Uncertainty in Civil Engineering and Technology Leveraging to Capture Reality

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ABSTRACT

Uncertainty has been studied in philosophy, sciences and engineering since Pascale's Wager in the 17th Century. In engineering, uncertainty is classified as aleatoric (due to chance or luck) and epistemic (due to a lack of knowledge). Different engineering disciplines deal with different sources and mechanisms of uncertainty, however, civil engineers deal with arguably the greatest levels of epistemic uncertainty. One reason is that every civil engineered system is unique, and civil engineering systems are not proof-tested such as the crash testing of vehicles. Further, many civil engineers work within codes and a deterministic mind-model, and do not even recognize that the actual loads, mechanical characteristics and performance of constructed systems may be as different as 10-20 times of what is estimated. A conceptual approach that civil engineers can leverage to understand the mechanisms of uncertainty that prevail in the performance and behavior of constructed systems is system-identification. This paper describes some of the tools required for system-identification in civil engineering and some striking examples.

1. CIVIL ENGINEERED (CONSTRUCTED) SYSTEMS AND UNCERTAINTY

In "Three-Dimensional Static and Dynamic Analysis of Structures," Wilson (2002) offers the following quote before the preface to the book: "structural engineering is the art of using materials ***that have properties which can only be estimated*** to build real structures ***that can only be approximately analyzed*** to withstand forces ***that are not accurately known*** so that our responsibility with respect to public safety is satisfied." Similar perspectives were offered by great engineers throughout history, including Vitruvius, Alberti, Maillart and Nervi. An anecdote attributed to Nervi is: "*the least likely state of stress in a reinforced concrete structure is the one that an engineer calculates.*"

Indeed, civil engineers face significant uncertainty regarding the actual mechanical properties (mass, damping, stiffness and strength; boundary and continuity conditions and deformation kinematics) and the performance characteristics of the constructed systems they produce. Other engineering disciplines that manufacture their products may ensure that little uncertainty remains with the characteristics of their products, and often warrant them for years to a decade. However, the mechanical characteristics, behavior and performance of a constructed system is governed by the socio-technical, geographical, geo-physical and geo-chemical characteristics of the region and site at which the system is constructed and the unique circumstances of how it is constructed. There are examples of "sister" bridges constructed side-by-side by the same contractor using identical materials and procedures. However, their performance may end up being very different, due to a variety of factors including the ambient temperature and humidity during the day concrete is cast or how construction cranes may have overloaded one of the bridges while the concrete is curing.

An effective approach to reducing uncertainty is system-identification (or, structural identification, St-Id) of a constructed system. St-Id is becoming a mature application (ASCE, 2013; Aktan and Brownjohn, 2013). However, there have been only a few dozen applications of St-Id to real constructed systems, and many of these applications uncovered only a small subset of the mysteries of a constructed system. Some reasons are noted below.

Moon and Aktan (2006) "*In addition to the complexities listed in Table 1, constructed systems (unlike manufactured systems) cannot be isolated from sources of uncertainty during the St-Id process. For example, a Boeing 747 can be removed from service and tested with controlled boundary*

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conditions in a controlled laboratory environment. In contrast, because of their size and fusion with their operating environment (e.g. soil-structure-interaction, temperature, etc.), constructed systems must be tested with their in-service, nebulous boundary conditions and in their non-stationary environments."

It follows that we have to reconcile the following when we make decisions about constructed systems, such as for their operations, condition evaluation, preventive maintenance, repairs, retrofits and renewal:

1. We can expect only an ***approximate ground truth*** that does not justify great precision when it comes to measuring the mechanical characteristics of constructed systems. At the same time, we cannot ignore the reality of physical laws. We should strive for a ***complete and accurate understanding*** of the ***kinetic and kinematic mechanisms*** through which constructed systems are loaded externally and intrinsically, how they deform, move and transmit their forces to the soil. In other words, we need to strive for accuracy and completeness in terms of understanding the mechanisms of behavior and the mechanisms of uncertainty governing behavior, but we cannot expect precision in ***quantifying*** these mechanisms. We should be bounding instead of quantifying.
2. Even when all pertaining code provisions are clearly understood and applied during design, there have been astonishing cases of failure performance revealing our lack of understanding of failure modes of constructed systems during overloads, accidents and other hazards (Oklahoma City Federal Building, World Trade Center Towers, I-35 Bridge, Fukushima Daiichi, I-5 Bridge and many others). These undesirable failure modes point to our failure of imagination during design, construction or evaluation. A critical responsibility of a civil engineer should be the mitigation of all probable undesirable modes of failure. This requires a different – creative – way of thinking and questioning during design and evaluation.

