An Effective Integrated Approach to the Operational Efficiency, Structural Preservation and Security of Transportation and Other Infrastructure Systems

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Introduction

The importance of our infrastructure systems as the foundations for our civilization, maintaining the health of our society and serving as the engines for our economy has been articulated by the NSF and other government agencies since the 1970’s. The National Earthquake Hazards Reduction Program (NEHRP), created by the US Congress by the Earthquake Hazards Reduction Act of 1977 was based on recognizing the impacts of earthquakes on infrastructures, and was instrumental for significant advances in earthquake engineering. Problem-focused research by engineers and scientists on earthquake disaster mitigation brought to us considerable advances in the understanding of how geotechnical and constructed systems are affected by and respond to earthquakes. New design and retrofit methods were found, various mitigation strategies were developed, and these were codified and implemented.

The dual-use initiative following the fall of the Berlin Wall in 1989 helped direct attention to the operational performance, maintenance and renewal of constructed systems as a focal area for research. Various technologies and application tools such as imaging by infrared, radar and laser, developed in the realm of defense, became available for civilian use. Government laboratories started contributing to technology transfer research on condition assessment and new materials for effective renewal of aged constructed systems. In 1992, NSF established a Civil Infrastructure Systems (CIS) Task Group that noted the fragility of infrastructures under natural hazards and accidents (NSF 93-5). The CIS Task group noted the impact of infrastructure systems on economic productivity and growth, and the need for a new strategy that approaches the issue from a systems perspective. A new research initiative to address the fragmented nature of infrastructure industry, to identify public policy issues, and other impediments to progress was recommended. The objective of the effort was noted as: “to enhance system performance and the longevity of existing and future infrastructure systems. New knowledge is needed in deterioration science, condition assessment of existing systems, and renewal engineering.”

The transportation system has attracted special attention as an especially critical and complex infrastructure system, including the highways, railroads, mass transit, ports and waterways and air transportation systems. Highway transportation is financed almost entirely by the public, and, is under the jurisdictions of a multitude of government and semi-government agencies at the federal, state, bi-state, local and municipal levels. The US Congress has signed the Intermodal Surface Transportation Efficiency Act (ISTEA) into law in 1991. This act was renewed in 1998 as the Transportation Equity Act of the 21st Century, and it is up for renewal again in 2004. These Acts that fund the transportation infrastructure have served as excellent drivers for research and technology development in transportation, and, starting from 1991 these have emphasized the importance of paradigms such as “intelligent transportation systems” for
enhancing the efficiency and safety of operations, and, “asset management” for optimizing the manner in which the infrastructure components are preserved in an integrated manner as assets (including their condition assessment and evaluation, maintenance, retrofit and renewal.

In the mid 1990’s, following the April 19, 1995 bombing of the Murrah Federal Building in downtown Oklahoma City, and also in anticipation of Y2K, President Bill Clinton established the President’s Commission on Critical Infrastructure Protection (PCCIP). The PCCIP identified eight systems as critical infrastructures, and examined threats and vulnerabilities of these systems. A national strategy was formulated for critical infrastructure assurance, and a plan was developed to implement the strategy. The eight infrastructures identified by PCCIP were: banking and finance; telecommunications; electric power; gas and oil storage and delivery; transportation; water supply; emergency services; and governmental services. The PCCIP also noted that these additional infrastructures deserve follow-up efforts. Some of these infrastructures were identified as: food/agriculture, medicine/health care, and the chemical industry, among others.

Following September 11, 2001, all agencies inevitably focused on the security of critical infrastructures. President Bush issued an Executive Order on Critical Infrastructure Protection on October 16, 2001, and the department of homeland defense was established through the homeland security act following President Bush’s request in June 2002. Critical infrastructure protection is now recognized as a most important element of homeland security. A recent NSF initiative (03-518) noted: “Our modern society is dependent upon an infrastructure of critical human-made structures and systems. These systems include such engineered elements as telecommunications, transportation, energy, water and wastewater, financial institutions, and the built environment, and related social, political, emergency planning and response and economic systems. These interrelated systems provide the “lifelines” of modern society. When they are damaged, destroyed, disrupted, or simply unable to function at an adequate capacity, the results can be disastrous for society. Disruption to these systems can be initiated by a variety of natural (e.g., earthquakes, floods), technological (e.g., power failures caused by overloaded grids, toxic releases initiated by failed mechanical systems) and intentional, human-induced (terrorist attacks) hazards. Due to the inherent complexity of these engineered systems and their interrelationships with political, social, and economic systems, cascading failures resulting in decreased system capacities and an increase in demands often create disasters for affected communities”.

It follows that in the snapshot of history since the 1970’s, there have been various events and drivers pointing to the challenges and opportunities of problem-focused research, technology development, education, training and services by academe, government and industry for: (a) mitigating the impacts of earthquakes and other natural hazards, (b) the operational safety and efficiency of infrastructures, (c) effective preservation and sustainability of infrastructures, and, (d) security and protection of infrastructures. As a community of researchers, practicing professionals and the users of infrastructures, we have a lot at stake to look at infrastructures and the associated research and development needs in an integrated manner. We need to agree that we cannot separate the problems (a)-(d). These problem areas have to be approached in a holistic manner in order to do justice to any one of them. The challenge is in being able to form a community of stakeholders, and, to formulate, sponsor and execute problem-focused research on infrastructures as discussed further in the following.

