Project Description

Introduction

The societal problems presented by aging civil infrastructures in the US are pervasive – cutting across diverse structures associated with our flood protection systems, existing building stock, and transportation networks. In recognition of the life safety risks posed by such systems under natural and anthropogenic hazards, there has been significant attention paid to the development of reliable safety assessment approaches to support their management, adaption, and reuse. What began with a near-exclusive reliance on visual inspections and simplified simulation models has evolved over the last several decades to embrace the impressive array of sensing technologies (inclusive of both global sensing and local nondestructive evaluation), highly refined simulation models, and model calibration techniques (both deterministic and probabilistic) now available. The resulting field, commonly termed Structural Identification (St-Id), is a rapidly growing and critical to developing cost-effective and safe approaches to reuse and adapt our existing infrastructure systems.

Current St-Id approaches for the safety assessment of structural-foundation systems are based largely on the collection of response data of the system being assessed under various inputs. The most common approaches include the use of static loading (Brena et al 2013), wind (Brownjohn et al 1994), temperature changes (Yarnold et al 2015), pull-release (Douglas 1976), impact (Raghavendrachar and Aktan 1992), or shakers (Salane et al 1981). While these inputs vary greatly in terms of their spatial distribution, temporal characteristics, ability to inform the identification of the full (input-output) transfer function, etc., they all may be characterized as low-level demands. That is, the response levels induced by these loading systems are generally very similar to operational limit states. As a result, the use of such responses to inform the safety assessment of the structural-foundation system under extreme events requires significant extrapolation. Of particular importance in this regard is the presence of behavioral mechanisms that only exist under very low levels of excitation (Figure 1). Such mechanisms are actually quite common within constructed systems (e.g. the participation of non-structural components in buildings, frozen bearings or unintended composite action in bridges, etc.) and represent a key distinction with manufactured systems (Moon and Aktan 2006).

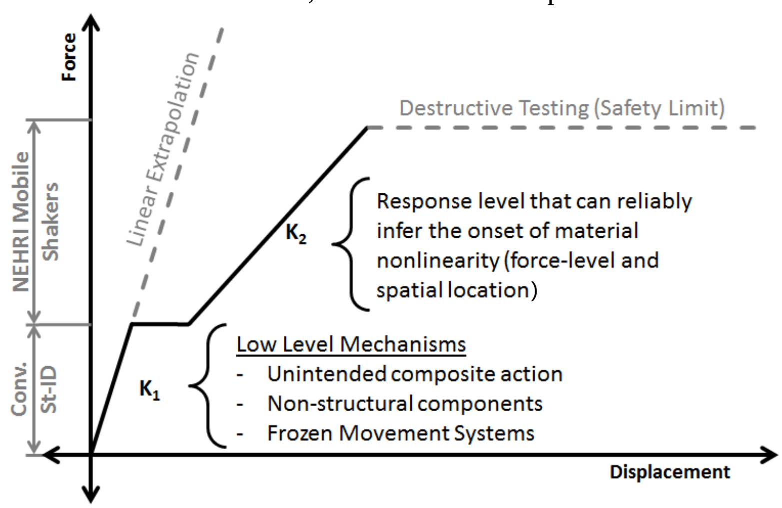

Figure 1 – Schematic comparing conventional St-Id techniques with the proposed use of NEHRI shakers

Although originally envisioned for seismic-related research, the large-amplitude mobile shakers that are available through the NSF NHERI Program offer significant potential to improve the reliability of St-Id by overcoming these low-level mechanisms in a controlled manner. It is emphasized that high-level destructive testing, as has been carried out for decommissioned structures, is not proposed here as this could compromise the future use of the system and render the assessment of little value. Rather, the current vision is to push the structural-foundation system beyond its low-level response (in a controlled manner) to reveal performance characteristics that are more representative of the expected behavior under safety limit states. For example, by overcoming the mechanisms that exist only at low-levels, a more realistic distribution of forces can be captured, which will greatly enhance the reliability of simulation model predictions associated with the onset (both load levels and spatial location) of material nonlinearity.

