University Transportation Research Center - Region 2

Final Report

Metrics, Models and Data for Assessment of Resilience of Urban Infrastructure Systems

Performing Organization: New Jersey Institute of Technology
Colorado School of Mines

December 2016

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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This document is a summary of findings based on this research as presented in several conferences during the course of the project. The research focused on identifying the basic metrics and models that can be used to develop representations of performance response that can be used to define resilience in urban environments, and to bring together data resources that can be investigated to understand and validate the interactive behavior of our complex transportation infrastructure systems, including the use of underground space..</td></tr>
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VERTICAL PLANNING OF URBAN UNDERGROUND SPACE USE IN CHINA

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The planning of underground space in China is one of the special aspects adopted in responding to urban growth, and almost every large Chinese city over the past few years has developed a plan for underground space usage. The vertical planning is one of features that differ from other types of planning since the underground facilities will be arranged at different levels in the urban underground, and because the materials in which the space will be created are geologic in origin and vary in both vertical and horizontal dimensions. This paper examines the importance of integrated vertical planning to include at-grade, above-ground and below-ground facilities, analyzes the lessons and experiences in developing the vertical planning for Chinese cities, and also discusses particular basic principles that can guide urban underground vertical configuration, and which may be used as reference for developing the urban underground planning.

Keywords: Underground space use, Vertical planning, Urban, China

1 Introduction

In China, the development and utilization of urban underground space is an important means to increase urban space capacity, relieve urban traffic pressure, and improve the urban environment. Underground planning is an important approach to the establishment of a resource-saving and environmentally-friendly city. Over the past years, China has experienced rapid development of urban underground space. Moreover, various recent studies indicate that it will continue to grow strongly in the coming years (see Table 1).

Table 1. The total area of underground space of some cities in China (million m^2)

City	Year			
	2004	2006	2011	2020
Beijing	18	30	>50.0	90.0
Shanghai		16	50.0	
Hangzhou			8.0	
Nanjing	2.8		>10.0	
Shenzhen			19.0	
Qingdao	2.0			25.4
Wuxi	2.0			15

(Source: "Research on Comprehensive Management of Underground Space Use in China")

The rate of growth is amazing. Taking metro transit systems expansions as an example, the aggregate length of metro systems in mainland of China was 318 km with only six cities having systems in 2006. This aggregate length had grown to over 1470 km by 2011, and today at least 33 cities in mainland China are actively constructing urban metro systems.
Planning of underground space in China is one of the special foci for responding to urban growth that has been developed by almost every large Chinese city over the past few years. Along with the rapid development of underground space, the use of the underground space use has been very intensive in the Central Business District (CBD) of many large Chinese cities. This means that it is not uncommon for underground projects to cross above and below each other in urban CBD areas of Chinese cities, so the vertical planning for underground space is becoming an important issue (see Figure 1).The goal of this paper is to provide a rational framework for urban underground construction by proposing several principles that may fit both technical and manageability requirements.

Figure1. A schematic drawing of the construction condition of the Bound tunnel in Shanghai's CBD
(Source: "Urban Underground Road and Urban CBD Traffic")

2 Vertical planning of urban underground space in China

Almost every large city in China (e.g., Beijing, Shanghai, Shenzhen, Nanjing, Hangzhou, Zhengzhou) has developed extensive and integrated planning document for urban development over the past years. As one of main contents, the plans of these cities commonly include vertical planning for underground space utilization in China. This paper provides the following two examples for analysis:

2.1 Example Ⅰ： Beijing City

In 2005, the major planning effort for underground space in Beijing city was completed. This plan aimed to not only encompass the current use of underground space, but also to propose requirements for future development whose content would include the scale, the function and configuration, the various types of underground facilities, as well as the vertical planning. Planning for different subsurface levels is summarized in Table 2, and the map in Figure 2 shows that underground space use is planned at many different levels under the central city of Beijing.