Heterogeneity	Materials, member proportions, detailing, etc. can vary considerably from member to member, and within a member. Deterioration and damage compounds these variations and makes discretization difficult and sometimes unmanageable without heuristics.
Boundaries	Constructed systems have unobservable soil-foundation interfaces that are often non-stationary in their contact properties. Soil and even rock properties change with pressure, moisture, temperature and time.
Continuity	Most constructed systems, and especially bridge systems are designed with movement systems and/or force releases. These systems are most often unobservable and behave differently under different levels of force and temperature.
Redundancy	Constructed systems have many types of local, regional and global/external redundancies. These redundancies are highly affected by temperature changes and temperature gradients (due to radiation), which results in intrinsic forces and changes in element properties.
Intrinsic Forces	Constructed systems maintain complex and non-stationary intrinsic forces due to dead weight, construction loads/staging, temperature effects, deterioration, damage, overloads, etc. These intrinsic forces are nearly impossible to measure in an absolute sense and just their changes often overwhelm the forces due to transient live loads.
Types of Nonlinearity	Element, connection and global behavior of real constructed systems exhibit many different types of nonlinearity that change at different limit-states. Cracking, material yielding, local instability, connection slip, interface friction, etc. are all associated with both hardening and softening type behaviors that are also frequently visco-elastic and/or visco-plastic.
Non-Stationary	Constructed systems are non-stationary due to the non-stationary nature of inputs (temperature, radiation, traffic, wind, etc.) as well as their various loading-level and loading-type related nonlinearities. Temperature and humidity effects are highly complex: changes and rate of changes in ambient, regional and local temperatures and humidity of the structure and the soil may lead to intrinsic forces and also induce changes in boundary and continuity conditions.
Uniqueness	Nearly all constructed systems are custom-designed for specific applications and their mechanical characteristics are strongly affected by events during and immediately following their construction. While types of constructed systems may be grouped based on their primary structural system, size, materials, etc., applying results from a single structure to a larger population of structures is challenging due to their inherent uniqueness.
Geometric, Temporal Scale, Cost, Lifecycle	Constructed systems such as major highway bridges or combinations of several bridges and tunnels within regional transportation networks may be longer than several miles, cost several billions of dollars (~15 Billion for the Big Dig in Boston), and be expected to remain in service for well over 100 years. The size and lifecycle impedes our ability to view such systems in a holistic manner over a sufficient span along their lifecycles and further compounds the natural variability and uncertainty in their mechanical characteristics.

Table 1: Some Unique Attributes of Constructed Systems

3. The ***performance of a constructed system*** is a complex multi-dimensional concept that requires a clear understanding of ***utility and functionality, serviceability and durability***, and ***life-safety associated with a very small (1/1,000,000) probability of failure*** under overloads or hazards with return periods of 25-50 years. Lesser levels of safety such as (1/100,000 – 1/10,000) probability of failure may be acceptable under occasional and rare hazards associated with return periods of 500-2,500 years. However, unlike airplane engine failure testing or automobile crash testing, constructed systems are tested to failure only by accidents or natural hazards.

   Based on the discussions above, the most fundamental distinction between the St-Id of manufactured and constructed systems is related to the level of both aleatory and epistemic uncertainty, and especially the latter, that must be managed (Ang and De Leon 2005). While the general definition of St-Id recognizes measurement uncertainty, traditionally, this uncertainty has been taken as random noise. In the case of constructed systems however, measured data and a priori models are also frequently subjected to significant epistemic uncertainty, which may be deterministic, and is often many times larger than the uncertainty due to natural randomness.