Why an EAGER

If successful, the envisioned project may contribute to the transformation of St-Id from low-level, linear data collection approaches, to large-amplitude testing approaches that can more reliably inform performance estimates associated with safety limit states. This effort is high risk, high reward since it relies on the performance of equipment that was originally developed for geotechnical applications. In addition, the ability to precisely control the level of nonlinearity induced, the refinement of St-Id approaches to leverage the resulting nonlinear (or intermittently linear) behavior, and the significance of the difference between the current and proposed approaches represent additional high risk, high reward components of the envisioned project.

Project Objectives

The overarching aim of the research proposed herein is to explore and establish the ability of large-amplitude, forced vibration testing to reveal the current performance and forecast the future system performance of structures, with the consideration of dynamic soil-foundation-structure effects. To meet this goal, the following more focused objectives will be pursued:

(1) Develop, evaluate, and refine a series of forced vibration testing and control strategies to capture response measurements indicative of key performance attributes of substructure/foundation and superstructure systems
(2) Develop, evaluate, and refine a series of both model-free[‡] and model-based[†] data interpretation frameworks for structural system (foundation-substructure-superstructure) identification and assessment
(3) Perform a validation of the testing/control strategies and data interpretation frameworks on an operating structure with known substructure, foundation, and soil characteristics.

Intellectual Merit

The intellectual merit associated with the proposed research lies in the examination of large-amplitude, multi-axis forced-vibration testing to assess and identify existing superstructure-substructure-foundation systems. Although various cost-effective dynamic testing methodologies for structural systems have been developed, they all suffer from a reliance on low-amplitude, uni-directional excitation, which is unable to overcome intermittent stick-slip mechanisms or to induce appreciable responses within the substructure-foundation system. The mobile shakers available through the NSF NHERI Program have the potential to overcome this shortcoming. This research aims to establish their potential in this regard and also to begin the development of new data interpretation frameworks that do not rely on the linearity of the system being tested.

Broader Impacts

The primary broader impact of this effort resides in the realm of infrastructure renewal. With the ability to perform reliable, quantitative assessment of superstructure-substructure-foundation systems of aging structures (buildings, bridges, etc.) owners will be provided with reuse and adaption options currently

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‡ Model-free data interpretation refers to methods based primarily on data processing, data visualization, and data fitting techniques. Examples include the use of impedance, time-frequency analysis, modal parameter identification, etc.

† Model-based data interpretation refers to methods that update simulation models of the system being identified, and then employ these models to examine behaviors that cannot be directly observed. In the realm of constructed systems this approach is referred to as Structural Identification (St-Id) and typically involves the updating of finite element (FE) models through either deterministic or probabilistic (Bayesian updating, multiple model) methods.

unavailable. In cases where the condition of the substructure-foundation systems will permit reuse, owners can realize significant savings and can employ accelerated construction, like for example accelerated bridge construction (ABC) approaches, which drastically reduce disruptions and maintain mobility. In addition to these technical contributions, this research will support the development and implementation of a competition based outreach effort to expose and attract high school students to the field of engineering. The PIs are committed to the recruitment of students from traditionally underrepresented groups and have identified a series of programs at Rutgers that will be used to facilitate their participation in this project.

Past Research

As alluded to in the introduction, significant work in the realm of field (or in-situ) testing of constructed systems has been conducted over the past four decades. Initially, these studies were principally motivated by the desire to better estimate the vulnerability of structural-foundation systems to earthquakes, but this focus has been expanded in recent decades to include issues related to fatigue, live load capacity, etc. An extensive review of these techniques was provided by Moon and Aktan (2006). For the proposed research, two relatively recent efforts are particularly relevant and are summarized in the following subsections (with a particular focus on how the proposed exploratory project differs).

Foundation-Substructure Identification and Assessment

Motivated by the need to identify and characterize foundations to estimate their vulnerability to scour, Olson et al. (NCHRP Project 21-05 and FHWA-RD-03-089), employed vertical shakers to perform forced vibration testing on structural-foundation systems. To help interpret the findings, they used the responses captured to update simple FE models in an attempt to distinguish different foundation types in a blind manner. They ultimately concluded however that this approach was infeasible, since the vertical responses of the structural-foundation system had little sensitivity to the type of foundation present.