Table 2. Vertical planning of underground space in Beijing

Depth	Human accessibility	Use of underground space
≤10m	Excellent to access	Municipal pipelines, parking lots, commercial facilities, pedestrian transitways, transportation hubs, utility tunnels, and subway lines.
10m-30m	Good to access	Parking lots, transportation hubs, subway lines, underground roadways, and underground logistics systems
30m-50m	Hard to access	Urban infrastructure, storage, and underground automobile roads
50m-100m		

(Source: "Planning of Underground Space in Beijing")

2.2Example Ⅱ：Shanghai City

The geological conditions under Shanghai are not good for underground space use, so that construction is more difficult and only possible at a relatively high cost. However, Shanghai city, is also one of the most densely populated cities in China, and the CBD area is facing the crisis of a lack of urban space. Therefore, the total area of underground space in Shanghai has grown rapidly over the past years (see Table 1).

According to the report "The Conceptual Planning of Underground Space in Shanghai," the vertical configuration of underground space should be divided into two parts: under-road area and under non-road area and this division should obey the guidelines shown in Figure 3.

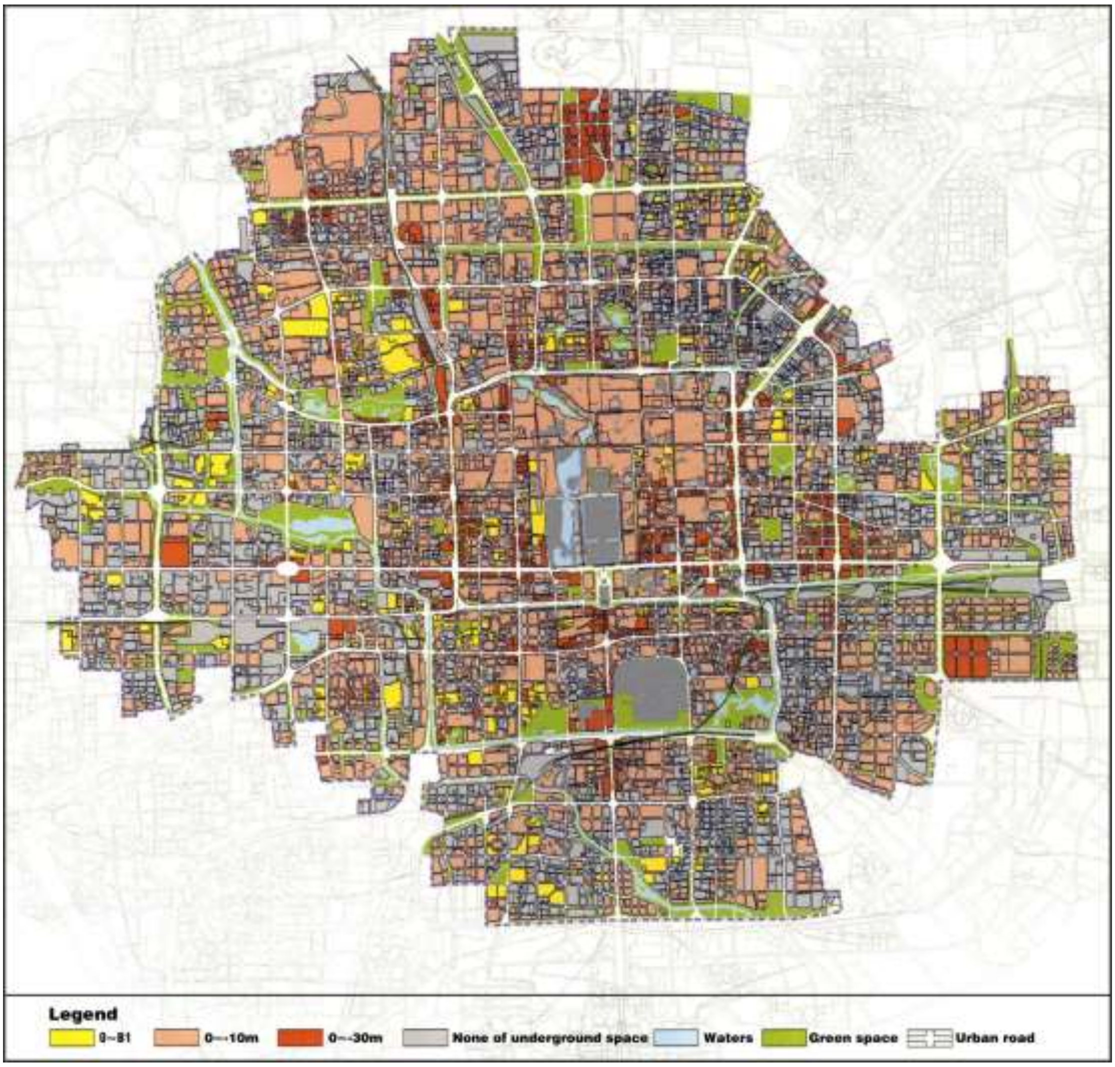


Figure 2. Planning for underground space use at different depth intervals under the central city of Beijing (Source: “Planning of Underground Space in Beijing”)

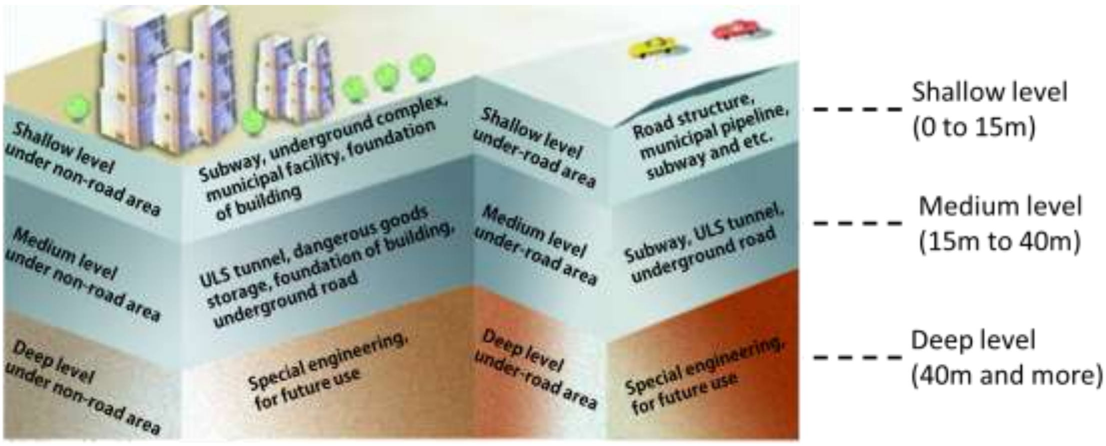
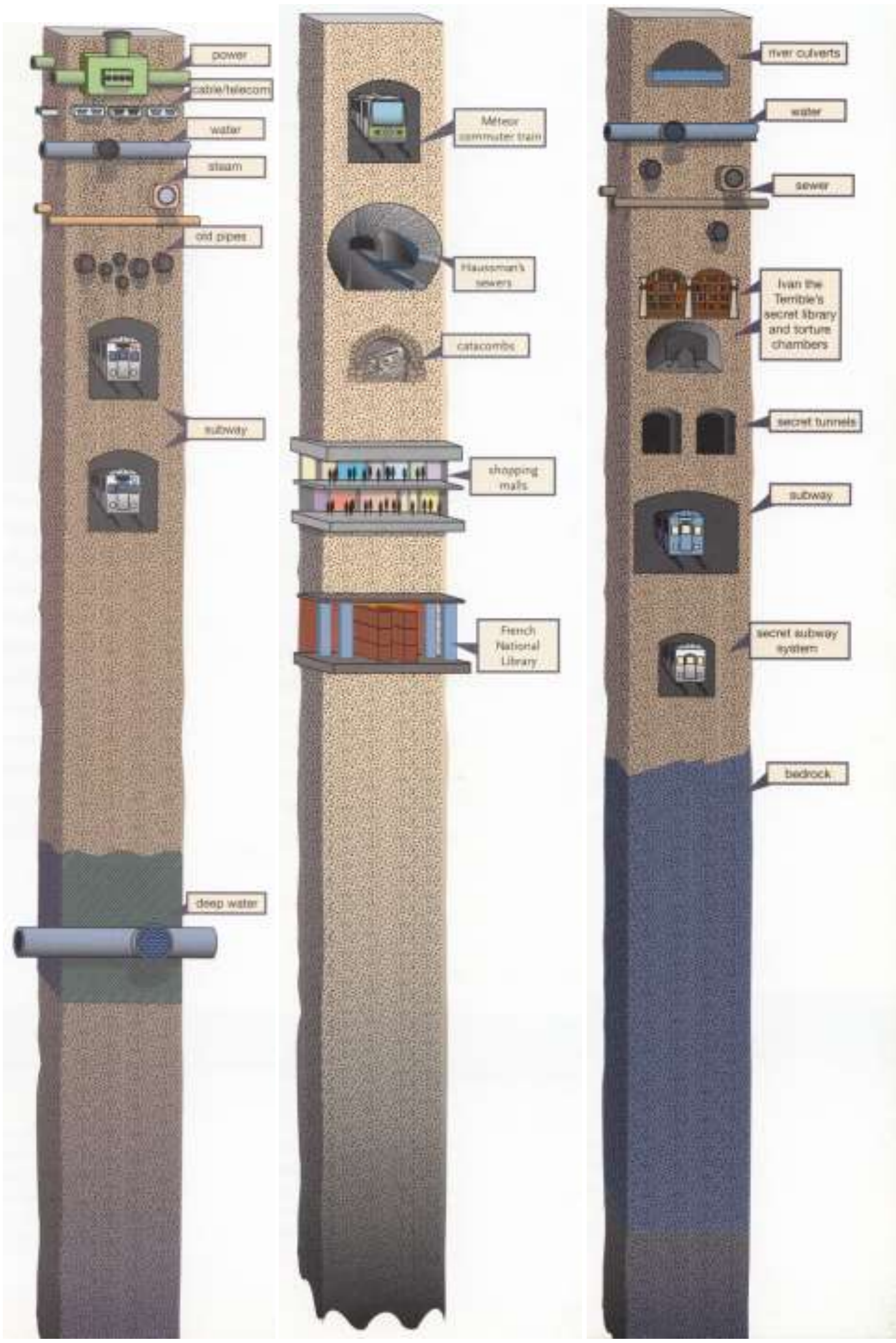


