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Coastal Road System Failures: Cause and Effect

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Abstract

Engineered and natural coastal systems benefit from integrating systems engineering with coastal and other transdisciplinary sciences. By analyzing incremental intensity measure (IM) hourly output data from coastal storm hindcast models, functional decomposition identified cumulative celerity dispersion functions that strongly predict likelihood and degree of coastal highway damage for extreme storm events. Discrete time integration of these functions provides additional information related to identifying likely damage or failure mechanisms. Identifying these provides opportunity to improve design and construction methods to enhance coastal road reliability and sustainability.

Keywords

Coastal; Failure Modes; Road Systems; Hazards; Engineered Systems

1. Introduction

External forcings are constantly changing and increasing for engineered and natural coastal systems subjected to increasingly extreme storm hazards as a result of climate change. Coastal populations and developments in coastal zones are increasingly at risk. Defining logical and physical system architecture for complex coastal systems is problematic given the many external interfaces and variable boundary conditions. Engineered, natural, and meteorological coastal systems also evolve both spatially and temporally during extreme storm events.

Coastal hazards (e.g., storm surge, hurricane force winds and waves, tidal and coastal flooding) place both population and coastal infrastructure at increased risk. Increased levels of development damage results from higher tides, greater intensity storms, natural wetland buffer loss, and beach erosion. Even in the absence of relative sea level rise (RSLR) or other equally significant climate change impacts, developed coastal system sustainability is at greater risk from increasing property development, coastal population growth, and dependence on coastal and marine related economies. The predictable stakeholder threat response is to protect developed areas and coastal infrastructure at great expense without regard to robustness and sustainability [1].

Applying systems engineering when assessing risk and predicting reliability of engineered coastal systems has been an active and growing area of research for several decades. The inevitable question in post-event analysis for catastrophic failures is “What caused the system to fail?” Identifying failure mechanisms for coastal road systems in nearshore environments can reduce risk of future occurrences. While research benefits from understanding a transportation system’s functional requirements associated with resilience; fragility functions based on modeled storm output data potentially reduces system damage and critical failures. Reliable transportation systems are essential to community resiliency and recovery. Understanding which components are likely to fail and why, improves reliability of coastal road systems when subjected to extreme threats or incidents. Applying system engineering theories in quantifying uncertainties associated with multivariate probabilities; or, not-mutually exclusive system failure modes; engages many in pursuit of developing the perfect predictive model that resolve all uncertainties.

This approach potentially creates additional risk with consistent application or misapplication of probabilistic methods or models potentially limiting identifying and resolving system failures. Research objective is to avoid such pitfalls by utilizing means and methods appropriate to the system of interest in applying systems engineering and analysis in a consistent manner. The desirement is to develop reliable hazard functions, not only in a manner that is scientifically defensible, but also broadly interpretable, implementable, and discernable by the system actors and stakeholders.

2. Coastal Road System Failures

Transportation system risk and resiliency models in coastal zones provide various system frameworks for assessing transportation network reliability [2-6]. FHWA has developed extensive design guidance for developing resilient coastal highways [7-9]. Regional resiliency studies propose various vulnerability and risk assessment frameworks [10-12]. Montoya et al [13] propose a vulnerability model for barrier island roads based on morphological data in relation to the roadway with three vulnerability indicators measured along shorenormal transects: island width < 305 m; dune crest elevation < 3 m above the highway; and, edge of pavement within 70 m of the ocean shoreline. Anarde et al [14] propose a coupled hydrodynamic, geomorphic, and engineering reliability model for assessing vulnerability.

When a coastal road, protective dune, armoring, or seawall fails along a coastal road, communities flood and local coastal roads typically experience catastrophic damage, precluding life-safety access, and delaying evacuation. Coastal system resilience represents the integrated capacity and capability of a coastal system to recover quickly to pre-event conditions when impacted by natural hazards such as hurricanes, coastal storms, and flooding, rather than simply reacting to impacts. Since passive infrastructure systems generally lack dynamic functionality to respond in an adaptive capacity manner, this creates a problem in defining resilience and adaptive capacity for coastal road systems.