2. BACKGROUND OF TECHNOLOGY LEVERAGING FOR ST-ID APPLICATIONS

The National Science Foundation (NSF) and Federal Highway Administration (FHWA) have promoted and sponsored research on smart structures since the early 1990's. Following the September 22, 1993 plunge of Amtrak's cross-country Sunset Limited passenger train off a bridge into Big Canot Bayou near Mobile, Alabama, which killed 47 people, the FHWA Advanced Research Office advocated an exploration into the feasibility of bridge monitoring as a means of mitigating similar events. Following early research in aerospace, space, automotive, defense and civil infrastructures, the first International Workshop on Structural Health Monitoring (IWSHM) took place at Stanford University in 1997, with the support of NSF, various defense research agencies and the aerospace industry.

When a Wind and Structural Health Monitoring System (WASHMS) was installed on the Tsing Ma Bridge in Hong Kong in 1997, structural health monitoring, smart bridges and/or intelligent bridges became the subject of many additional research and application projects throughout the world. For example, Drexel University's Intelligent Infrastructure Institute, with the support of the FHWA, demonstrated an application on a long-span bridge crossing the Delaware River (Aktan et al, 2000, Aktan and Faust, 2003). This application demonstrated the feasibility of constructing a field-calibrated Finite Element (FE) model and developing a real-time, multi-scale integrated imaging, sensing, communication and computing system to support the operational and structural safety and security of a major long-span bridge. This application, however, also revealed the challenges in convincing bridge owners and their consultants to embrace such a leap toward leveraging advanced technology for operating and managing bridges in the United States.

Following September 11, 2001 (9/11), homeland security considerations took precedence over other infrastructure research areas and a new industry capitalizing on the threats and protective measures developed. In particular, closed-circuit imaging systems for security became commonplace. Following the collapse of the I-35 Bridge in Minnesota, the August 13, 2007 issue of *Engineering News Record* (ENR) included an article titled "Structural Health Monitoring is Sensitive Subject", quoting numerous consultants offering health monitoring services. The owners and designers of the replacement bridge hired Swiss company SMARTEC to install a SHM system during construction that mainly utilizes fiber-optic sensors. Data is being retrieved by researchers at the University of Minnesota. Subsequently, the Technology Innovation Program (TIP) that was launched by the U.S. Department of Commerce's NIST in 2009 created a renewed public interest in smart infrastructures. Some of the stakeholders of these projects were interviewed, highlighting technologies that will lead to smart bridges (e.g. Economist article "Self-Monitoring Smart Bridges").

In the February 17, 2009 issue of the *Wall Street Journal*, Michael Totty wrote "Smart Roads, Smart Bridges, Smart Grids." In it, he stated, "If we are going to spend billions of dollars to fix our ailing infrastructure, let's make sure we do it right. Here are the technologies to make that happen." Totty continued, "Looking for structural problems with the nation's 600,000 bridges mostly still requires a visual inspection, which can be inconsistent and expensive. A better alternative, engineers say, would be continuous electronic monitoring of bridge structures using a network of sensors at critical points. These devices can deliver data about how a bridge behaves under heavy traffic, in high winds or other conditions. And they can spot potentially serious problems long before they might be apparent to a human inspector."

While the press was fascinated by technology-push research even without a buy-in by all stakeholders, especially bridge owners, FHWA was more realistic in defining what would constitute a smart bridge. For example, in the July 2003 issue of *Roads & Bridges* magazine, FHWA's Chief Science Officer Dr. Steven B. Chase outlined "The Bridge of the Future". Chase stated, "*To meet the need for longer-lasting, low-maintenance, high-performance bridges in the decades to come, FHWA has identified specific performance* *goals to help direct the research initiative for the Bridge of the Future. The goals take into account initial costs, service-life costs and the indirect costs of safety and time."*

The proposed performance goals include:

- Achieving a service life that is no longer controlled by corrosion and involves little or no structural maintenance;
- Reducing construction time significantly;
- Designing bridges that can be widened easily or adapted to new traffic demands;
- Reducing life-cycle costs significantly (pointing to improved drainage, durable materials, providing access and other measures for facilitating and improving the reliability of inspections and NDE applications, and, eliminating common causes of early deterioration requiring expensive continued maintenance and repairs through the life-cycle);
- Immunity to attack, flooding, earthquake, fire, wind, fracture, corrosion, overloads and collisions;
- Integrating design and construction of foundations, substructure and superstructure; and
- Eliminating vertical and lateral clearance problems.