Figure 3. Guidelines for underground vertical planning in Shanghai City
(Source: http://www.shanghai.gov.cn)

2.3 Difficulty for the vertical planning of underground space use in China

Realizing the importance of vertical planning for underground space, the underground planners have stressed that vertical planning is one of the features that is different from other special planning, and this is becoming one of the critical issues in underground space use as previously stated. Although some large Chinese cities like Beijing, Shanghai etc. have developed the vertical planning for underground space use, the underground facility configuration has varied from city to city, and it is difficult to find a single guideline rule that can be applied. Similarly, this is also true for other big cities in the world such as New York, Paris, and Moscow - the underground vertical configurations vary from city to city as is indicated in Figure 4.

In fact, issues involved in underground vertical planning include technology, management, and even consideration about the integration models of above-ground and underground space with long term and sustainable development perspectives. These issues are so broad that scientific guidelines and potentially mandatory standards are not easy to identify. This topic is discussed below, seeking to identify some useful principles for application.



New York City Paris City Moscow City

Figure 4. Examples of vertical configuration in New York, Paris and Moscow City (Source: "Beneath the Metropolis")

3 Principles for vertical planning of urban underground space

3.1 The factors to be considered

3.1.1 Assessment of urban underground space resource

Firstly, the location of favorable conditions for future subsurface placement of different facilities should be identified before developing the underground planning. The following conditional information should be included:

- The geological and hydrological conditions
  - (a) general soil and rock presence – variability of depth to top of rock;
  - (b) soil characteristics and ease of creating and maintaining underground space;
  - (c) rock and rock mass characteristics and in situ stresses, and ease of creating and maintaining underground space;
  - (d) hydrologic resources (e.g., development of underground aquifers and water supplies, hydro developments for power);
  - (e) regional development of water resources in urban areas (e.g., pre-emptive development of de-watered volumes under urban areas)