Damage from overtopping weir flow of pavement, base, and embankment routinely occurs seaward of coastal roads during ebb flow as storm surge retreats, overtops, or breaches barrier islands. This failure mechanism at pavement sections is well documented, particularly for riverine floods overtopping a broad-crested weir pavement section [15-17]. Evaluation of overtopping storm surge for Highway 82 in Southwest Louisiana utilized CFD flow simulation and acoustic analysis to assess flood flow from storm surge and resulting differential pressure flow fields [18, 19].

Significant damage to Brazoria County Coastal Road 257 (CR 257) occurred during Hurricane Ike in September 2008. Post-Ike road conditions included extensive damage to pavement, base, and embankment [20]. CR 257 serves as a direct link between Galveston Island and south Brazoria County. Damage ranged from partial failure at the edge of pavement to complete breaching and destruction of both pavement and embankment. Damage assessment teams observed that damage appeared to occur when ebbing storm surge accelerated seaward as the hurricane moved inland, reversing nearshore wind directions. Photographic records of damage indicate that many deep asphaltic overlay sections failed [21]. While pavement materials and typical sections do not appear to be critical components in determining the likelihood of failure, these are important for sensitivity analysis and damage reduction considerations.

Some pavement failures and material displacement observations suggest that rapidly varying hydrodynamic pressure gradients between the subgrade and surface may generate moments that initiate rotational failures in pavement slabs [22, 23]. It is known that the pressure oscillations for pore water under spillway chutes (underpressure) propagate instantaneously without damping effects, sometimes producing a hydraulic resonance in the slab [24]. Protective measures constructed along CR 257 now include large dunes and overwash scour protection armoring that extends deep into the sand embankment, similar to a system that constructed in Surfside after Hurricane Rita [21]. Research evaluated pre- and post-event using plans and damage assessment records to confirm damage extents along CR 257. Damage severity ratings characterized damage states from 0 (no damage) to 4 (road/embankment washout). Initial binary damage states assumed that 0–1 collectively represents ‘no road damage’ and 2–4 represents ‘damage’.

3. Developing the Failure Model

Evaluating system reliability for diverse natural and built coastal systems exposed to extreme natural hazard events challenges system models developed for normal design forcings. Extreme events often cause irreversible damage to the natural environment and built systems. Quantifying resiliency and response of a built system subjected to an extreme event facilitates adapting infrastructure to improve reliability. Predicting system vulnerability and failure limit states typically involves complex stochastic and empirical models. Modeling community disaster resilience requires transdisciplinary experts to collaborate in modeling how physical, economic, and social infrastructure systems within a real community interact and affect recovery efforts.

A transdisciplinary research team from 10 universities evaluated diverse engineered and socioeconomic systems in assessing hurricane hazards for the Galveston Test Bed Model, along with all other types of natural disasters as subsystem models for the parent Interdependent Networked Community Resilience Modeling Environment (IN-CORE) all-hazards model (http://resilience.colostate.edu/index.shtml). Model evaluates community impacts during extreme events and quantitatively measures resilience (https://ssa.ncsa.illinois.edu/isda/projects/in-core/).

The Colorado State University (CSU) Center for Risk-Based Community Resilience Planning integrates engineering, social sciences, and economic disciplines in comprehensively modeling community resilience [25, 26]. Systems that are essential for the recovery and vitality of a community (technological, financial, social/political support, healthcare delivery, education, and public administration) integrate within the IN-CORE model by simulating natural hazards and geospatially applying system fragility functions to publicly available asset inventories and databases. The model provides a quantitative and science-based approach to assess community resilience at the local and regional levels in response to natural disasters of varying intensities. The goal is to make local communities more resilient, and in doing so, improve the likelihood of long-term sustainability [27]. Developing the underlying systems science is challenging.

FHWA developed guidance for hydrodynamic modeling in the coastal environment [28]. Hydrodynamic models numerically simulate coastal storms to assess resultant impacts on coastal highways due to flooding, wave damage, and scour. Probabilistic systems analysis applied to ADCIRC+SWAN coastal model data [25] for Hurricane Ike that struck Galveston in September 2008, identified strong correlations between road system damage relative to nodal site characteristics and coastal storm model data. Initial analyses compared various incremental intensity measure (IM) data from coastal model output to other measured and modeled attributes of the storm event, engineered, and natural system components. Systemigram in Figure 1 identifies critical functional relationships for subsystems and forcings.

