puerto Rico
- Extreme agricultural impact and water supply scarcity



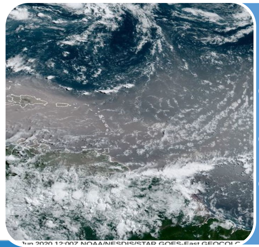
Hurricane Irma-Sept. 6, 2017

- FEMA-DR-4339-PR)
- Category 5, affected the north of the Island
- Prepared vulnerable flooding and landslide conditions for Hurricane Maria



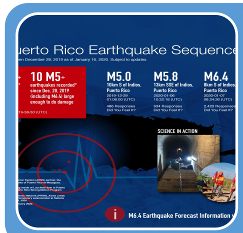
Hurricane María (September 20, 2017) FEMA-DR-4339-PR (near $100 B damages)

- Worst natural disaster in Puerto Rico's history
- Approx. 3000 deaths, floods, 70K landslides, total shut down and chaos



Sahara Dust Cloud-2020

- Worst event in 50 years
- Extreme high temperatures
- Asma and respiratory diseases



Earthquake Sequence (December 2019-date)

- FEMA-DR-4473-PR ($41 M and counting)
- 10 earthquakes with M-5 or higher (3 week)
- Heavy Infrastructure in damages, people still stressful, shaking continues

Tropical Storm Isaias - July 29-31, 2020

- FEMA-DR-4560-PR ($10 M and counting)
- Extreme wind gusts and heavy rainfall.
- Torrential rainfall, floods, and landslides.

Pandemic (January 2020 – date)

- FEMA-DR-4493-PR
- Total lock down
- Extreme impact on the economy and the community

Floods (2019 and 2020)

- FEMA-EM-3417-PR (August 26, 2019) TS Dorian
- FEMA-EM-3537-PR (August 21-23, 2020) TS Laura
- FEMA-DR-4571-PR (September 13, 2020) Storm/Flood ($3.2 M initial estimate)

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https://www.google.com/earth/

Project Description and Summary

HSE Educational Gap

Resiliency of Coastal Infrastructure (RCI)

Goal

Help educate the community by **transferring state of education and practice** knowledge and experiences to stakeholders

Motivation

Engage stakeholders in advancing state of knowledge in coastal resilient infrastructure

Target Stake Holders

Students, faculty, professionals, first responders, work force **(FEMA, municipalities, government, community)**

Formal Education

New Courses, internships, projects

(MS theses, undergraduate research, special professional projects)

Informal Education

Conferences, workshops, seminars, lectures, short courses,

"Conversatories",

Webinars

Help develop Education Culture in Resilient Coastal Infrastructure (RCI)

Provide Education → **Engage Stakeholders** → **Attract Work Force**

Major Outcomes and Impacts

Informal Education

- Webpage (job opportunities, presentations, videos, webinars, etc.)
- Conferences
- Workshops
- Seminars
- Lectures
- Short courses,
- "Conversatories"
- Webinars

Formal Education

- Courses and curriculum (capstone course, graduate research, undergraduate research, special projects)
- Faculty involvement
- Educational resources
- Faculty engagement, expertise advise, and community service

Networking Leverage

- Partnerships
  - Internal
  - External
- Sponsorships
- Proposals
- Community Service
- Media/Webpage

Informal Education

- Webpage (job opportunities, presentations, videos, webinars, etc.)
- Conferences
- Workshops
- Seminars
- Lectures
- Short courses,
- "Conversatories"
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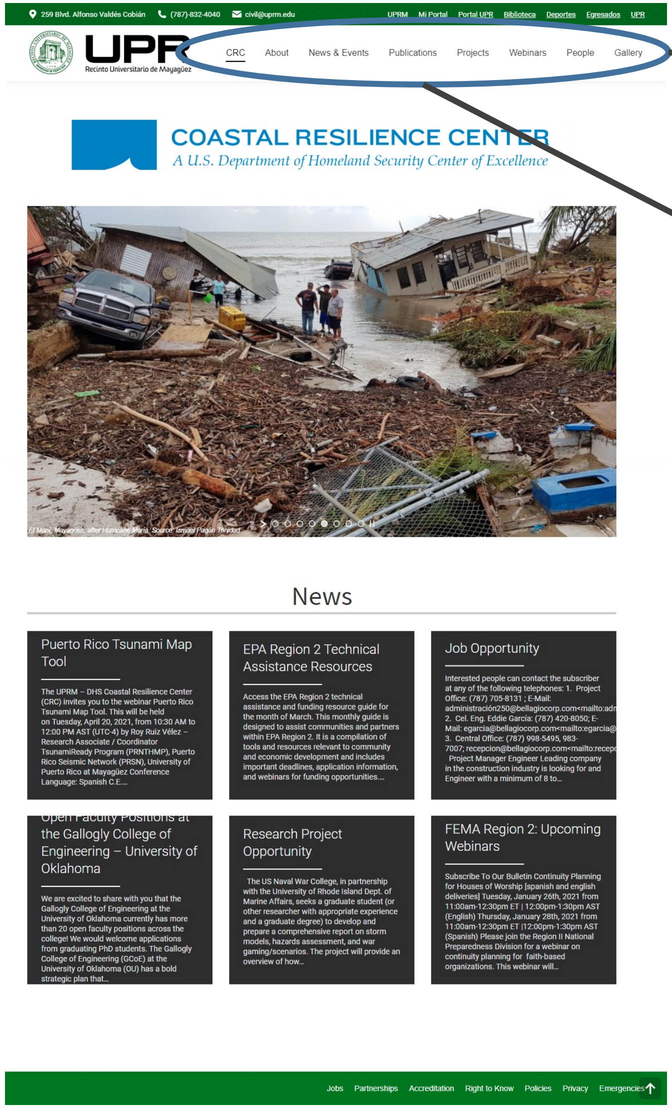
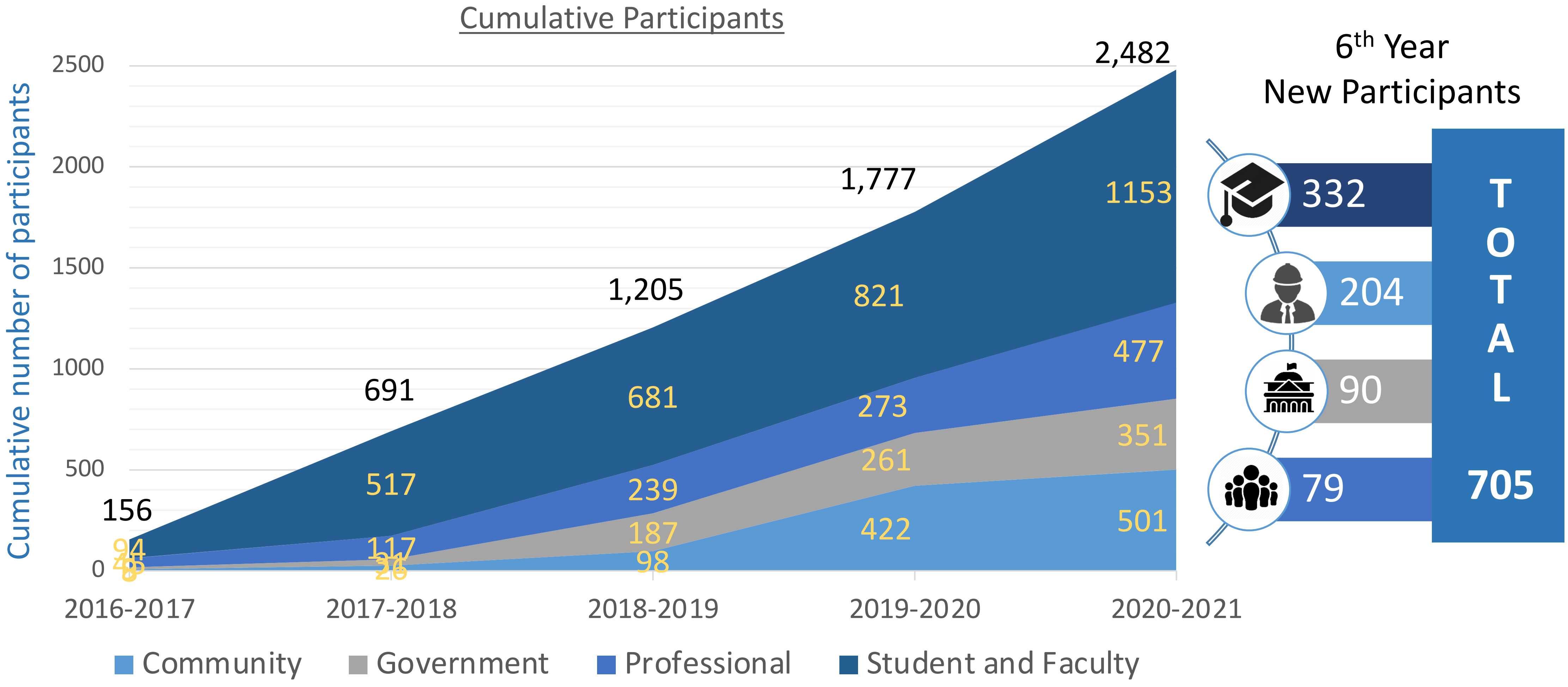
UPRM-DHS CRC
https://www.uprm.edu/inci/crc/

