Engineering to Enhance the Resilience of the Built and Natural Environments

DHS University Network Summit
March 2009

Department of Civil, Construction, and Environmental Engineering, NC State University

Resilience of the Built and Natural Environments

- **System Observability, Diagnosis and Prognosis**
  Rudi Seracino, George List, NCSU

- **Innovative Component Design and Retrofit of Critical Civil Infrastructure**
  Mo Gabr, NCSU

- **Evolving and Engineered Landforms**
  Margery Overton, NCSU

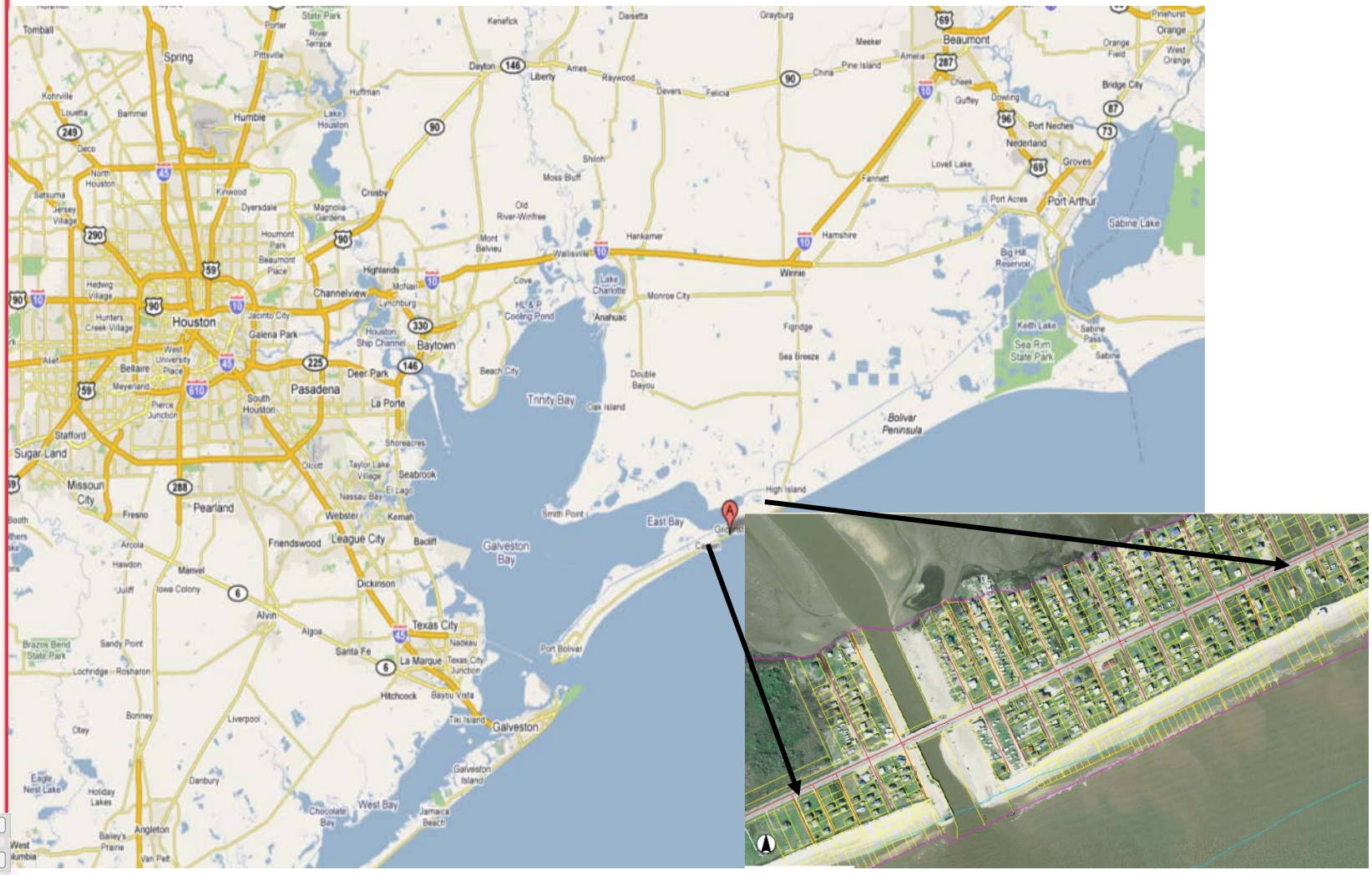
- **Cyberinfrastructure**
  John Baugh, NCSU

- **Integrated Systems Modeling of Civil Infrastructure and the Environment**
  Ranji Ranjithan, Downey Brill, NCSU

- **Infrastructure Modeling – Decision Technologies**
  William Al Wallace, RPI

- **Risk Analysis of the California Bay Delta Levee System**
  Robb Eric S. Moss, Cal Poly