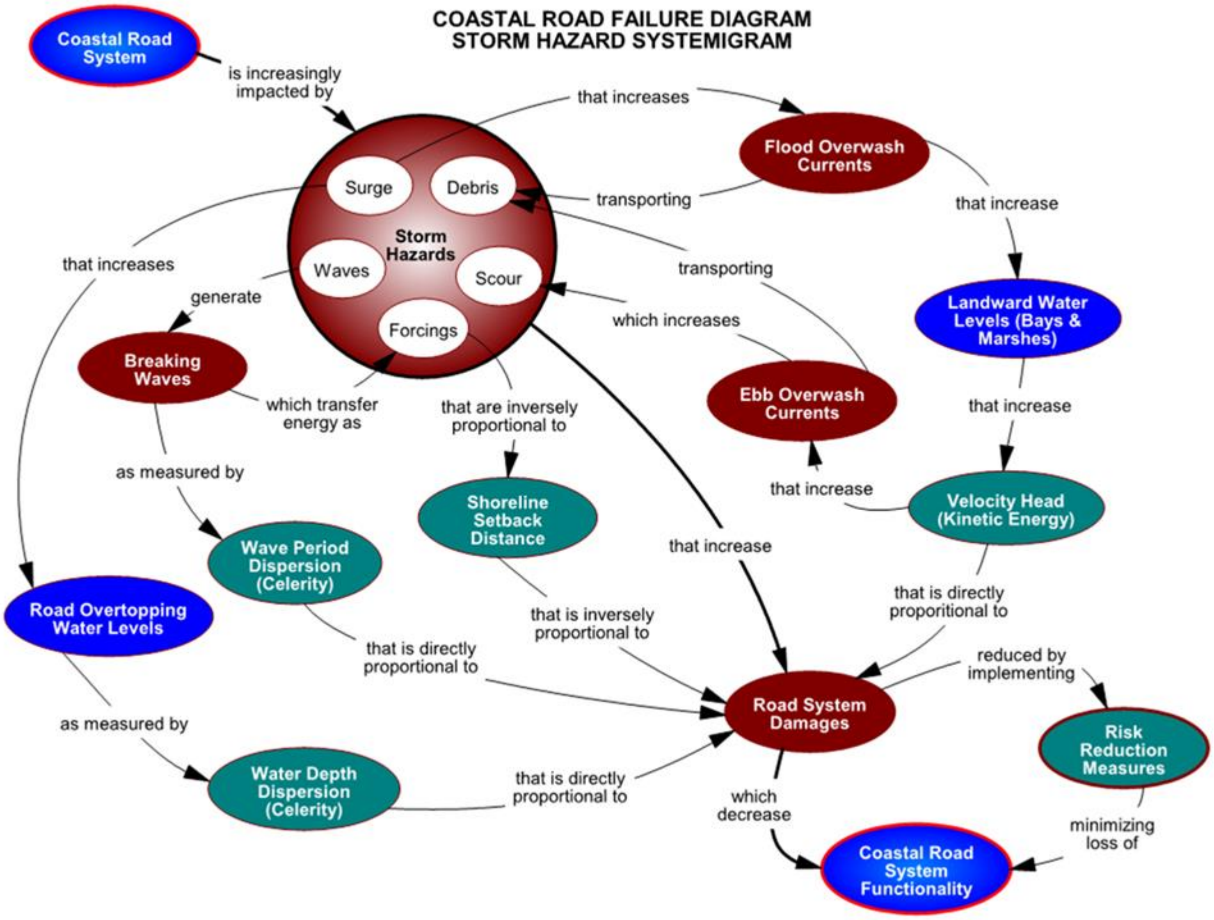

Figure 1: Coastal road resiliency systemigram.