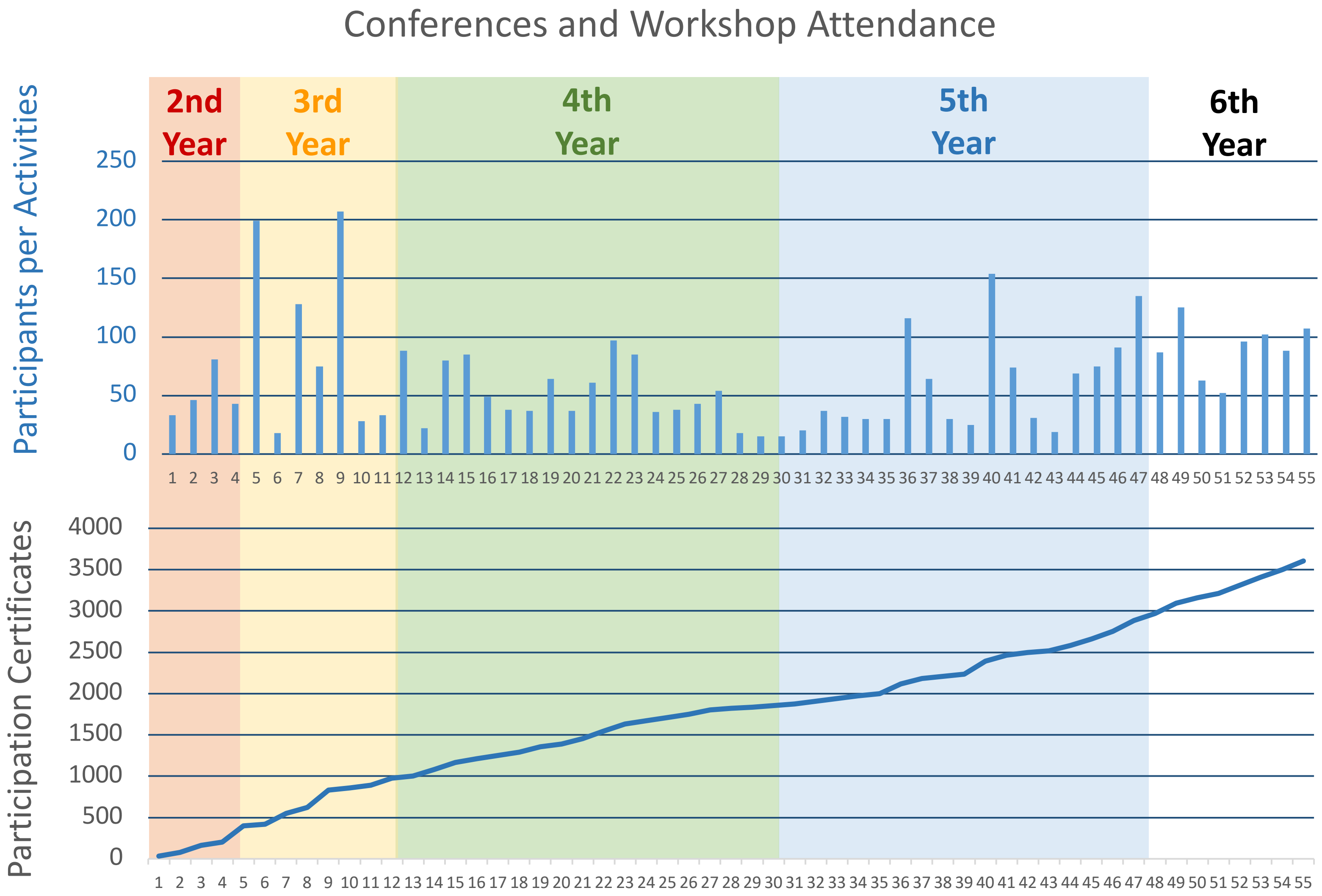


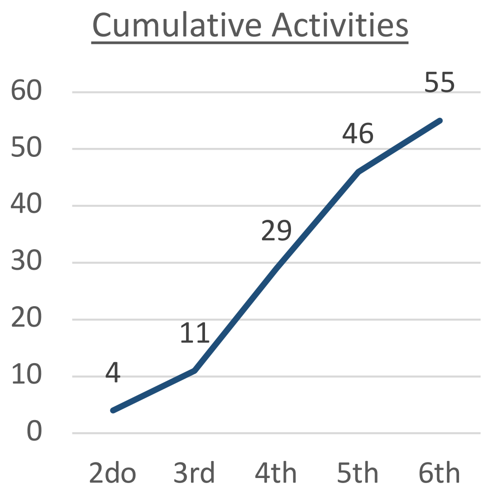
Number of participants: 2,482
Total contact hours of participation: 10,861

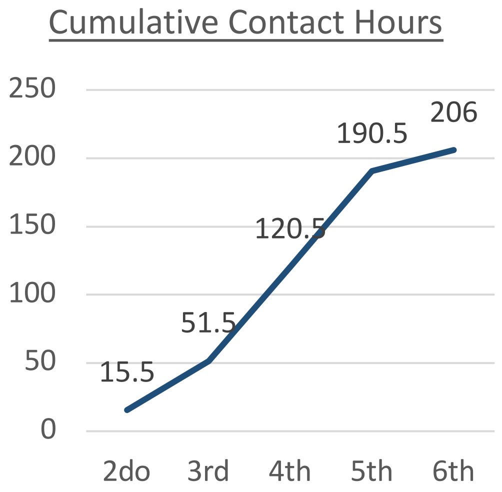


Participation Certificates: 3,605
Contact Hours Offered: 206

Conferences and Workshop: 55
Instructor Recognitions: 116

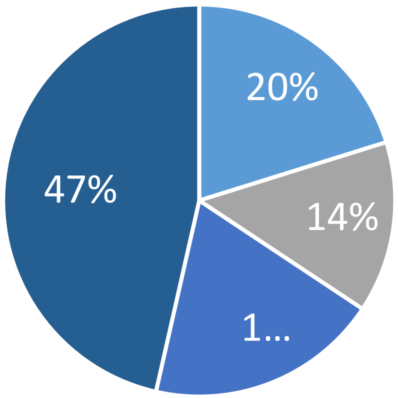




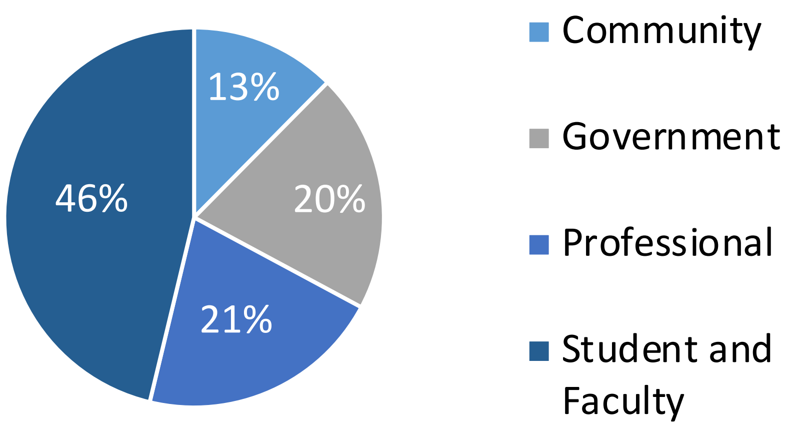


Community, private sector, government and academic participation distribution

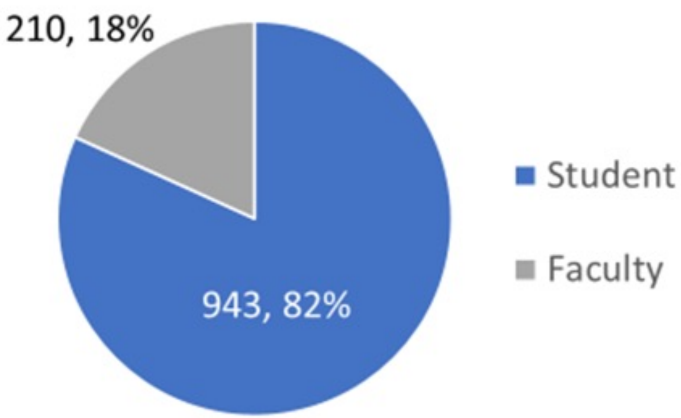
Participants per sector



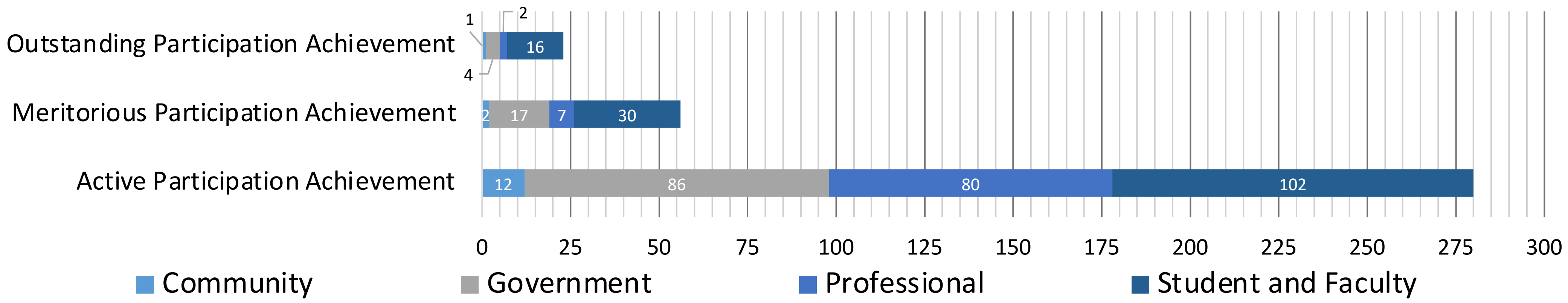
Contact hours per sector



Student and Faculty



Achievement program – sector distribution



Certificate of Participation
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CERTIFICATE OF PARTICIPATION
UPRM-DHS Coastal Resilience Center of Excellence


Certificate of Achievement
COASTAL RESILIENCE CENTER
CERTIFICATE OF ACHIEVEMENT
ACTIVE PARTICIPATION
UPRM-DHS Coastal Resilience Center of Excellence
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CERTIFICATE OF ACHIEVEMENT
MERITORIOUS PARTICIPATION
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COASTAL RESILIENCE CENTER
CERTIFICATE OF ACHIEVEMENT
OUTSTANDING PARTICIPATION
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Webinars Recordings Depository

www.uprm.edu/inci/

In the Webinars Recordings Depository (WRD), you will find the recordings of some of the webinars offered by the UPRM-DHS Coastal Resilience Center of Excellence. The objective of the WRD is to provide resilience education and help develop the workforce of first responders, professionals, students, faculty, and the whole community who work against hazards affecting the coastal infrastructure with a particular focus on our Island.

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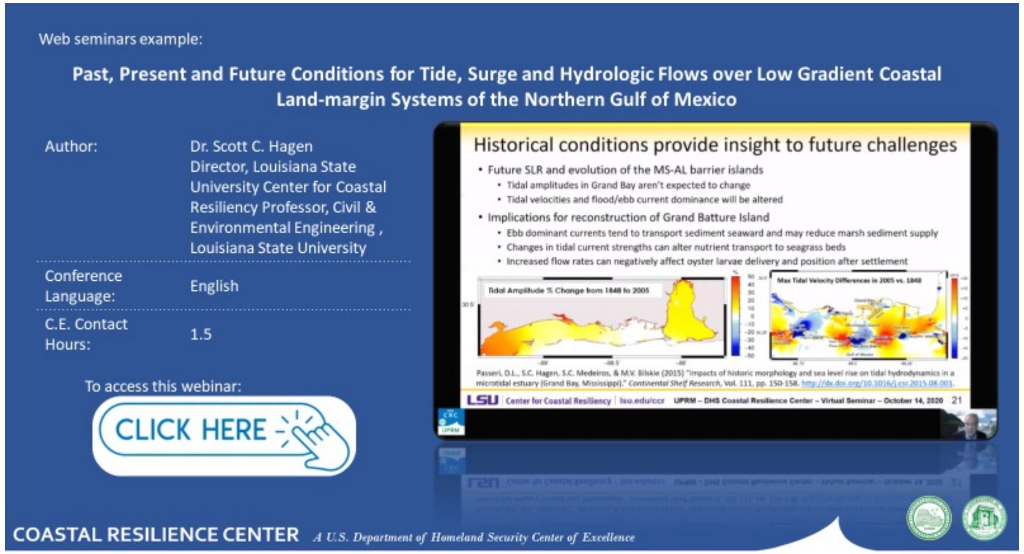
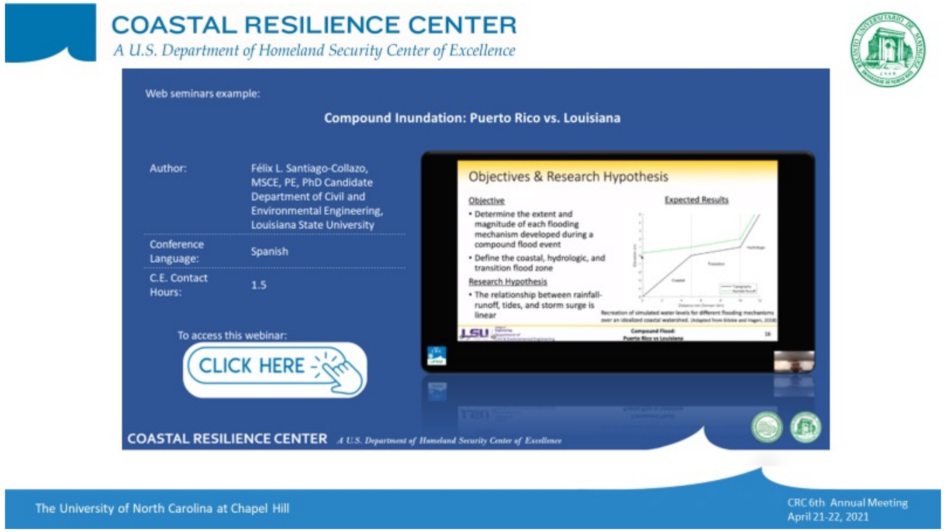
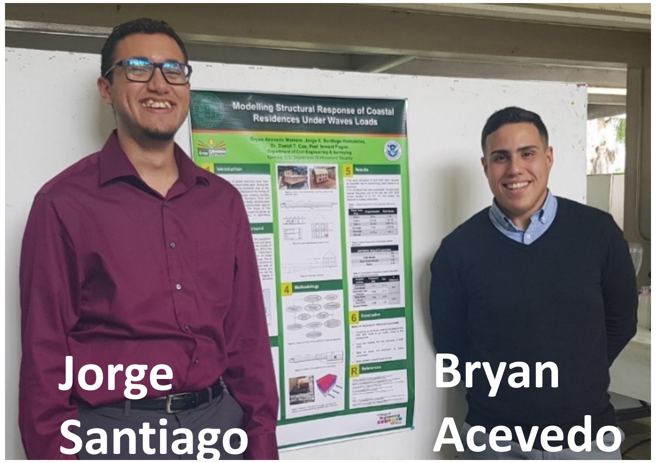