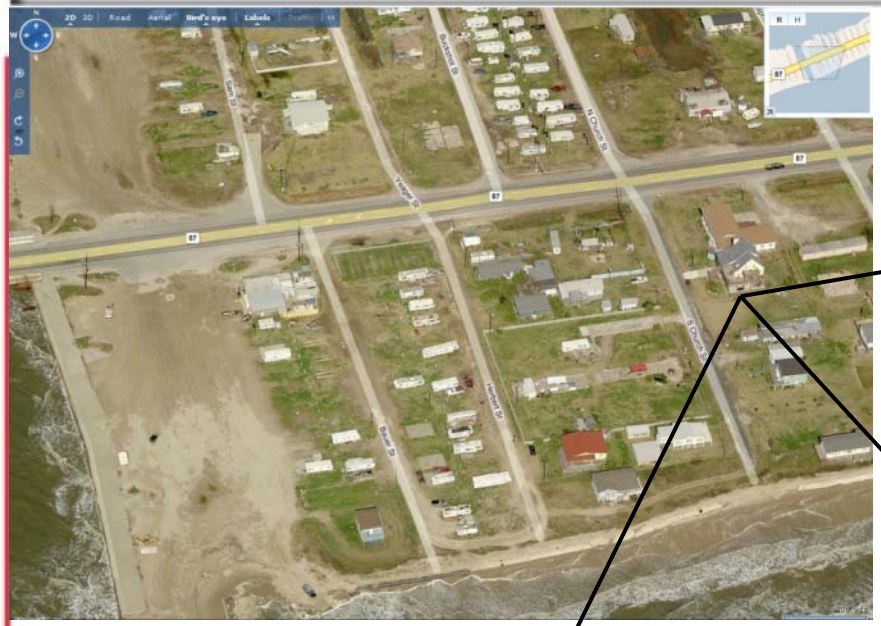
Overview

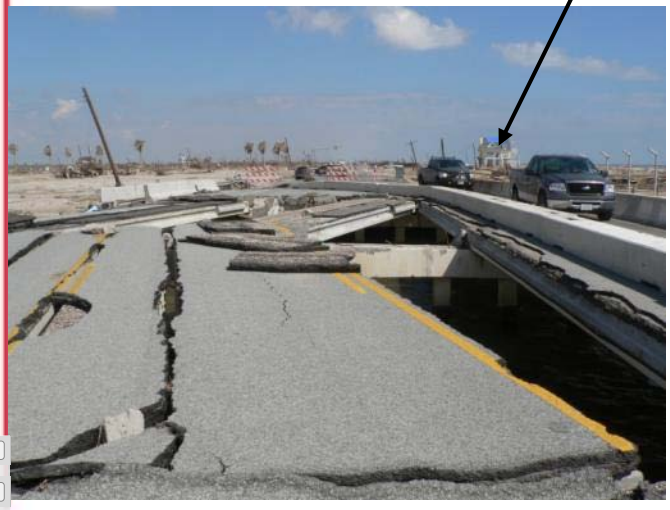


Spring
Humble
Houston
Pasadena
Baytown
Channelview
Deer Park
La Porte
Sugar Land
Missouri City
Pearland
Friendswood
League City
Texas City
Galveston
Galveston Bay
Trinity Bay
East Bay
Beaumont
Port Arthur
Sabine Lake
Bolivar Peninsula
Port Bolivar
Port Neches
Nederland
Groves
Winnie
Anahuac
Seabrook
Webster
Dickinson
Alvin
Santa Fe
La Marque
Hitchcock
Angleton
West Bay
Smith Point
High Island
Sea Rim State Park

Pre Hurricane Ike

Post Hurricane Ike





Engineered Success - Engineered Failure?

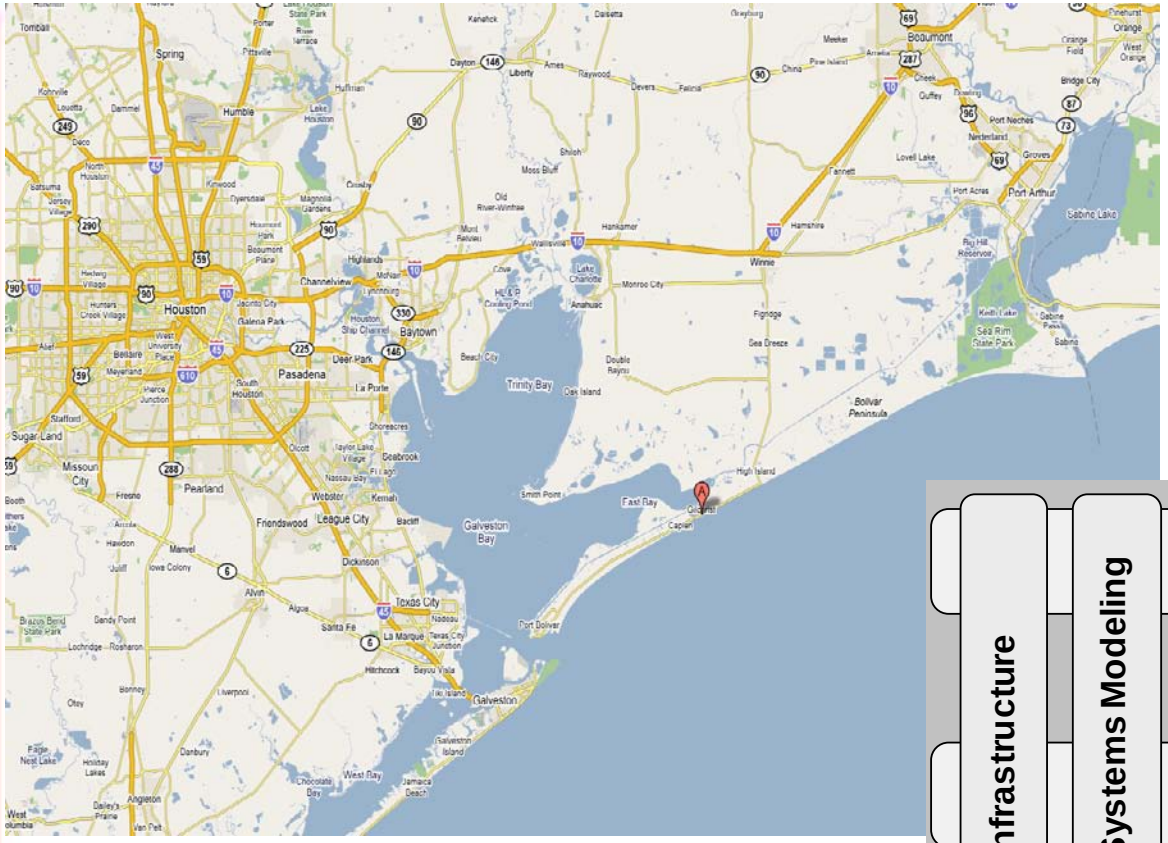
Individual success?

Failed connection?

Failed protection?

Failed link?