3. SOME BARRIERS TO INNOVATION

The American Society of Civil Engineers (ASCE) offers five Key Solutions to improve infrastructure conditions: (1) Increase Federal Leadership in Infrastructure; (2) Promote Sustainability and Resilience; (3) Develop Federal, Regional and State Infrastructure Plans; (4) Address Life-Cycle Costs and Ongoing Maintenance; and, (5) Increase and Improve Infrastructure Investment from All Stakeholders.

ASCE's list does not touch on a need for "***innovating the engineering and management of infrastructures by adopting new paradigms and integrating and leveraging technology to implement these paradigms.***" Recently ASCE acknowledged the limitations and shortcomings of the current state of practice, and called for innovation, in addition to a lack of investment, as an essential approach to address the infrastructure problem. Many engineers acknowledge the pressing need for new knowledge for objective condition assessment, understanding the root causes of deterioration and damage, renewal engineering and organizational effectiveness. Paradigms such as ***Performance-Based Engineering*** (Aktan et al 2007), ***Lifecycle Cost Analysis and Asset Management*** (Moon et al, 2009), ***Structural Identification and Health Monitoring*** (Aktan, et al, 2000), and ***Systems Engineering of Complex Multi-Domain Infrastructures*** (Sussman, 2012) offer powerful concepts and strategies for innovation.

It should be noted that performance-based engineering and asset management are complex paradigms and are not yet widely recognized in civil engineering education. They still require technology development, technology transfer and technology integration for proper applications. Further, the adoption of just one paradigm, such as Asset Management, without also adopting Performance-Based Engineering may not have a significant impact on current practice. This is especially relevant in the case of structural health monitoring as this concept may not be useful without first implementing structural identification. ***Unfortunately, current research on infrastructure paradigms and technology for applications is also fragmented and these interdependencies between paradigms, concepts and technology are missed too often by many researchers and even research support agencies.***

4. CLASSIFICATION AND STRUCTURING OF TECHNOLOGY

Infrastructure technology tools may be broadly classified as: (a) sensing and imaging, (b) analytical (and sometimes physical) modeling and simulation, (c) information, communication, computation and (d) risk/decision-engineering tools.

Sensing technology includes every aspect of measurement in the field, whether measurements are for local or global quantities, and whether they are under regular operations or controlled testing conditions. Non-destructive evaluation (NDE) is a subset of sensing. Simulation technology includes mathematical, numerical and computational modeling and simulation, with the FE approach being the most common and relevant. Information technology covers everything related to data and information communication, processing, visualization, interpretation, and archival. Finally, decision-making technology covers paradigms and methodologies for statistical analysis, risk assessment, quantitative performance metrics and multi-objective constrained optimization.

To formulate a context-based classification (or an Ontology) for bridge terminology, Table 2 has been developed to identify the spectrum of applications that may be justified for condition assessment, decision-support, monitoring, and lifecycle management of a major bridge or a population of common bridge types. This table is organized based on the following six critical steps (shown in dark orange cells across the first row):

1. High-level risk-assessment of a bridge inventory and prioritization of bridges for in-depth evaluation;
2. Next-generation bridge inspection for condition and performance evaluation;
3. Quantitative measurement and conceptualization of geometry and materials;

4. Simulation, NDE, short-term structural testing and model calibration;
5. Prognosis, risk assessment, and selection/ implementation of corrective actions;
6. Operational, security and structural health monitoring to serve for asset management.

The listing order of the columns is intended to reflect a logical hierarchy of investing into technology leveraging to improve:

a. How we may identify common performance concerns of a bridge population.

b. How we may better prepare for and more effectively execute bridge inspection(s) for a more complete and reliable understanding and documentation of condition and performance.

c. If needed, how we may measure the as-is geometry and material characteristics to perform bridge-specific analysis and or intervention design.

d. If needed, how we may proceed for a structural identification of a bridge after geometry measurements and material characterizations.

e. If needed, how we may perform prognosis.

f. If needed, how we may leverage monitoring technology (integrated, wide-area, multi-modal imaging, sensing, communication and computing) in addition to heuristics as a means of managing the operations, preservation and capital management of a bridge in the realm of asset management.