10 UPRM STUDENTS AT SUMREX INTERNSHIPS (OSU, LSU, UCF)

No.	Name	University	Status
1	Diego Delgado	OSU	BSCE, MS- Coastal Engng.(Holland)
2	Kevin Cueto	OSU	BSCE,MS- Structural Engng.
3	Felix Santiago	UCF/LSU	BSCE, PhD Cand. LSU (Coastal)
4	Diego Delgado	UCF/LSU	BSCE, MS- Coastal Engng.(Holland)
5	Héctor Colón	UCF/LSU	BSCE – Professional Practice PR
6	Peter Rivera	OSU	BSCE, MS (Coastal Engng-UPRM
7	Bryan Acevedo	OSU	BSCE, Professional Practice USA
8	Jorge Santiago	OSU	BSCE, PhD Student LSU???
9	Ihan-Jareck Acevedo	OSU	BSEC, MS Students (Coastal) UPRM
10	Robert Lewis	OSU	BSCE, Professional Practice



Second Prize Winners Creative Open Capstone UPRM, Dec. 2018

Formal Education

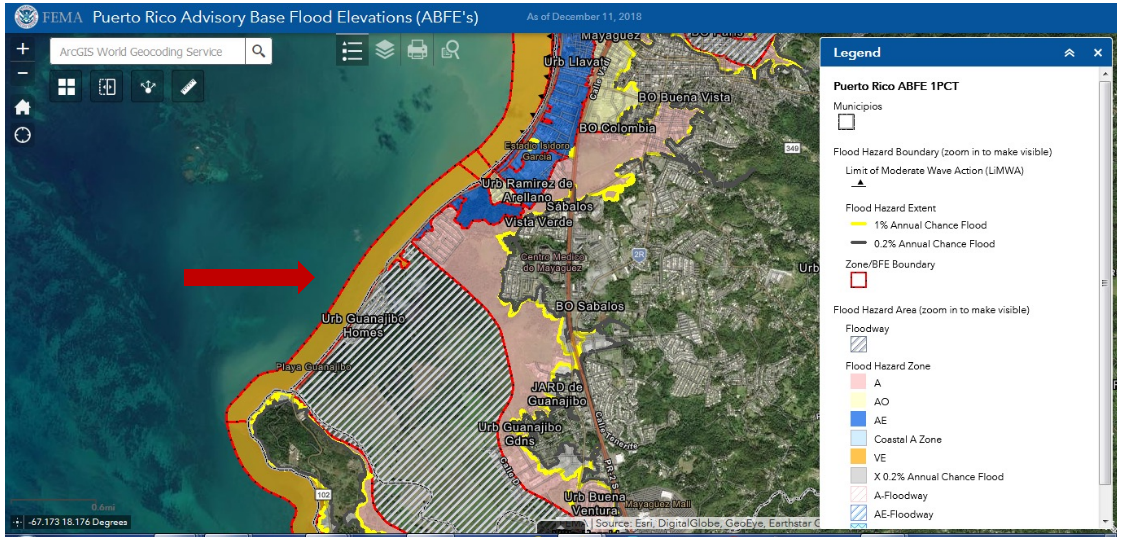
- Courses and curriculum (capstone course, graduate research, undergraduate research, special projects)
- Faculty involvement
- Educational resources
- Faculty engagement, expertise advise, and community service

INCI 5996 Special Problems - Managing Riverine and Coastal Floods for Resilient Communities

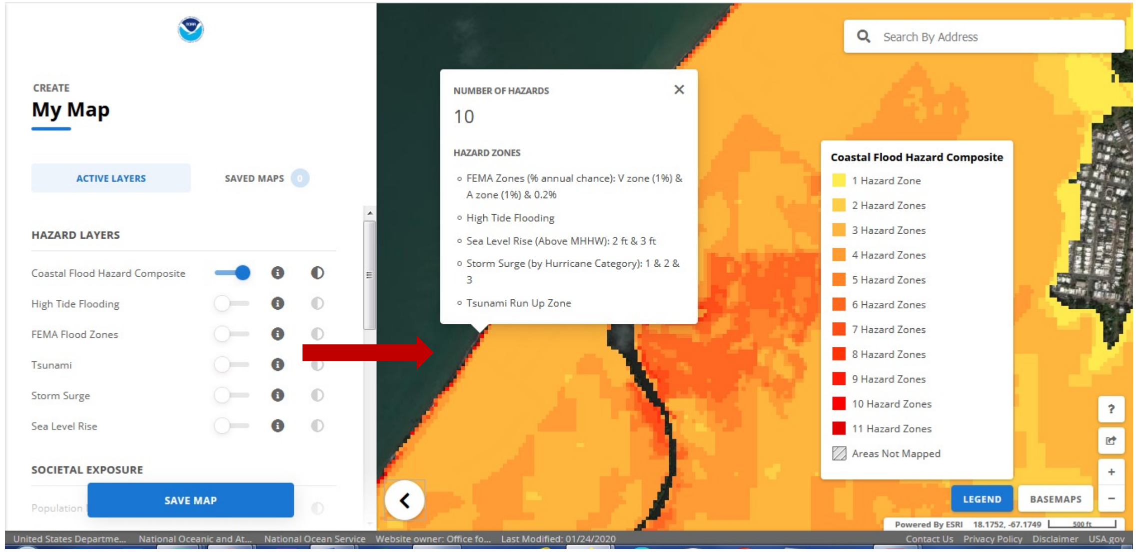
- **Course mission**: Improve the social, infrastructural, economical and the natural environment's resilience towards natural disasters (such as flash floods, hurricanes and any other abrupt change in weather) within coastal zones by conducting research and educating the community. It will gather more information alongside the Department of Homeland security (DHS) Coastal Hazards Center of Excellence.

- **Topics presented include:**
  - **Introduction and Overview**
  - **Complex Project Management Fundamentals**
  - **Riverine and Coastal Floods Multihazards**
  - **Risk and Vulnerability data assessment and evaluation**
  - **Basin and Urban Drainage Systems and Infrastructure**
  - **Field Trip Experiences**
  - **Flood Control Alternatives: Structural and Non- structural**
  - **Nature based Approaches Low Impact Development and Green Flood Control Infrastructure**
  - **Final Project Report and Presentation**
  - **Independent Project Team Works**

- **Selected study area**: Guanajibo River Floodplain at the Mayaguez Bay Coast (1975 TS Eloisa causes the second largest flood ever observed at the area. FEMA, NOAA and PRPB has identified as hazard area with 10 possible water related hazard conditions. The urban infrastructure, commerce, environmental sensitive areas and one protected are at risk.



https://gis.fema.gov/PuertoRicoABFEs/



https://www.coast.noaa.gov/floodexposure/#-7475438,2061944,15z/eyJiIjoiaW1hZ2VyeSJ9

5 Dimensional Project Management for Coastal Communities - Dr. Carla López del Puerto

Educational Objectives

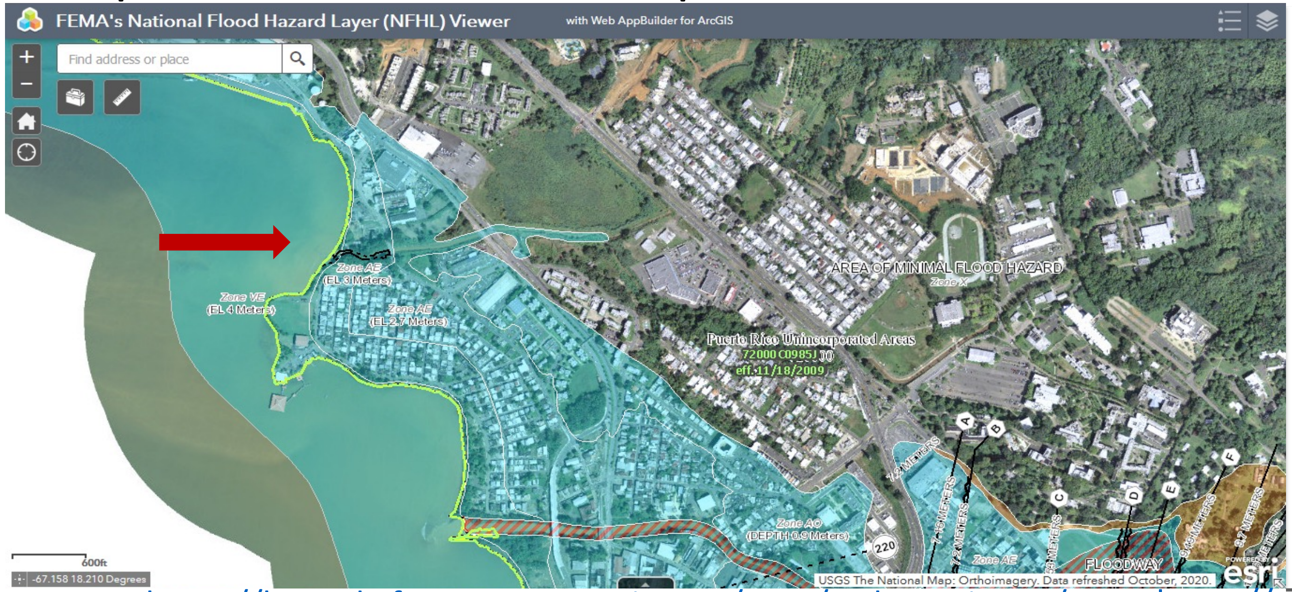
These modules has been designed to give participants the tools needed to manage complex projects effectively, particular emphasis is given to managing complex projects in coastal communities. The modules provide an overview of a 5-dimensional project management model (5DPM) and discussions, team exercises and case studies of actual complex projects.