4. Identifying Failure Mechanisms

Output data for the Hurricane Ike hindcast model included wind fields, currents, storm surge elevations, flooding depths, and wave characteristics. Other transdisciplinary research teaming partners collaboratively and concurrently assessed storm model data and pre- and post-event records, including detailed damage assessments, in developing fragility function models [25]. These geospatial damage and recovery models evaluated economic, social, building, utility, and transportation infrastructure systems. Hurricane simulations for different event frequencies impacting the same area validated subsystem assumptions and models for incorporation into the parent IN-CORE model.

By analyzing incremental IM hourly output data from coastal storm numerical hindcast models, functional decomposition and coastal engineering disciplinary research identified cumulative celerity dispersion (CCD) functions that strongly predict likelihood and degree of coastal highway damage during extreme storm events as shown in Figure 2. The coastal road system reliability model responding to a significant hazard event also includes several key external rate controllers determined by the storm events intensity, duration, and frequency.

Storm duration affects the cumulative aggregate values within the CCD model such that the longer the duration of storm event for overtopped road sections, the greater the damage. As storm intensity increases, generally storm surge elevation increases due to the energy of the extreme weather system with increased wave periods frequency (shorter waves), along with increased maximum (significant) wave heights. Damage mitigation measures conversely typically reduce the degree of road damage, which reduces the resultant damage functions (i.e., improves reliability function).

Subsequent analysis identified cumulative celerity, distance to shoreline, and cumulative flow velocities as critical variables in determining likelihood and degree of damage during a major storm event. Systems analysis applying coastal nearshore hydrodynamics determined that the CCD function strongly predicts likelihood and degree of damage for coastal roadways impacted by coastal storm surge and wave hazards. Evaluating the cumulative function with time-step integration assists with identifying probable damage failure mechanisms at critical damage limit states.