To help organize the table, the sensing technology applications are shown in blue text on a white background, the information technology applications are shown in white text on a light blue background, the simulation technology applications are shown in white text on a dark blue background, and the risk/decision engineering technology applications are shown in white text on a grey background. In some cases (especially the last column) various applications incorporate elements from more than one category of technology, but for organizational simplicity, the predominant technology was used for color coding.

The ultimate objective of technology applications would be Asset Management, a meaningful application of which requires the applications of many of the technology tools described in Table 2. Please note that while it would be an extremely rare case that would require a comprehensive employment of all the applications listed in Table 2, it would also be a rare case that would only require a single application.

In the case of a major long-span bridge that serves a vital role in the economic vitality of a dense urban region, such as the San Francisco – Oakland Bay Bridge and the George Washington, Verrazano and the East River Bridges in New York City, we would expect an integrated application of most of the cells in Table 2 to be justified. The cost of proper technology leveraging for a major, long-span bridge, especially if aged and deteriorated, may reach $Millions while any intervention may cost in $Hundreds of Millions given user costs. It is therefore quite sensible to leverage technology as a means of insuring that intervention needs and intervention designs and constructions are based on the best engineering that may be envisioned in addition to the leveraging technology.

To fully enjoy the benefits of technology it is necessary to integrate various applications seamlessly across information, sensing, simulation and decision boundaries. So while the cells do not represent applications that must be followed thoroughly for each bridge challenge that arises, the Table's organization (from left to right) does provide a broad roadmap for the various stages that must be addressed and the potential technology applications available to aid owners as they address them. In addition, it is important to point out that the first column depicts the scenario of managing an entire bridge population, and if technology is to be leveraged by owners of a large number of similar bridges it is recommended that this column be completed in full before any more detailed bridge-specific applications are pursued.

The first column of Table 2 therefore focuses on the entire bridge population and aims to structure it based on risk levels and performance deficiencies of various types of bridges. This is important as in many cases it is not cost-effective to employ detailed simulation and sensing technology applications for a single bridge unless this is a uniquely critical and major bridge with a great economic impact of non-performance. This critical step will allow owners to identify representative test bridges that may be examined in detail to inform decisions for a fleet of bridges with similar risk or performance issues. While this approach adds little to the overall cost of individual technology applications, it has the potential to greatly magnify the benefits as it allows them to be used repeatedly across a population of similar structures.

The second column of Table 2 represents an enhanced visual inspection and performance documentation procedure that should become commonplace in the next decade. This approach not only allows for more complete documentation, but also provides inspectors with access to previous documentation on site, which is critical to identifying changes, vulnerabilities missed by previous inspections, and when deterioration has begun to accelerate. In addition, practical NDE and ambient vibration monitoring has been included within this column as they add little cost and can provide significant benefits by permitting an experienced inspector to quickly and quantitatively examine their