In contrast to Olson et al.'s approach, the proposed exploratory project will make use of high-level, multi-directional excitation. This will allow responses far more sensitive to soil-foundation type and stiffness to be obtained. This becomes especially important for structures with high height-to-width ratio (for example tall buildings) where the rocking response of foundations may have a dominant effect on the swaying and torsion of the superstructure. In addition, the proposed research will also employ more comprehensive and extensive monitoring of the dynamic response on the surrounding soil, foundation, structure, which will permit capturing the interaction of these subsystems and the estimation of foundation impedance functions. Finally, more sophisticated data interpretation frameworks inclusive of both model-free and model-based approaches will be employed.

Figure 2 – Vibroseis truck delivering vertical excitation to a bridge pier (Olson et al. 2005)

Rapid Structural Identification and Assessment

Over the last five years Co-PIs DeVitis and Moon led a NIST-funded effort to develop a mobile system capable of performing rapid St-Id of constructed systems through modal impact testing. The result of this research was a system known as THMPER^{TM} (Targeted Hits for Modal Parameter Estimation and Rating) which Drexel University is in the process of patenting (Patent Application Number: PCT/US2015/036115).

The THMPER System is composed of a testing trailer/vehicle capable of carrying out modal impact testing of parking garages and highway bridges in a rapid manner (approximately 30 min per span) with only partial closures. The primary shortcoming of this approach is related to the short duration of the impact (approximately 0.02 sec), which is not able to induce sufficient response to overcome intermittent, stick-slip mechanisms. Although the use of the large NEHRI shakers will add considerable time and may require full closure of the facilities, the ability to load the structural-foundation system to larger force levels will likely produce far more reliable estimates of capacity.

Figure 3 – Photograph of the THMPER System during a recent test

Research Plan

The research plan is broken into three tasks that are associated with each of the objectives listed above.

Task 1 – Development of Forced-Vibration Testing Strategies

- This task will begin by designing a parametric study to examine the correlation between certain measureable responses (of both foundations and superstructure) and the foundation/substructure type/condition. Because bridges provide much higher accessibility to their foundations and structural components for experimental validations than other types of structures, the parametric study will be conducted on hypothetical bridge structures. It is envisioned that the following parameters will be included:
  - Soil-foundation elastic and nonlinear properties (indicative of different foundation systems, e.g., piles, drilled shafts, footings, etc.) incorporated through impedance functions (frequency dependence) and large deformation (strain dependence)
  - Substructure type (multi-column piers, hammerhead piers)
  - Substructure aspect ratios (height-to-bridge width)
  - Superstructure type (PS concrete vs steel, and continuous vs simple span)
  - Transverse distribution parameters, including the presence of low-level stick-slip mechanisms
- It is envisioned that these parameters will be sampled either through a full-factorial approach (for discrete parameters) or through a latin hypercube approach (for continuous parameters)
- Once completed, 3D FE simulation models of each notional bridge system will be constructed via the Strand7-Matlab API using software previously developed
- This suite of bridges will then be subjected to various dynamic inputs (frequency, direction, location, etc.) to identify response metrics that are sensitive to changes in the selected parameters across the population
- Using this information the research team will identify a strategy or strategies on how to best utilize the large-amplitude NHERI mobile shakers to collect the identify metrics