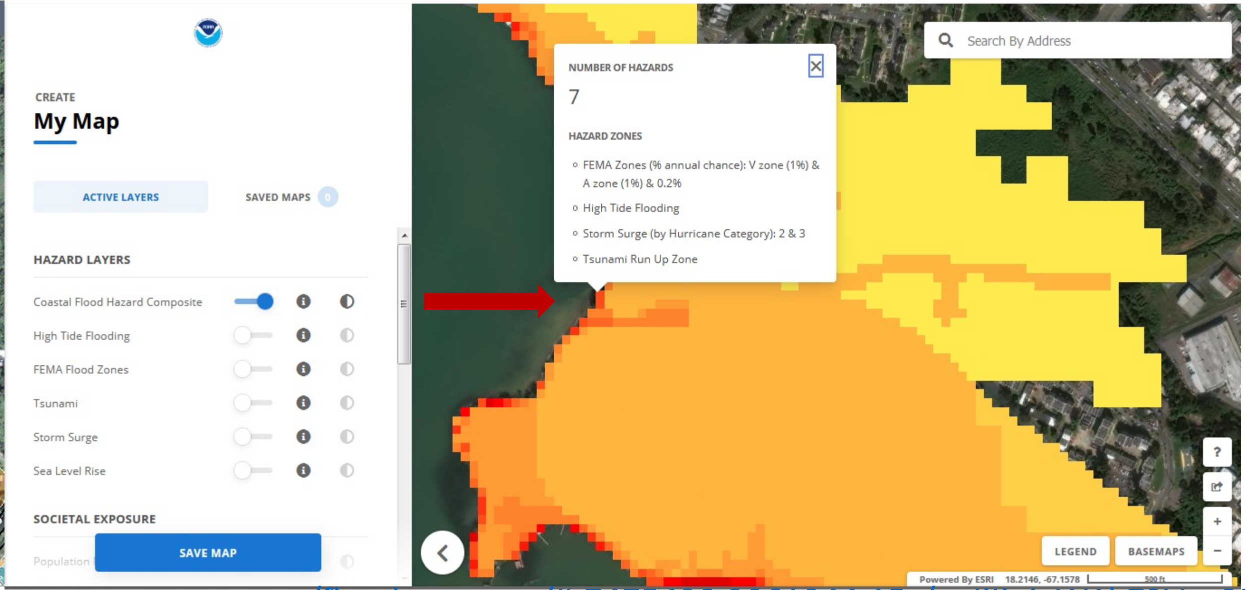
Complexity Mapping for Resilient and Sustainable Infrastructure: The Doppler Radar in Puerto Rico Case Study (Proceeding ASCE conference)

Repairs and Refurbishing of The Guajataca Dam following Hurricane Maria: A Case Study (Proceeding LACCEI conference)

INCI4138 Water Resources Engineering

- Three class periods have been developed to present the concept of water related single and multi-hazards from natures events. The risk and vulnerability of the infrastructure based on its location and exposure to natural hazards is used to bring consciousness of the needs for good planning schemes and provide hazard mitigation to these events.
- **Class project:** Study the risk and vulnerability of a relevant infrastructure facility exposed to natural hazards, then propose mitigation activities. Selected project is the Regional Sanitary Water Pumping System at Mayaguez located next to the beach and the Quebrada de Oro outlet. FEMA, and local government agencies web pages shows this location with seven (7) water related possible hazards. Earthquake is another hazard to this facility.





https://hazards-fema.maps.arcgis.com/apps/webappviewer/ https://www.coast.noaa.gov/floodexposure/#-7475438,2061944,15z/eyJiljoiaW1hZ2VyeSJ9

Regular Courses (INCI 4950):The Senior CE Capstone Experience

Incorporate Coastal Resilient Design

- Design a model coastal urban cluster
- Found a design professional company
- Develop a Feasibility Study
- Conceptual Design
- Preliminary Design
- Final Design

Location

Mayagüez Bay Area

Resources

Ten students/company

Five Professors

Five Graduate Students

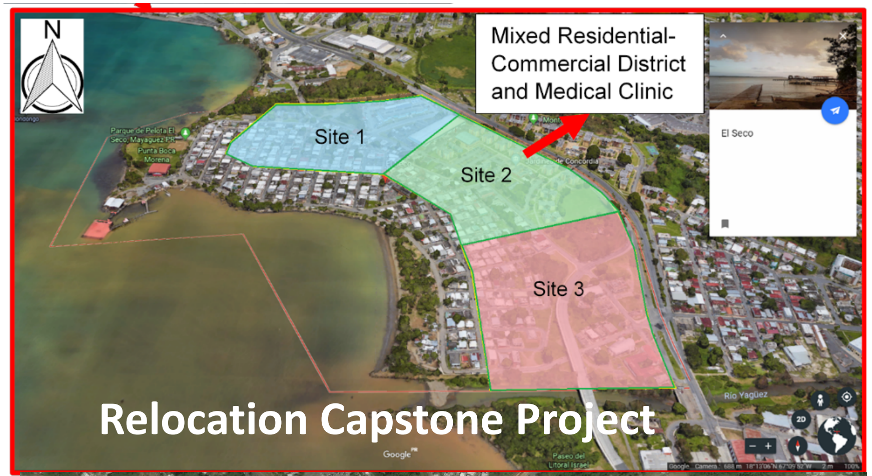
Feasibility & Sustainability

Legal, Political, Social, Cultural, Environmental, Technical, Economical

Components

Site Development, Environmental ,

Transportation, Water/Waste Water , Geotechnical , Structural/Architectural



CAPSTONE DESIGN PROJECT

Site: El Seco Community - Spring Semester

Participants: 31 Students, 5 Faculties, 2 Grad Students

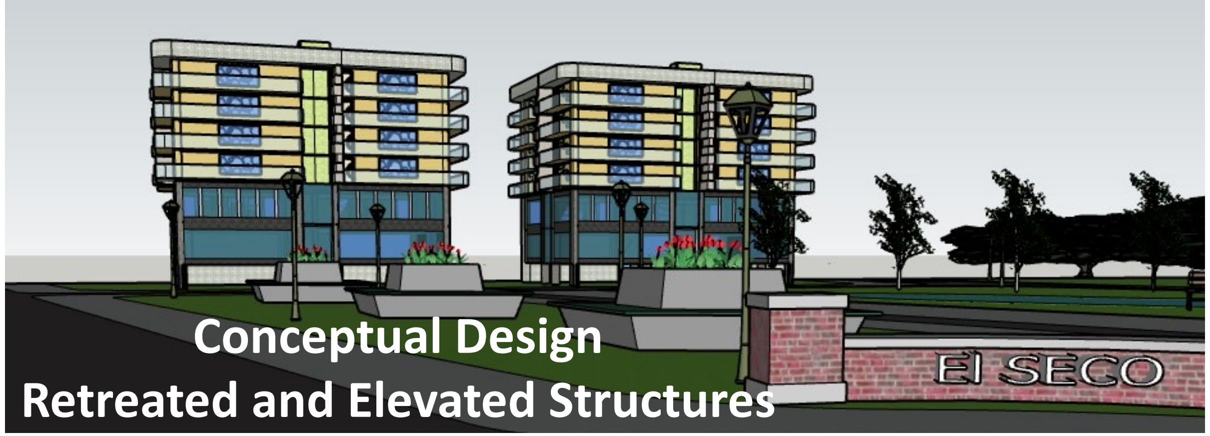
Purpose: Mixed Use Project (Commercial, Offices , Housing)

Hazards: Coastal and riverine floods, wind, earthquake, soil instabilities

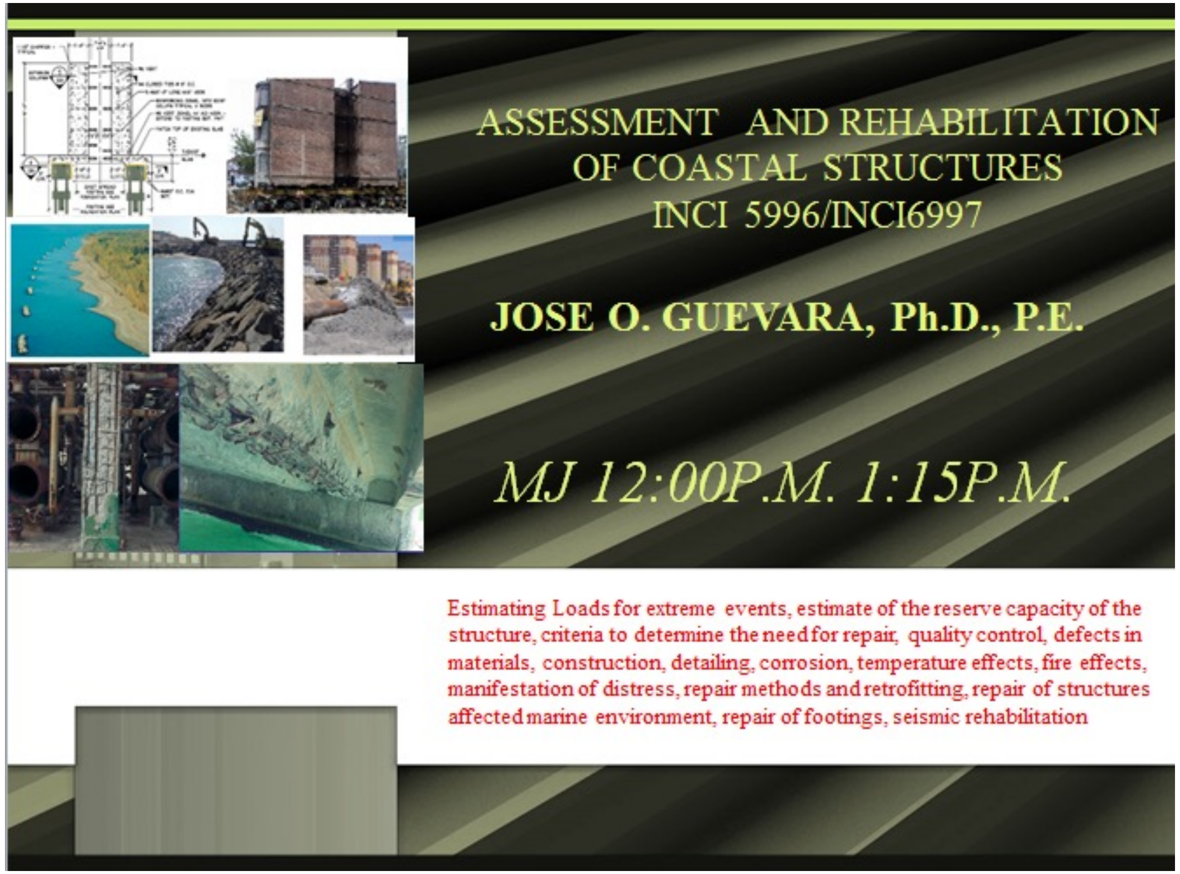
Objective: Flood Relocation Project (adjacent to the neighborhood)

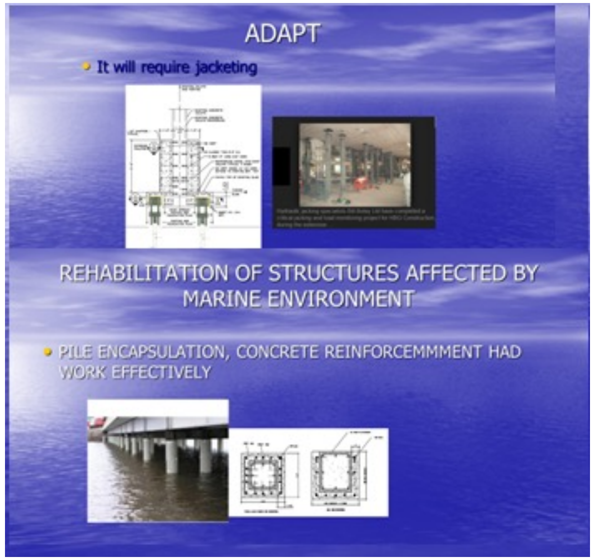
Buyout – Relocation Project

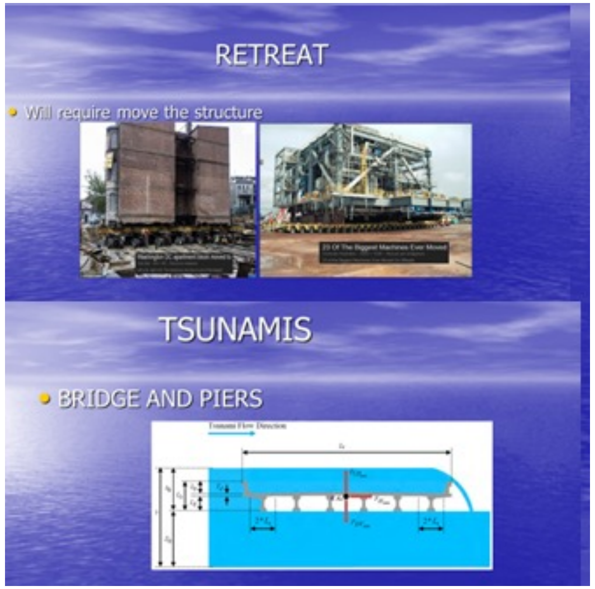
3D view of overall alternative 3 project site - Conceptual Plan-El Seco Community