Resilience of the Built and Natural Environments



Cyberinfrastructure

Integrated Systems Modeling

Observability

Innovative Designs

Landforms

System Observability, Diagnosis, and Prognosis

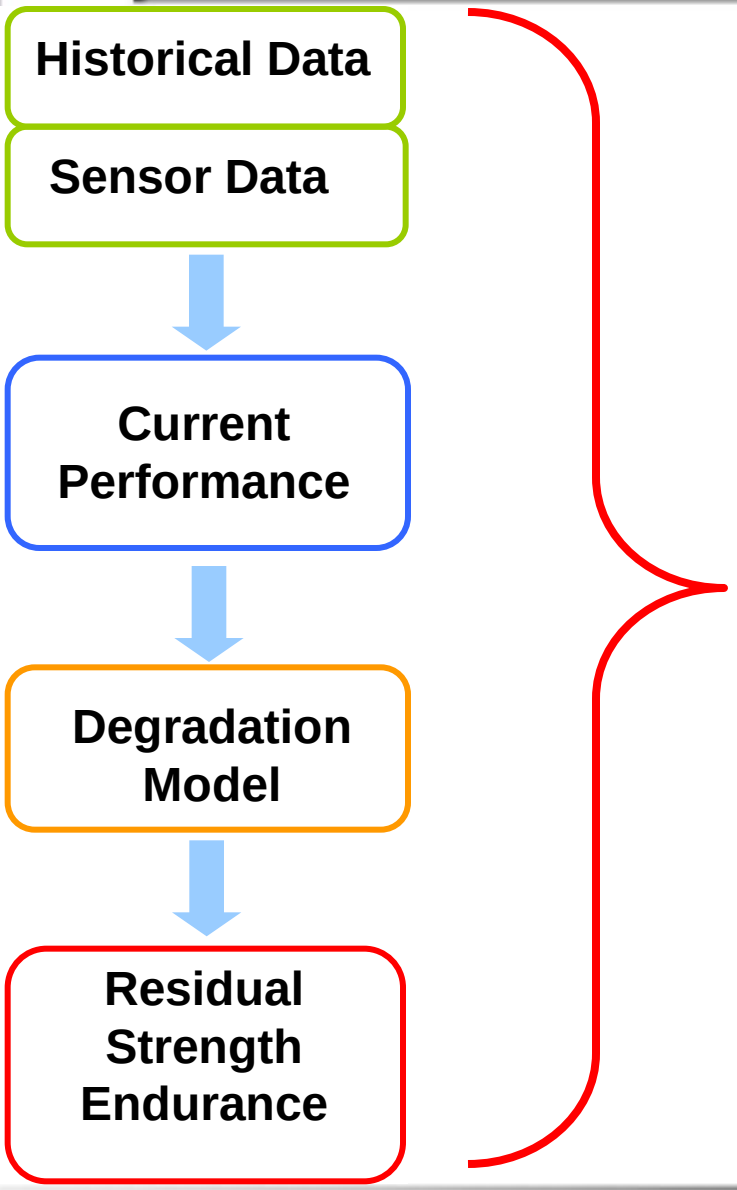
- System observation

- Structural Health Monitoring of critical infrastructure

Diagnostic (fail and fix)
vs
Prognostic (predict and prevent)

- Sensor development

Structural Health Monitoring Process



Prognositc Architecture

- Maintenance/repair programs
- Improved component design
- …

Characterization of Loading (Short-term)

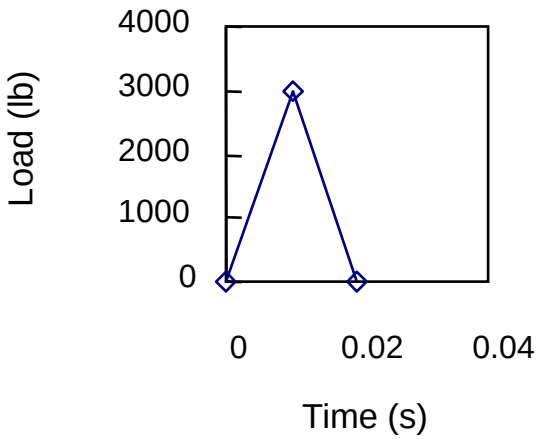
Historical Data

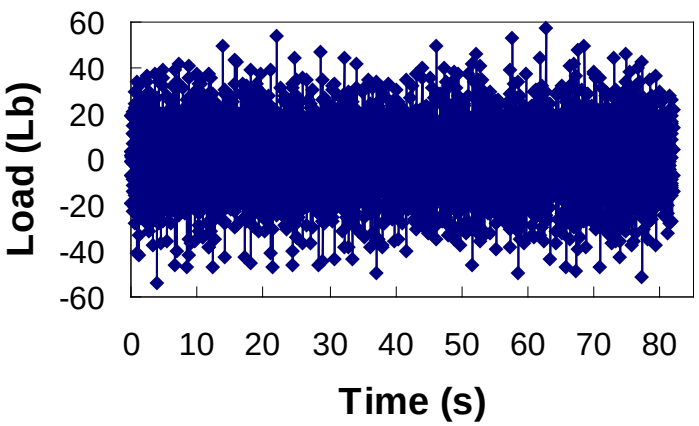
Sensor Data

Current Performance

Degradation Model

Residual Strength Endurance





Induced vs Ambient

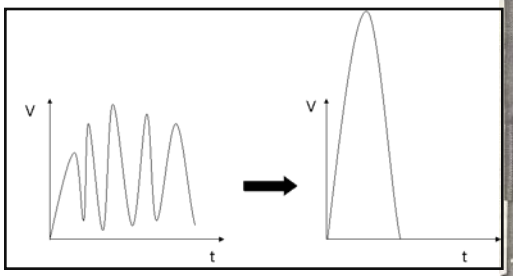
Sensor Development

Scour & Erosion

- New Infrastructure
  - Velocity-Time Profile
- Existing Infrastructure
  - Condition Assessment
- Portable, Rapid, and Wide Range of Velocity Profiles

Scour and Erosion

Development of In-Situ Scour Evaluation Probe (ISEP)



i. Prototype and basic premise

ii. Physics of sheet flow vs. jet flow

iii. Laboratory proof of concept

iv. Field testing and verification

New paradigm and criteria for resilient design

- EC 1110-2-6067: Conditional Non-Exceedance Probability (CNP)
- Deterministic Geotechnical Analysis
- Hazard function analysis considering past history

- **Past history effect on properties (past events)**
- **Coupled probability of failure: Capacity-Demand Model**
- **Hazard Function to address time effect (e.g. Weibull)**
- **Simplified analysis (6-σ approach)**
- **Application to case study**

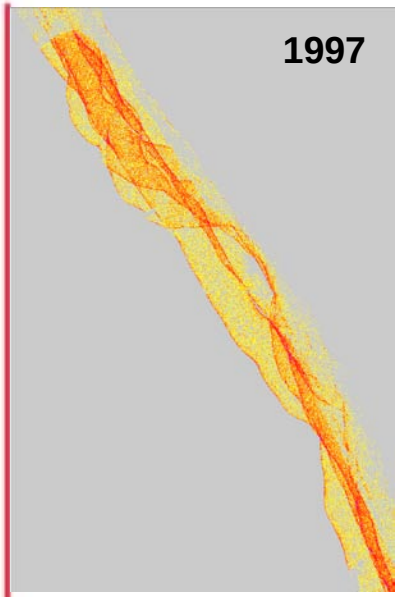
Demonstrating resilient design

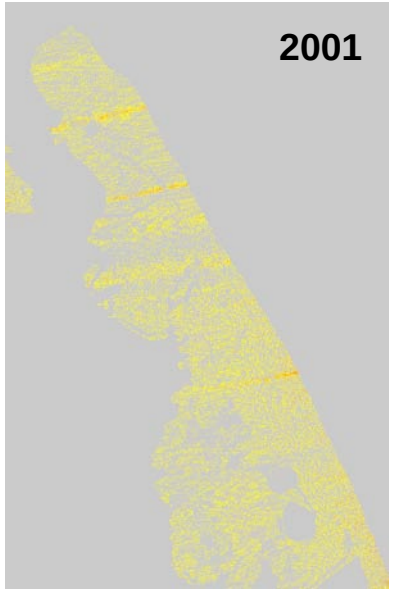
Marshland Levee Failure, 1983
J. David Rogers, Missouri University of Science & Technology