High-Level Risk Assessment and Prioritization of Bridge Population	**Next-Generation Bridge Inspection and Performance Documentation**	**Quantitative Conceptualization of Geometry and Materials**	**Simulation, NDE, Short-Term Structural Testing, and Model Calibration**	**Prognosis, Risk Assessment, and Selection/ Implementation of Corrective Actions**	**Operational, Security and Structural Health Monitoring within Asset Management**
Development of a Searchable and High-Level Database to house comprehensive condition/risk information about the entire bridge population	**In-depth Visual Inspection** aided by voice-command tablets linked to e-archive for past photos, notes and real-time reporting.	**Surveying and GPS** to capture a sparse but accurate number of dimensions to reconstruct or validate plans/drawings	**Development of FE Models and Simulations** to identify critical sections, members, connections, and associated failure modes	**Establish Critical Demand and Capacity Envelopes** and obtain reliable load capacity rating and reliability	**Operational Enhancements** including variable lanes and speed limits, warning systems for wind/ice, open-road tolling, etc.
Automated Finite Element Construction and Analysis to flag significant structural vulnerabilities and potential design errors	**Practical Local NDE** as needed to enhance and validate visual inspection	**Non-Contact Geometry Capture** (photogrammetry, laser scanning) to obtain a higher resolution and more precise geometric representation of complex regions	**NDE** of critical sections, members, connections with clearly identified uncertainties	**Identification of Critical Hazards** that may mobilize the inherent vulnerabilities of the structure.	**Automated Operational Monitoring and Law Enforcement** including speed and lane change monitoring, weigh-in-motion, license plate ID, auto flagging/enforcement, etc.
	Practical Ambient Vibration Monitoring for global assessment		**Controlled Load Testing** at either Diagnostic- or Proof-Level loads to establish force-resisting mechanisms and load paths	**Scenario Analysis and Risk Assessment** to identify and rank the most critical risks	**Security Monitoring** including comprehensive surveillance, video analytics, weigh-in-motion, explosive sniffing sensors, etc.
Effective Structuring of the overall population through data mining and heuristics		**Material Sampling and Testing** to fully characterize in-situ materials related to their mechanical properties (strength, stiffness), chemical composition, microstructure, etc.	**Short-Term Monitoring** of live load and temperature induced responses to characterize loading environment	**Estimate the Cost of a Failure to Perform** including potential loss of human life, direct costs, user costs, economic impact, etc.	
	Knowledge Engineering informed by interviews with experienced engineers to capture related heuristics		**Forced-Vibration Testing** and modal analysis to capture global dynamic properties and modal flexibility	**Identification of Appropriate Actions** that may consist of risk mitigation through retrofit or hazard minimization (e.g. posting), monitoring, or "do nothing".	**Structural Health Monitoring** to track critical responses, real-time image/video, automated comparison with simulation models, real-time rating, automated reporting, etc.
Identification of Test Clusters to diagnose and inform the mitigation of common performance problems	**Development of an Information Warehouse** complete with a chronology from historic records, narratives, legacy data and information for archival	**Development of 3D CAD** to fully conceptualize the structural form and to serve as the interface with the information warehouse (3D fly-through) and basis for an FE model	**Ambient Vibration Testing** to capture operating global modal parameters		
			Calibration of FE Models by reconciling measured and simulated responses through modification of uncertain aspects	**Implementation of Corrective Action** monitored to validate design, staging and to provide baseline response for future performance assessment	**Special and Custom Inspections** based on SHM – Lifecycle Costing, Asset Management

Table 2: Classification and Structuring of Bridge Technology

intuition about performance issues and their potential causes. The inspector who will be leveraging such tools would require special education and training and should also be an experienced engineer.

The third column of Table 2 focuses on a quantitative characterization of both geometry and materials. In the last decade, significant advances have been made in various non-contact scanning technologies that offer the ability to quickly and accurately capture high-density geometric information about structures. This is obviously important for bridges without documentation, but also useful to check design/as-is drawings and is critical for the construction of a representative 3D CAD model which can be employed as an interface to a comprehensive database, aid in visualization, and serve as the foundation of an FE model. Finally, there are many conventional and more modern material sampling and characterization approaches which can add important information about the quality, variability and mechanical properties of materials.

The fourth column of Table 2 provides technology applications that have traditionally fallen under the paradigm of Structural Identification (St-Id). This paradigm, introduced in the late 1970s, was the focus of a recent state-of-the-art report released in 2012 by ASCE. This process begins with the conceptualization of the performance issue of concern and the identification of sources of uncertainty that are challenging the associated decision-making. Through the use of an FE model, together with parametric studies, the sensitivity of the uncertain behaviors on the desired performance is established and a sensing application capable of providing information about the uncertain (and influential) behaviors is designed. This application is then carried out and the data is processed, visualized and interpreted to both establish data quality and to begin to understand the uncertain behavior mechanisms. The final step of the process is to reconcile the original simulation model with the results of the experiment by perturbing the uncertain aspects of the model until it is able to replicate the observed responses. While the ‘devil is in the details’ of this model calibration process, if done with a proper focus on a bridge’s behavior mechanisms it can be a highly effective tool in guiding decisions.