INCI 5996 - Regular Courses –Rehabilitation



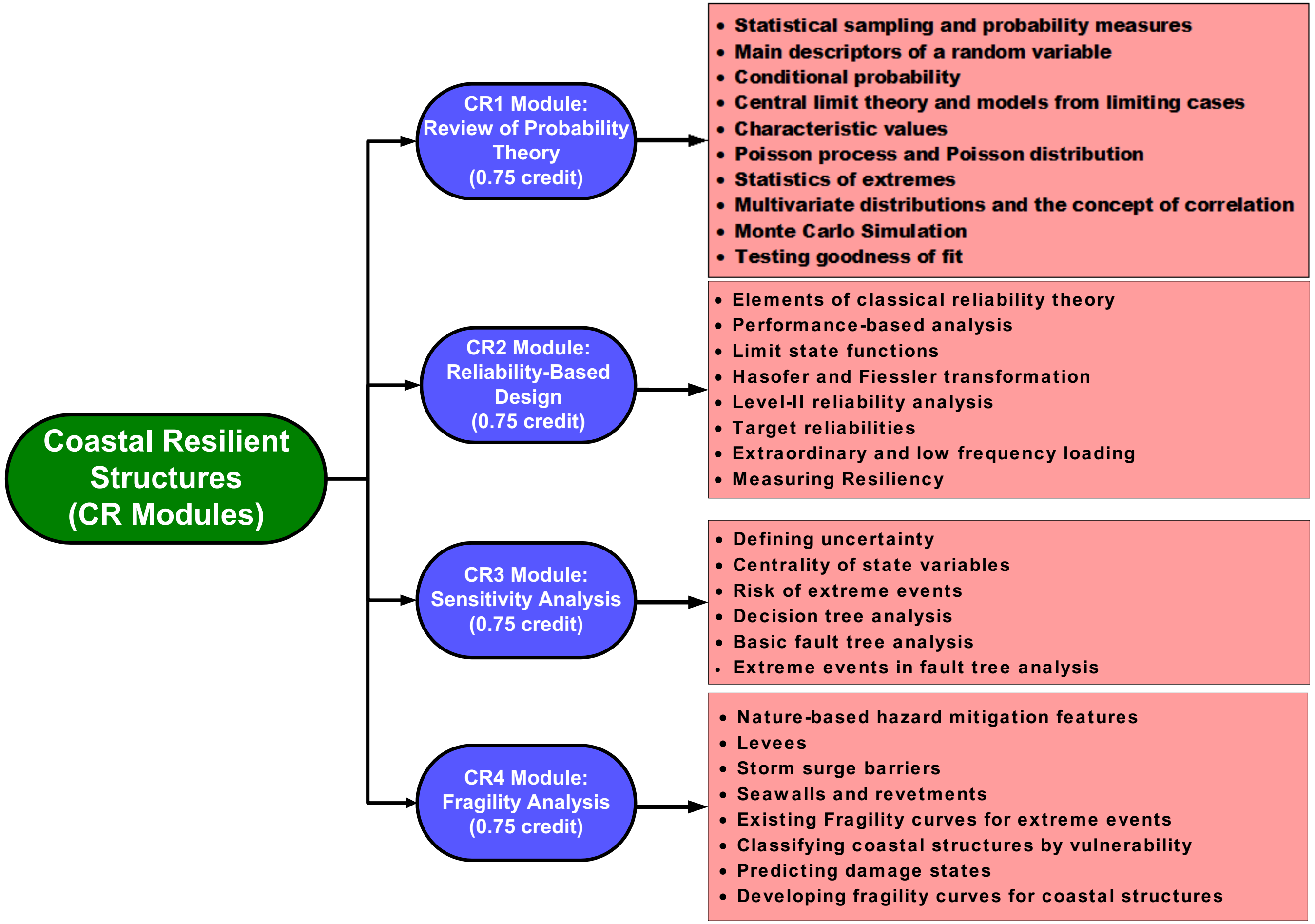




Proposed New Course: *Nature's Multi Hazards and Man-Actions for Sustainable and Resilient Infrastructure*

- **Nature's Behavior**
  - Nature is needed for life as we know it.
  - Nature is our responsibility
  - Nature is continuously evolving
  - We can not eliminate hazards but mitigate hazards
- **Natural Hazards**
  - Natural Hazards to whom (mankind, nature itself, . . .)
  - Types of Risk Hazards
  - Common relationships among the natural hazards: Hurricanes (wind, storm surge, heavy rainfall, flooding, debris, erosion, deposition, landslides, …)
  - Environmental issues (concerns and precautions before, during and after) are priority to keep us a life
- **Resilient and Sustainable Response**
  - Infrastructure priorities
  - Complexity matrix of the analysis and recovery issues
  - Assessment studies
  - Planning and action plans
  - Mitigation alternatives for given single hazard
  - Mitigation issues for multi hazard events
  - Community awareness
- **Coastal Zone Multi Hazards**
  - Possible multi hazards of this zone
  - Frequency of riverine and coastal flooding effects
  - Hurricanes producing higher storm surge, tidal effects,
  - Earthquakes generating Tsunamis, liquefaction, subsidence or uplift
  - Data collection needed
  - Available action plans for single events and for multi hazard events
  - Regulations (current ones and the ones to be improved)
  - Resources available (materials, working labors,
  - Economic resources to sponsor mitigation activities
  - Mitigation activities

Resilient Design of Coastal Structure-Dr. Alí Saffar (showcase video)



Educational Objectives

The problem is viewed primarily from a designer's perspective.

Coastal hazard frequency maps are examined and utilized to assign event scenarios and the associated combinations of loads.

These include: existing flood and tsunami maps, surge maps of the type being developed by the US Army Corps of Engineers.

Test cases are taught using level II reliability analysis.

The risk assessment toolkits are developed to assist stockholders of differing backgrounds.

Graduate Students - Graduated

Research Theses and Projects at UPRM

- **Angel Alicea (PhD): "Dynamic Identification and Nonlinear Modeling for the Structural Health Assessment of Aged Coastal Infrastructure in Puerto Rico", PhD dissertation completed in December 2018, also worked in educational activities for the project, wasco-sponsored by FHWA Eisenhower Fellowships.**
- **Kevin Cueto (MSCE):"Modeling considering Computational Fluid Dynamics of hydraulic pressure exerted on coastal structures", MS Completed. Also works in educational activities for the project.**
- **Jorge Romeu (MECE): "Structural Analysis of Common Coastal Structures Found on the West Coast of PR using FEMA P-646", ME. Also works in educational activities for the project, serves as instructor for Capstone course.**
- **Efraín Ramos (MSCE): "Stochastic Simulation of Tropical Cyclones for Quantification of Uncertainty associated with Strong Recurrence and Intensity", MS thesis in progress. Currently working on his thesis at CHL-ERDC.**

Graduate Students - Ongoing

Active Research Theses, Projects and Students at UPRM

- **Alexander Molano (MSCE-Transportation): "Education and Awareness in Resilience of Coastal Transportation Infrastructure", MS thesis in progress, also works in educational activities for the project, prepared several presentations and participated in Special Topics courses, FHWA Eisenhower Fellow.**
- **Juan Rodríguez (PhD - Structures): 1. "Variation of the nonlinear dynamic response of three-dimensional buildings of reinforced concrete considering the directionality of seismic accelerations", PhD dissertation in progress. 2. Also works in educational activities for the project preparing presentations, certificates and collecting information.**
- **Nelson Cordero (MSCE-Coastal): " Configuration and Validation of the Weather Research and Forecasting Model (WRF) for Tropical and Extratropical Cyclones with Applications in Hydrodynamic Modeling" , MS thesis in progress.**
- **Yesenia Franqui (ME- Construction Management). Works as the Webmaster and activity coordination.**
- **Ivelisse Ramos (PhD Transportation): "Development of New Work Zone Traffic Signs for Road Re-Construction Process"**

Networking Leverage

- **Partnerships**
  - **Internal**
  - **External**
- **Sponsorships**
- **Proposals**
- **Community Service**
- **Media/Webpage**

HSOAC-RAND (Ismael Pagán-Trinidad, Carla Lopez del Puerto, Ricardo López,, Francisco Maldonado, Alberto Figueroa, Raúl Zapata, José Guevara, José Cedeño, Ivelisse Ramos); **Resilient Design Course** (Ali Saffar); **USARMY ERDC- SOUTHERN COMMAND Resilient Design**; **EPA Radon Sampling in PR; Transportation T2 Center** (Benjamín Colucci); **JSU-TAMU PIRE Program** (Dr. Robert Whalin) ; **Oregon State University** (Dan Cox); **Notheastern University** (Dr. Ganguly Auroop); **NCSU** (Gavin Smith); **Louisiana State University** (Scott Hagen); **HUD** (Francisco Maldoando, Ismael Pagán Trinidad)

Networking and Collaboration with:

Posters from UPRM Students

Nonlinear Dynamic Response of Reinforced Concrete Buildings and the Effect of the Directionality of Seismic Accelerations: An Innovative Structural Analysis Program

Student: Juan A. Rodríguez, MSCE, PE, PLS, PhD Student
Research Mentors: Luis E. Suárez, PhD, Professor and Ricardo R. López, PhD, PE, Adjunct Professor
Department of Civil Engineering and Surveying, University of Puerto Rico (UPRM)

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Homeland Security Challenge

The security of a nation implies having a complete overview of all possible risks, and since time immemorial, humanity has known about the rare but inevitable seismic risk. History serves as a reference to establish how catastrophic an earthquake can be for a region where its inhabitants do not take precautionary measures to face this natural event resiliently. In the United States, the 1994 M6.7 Northridge earthquake in California remains the third costliest disaster in U.S. history; and it was one of the most expensive disasters for the federal government (FEMA, 2017). The entire west coast of the continental United States, the south coast of Alaska, Hawaii, and Guan, over twenty-three thousand miles of coastline, are identified as very high risk areas by the USGS (FEMA, 2016). Puerto Rico and the Virgin Islands are categorized as high and moderately high seismic risk, although recent technical studies indicate that the risk could be underestimated. This study develops a program to model the behavior of reinforced concrete structures during an earthquake and will be used to study the effect of the directionality of seismic accelerations, in order to provide an alternative to understand better the interaction between essential components of our infrastructure, buildings, and these natural phenomena. As the knowledge of structural performance during earthquakes is improved and tools that can be used during design are added, we will move towards safer and more resilient communities.

Methodology

To synthesize the methodology of this work, will first present what is related to coding the analysis program in terms of programming and computational capacity. The analysis program is coded in two main parts: a computational executor and a graphical user interface (GUI). Everything related to the analysis calculations is coding in the Fortran programming language, using the standard adopted in 2010 (ISO / IEC, 2010). This language was selected for its characteristics of computational speed and numerical precision (machine epsilon = 1.92×10^{-34}, zero in logical comparisons = 1×10^{-33}) and is a widely known language in the field of science and engineering. The GUI is built with the Visual Basic 2017 coding language as an MS Windows Forms App with .NET Framework 4.6.1. In summary, compatible with the vast majority of current Windows OS computers with 64-bit CPUs.

The structural analysis model is based on the typical three-dimensional cartesian coordinate analysis environment where nodes are defined and linked together with elements to simulate structural elements' behavior. The nodes are characterized by their three coordinates, associated mass, and six degrees of freedom (DOF) (three displacements or force and three rotations or moments). Elements are defined by up to 85 parameters and a diagram to define geometry and steel reinforcements' location in their cross-section. The main behaviors of non-linearity and inelasticity of reinforced concrete structures are considered through the parameters that define the elements. The definition of floor slab-type elements that maintain elastic behavior is included as special elements. Once the structure's geometry and the mechanical characteristics of its components are defined, the analysis model simulates the building's nonlinear inelastic dynamic response. Figure 1 is a synthesis of the model.