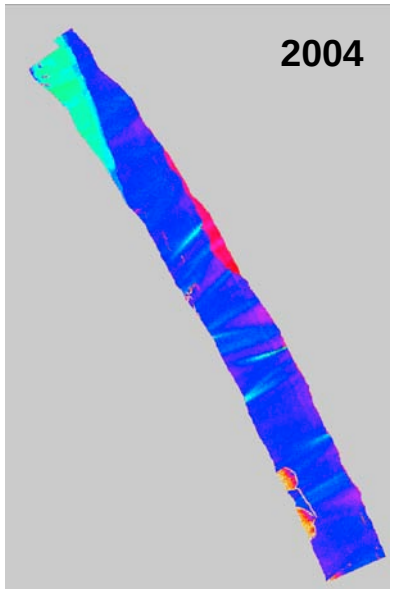
Integrated Failure Modes of Earth Infrastructure

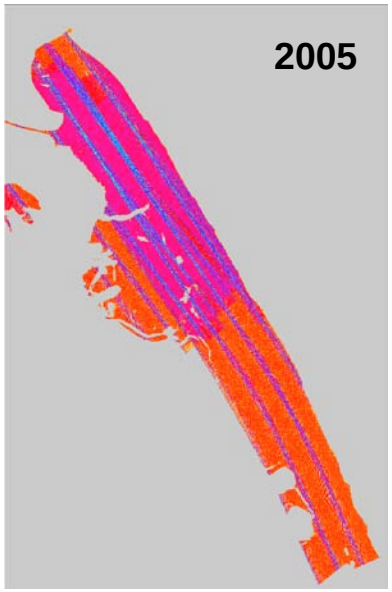
- Focus on Probabilistic Assessment of Earth Structures
- Short Term
  - New paradigms and criteria for resilient design with linked failure modes
  - Resilient behavior of interdependent infrastructures
- Long Term
  - Emerging advanced material for enhanced performance
  - Life-cycle analysis of retrofits and upgrades of critical structures

Evolving and Engineered Landforms



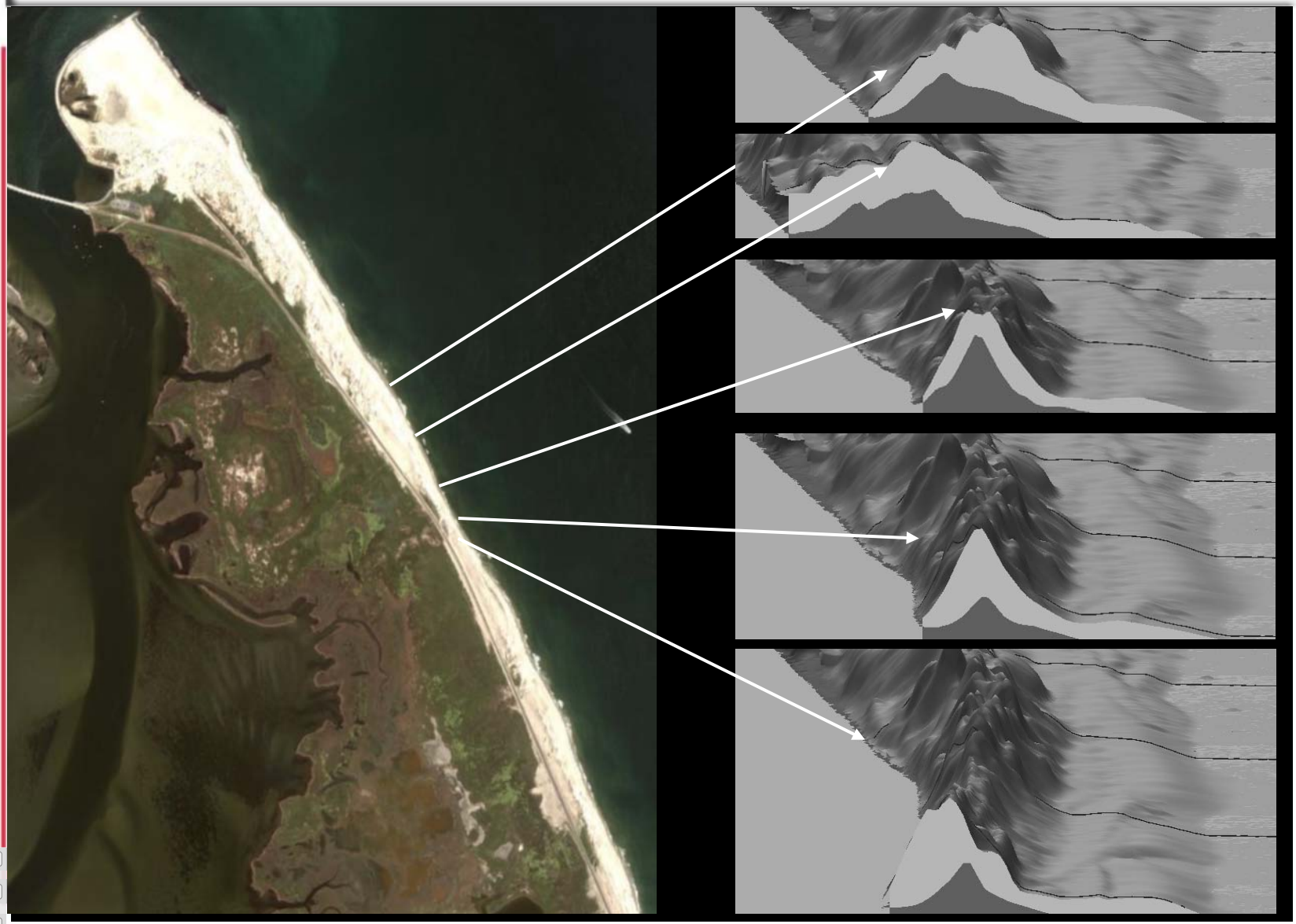






Decadal scale, high resolution geospatial data

Maximum and Minimum Surfaces – Core Volume



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Observations to predictions

- Develop visualization analytics to enhance spatial and temporal analysis
- Identify geomorphic vulnerabilities predictive of landforms “in transition”
- Develop descriptive and predictive metrics/procedures
- Improve process based predictive models

- **Sept 26, 1997**
- **Sept 7, 1998**
- **Sept 9, 1999**
- **Sept 18, 1999**
- **Oct 10, 1999**