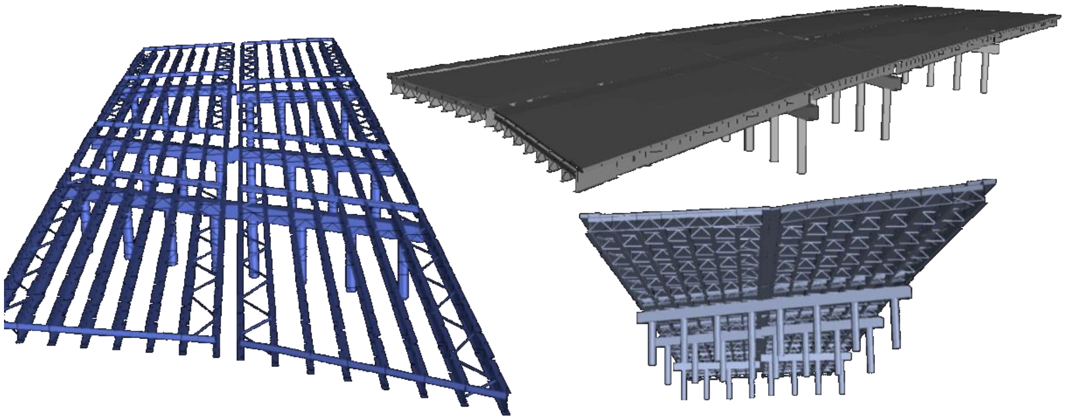

Figure 4 – Example 3D FE model of bridge super- and substructure systems developed through the Matlab-Strand7 Application Programming Interface (Dubbs and Moon 2016)

Task 2a – Development of a Model-Free Data Interpretation Framework

- This task will focus on the use of impedance functions, or simplified dynamic soil-foundation models, and will utilize the same suite of bridge system models developed under Task 1
- In particular, this task will aim to establish how sensitive and robust the model-free techniques are when exposed to data with various levels of measurement noise and spatial resolution/density

Task 2b – Development of a Model-Based Data Interpretation Framework

- Using the same suite of FE models develop under Task 1, this task will examine the ability of using various St-Id approaches to identify the changes in the soil-foundation-substructure parameters and the transverse distribution parameters (which have significant influence over capacity estimations) sampled under Task 1
- This task will identify both nonlinear and smeared linear models using the St-Id technique listed below to assess both sensitivity and robustness
    - Conventional deterministic model updating (Chen and Garba 1980; Imregun and Visser 1991; Hjelmstad et al. 1992; Mottershead and Friswell 1993; Sanayei et al. 1999; Mares et al. 2000; Brownjohn et al. 2003)
    - Threshold method (Robert-Nicoud et al. 2005, Smith and Saitta 2008, Kripakaran and Smith 2008, Goulet et al. 2010)
    - Semi-deterministic multiple-model method (Dubbs and Moon 2016)
    - Bayesian model updating (Beck and Katafygiotis 1998, Ching and Chen 2007)

Task 3 – Field Implementation and Validation

- This task will focus on the field implementation of the most promising testing strategies and data interpretation frameworks (identified in Tasks 1, 2a and 2b) on an actual bridge.
- The test bridge will be selected based on:
    - Access issues as well as the presence of detailed information on the substructure and foundation systems. The research team has well established relations with a number of regional transportation agencies (NJDOT, Delaware River Port Authority (DRPA), Delaware River Joint

Bridge Toll Commission (DRJBTC), New Jersey Turnpike Authority (NJTA)), which will be of high benefit in selecting best candidate bridge(s).
    - Discussions with the NHERI team at the University of Texas at Austin (UTA) regarding the shaking (forced vibration) scenarios.
- A detailed test plan based on the results of Tasks 1, 2a, and 2b will be developed and carried out with a UTA shaker (preferably T-Rex) and dense instrumentation arrays. A general instrumentation plan is illustrated in Figure 4. The objective of such a plan is:
    - To measure the response of all components: ground, foundation, substructure and superstructure in both vertical and horizontal directions, to infer the contributions of soil-foundation-substructure interaction on the overall response of the superstructure.
    - To enable assessment of transmissibility (motion transfer) and force transfer between superstructure and foundation, and from the foundation to surrounding soil.
    - To enable assessment of foundation impedance functions for both vertical and rocking motion.