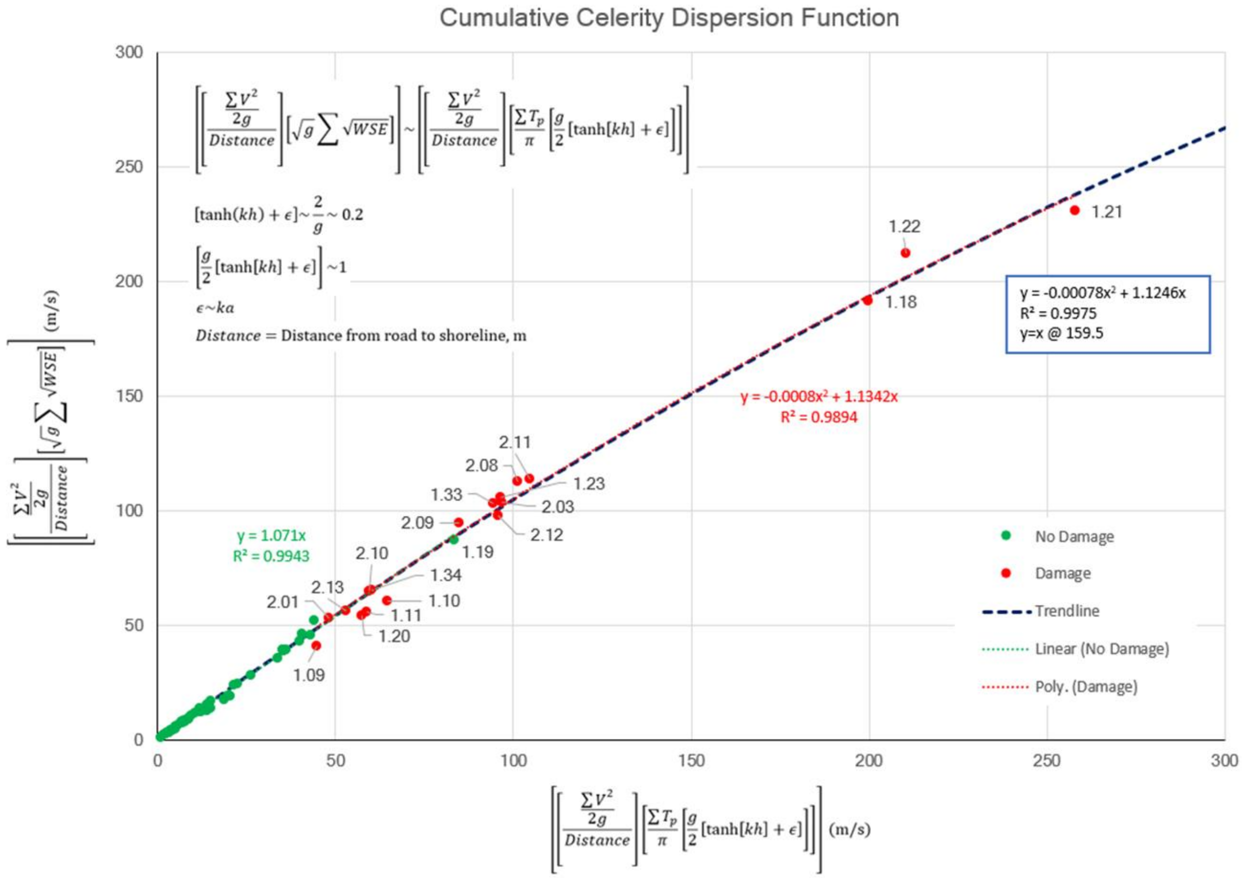

Figure 2: Cumulative celerity dispersion function**.**

5. Resilient Design and Construction

The CCD function, using cumulative overtopping water surface elevation and cumulative wave period hourly incremental IMs for overtopping flows, strongly correlate in predicting road damage along CR 257 on Follet's Island in Brazoria County, Texas. The model strongly predicts road failure when cumulative modified celerity dispersion function exceeds a critical threshold value or limit state. Discrete time integration of the CCD function finds that it reaches the threshold or limit state with significant road damage likely occurring shortly after flow velocity vectors redirect seaward (ebb flow) across the barrier island, which is consistent with other event observations. Analysis of peak IM data also shows that failure limit state coincides with depth-limited irregular sea state wave breaking depths, when wave heights reach critical wave breaking depth relative to overtopping water surface depths. Breaking wave impacts likely create soil liquefaction and rapidly varying pressure gradients under the pavement, increasing trapped air uplift dynamic forces, displacing pavement upward, and subbase material seaward (i.e., like compressing bellows).

Other critical parameters include duration of event which affects the magnitude of cumulative CCD values. The distance to shoreline also strongly influences likelihood of failure, correlating to previous research findings by others. Cumulative velocity is also critical to failure since it provides the mechanism for sediment scour and transport away from the damaged site. Model application to assess US Highway 80 damage during Hurricane Katrina subsequently confirmed the underlying hydrodynamic coastal theories with publication pending in coastal science journals.

While these functions predict the likelihood of coastal road failure during extreme storm events, they also provide opportunity to improve resiliency. In identifying the key variables that determine the likelihood of failure, some can be adapted in design to reduce system vulnerability and to improve reliability. The critical hazard variables associated with the storm event provide opportunity to mitigate impacts during design based on a design probability of recurrence, including considering climate change impacts such as sea level rise over the system's design life cycle. As one example, determining the optimal road elevation at a given location by evaluating the CCD function over a range of extreme storm events, provides opportunity to minimize damage risks for hurricane hazards. Elevating the entire roadway along a barrier island restricts overtopping flow, thereby causing unintended consequential damage to other built and natural systems. Lowering road elevations farther away from the shoreline facilitates overtopping flow at depths and velocities that deposit a sand layer that protects, but does not damage, the underlying pavement structure.

System modeling tendencies are to integrate system component functions to a point that the complexity of engineered systems placed into a natural system potentially fails to identify the most likely failures. By evaluating engineered system failure during extreme events, storm model output data evaluated using both systems and coastal engineering analytics, led to significant findings regarding catastrophic coastal road system failures. A systematic approach has identified many critical correlations not previously described, with coefficients of determination 0.98 or greater for damage likelihood models. Understanding these critical failure functions provides opportunity to consider those risk factors in both design and construction, and in so doing improve coastal road system reliability and sustainability.

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