Hurricane Bonnie

Hurricane Dennis

- **Feb 2001**
- **June 22, 2003**
- **Sept 18, 2003**
- **Sept 21, 2003**
- **Aug 28, 2004**
- **Oct 1, 2005**
- **Mar 17, 2008**

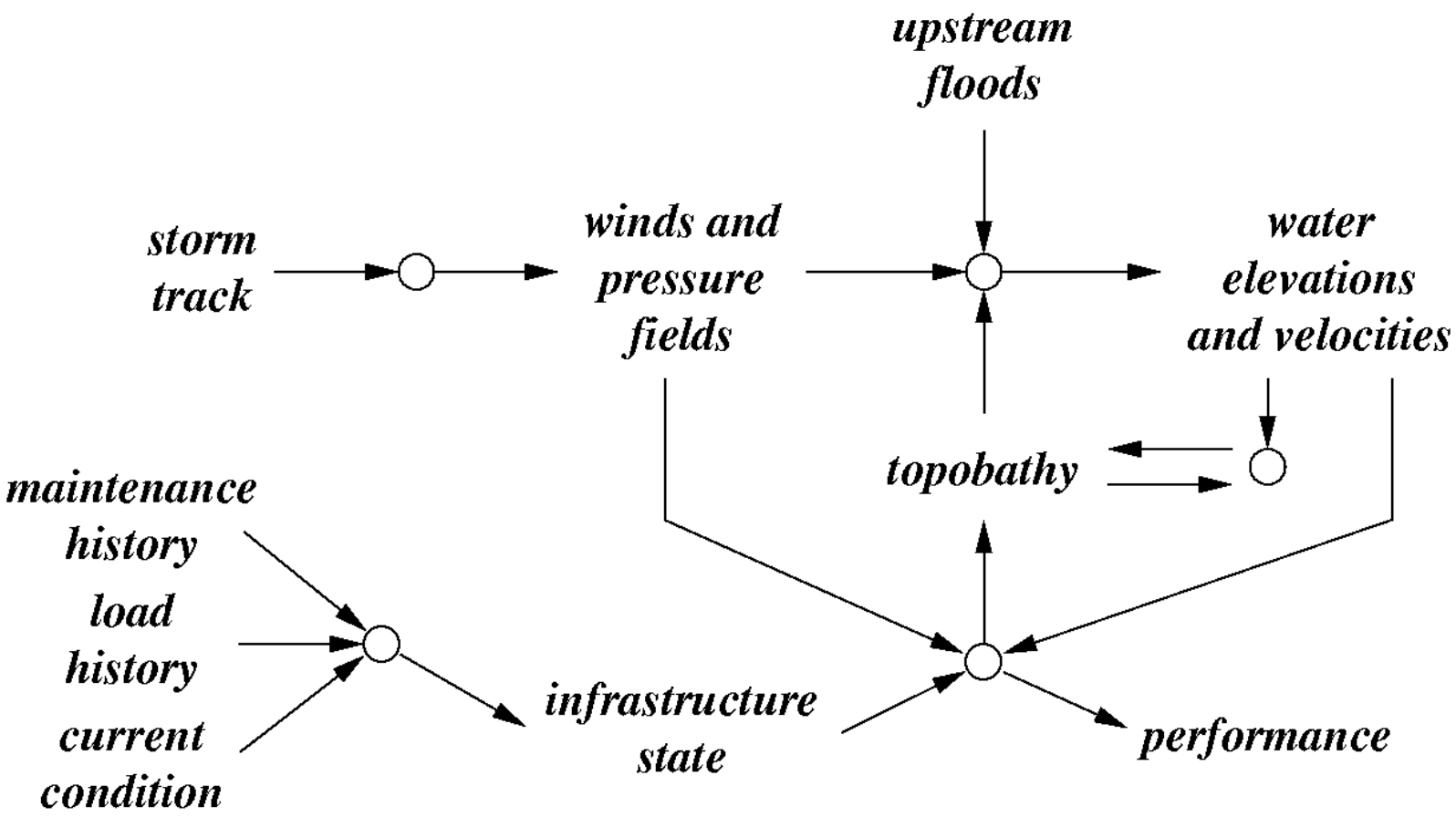
Hurricane Isabel

Hurricane Ophelia

Cyberinfrastructure

- Analysis
  - – Assessing performance under hypothetical events
  - – Enabling interaction between existing models and developing new approaches and tools
  - – Using complementary approaches that incorporate varying levels of refinement
- Sensing and monitoring
  - –Gathering information before, during, and after an event
  - – Implementing hybrid sensor networks with remote access to data
- Optimization
  - – Seeking alternatives that improve system-wide performance
  - – Developing formal search procedures in an integrated computational framework
  - –Designing high performance multiprocessor implementations

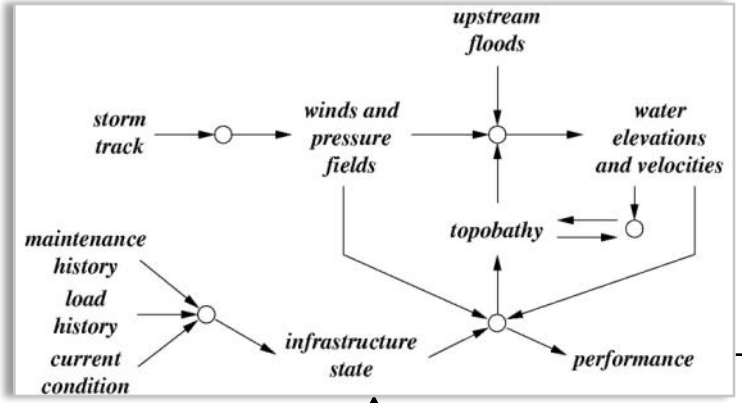
Simplified Analysis Scenario



Simplified Analysis Scenario

- Simulation examples
  - Evolution and potential collapse of landforms and cascading effects on inland structures
  - Degradation of levees as a result of loading histories
- Hidden complexity
  - Shows a single analysis scenario under a single storm event
  - Data sets vary over time and space
  - Civil infrastructure models include dams, levees, bridges, etc., within a particular geographic region
- Cyclic dependencies
  - Storms generate flood conditions which can change topography
  - Failure of an infrastructure component can change loading conditions on another component

Integrated Systems Modeling, Analysis & Optimization

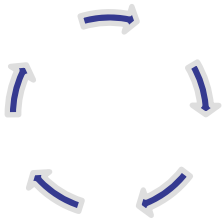


Component interdependencies and interactions

System Performance
- e.g.,
  - transportation services
  - property damage
  - lives displaced

Performance metrics

Goals/ Targets



**** What-If Analysis***
**** Optimization using Systematic Search***

Civil Infrastructure Improvement Options
- e.g., options for strengthening the engineering components such as levees, roads, bridges, houses

Engineering decisions

?