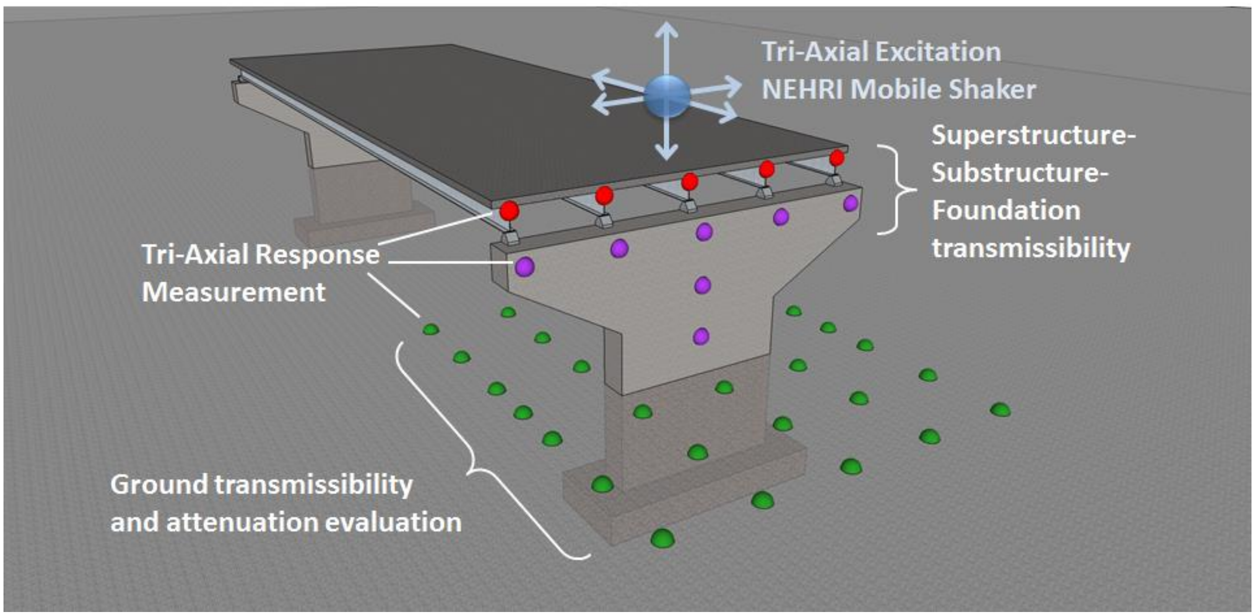

Figure 5 – Schematic illustrating envisioned instrumentation strategy

- The results will then be compared against the models within the parametric study to place the field test in context, and to develop recommendations for future research and implementation of the research products into practice.
- The testing will be also used as an opportunity to compare the results obtained from the bridge excitation using a NHERI shaker (vertical mode only) and THMPER, which is owned and operated by the research team.

Dissemination of Results

Results will be disseminated through a dedicated web-site and by presentations and publications at national and international conference proceedings, academic journals and research reports. Through the maintenance of close relations with professional organizations such as the ASCE and ISHMII, we expect further dissemination directly to infrastructure stakeholders through special workshops at various annual meetings and conferences.

Education and Outreach Component

The proposed education and outreach plan incorporates two primary activities: (1) recruiting, advising and mentoring graduate/undergraduate research assistants, and (2) development and implementation of a competition-based outreach effort aimed at engaging high school students and promoting STEM.

Recruiting, Advising, and Mentoring

Graduate and undergraduate students will conduct the proposed research and be exposed to the complexity of constructed system behavior inclusive of soil-foundation-structure interaction. This highly integrated, multi-disciplinary effort offers a unique opportunity for the faculty and students alike to contribute to better integrating the fields of geotechnical and structural engineering. The students funded through this project will be supported to attend conferences and encouraged to present and publish their results. To aid in the identification of qualified students, the research team has partnered with the NSF-supported Louis Stokes Alliance for Minority Participation (LSAMP) program at Rutgers University (access.rutgers.edu/lsamp). This program has an excellent track record of identifying and placing qualified students from under-represented groups, and is connected to the numerous other LSAMP programs throughout the U.S. Along with this partnership, the PIs will continue to use the Governor's School program at Rutgers (soe.rutgers.edu/new-jersey-governors-school-engineering-technology), REU opportunities, and their courses to identify and recruit top quality students.