**Fundamental Issues:**

We cannot dispute that as a society we need to advance our capabilities and become more effective in operating, protecting and preserving our critical infrastructure systems. It is also clear that reductionism
is a principal shortcoming in any thinking or approach related to infrastructures that are very complex heterogeneous hyper-systems. A holistic approach requires education, research and practice related to infrastructure systems that will recognize and incorporate the following fundamental attributes:

- Infrastructure systems are made up of interacting engineered, human and natural sub-systems and elements. Engineered systems or elements should be further classified into constructed and manufactured due to distinctions in their design, financing and cost, size, lifecycle, ownership, uncertainties and risks affecting their functions and operation, etc. Successful engineering of such heterogeneous hyper-systems requires new knowledge and tools. The transformation and integration of systems engineering principles and implementations that have been developed for various systems by their respective disciplines is the logical starting point for creating a new discipline for the engineering and management of hyper-systems;

- Operation, protection, preservation and sustainability are three fundamental areas of concern, closely integrated and affected by the interactions between the engineered, human and natural elements, and the interconnectedness between different infrastructures;

- There is a compelling need for improving how we plan, finance, construct-manufacture, operate, preserve and protect infrastructures. Currently, the operational efficiency and safety of most infrastructures are not satisfactory, public funds available for this purpose are clearly insufficient, and the natural resources are not sustainable if we maintained the status-quo. The risks in not making major improvements in the operational safety and efficiency, preservation and protection are simply too great for every stakeholder.

- Current education, research and practice regarding any aspect of infrastructure operation, preservation or protection are greatly fragmented. Integrative, multi-disciplinary education, research and practice is essential, however, we have not yet fully discovered the keys to integration. We need to do research for learning and teaching how we can treat infrastructures as interconnected and integrated systems, by taking full advantage of systems engineering and the related sciences, and by adopting and further improving on these to become effective and suitable for large and complex heterogeneous hyper-systems;

- Research and education is needed to adopt the current systems engineering and operations research tools for meaningful implementations for solving real infrastructures concerns. The size, complexity, cost, heterogeneity, incremental constructions over Decades to Centuries, and long life-cycles of infrastructures makes it very difficult to observe, measure, model and simulate, analyze, synthesize and control them using generic systems engineering tools. We reiterate that “we need a new systems engineering and management toolbox for dealing with unobservable, non-stationary, highly dynamic heterogeneous hyper-systems governed by many complex mechanisms of uncertainty and risk.”

- There is great promise in adopting powerful concepts and paradigms that we are not currently fully taking advantage of for improving infrastructure efficiency, protection and preservation. Some of these are: integrated asset and risk management, performance-based engineering, health monitoring and proactive health management, and, systems engineering tools such as identification, control, optimization, decision theory and intelligent systems. The issue is in being able to transform and adopt these paradigms to infrastructures. This cannot happen by hypothesis, or just by computer simulations. Research and demonstrations have to be carried out on actual infrastructures as we cannot yet properly simulate infrastructure systems.

- The creation of an integrated community of stakeholders, a connected multi-disciplinary nexus, dedicated to advancing infrastructures operation, preservation and protection in a problem-focused manner, is needed. If this community includes infrastructure owners and industry representatives, we may find an opportunity to conduct research on actual operating infrastructures. An important question relates to the leadership and coordination
of this community. Writers believe and submit that renaissance civil engineers are perhaps the best equipped to frame the problems of large, heterogeneous hyper-systems, and help develop a new language, data, information and knowledge so that we may adopt and develop new systems engineering tools for a holistic, integrative approach to infrastructure concerns.

Objectives

The first objective of this paper is to advocate an effective, integrated effort towards an international nexus for infrastructure innovation. There are currently many communities dealing with various aspects of different infrastructures. For example, if we take transportation, there are vibrant communities that specifically focus on Earthquake Hazards Mitigation (e.g. EERI), Intelligent Transportation Systems (e.g. ITS America, ITS International), Nondestructive Evaluation Technologies (e.g. SPIE), Structural Health Monitoring, Knowledge-Intensive Intelligent Systems, Operations Research Applications to Infrastructure, Asset Management Applications to Infrastructure, Protection of Infrastructures, Information Technology Applications to Infrastructures, Systems Engineering Applications to Infrastructure, etc. There are various other communities, often under professional engineering societies such as ASCE, IEEE, etc., that have traditionally focused on the design, construction, operation, evaluation and maintenance of a specific infrastructure system, sub-system or element, such as environmental engineering, geotechnical engineering, reinforced concrete structures, steel structures, asphalt pavements, engineering management, power systems, telecommunication systems, etc. A matrix of all related communities should be formed and members of these various communities should be asked to join the researchers and practicing experts in government, organizational science, human science and health science to design and form a nexus.