The fifth column of Table 2 focuses on how the calibrated model developed in column four can be used to better understand performance issues. It is important to stress that this simulation model is a mechanistic representation of the bridge’s performance, and as such can aid in diagnosis, prognosis and the design of various interventions. Although it is conceded that qualitative visual inspection information provides important input to preservation and renewal activities, in many cases (especially when structural concerns arise) a quantitative and mechanistic understanding of bridge performance proves decisive. Such an understanding allows various scenarios to be examined and provides a consistent approach to both diagnosing and mitigating performance concerns.

The sixth and final column of Table 2 outlines a number of potential interventions that include various operational strategies, monitoring applications and management policies. While many of these have been implemented without the input from other technology applications (columns one through five), the benefits enjoyed from such applications nearly always fall short of expectations. This is because to identify the appropriateness of a cell in column six, a great deal of preparation and objective data collection must be completed. There is no substitute for this preparation and knowledge gathering, and owners are particularly cautioned about commercial entities whose entire business plan is based exclusively on column six. Just going in with an application on column six based on subjective, untested and incomplete data and information is not responsible. A careful application of columns 1-6 will be the proper and prudent investment into technology.

The following observations and conclusions follow from the above discussion on technology:

- Leveraging technology for infrastructures is not exclusively a technical challenge. This requires proper policy, organizational strategies, incentives, budgeting flexibility, an understanding and valuing of benefit/cost ratios, and an appreciation of the complexity and integration requirements of technology.
- Given the significant breadth associated with the Technology Classification Table (Table 2), a coordinated multi-disciplinary team is required for proper technology applications. At the present time this cannot be accomplished by offering a contract to a typical civil engineering consultant.
- Heuristic/empirical insight/knowledge is critical and essential, but is also distinct from the objective mechanistic knowledge and risk-based decision-making enabled by proper technology applications. It is not possible to leverage technology unless this distinction is clearly understood and can be properly bridged within an organization.
- Unless technology applications are well-planned, designed, resourced, and implemented properly, value cannot be expected from the ability to address concerns related to efficiency, serviceability, safety, security, and reliability. The experience of the Project Manager (PM) in technology application and integration, and the infrastructure that is provided to support the PM, remain as critical factors for achieving success.

5. APPLICATIONS TO THE BURLINGTON COUNTY BRIDGE COMMISSION BRIDGES

The Burlington County Bridge Commission in New Jersey has approximately 150 employees consisting of toll collectors, police officers, maintenance staff, clerical and administrative personnel in two locations, Palmyra and Burlington. The Commission operates the historic, movable Tacony-Palmyra and Burlington-Bristol Bridges. Researchers and engineers have been engaged in the demonstration and leveraging of structural identification, performance and health monitoring, and asset management of these long-span bridges through the last decade. The application of these paradigms required many of the technology tools listed in Table 2. Structural Identification of the Tacony-Palmyra Bridge

Constructed in 1929 by the renowned Ralph Modjeski, the Tacony-Palmyra Bridge crosses the Delaware River connecting Tacony, PA and Palmyra, NJ. The 3,660 foot long structure includes a 550-foot steel tied arch span (Figure 1) and a 260-foot Scherzer, rolling lift, bascule span (see Figure 2). The policy of the Commission is to indefinitely preserve this historic and irreplaceable structure by leveraging modern technology.

The entire structure of the Tacony-Palmyra Bridge was tested by ambient vibration monitoring over a period of several months. The results were used for structural identification. The structural systems of the bridge, especially of the bascule span, are quite complex. The bascule becomes a dual cantilever structure when open but is transformed into a continuous system after the two cantilevers are closed and compressed, locking the bascule span for continuity. The structural identification process, along with an in-depth review of the history and anatomy of the bridge led to a careful vulnerability assessment.

River navigation, under the jurisdiction of the Coast Guard, has priority over highway transportation. If and when a vessel is announced, it cannot stop unless it runs aground. The bascule has to open several times a day, and a risk of its being stuck is not acceptable. For this reason, the bascule cantilevers are delicately balanced in weight around their pivots as a backup, they can be opened by hand-cranking in the case of a power loss.

Given the importance and need for the flawless operation of the bascule span, and the complexity of this electro-mechanical system which becomes as tall as a 12-story building when open, a real-time operational and structural health and performance monitoring system (MONITOR) was designed and installed.