STOP

Integrated Systems Modeling, Analysis & Optimization

Objective: Improvement to protect critical lifelines and the environment.

Decisions: Upgrade type for each levee segment & road segment
Criteria: Maximize serviceable roads

Data
- Elevations
- Road and Levee Conditions
- Upgrade Types and Costs
- Budget
- Storm Conditions

Figure 3.a. Input Data

Simulations
- Storm Model
- Flood Model
- Levee Failures

Figure 3.b
Possible Simulations.

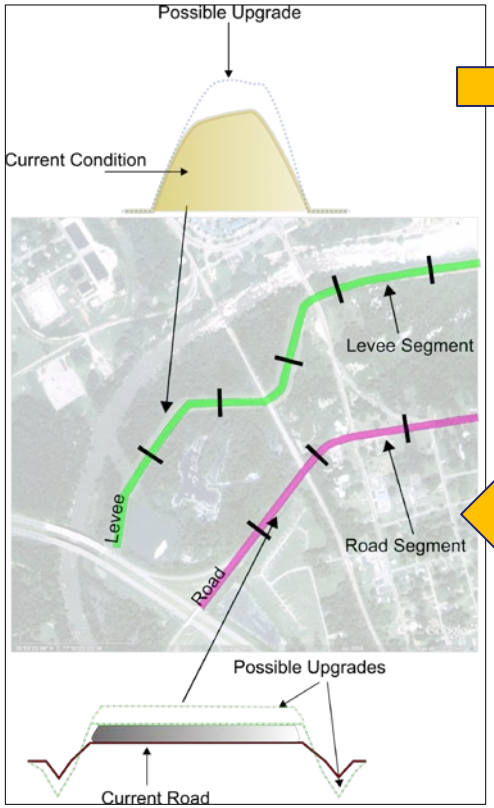


Figure 3.f. Discretization of segments and cross-section examples of component upgrades.

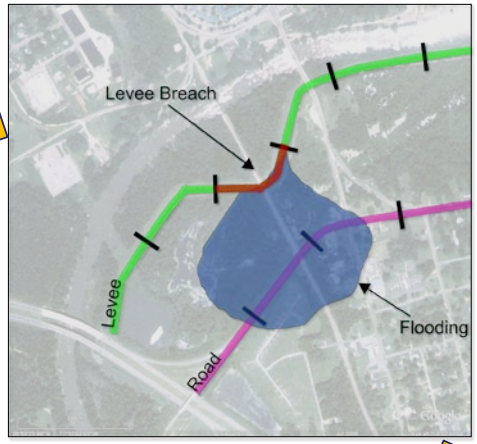


Figure 3.c. Flood inundation due to levee failure

Mathematical Formulation

Find $L_i^k, R_j^m \ \forall i, j, k, m$ that

$$\textit{Minimize} \quad \mathrm{E}\left[\sum_j \mathrm{RF}_j(L_i^k, R_j^m)\right]$$

or

$$\textit{Minimize} \quad \sum_j \left[\sum_f P_f - \sum_k LB_f^k L_f^k - \sum_m RB_j^m R_j^m\right]$$

subject to

$$\sum_{i,k} LC_i^k L_i^k + \sum_{j,m} RC_j^m R_j^m \le B$$

$$\sum_k L_i^k \le 1 \quad \forall i$$

$$\sum_m R_j^m \le 1 \quad \forall j$$

$$L_i^k, R_j^m \in \{0,1\} \quad \forall i, j, k, m$$

Figure 3.e. Mixed Integer/Linear Programming Model.

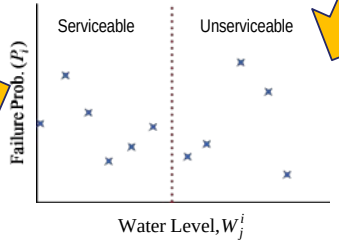


Figure 3.d. Estimation of Probability Road is Unserviceable

Integrated Systems Modeling…

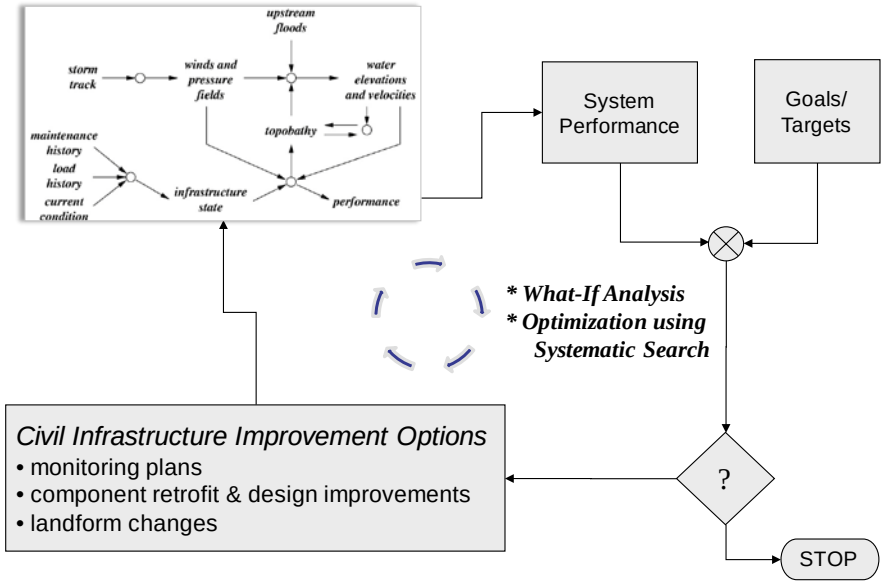
- Hierarchical modeling approach
  - Component-level to integrated system-level
- Models for systems analysis and optimization
  - Simplified to detailed representations
  - Strategic planning to operational levels
  - Retrofit improvements to new design options
- Multi objective optimization and analysis
- Search algorithms
  - Mathematical programming to heuristics

Integrated Systems Modeling & Cyberinfrastructure

- Iterative model development and testing
  - Illustrative example applications
    - e.g.,. City of Princeville, New Hanover County
  - General-purpose prototype decision support tools utilizing the cyberinfrastructure
    - Models to assist in making strategic planning and mitigation/retrofit decisions
    - Extendable/flexible modeling framework
    - Computationally tractable solution procedures