APPLICABILITY OF LOADS

- Gradual application of dead loads
- Gradual application of live loads
- It allows the gradual application of other static loads or displacement considering the nonlinear inelastic behavior
- The program permits a pushover analysis
- Application of seismic loads using acceleration records at the base (1, 2, or 3 orthogonal directions)

PRINCIPLES CONSIDERED IN THE ANALYSIS

- Coordinate transformations of stiffness for the correct interrelation between DOF
- Relationships between rotations and curvatures of sections
- Static load application by the incremental method
- Conservation of the balance of static forces
- Condensation of DOF
- Application of dynamic loads by the incremental method
- Numerical solution using Newmark-beta method
- Consideration of proportional damping to stiffness and mass
- Conservation of the dynamic balance of forces

SOURCES OF NON-LINEARITY

- Cracking in the element section
- Yield stress in reinforcing steel
- Decrease in capacity due to ultimate stress in reinforcing steel
- Hysteretic behavior in four rotational springs per element
- Decrease in the capacity of the element due to failures:
  - shear
  - shear-torsion interaction
  - torsion moments
  - interaction between axial loads and bending moments.

FIGURE 1: Key elements on the analysis model

Once the analysis program is completed and validated, it will be used to model different buildings designed according to current building codes, to contrast the response before different incidence scenarios of seismic accelerations in terms of the directions. The idea is to make the applied acceleration records orthogonal directions that do not match the elements orthogonal axes and the frame arrangement, which are typically defined during design.

Outcomes

The present research is undergoing; the phase where the structural analysis model is defined was completed, and its mathematical execution was coded. The GUI was prepared, and dozens of analyses were carryout to validate the model. Figure 2 shows some example screenshots of the analysis program (alpha version). In the process, inclusions have been identified to improve the analysis model. Additional considerations for shear deformations were added, the possibility of rigid segments in the elements was included, and mathematical operations were reformulated for better computational efficiency. This reformulation had a significant impact on the execution time of the analysis since, by the nature of the model, it is required to solve systems of equations with several hundred unknowns continuously for thousands of times. The new version solves 76% faster for gradual application of static loads and 32% faster for the base accelerations' analysis. This work is currently in the validation phase of the new version to start analyzing and studying the change in seismic performance influenced by the directionality of seismic accelerations.

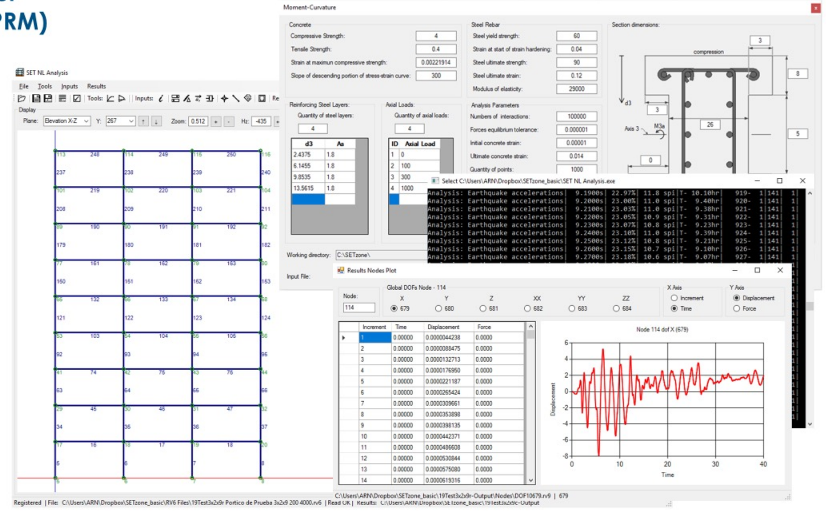

FIGURE 2: Examples screenshots of the analysis program (alpha version)

Conclusions

This research is not yet at the stage to issue conclusions. However, it is expected that a new tool will be obtained that will serve for future works and designs. This tool has more flexibility for the inclusion of parameters and methodologies than commercial programs, which do not offer access to their source code. It is expected that the study of comparative performances between different incidence scenarios of seismic accelerations in terms of the directions will serve to issue design recommendations to complement currently used analysis methodologies. This work's ultimate goal is to improve our infrastructure's resiliency, protecting the life, safety, and property of hundreds of communities in seismic risk areas.

Acknowledgements

This material is based upon work supported by the U.S. Department of Homeland Security under Grant Award Number 2015-ST-061-ND0001-01. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S Department of Homeland Security.

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Critical Infrastructure and the Resilient-Sustainable Reconstruction of Puerto Rico After Hurricane Maria

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UPR Recinto Universitario de Mayagüez

COASTAL RESILIENCE CENTER
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Introduction

Critical infrastructure poses a substantial risk in the face of hazardous natural phenomena. Hurricanes, storms, earthquakes, heavy rains and other natural disasters are the most likely and most impacting events. Puerto Rico's location greatly exposes the island to these phenomena and makes it vulnerable to extreme damages, as was the case of Hurricane Irma and María. Category 5 Hurricane Irma skirted the northeastern side of Puerto Rico on September 6, 2017, causing damages to part of the Island. Two weeks later, Category 4 Hurricane María made landfall in Puerto Rico through the southeast region in the early morning of September 20, 2017. The event caused severe damages to the Island's critical infrastructure which was determined to be in poor condition and mostly below updated and adequate engineering resilient design standards. For its reconstruction, increasing the resilience of Puerto Rico's infrastructure is of upmost importance. As a response, objectives are set forth to identify design and construction concepts that apply to the Island's critical infrastructure. Furthermore, recommendations to work with the interdependence of critical systems are paramount for this investigation.

Approach / Methodology

CISA Critical Infrastructure Sectors

https://www.cisa.gov/critical-infrastructure-sectors

Puerto Rico's Multi-Hazards Exposure

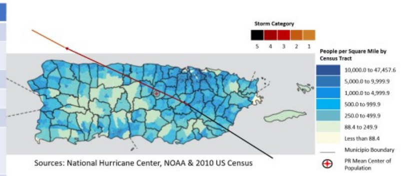
Hurricanes/Storms /Tropical Cyclones	• Winds • Storm Surges • Waves • Tides
Earthquakes	• Tsunamis • Landslides • Mudflows • Subsidence
Rainfall	• Droughts • Riverine Flash Floods • Urban Floods • Scour
Others	• Ambient Temperature • Cold and Warm Fronts • Orographic Effects • Wildfires

Structures Within 1 km of the Coast

(Díaz, 2021; Pagán-Trinidad et al., 2019)

Coastal Assets at Risk	Public and Private Infrastructure
Ports	12
Airports	11
Hospitals	3
Schools	36
PR Power Generation Plants	7 (5 Public – 2 Private)
PR Aqueducts and Sewers Authority	200 km potable water network 260 km sanitary infrastructure 28 wastewater treatment plants
PR Industrial Developments Co.	81 Industrial Parks

Hurricane Maria Trajectory



Sources: National Hurricane Center, NOAA & 2010 US Census

Outcomes / Results

Grading Scale for Puerto Rico's Infrastructure

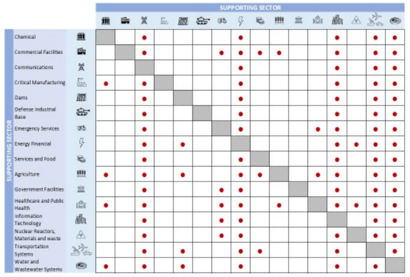
(ASCE, 2019)

Dams	D+
Bridges	D+
Drinking Water	D
Energy	F
Ports	D
Roads	D-
Solid Waste	D-
Waste Water	D+
G.P.A.	D-

A Exceptional, Fit for the Future
B Good, Adequate for Now
C Mediocre, Requires Attention
D Poor, At Risk
F Failing/Critical Unit for Purpose

Critical Infrastructure Dependency Matrix

(Homeland Security, 2018)



Damages caused by Hurricane Maria

(Pagán-Trinidad et al., 2019)

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Conclusions

Sector's Damages and Repairs

(HSOAC, 2020)

Dams	Bridges	Ports	Wastewater	Roads	Energy
Failure of Guajataca Dam	Severely Damaged: 27%	Over $11.2 million was obligated to the PRPA work that includes repairs to 12 piers	PRASA pump station Damage: ~575 millions (FY 2018 dollars)	Estimated damage value in millions of dollars (roads and bridges): 646.7	Downed or damaged transmissions: 115 kV – 1,482 (27%), 230 kV – 511 (21%)
Reparations are estimated to go as high as 500 millions	Moderately Damaged: 63%		Damaged stormwater pump stations: 17	Less than 8% of the roads were open a month after Maria	Downed towers and poles: 115 kV – 648 (12%), 230kV – 107 (4%)
	Collapsed or destroyed: 50		70% of potable water treatment and distribution systems were affected	PRHTA estimates that it will need $3.1 billion of capital expenditures	Damaged insulators and other components: 115kV – 834 (15%), 404 (17%)
			A total of $551 is needed for renewal and replacement		

Main Resiliency Recommendations for Puerto Rico's Infrastructure

(ASCE, 2019)

Dams	Bridges	Ports	Wastewater	Roads	Energy
• Implementation of a yearly dredging plan • Hydraulic barrier system • Increase funding • Increase capacity and lifespan • Rehabilitate, maintain and maximize the use of hydropower resources in the system	• Higher weight allowance. • Considerations of stronger side effects caused by natural disasters or extreme events for new designs • Life cycle approaches • Preventive maintenance programs	• Repair and rehabilitate Piers 11-14 • Invest in resiliency improvements for critical piers throughout the island.	• Implementation of sewer line replacement and renovation programs • Improve detection and repair of infiltration and exfiltration • Consider the use of alternate energy systems in wastewater treatment facilities	• Improve pavement conditions • Establish an effective and systemic pavement preventive program • Encourage collection, dissemination, and processing of real-time data for day-to-day benefits and long-term planning	• Adopt ASCE 7 codes and standards or consensus industry standards with at least a 160-mph design wind speed • Utilize smart grid technologies, redundant power delivery, and hardened communications • Increase use of readily available solar and wind generation

- Critical infrastructure requires conscientious operation and consistent, adequate maintenance investments to provide the levels of service and protection developed by the designer and expected by the customer and affected public.
- Design criteria needs to always consider how the performance of individual components affects the overall performance of a system.
- Puerto Rico needs to increase infrastructure investment by $1.3 to $2.3 billion annually in order to reach a desired range of 2.5%-3.5% of GDP (ASCE, 2019).

Acknowledgements

This material is based upon work supported by the U.S. Department of Homeland Security under Cooperative Agreement Number 2015-ST-061-ND0001-01. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing official policies, either expressed or implied, of the U.S Department of Homeland Security.

Assessment of Hurricane Vortex Models and Boundary Layer Models for the Development of Wind and Pressure Profiles and Fields

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Research Mentor(s): Efraín Ramos-Santiago and Norberto C. Nadal-Caraballo
Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers
Ismael Pagán-Trinidad and Raúl Zapata-López, University of Puerto Rico

Homeland Security Challenge

The probabilistic assessment of risk posed by flooding and other coastal hazards has been an area of concern and recently the focus of a revaluation by different agencies. This research project is part of the CHS's PCHA* framework and will aid in the development of regulation and guidance that incorporates the latest developments in coastal hazard analysis and quantification of related uncertainties.