The MONITOR leverages distributed sensing, imaging, data acquisition and communication. Sensing and imaging design was driven by the need to capture the changing state of force and displacements at critical regions of the structure as it transforms, as well as to provide an accurate feedback to the human operators as to where each point of the structure is during the opening and closing of the leaves.

Sensors include electrical resistance and vibrating wire strain gages, tilt sensors and a weather station. Digital cameras were positioned at selected locations on and around the structure. The synchronization and integration of data and images was accomplished through the development of a live web portal and a customized playback program following and adapting the principles of Supervisory Control and Data Acquisition (**SCADA**) Systems used in nuclear reactors. The live web portal allows for real-time remote viewing of the data and video over the internet. The structural monitoring software includes the ability to record events such as bascule openings and the presence of an overloaded vehicle. These events can be viewed in the playback program (see Figure 3). This program allows data to be viewed both spatially and temporally to maximize data interpretation and benefit for the end user of the SHM system. The system is also equipped with trigger and alert functionality for specified events.

Meanwhile, the Tacony-Palmyra Bridge tied-arch span is being evaluated through a new approach termed Temperature-Based Structural Identification (TBSI). Bridges experience significant daily and seasonal temperature variations causing relatively large changes,

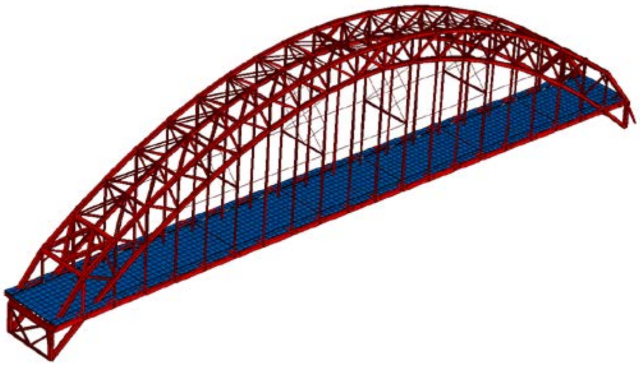

Figure 2: Arch Span FE Model

Figure 1: The Tacony-Palmyra Bridge

strains and displacements, often more significant than those due to live loads. TBSI uses temperature as the forcing function for leveraging differences in constant ambient temperature states along seasons (which may occur typically after a windless midnight and before sunrise) as controlled tests for a long-span bridge. TBSI leverages an extensive number of temperature and intrinsic strain measurements distributed to the critical nodes and especially the boundaries of a bridge and takes advantage of the changes in the temperature-induced intrinsic forces for a better understanding of the structural boundary conditions, movements, and internal force distribution for structural identification and performance assessment of the critical continuity, bearing and movement systems. The Tacony-Palmyra Bridge arch span has therefore been instrumented for: (1) finite element model calibration for reliable structural ratings; (2) evaluation of long-term performance criteria, and (3) development of automated alert criteria for the real-time structural health monitoring system.

The examples above illustrate the components of a long-term structural health and performance monitoring system that is being implemented on the Tacony-Palmyra Bridge, and also reveals the intersections and interconnections between various technologies listed in Table 2. The structural identification, scenario analyses and MONITOR allow for the identification and tracking of key operational and structural performance measures. In addition, an enhanced mechanistic understanding of the structural behavior of the bridge has been achieved. Therefore, the systems that are implemented, especially when completed, will provide the bridge owner and engineers data, information and knowledge that will enable effective and reliable decision making to better manage the structure as an irreplaceable asset.

Figure 3: Playback program for detailed review of recorded openings

6. CONCLUSION

Planning, architecture and engineering of the built environment remains an empirical art since the prehistoric settlements in Mesopotamia, Anatolia and Egypt. A formal civil engineering education was not established until mid-1700 in France and early 1800 in Great Britain and the United States. After the 1950s civil engineering education gradually transformed into science-based, and after the 1980s the practice became increasingly dependent on leveraging computer software. We are reminded, however, of the significant uncertainty prevailing in civil engineering with spectacular as well as daily failures associated with a lack of performance of the built environment. This paper summarizes research conducted in the past several decades and leads to a better understanding of how we may deal with uncertainty in civil engineering.

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