The international nexus for infrastructure innovation would have to represent academe, government and industry as the three major classes of stakeholders that have fundamentally different perspectives of the problem. When we review the many communities listed above, we note a shortage of those that in fact integrate all of academe, government and industry successfully. Noting the success of the NEHRP program administered jointly by NSF, FEMA, NIST and USGS in forming a multi-disciplinary and multi-cultural community dedicated to earthquake hazards mitigation, it makes sense to start forming the nexus for infrastructure innovation by first bringing a cross-section of bureaus, divisions or programs from federal agencies such as FHWA, GSA, NSF, NIST, US Army Corps, FEMA and others, together.

The second objective of this paper is to advocate a return to problem-focused as opposed to a technology-push or “gadget-push” drive for research on infrastructures. The distinction between these two paradigms may be blurred in many research and technology integration initiatives, however, the outcome is becoming clear. There are enumerable success stories in new algorithms, devices, sensors, etc while there has been a glaring absence of credible implementations of innovative technology for solving any real infrastructure concern. We should recall the success of the NEHRP program and how this success was accomplished by a focus on the basic understanding of the problem through research at Urbana-Champaign, Berkeley and other major research universities starting from the 1950’s.

It is therefore important to return to NSF 93-5 for a deeper, fundamental understanding of the problems related to infrastructure operational efficiency and safety, hazards mitigation (protection) and preservation, and to take advantage of the advances in information technology and other recently developed analytical and experimental research tools for this purpose. We cannot understand the problem unless we form successful partnerships between academe, government and industry and go to the source of the problem, i.e. operating infrastructures. For partnerships to be effective, individuals coming together would all have to be champions for infrastructure innovation, and must include owners, practicing professionals, researchers and educators. Then we may be able to observe and measure the human, natural and engineering elements of actual operating infrastructures, and gain a deeper, factual understanding of
the problem. Generic, theoretical research on systems and operations research may take advantage of real data, and, innovations such as data fusion, multi-mode image and data fusion, synthetic agent-based modeling and simulation, and, knowledge-intensive multiple-agent intelligent systems, etc. may become effective tools for solving infrastructure problems.

The third and related objective is to advocate the importance of constructing real-life test-beds-and-demonstration sites for exploring and demonstrating innovative concepts, technologies and materials just as NSF is advocating and supporting the construction of distributed-connected experimental laboratories for earthquake engineering research (the NEES program). We need such sites as observatories for directly measuring and documenting the day-to-day behavior of infrastructures as systems. Research on exploring how to adopt and create new systems engineering tools based on observations and data from actual operating infrastructure test-beds is essential as an element of problem-focused research on infrastructures. This type of research is as relevant to infrastructure research as seismic monitoring and post-earthquake investigations have been in earthquake disaster mitigation research. Yet, funding agencies do not have a program or even an initiative for this type of research! In fact, observations and measurement on actual operating infrastructure test-beds and the use of such data for modeling and study of factual infrastructure problems are often not considered as “research” by the current “technology-push” initiatives and programs.

In the last two decades the first writer has had the opportunity of exploring how to develop field test-sites by taking advantage of operating or decommissioned highway bridges in order to make meaningful short-and-long-term observations, measurements and controlled tests. These studies led to an understanding of how to model, identify, simulate, and in some cases, control these constructed systems and how to diagnose their health. Bridges have the potential to serve as microcosms of actual, complete infrastructure systems, with interacting constructed, manufactured, natural and human elements. In the last five years, by partnering with the second writer who, as an infrastructure owner, is also a champion for innovation, a long-span toll bridge over the Delaware River close to Philadelphia has been converted into an operating test-site, and both the scale of this bridge and its dense urban setting proved invaluable for a deeper understanding of the requirements for effectively observing and measuring the infrastructures and the interactions between their engineered, human and natural elements.

As the researchers continued to acquire data from the long-span bridge test-site, and try to improve their capability to analytically simulate the observed and measured phenomena, the potential of taking advantage of wide-area real-time structural health monitoring platforms as effective virtual shields for the safety, protection and preservation of infrastructures also became apparent. The wide-area real-time health monitoring system that is now operating on the Commodore John Barry Bridge close to Philadelphia has been very useful for understanding the longer-term impacts of wind, temperature and solar radiation on a large constructed system, the issues that govern the long-term structural health, and the need for integrated strategies for effective preservation, i.e. the management of inspection, maintenance and retrofit of such large constructed systems.

The monitor system further provided a closer understanding of the coupling between engineered, human and natural elements, and the need for constructing an explicit objective function for more effectively managing the operations, security and preservation by an integrated asset management approach. Finally, the monitor system offered an excellent understanding of how research on innovative sensing, networking and other aspects of information technology can be formulated in a problem-focused manner, and provide immediate benefits to current infrastructure concerns in addition to fostering innovations for the much longer-term. The final objective is to briefly describe the system and its potential future applications.