Approach / Methodology

- Wind/Pressure Profiles MATLAB scripts
- Vortex model fitting, RMSE minimization
- Conversion of gradient to surface winds
- Interpolation for Wind Fields

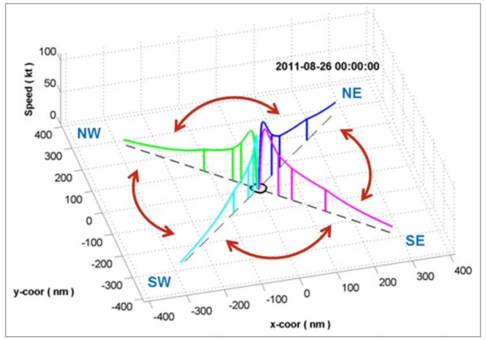

Figure 1: Example wind profiles. Taken from Gao et al. (2015)

* (CHS) Coastal Hazards System program
* (PCHA)Probabilistic Coastal Hazard Analysis

Outcomes / Results

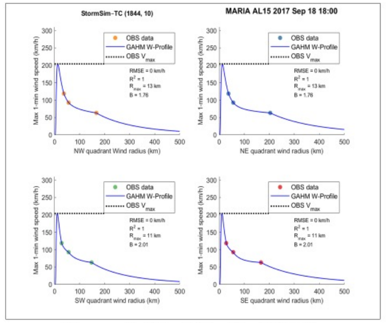

Figure 2. Wind Profile GAHM

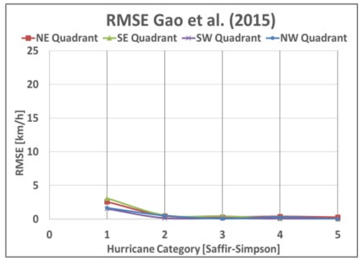

Figure 3. RMSE Plot for the model presented by Gao et al. 2015

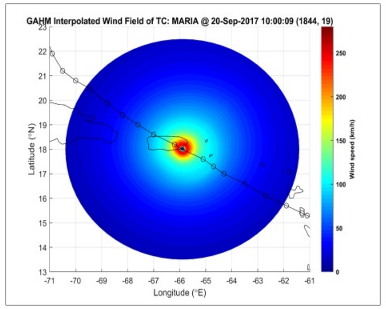

Figure 4. GAHM Wind Field interpolated wind field

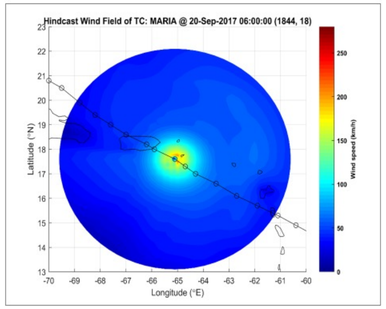

Figure 5. Hindcasted data interpolated wind field

Acknowledgements

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Conclusions

All Hurricane categories (1-5) were best represented by:

- –The model presented by Gao et al. (2015) (GAHM)
  - 0.08 km/h ≤ RMSE ≤ 2.22 km/h
- –The model presented Hu et al. (2012)
  - 0.09 km/h ≤ RMSE ≤ 2.48 km/h

Tropical Storms were best represented by the model presented by Holland et al. (2010) with:

- –RMSE = 1.75 km/h.

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Corridor Resilience in Multi-Hazard Settings: The Case of PR-2 in Western Puerto Rico

Student Name(s): Alexander Molano, BSCE, MSCE Candidate
Research Mentor(s): Benjamín Colucci, PhD, PE; Ismael Pagán, MSCE, Department Chair; Luis D. Aponte, PhD, PE

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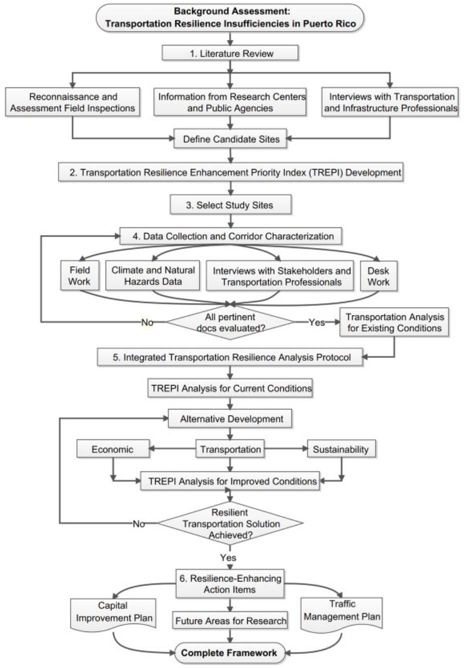
Homeland Security Challenge

- Puerto Rico, a US territory in the northeastern Caribbean, has confronted major natural disasters from September 2017 to April 2021, including major hurricanes, earthquakes, coastal erosion, landslides, and extreme precipitation.
- The Island's aging transportation assets have experienced damage and disruption, requiring best engineering practices for construction, operation and maintenance of resilient transportation infrastructure.
- Ongoing climate change trends of sea level rise and extreme precipitation, combined with the seismic setting and a population concentrated in coastal areas, turn coastal highway corridors into a critical case for resilience-enhancing analysis and investments.
- **This research examines the National Highway System PR-2 western corridor and its associated detours between the cities of Aguadilla and Mayagüez. This primary highway is highly exposed to natural hazards, operates as the region's lifeline route, and is full of infrastructure enhancement opportunities.**

Approach / Methodology

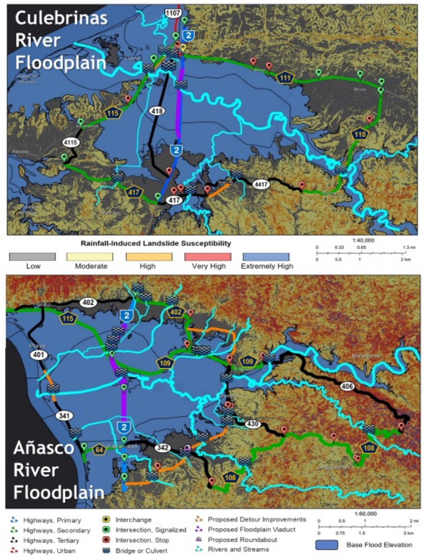


Transportation Resilience Methodology

- **Data collection** using GIS and the latest publications on climate, extreme weather and other natural hazards representative of the recent observed and anticipated impacts.
- **Field observations** of existing infrastructure assets, traffic operations, and observable effects of natural hazards affecting the corridor.
- **Development** and **application** of a **Transportation Resilience Enhancement Priority Index (TREPI)** to quantify exposure to hazards (40%), traffic characteristics (40%), and infrastructure condition (20%).
- **Traffic analysis** based on the Highway Capacity Manual macrosimulation models applied to typical, breakdown (e. g. under natural hazard disruption), and enhanced resilience scenarios.
- **Economic analysis** using Life Cycle Cost Analysis
- **Sustainability analysis** using Life Cycle Assessment.

Puerto Rico's surface transportation infrastructure experienced damage and mobility disruptions caused by extreme natural events between September 2017 to April 2021.

Conclusions



Proposed transportation infrastructure improvements (purple and orange lines) for the Culebrinas and Añasco study sites.

- **In the Añasco River floodplain, NHS PR-2 attains the highest score, by a wide margin (69.9), based on the TREPI analysis.** This lifeline arterial, with an ADT of up to 54,000 vpd, is exposed to coastal flood hazards (tsunami, storm surge, sea level rise), has detours incapable of accommodating heavy vehicle traffic, and deficient bridge design and condition relative to its functional classification. Redundancy can be added by connecting coastal highways PR-341 and PR-401.
- **In the Culebrinas River floodplain, NHS PR-2 attains a close 2nd place based on the TREPI analysis, attaining a score of 53.0.** Its sheltering relative to coastal flood hazards, greater adequacy of detour routes and slightly lower traffic (ADT of 50,200), however, contrast with greater levels of bridge deterioration along the detours.
- In both sites, **elevating NHS PR-2 above the floodplain using viaducts** is a reliable but costly resilience-enhancing option. **Preliminary construction cost estimates put the Añasco viaduct at $362 M and the Culebrinas viaduct at $138 M.**
- Inland detours require re-alignments and bridge retrofits to provide redundant routes able to accommodate detoured traffic away from landslide-prone areas, while coastal detours require careful designs to cope with storm surge, coastal erosion, sea level rise and tsunami impacts. **The combined construction cost of detour improvements is preliminarily estimated at $139 M.**
- **The wind loading adjustment factor increases TREPI scores of inland detours due to topographic wind acceleration** effects identified in the 2018 Puerto Rico Building Code, relative to the ASCE 7-16 code wind loads. This reflects additional vulnerability and recovery demands associated to wind damage.
- Risk and vulnerability assessment of transportation assets is critical to ensure the efficacy of emergency response and recovery efforts when confronting extreme events. **Lifeline transportation assets must be robust, possess redundant routes, and be maintained consistently to reduce the magnitude, duration and cost of disruptive events, thus saving lives and contributing to the mission of the Department of Homeland Security.**

Outcomes / Results

*Evaluation of the critical highways of the study sites using the **TREPI.** Equations are explained in further detail in reference 6.*

Variable Description and Associated Equation	TREPI Weight of Variable	Values, Culebrinas Floodplain			Values, Añasco Floodplain		
		PR-2	PR-110	PR-115	PR-2	PR-341/401 (Proposed)	PR-430
Highway Length (km)	Not Applicable	3.9	3.9	3.25	5.9	6.48	4.4
Federal Functional Classification	5%	Interstate	Non-NHS	NHS	Interstate	Non-NHS	Non-NHS
State Functional Classification	5%	Primary	Secondary	Secondary	Primary	Tertiary	Tertiary
Average Daily Traffic (ADT, vpd) (Eq. 1)	10%	50,200	7,600	18,200	54,200	4,200	2,300
Truck Traffic Index (T_{index})(%) (Eq. 2)	5%	9	5	5	9	5	5
Highway PRHTA Design Class	Not Applicable	RE-3	R-8	R-6	RE-3	R-9	R-10
Detour Option Design Class	Not Applicable	R-6	RE-3	RE-3	R-10	RE-3	RE-3
Detour Inadequacy (DI) by Design Class Number (Eq. 3)	10%	3	0	0	7	0	0
Detour Length (km) (Eq. 4)	5%	7.4	12.9	8.0	17.8	10.7	16.8
1% Annual Chance Flood Exposure ($FIRM_{1\%}$) (%) (Eq. 5)	8%	36.3	10.3	86.2	62.7	100	6.8
Floodway Exposure (FW) (%) (Eq. 6)	8%	42.5	7.1	46.0	74.6	43.2	6.8
Tsunami Evacuation Zone Exposure (TEZE) (%) (Eq. 7)	8%	34.0	0.0	83.0	100.0	100.0	0.0
Rainfall-Induced Landslide Susceptibility (RLS) (Eq. 8)	8%	Low	High	Low	Low	Low	Very High
Seismic Hazard Exposure (PGA as %g) (Eq. 9)	8%	0.83	0.83	0.83	0.83	0.83	0.83
Bridge Insufficiency Rating (BIR) (Eq. 10)	10%	7.75	40.7	36.4	34.0	37.0	50.0
Overall Pavement Condition (PC) (Eq. 11)	10%	Fair	Fair	Fair-to-Poor	Fair	Fair-to-Good	Fair
Base TREPI Score	Not Applicable	**53.0**	**37.8**	**53.8**	**69.9**	**46.7**	**38.5**
Wind Speed, Mean Return Interval of 25 years (mph, PRBC-18)	Not Applicable	96	107	91	94	96	116
Wind Speed, Mean Return Interval of 25 years (mph, ASCE 7-16)	Not Applicable	91	91	91	94	94	94
Wind Loading Adjustment PRBC-18/ASCE 7-16 (Eq. 12)	Not Applicable	1.11	1.38	1.00	1.00	1.04	1.52
Wind Loading Adjusted TREPI Score (25-year MRI)	Not Applicable	**59.0**	**52.2**	**53.8**	**69.9**	**48.7**	**58.6**

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- *This material is based upon work supported by the U.S. Department of Homeland Security under Grant Award Number 2015-ST-061-ND0001-01. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S Department of Homeland Security.*

Assessing Flood Risk and Mitigation Strategies for a Coastal Community near the Guanajibo River

Recinto Universitario de Mayagüez

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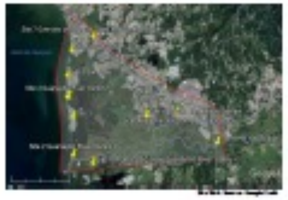
Research Mentor(s): Ismael Pagán Trinidad, Raúl E. Zapata López, Carla López del Puerto

Introduction

This poster presents the outcome of a site visit to the Guanajibo River Valley, part of the course: "*Managing Riverine and Coastal Floods for Resilient Communities*" of the project funded by the UPRM-DHS Coastal Resilience Center (CRC). Its main objective is to document, assess, and identify possible solutions for the flood risk situation of the river valley infrastructure. Currently, the valley is exposed to multiple hazards because of its location in a seismic and hurricane-prone area, near the ocean and other water bodies; for example Guanajibo River. The lack of ecological and infrastructural maintenance, along with an outdated infrastructure and limitations in enforcing flood zones regulations, has placed the Guanajibo River Valley in a vulnerable position. The infrastructure must be updated to follow current regulations and design codes, while complying with the environment with eco-friendly solutions such as Nature-Based or LID (Low Impact Development).