Short term

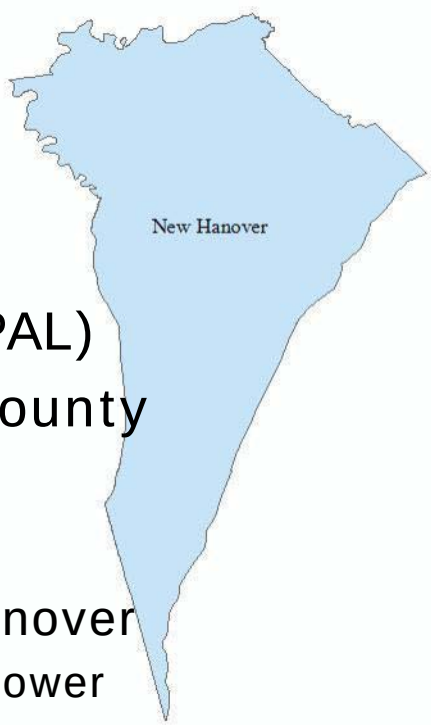
Long term



Infrastructure Modeling – Decision Technologies

Principal Investigator: William Al Wallace
Rensselaer Polytechnic Institute

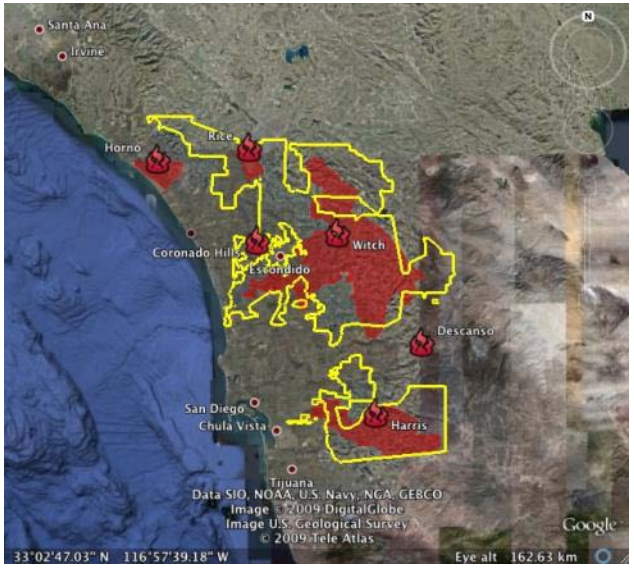
- Interdependence of infrastructure systems
- Research on restoration
  - Restoration plan
  - Assignment and scheduling
- Prototype decision support tool (MUNICIPAL)
- Hypothetical example for New Hanover County
  - Power and phone infrastructures
  - Disrupted power lines
  - Implementation of MUNICIPAL for New Hanover
    - Solution for which lines will be restored in power infrastructure
    - Assignment of restoration tasks to the workforce
    - The order in which tasks will be performed

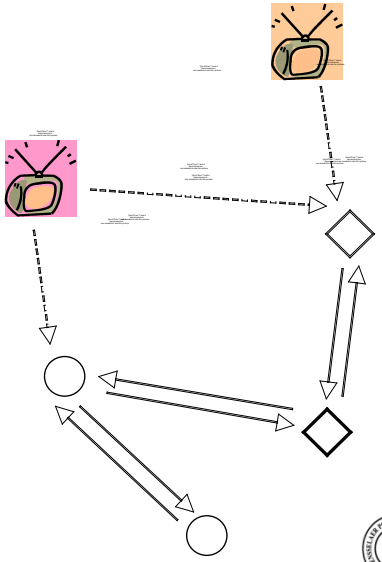


Diffusion of Warnings – Decision Technologies

Principal Investigator: William Al Wallace, Rensselaer Polytechnic Institute

- Diffusion of warnings: (In collaboration with the Institute of Discrete Sciences Center for Dynamic Data Analysis IDS-DyDan)
  - Formulate diffusion framework using the concept of trust
  - Simulate broadcasting of warning notifications on large-scale networks
  - Configure parameters using real data
  - Calibrate the parameters to perform scenario analysis
- Goal: Promote effective use of warnings technologies