Engagement of High School Students through a Competition-based Outreach Effort

To engage and expose high school students to engineering concepts, this project will develop and implement a competition-based outreach effort. To facilitate this effort, Co-PI Moon will leverage his current relationships with local high schools in Central NJ, the Philadelphia region, and Brooklyn Technical High School (the largest STEM high school in the U.S.). Over the last six years Co-PI Moon and his colleagues have hosted more than a dozen "Bridge Day" events at the educational facility at the base of Tacony-Palmyra Bridge (in Palmyra, NJ). These one-day events host between 30 and 100 high school students and teachers, and challenge them to engage in bridge design and construction activities using K'NEX^{TM} with goals of structural efficiency, economy, load-carrying capacity, and aesthetics. Similarly, for the past decade, PI Gucunski has been mentoring and instructing high school students participating in the New Jersey Governor's School of Engineering and Technology (which includes approximately 100 students per year).

Figure 6 – Students during a recent "Bridge Day" event

As part of this research, these activities will be expanded to address issues associated with soil-foundation-structure interactions. For example, this will be accomplished through enhancing the T-P Bridge tour (which includes an opening of the 3rd largest bascule span within the U.S.) to include explicit discussions of the three different foundation types (caissons, piles, and footings) and the varying soil conditions across the Delaware River that necessitate these differences. In addition, the competition will be expanded to include the design and construction of foundations and substructures for their K'NEX^{TM} bridges. To implement this it is envisioned that students will be required to found their bridges in buckets of sand, which will have a large negative impact on the overall load carrying capacity of their structures unless they devise a means of distributing forces (through piles or footings) to stiffen support conditions. Similarly, this competition will be integrated within the Governor's School activities.

Results from Prior NSF Support

PI Nenad Gucunski – IIS-1426828

Dr. Gucunski is a Co-PI on an NSF Project (IIS-1426828, $628,499, 8/2014-7/2017, PI: J. Yi) entitled "NRI: Collaborative Research: Minimally invasive robotic non-destructive evaluation and rehabilitation for bridge decks (Bridge-MINDER)." The goal of this NRI project is to develop a novel minimally invasive robotic non-destructive evaluation and rehabilitation for bridge decks.

Intellectual Merit: The proposed Bridge-MINDER system will generate knowledge, algorithms and enabling tools for designing new robotic technologies for sustainable civil infrastructure. We have already built both the non-destructive evaluation and rehabilitation robots as well as the conebot and signbot platforms. Two conference papers have been published so far and several are in preparation.

Broader Impacts: We have integrated a number of research activities into education programs to attract students from under-represented groups into engineering fields, such as participating into the Rutgers TARGET and SUPER programs. Three graduate students and several undergraduate assistants have been working in the project.

Co-PI Franklin Moon – CMMI-0864591

Dr. Moon received a NSF CAREER Award (CMMI-0846591, $400,000, 9/2009–8/2015) entitled "CAREER: Structural Identification to Inform Infrastructure Decision-Making." The objective of this research is to develop and validate a novel, multiple-model structural identification approach to transform sensor data from signature civil infrastructures into actionable information related to management, preservation and renewal.

Intellectual Merit: The intellectual merit of this research effort focused on three primary areas. First, the project developed, characterized and refined several novel multiple model St-Id approaches to quantify non-uniqueness and explicitly address the level of correlation between the observed response and vulnerability estimates (Moon et al. 2012, Dubbs and Moon 2015, Dubbs and Moon 2016). Second, this research developed and validated a unique approach to St-Id that leverages temperature as a forcing function and utilizing the resulting responses for St-Id and SHM applications (Yarnold et al. 2012, Yarnold and Moon 2015, and Yarnold et al. 2015). Third, this research developed an of approach to St-Id for populations of similar structures, which represents a significant paradigm shift as all past applications have focused on single structures (Masceri and Moon 2012, Deal et al. 2012, DeVitis et al. 2013, DeVitis et al. 2014).

Broader Impacts: The project enhanced several applications of St-Id and SHM of long-span structures, including the tracking of critical responses of the Bayonne Bridge during the $1.2 billion "Raise the Roadway" project. In addition, this project has produced several teaching modules and exposed over 500 high schools students over the last six years to engineering through a series of competition-driven one-day workshops.

Schedule

The proposed project will occur over a 12 month period. Tasks 1 and 2 are expected to require 8 months to complete and Task 3 is expected to require 6 months to complete (including planning and preparation). Field testing is anticipated to initiate during the 10th month of the project (May 2017) assuming a start date of August 1, 2016.