Approach / Methodology

- Understanding the Dangers of Flooding in Coastal Communities
- Studying Flood Zone Maps
- Site Visit



Outcomes / Results

PANORAMIC GUANAJIBO VALLEY

- Perspective
- Type of Soil
- Vegetative state

GUANAJIBO RIVER OUTLET 1&2

Flood challenges presented of new and old bridges

Modern flood proof structure

ELDERLY COMMUNITY SAN JOSE AND URB. VALLE HERMOSO

- Upstream Flood zones
- Example of Nursing Home
- Temporary Solutions
- Flap valves under flood control dike

GUANAJIBO HOMES COMMUNITY

- Building code 1950s
- Evacuation Routes
- Structural Problems
- Structural Solutions
- Community Leader

Conclusions

- Implementing resiliency in an already established community is a complex process
- Effective projects for resiliency:
  - Do not compete with or affect nature
  - Has community's support
- Social value in community contributes to project complexity

- Future work:
  - Continue working on literature review
  - Research & evaluate possible solutions

Acknowledgements

This project would have not been possible without the help of the mentors, and the resources provided by UPRM-DHS Coastal Resilience Center (CRC).

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Development of New Work Zone Traffic Signs for Road Reconstruction Processes

Student: Ivelisse M. Ramos López[1], PhD Candidate

Research Mentor(s): Dr. Didier Valdés Díaz[1]

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Introduction

After a natural disaster, one of the infrastructure sectors requiring rapid recovery is the transportation network. Rescuers, emergency management officers, and supplies of vital commodities use the highway system to access the affected zones. Therefore, it is necessary to expedite the reconstruction of roads to serve the community better. After hurricane María, 17% of the bridges in Puerto Rico were damaged, 1.1% collapsed and more than 70,000 landslides greatly affected the island's roads system.

Searching for alternatives to improve safety for both drivers and construction workers during the reconstruction process, a total of 11 contractors and highway project managers were interviewed to identify which have been the most recurrent incidents involving workers' safety on their projects. In addition, an online survey was performed to gather driver's road safety concept and work zone signage interpretation

Based on the results of the interviews and an online survey, several alternative signs will be developed to guide drivers when traveling through a construction work zone. These alternatives will then be tested using a driving simulator.

Methodology

1 Contractors Interviews

- Focused on identifying what type of safety issues related to drivers and construction workers they experience in developing of their projects.
- Also, they were asked about other alternatives to improve safety in construction work zones.

2 Online Survey

- To assess driver's road safety knowledge and signage interpretation, an online survey was performed.
- The survey was distributed using Google Form and was administrated in Spanish.
- Social media like Facebook, LinkedIn, Instagram and WhatsApp were used to advertising drivers to participated in the survey. Also, the University institutional email was used for announcements during November to December 2019.
- Participant had to be at least 18 years old and be an authorized driver in Puerto Rico.
- The survey results provided the basis for generating of new traffic signs to be use in construction work zones.

Results

Contractors Interviews

81.8%

Experienced intrusion of a vehicle into the construction work zone.

40% 33% 20%

They identified speeding, distraction, and the lack of traffic signs as main factors of crashes in construction work zones

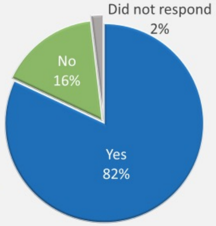
Contractors also suggested the use of flashing arrows and variable message sign as a safety countermeasure.

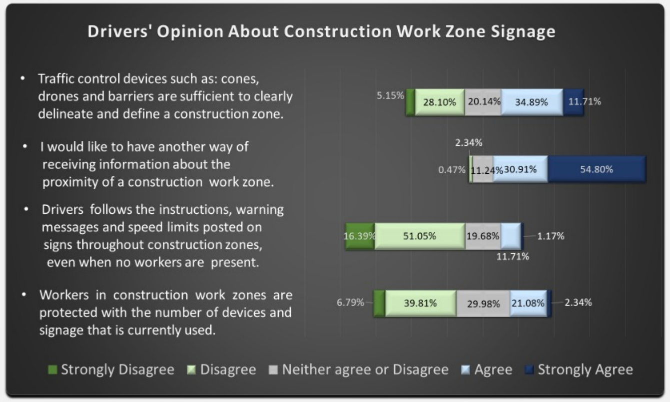
Online Survey

43% Male 56% Female

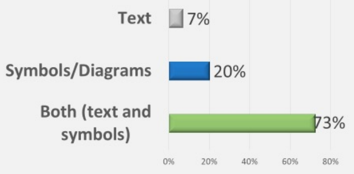
Age range 18 -80

82% Would like changes in signage currently used in construction work zone.





Drivers suggested using more traffic signs in advance and throughout construction work zone to improve safety.



Most of the respondents indicated that they prefer traffic signs with diagrams or symbols in combining with text.

Findings

- Both contractors and drivers suggested using more traffic control devices in advance to construction work zones as safety countermeasure.
- Education for both workers and drivers was identified as a necessary measure to improve safety in construction work zones.
- Although statistically, in Puerto Rico, no significant fatalities are reported in construction areas, more than 80% of contractors and project manager reported witnessing vehicles entering construction zones. This fact shows the daily occurrence of dangerous situations to which workers are exposed.
- After a natural disaster and during the response process mobility, is vital, so alerting drivers with enough information about what they can expect ahead is a prevailing need. Based on the information collected in this study, it is evident that drivers would like changes to existing signage in construction zones.
- Based on the drivers' needs and preferences, a signage alternative will be generated, which will then be tested using a driving simulator located at the Transportation Laboratory at UPRM. That evaluation will allow the opportunity to safety examine drivers' behavior in the presence of signs incorporating the suggested changes. This is an ongoing PhD research work.

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Construction Cost Variations After a Natural Disaster

Student: Ivelisse M. Ramos-López[1], PhD Candidate

Research Mentor(s): Francisco Maldonado-Fortunet[1], Ismael Pagán-Trinidad[1], Alberto Figueroa-Medina[1], Ricardo López-Rodriguez[1] , Raúl Zapata-López[1]

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Research Objectives

- Recovery and reconstruction processes after a disaster represent great uncertainties.
- Construction costs tend to increase caused by the increase in demand and the scarcity of supply.
- The reconstruction process require to project construction budgets and distribution of funds for emergency projects and permanent resilient construction.
- This project focused on developing the mechanisms to monitor costs variations which can help FEMA establish reliable and accurate cost estimates and allocate project funding, a process highly affected by multiple sources of uncertainties.
- Undergraduate and graduate students joined a team effort led by multidisciplinary faculty to evaluate the impact of Hurricanes Irma and María on costs and prices of materials, equipment and labor required for the reconstruction of Puerto Rico.
- The team sponsored by RAND Corporation collected costs of materials data from different sources.

Objective

- The main objective of this project is to identify trends and variations in costs throughout different periods of the year caused not only by the hurricanes but also by other natural events that impacted the Island during the past three years, namely, the seismic sequence of January 2020, a drought, and the COVID-19 pandemic. Cost tendencies could identify differences in costs by geographic regions and periods of time.

Methodology

- A team of five professors, three graduate students and three undergraduates' students outlined strategies to obtain construction material costs in Puerto Rico after hurricanes in 2017.
- Eleven construction materials were identified as the most used in construction projects in Puerto Rico. These materials were identified as Cost Drivers (Figure 2).
- A series of calling guides were created to define the specifications and units of the materials for which costs were required to be obtained.
- Six representative homogeneous geographical regions were defined in which at least two construction material suppliers of each material per region were identified (Figure 1)
- A monthly calling strategy was defined for which we a weekly order was placed to collect the cost data for each construction material. A comprehensive data base was developed which help identify construction costs trends.

Outcomes / Results

Figure 1. Geographic Regions Identified for Cost Data Collection

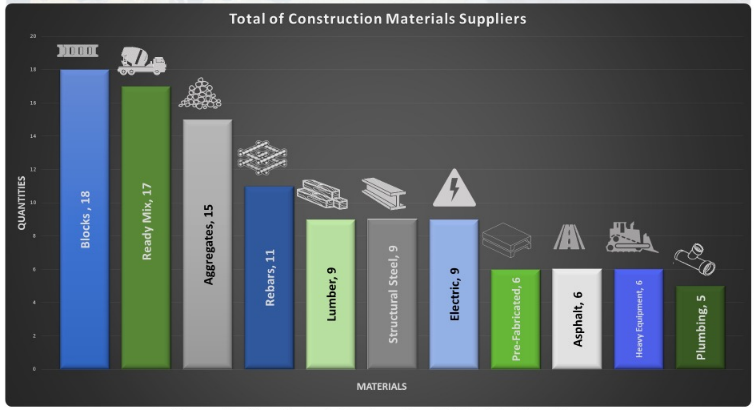

Figure 2. Number of Construction Materials Suppliers

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Findings

- Developed call guides with the technical specifications of the construction materials are a tool that facilitates and standardizes data collection and monitoring. This also helps in the process of making projections and establishing budgets for recovery and reconstruction projects after a disaster based in historical costs specific of Puerto Rico's construction industry.
- Maintaining a periodic process of monitoring the costs of construction materials helps to identify the moment in which there is a shortage of some type of material and what factors may be influencing.
- The project helped to developed a suppliers' directory around the Island which helps to know the availability and accessibility of different materials needed for construction and recovery in the eventuality of a future event.
- After approximately one year of monitoring the costs of construction materials, one of the most significant finding was a scarcity in supplies of 4 and 6-inch concrete blocks during the month of July 2020, after the lockdown due to the coronavirus pandemic.
- An increase of approximately 5% in the cost of concrete cubic yard between May 2019 and December 2020 was identified.
- Despite being a small island, a difference between costs of some construction materials by geographic region was identified. This difference could be observed in locally manufactured materials such as concrete blocks and ready-mix. The main reason for the difference is the cost of transportation of raw materials for its manufacture.

Acknowledgements

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Conclusions

After the worst natural disaster under the worst possible social, economic and infrastructure conditions Puerto Rico has faced in history, the catastrophe turns into a great opportunity to innovate and reconstruct it under the most rigorous, resilient, sustainable, educated and just standards to ensure its people a brighter future.

The DHS-UPRM CRC constitutes an excellent vehicle for the University to engage in the required capacity building process to help reconstruct Puerto Rico and rebuild USA's resilient infrastructure.

Acknowledgement and Disclaimer

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Questions and Comments   Thank you!


Thank You!