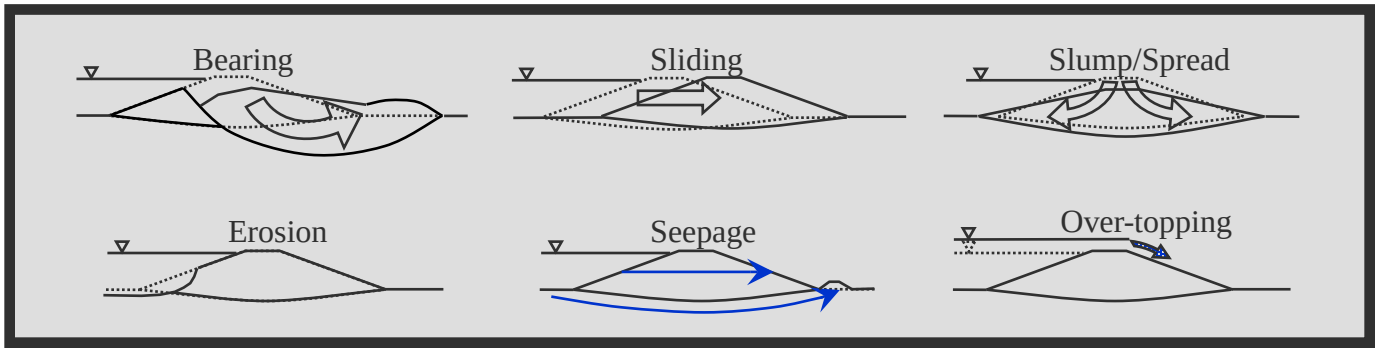


Possible Future Collaborations – Decision Technologies

Principal Investigator: William Al Wallace
Rensselaer Polytechnic Institute

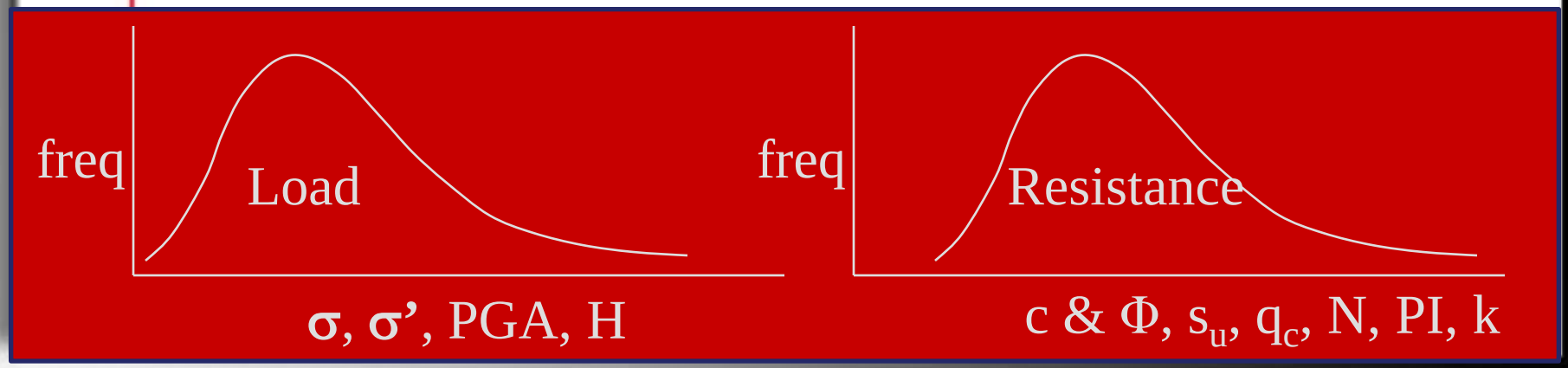
- Diffusion of warnings
  - In collaboration with the Center for Maritime, Island and Port Security led by the University of Hawaii in Honolulu
- Information Fusion for Maritime Safety and Security
  - In collaboration with the Center for Maritime, Island and Port Security led by the University of Hawaii in Honolulu for maritime and island security and Stevens Institute of Technology in Hoboken, N.J. for port security
- Enhancing Resilience though Market Mechanisms
  - In collaboration with the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) at the University of Southern California

Risk Analysis of the California Bay Delta Levee System
Robb Eric S. Moss, Cal Poly



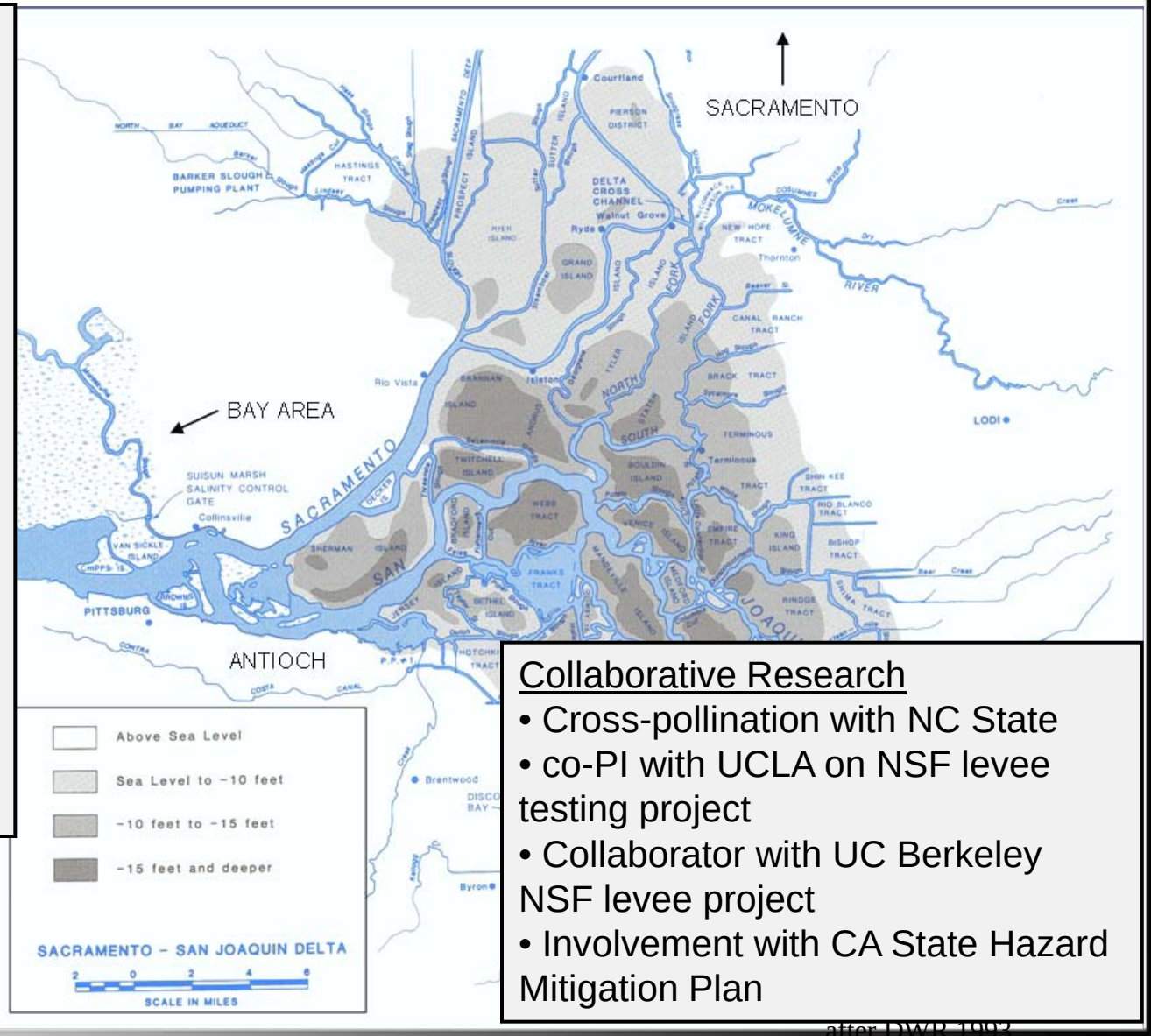
<u>Novel Concepts Being Applied in this Research Project</u>

- spatial variability to define reach length and correlation
- extreme value distributions for locating failure initiation
- temporal distribution modifiers for time varying properties
- reverse risk modeling to highlight critical failure modes
- FORM/SORM and MC-based reliability for robust analysis



Risk Analysis of the California Bay Delta Levee System
Robb Eric S. Moss, Cal Poly

- Interstate and State Highways
- Rail Corridors and Infrastructure
- Deep Water Port Facilities
- High Dollar Agricultural Land
- Residential and Municipal Land
- Power Transmission and Storage
- Aquaducts and Canals (>20 million users)
- >17**00 km of levees**



after DWR 1993

Collaborative Research

- Cross-pollination with NC State
- co-PI with UCLA on NSF levee testing project
- Collaborator with UC Berkeley NSF levee project
- Involvement with CA State Hazard Mitigation Plan

Collaborative Opportunities

- Visualization and analytics
- Process modeling
- Emergency management and social behavioral aspects, planning
- DyDAn dynamic analysis, massive data analysis and inference
- PACER – Preparedness and Catastrophic Event Response, Analysis Modeling and Simulation, Wireless Sensor Networks
- Marine Island and Port Security

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