- geologic resource development
  - (a) aggregates, building materials;
  - (b) mining and mineral resources (e.g., ores, oil and gas);
  - (c) geothermal (e.g., power production, heat exchange, thermal moderation);

3.1.2 Pre-existing conditions (unavailable underground space)

- Preservation and/or conservation of buildings (e.g., relics, heritage)
- Constructed underground space (e.g., utility pipelines, traffic facilities, commercial facilities, shelters, building foundation)

- Obstacles

3.1.3 Considerations about 3D and design of underground space

- Human and societal perceptions and willingness to go underground

- Environmental issues and the planning for underground space

- Archeological/anthropological issues

- New opportunities for change offered by technical innovation making underground systems smarter and/or more flexible for the future
  - a. use of monitoring and sensing/control systems
  - b. use of new/smart materials

- Thinking about multi-functionality: ground structural support should be designed for loads from eventual full planned usage of space rather than designing for clearance and loads based on what is there now (e.g., overdesign of tunnel lining beyond current use in anticipation that other space usage nearby can be anticipated based on future placements)

- When should engineers be making actual codes for underground design, construction and operation of underground space – to include provision of light, ventilation, emergency response and safety, etc. and requirements for planning underground space usage

- Is there any special consideration required for public vs private use of underground space in urban environments?

- Underground space and policy - legislation to rationalize issues of ownership of underground space

3.2 The basic principle: The greater the depth, the lower the degree of human activity

The first basic rule regarding underground depth should be that the greater the depth, the lower the degree of human activity (Golany, 1996). That means that the examples of shallow level are entertainment, cultural, and sport centers; creative activities, such as painting, sculpture, or music; and some light infrastructure limited to, shopping centers and public gathering halls. The deep zone should feature few human activities and more automated, programmed systems, will provide in the future high-speed inter-urban transportation, heavy-duty infrastructure network, high-speed cargo delivery systems, large long-range storage spaces, and other limited-use activities.

Most of urban underground space in China was built in the past 20 years (see table 1), with aiming to move conventional land uses in particular transportation and utilities to underground. In so doing, more aboveground space for greenery and natural environment, for pedestrians, and for leisure will be created. Yet, almost all of underground space for both intensive and low human activities is at a relatively shallow level below ground (e.g., typically at less than 20 m depth, not more than 30 m), see Figure 1. One of the main reasons for the current situation is that underground space use without the long term goal.

3.3 The basic principle Ⅱ: Design the underground space configuration to address the long term goals for underground space use (beyond first come, first served）

The consequence conducting underground space use without a long term goal will result in relocating only project by project at shallow level. If it were decided to conduct a campaign of extensive shallow utility relocations in advance of underground space development, this means that costs would not impact each project. Without such wide-spread relocation in anticipation of broad usage in the future, it will be very difficult to access the underground deep level, and only possible at a relatively high cost (see Figure 1). This will also be true for other cities in the world (e.g., New York City) as shown in Figure 5.

From the long term point of view, the underground vertical design is the most sensitive and necessitates careful work by a team of specialists, including architects, artist, social scientists, economists, health experts, physiologists, and environmentalists in need of taking into account all aspects of urban design(e.g., How does this include spatial planning as layers versus volumes versus networks? How does a city go about reserving underground space for future uses? Can it require consideration of multi-functionality, interdependencies or adjacency by public or private owners?). So it should be definitely cheaper in the long term to do all at once rather than project by project (beyond first come, first served); this would reduce the probability for significant interferences with each project.

Figure 5. 1916/1917 Beekman Street Subway, NYC
(Source: http://boingboing.net/2009/09/15/1917-beekman-street.html)

3.4 The basic principle Ⅲ: Different patterns result from different planning goals

As stated above, the definitions for underground layers vary from city to city, and depend on the goals and conditions of urban planning. In our view, the single pattern for urban underground vertical configuration can’t be provided, between large and small city, old and new city, as well as the cities with and without metro transit system. Even the same planning condition, the difference on planning idea can conduct the different underground vertical use patterns (see Figure 6). So that means the different pattern should be developed for application in China by different urban planning goal in the future.

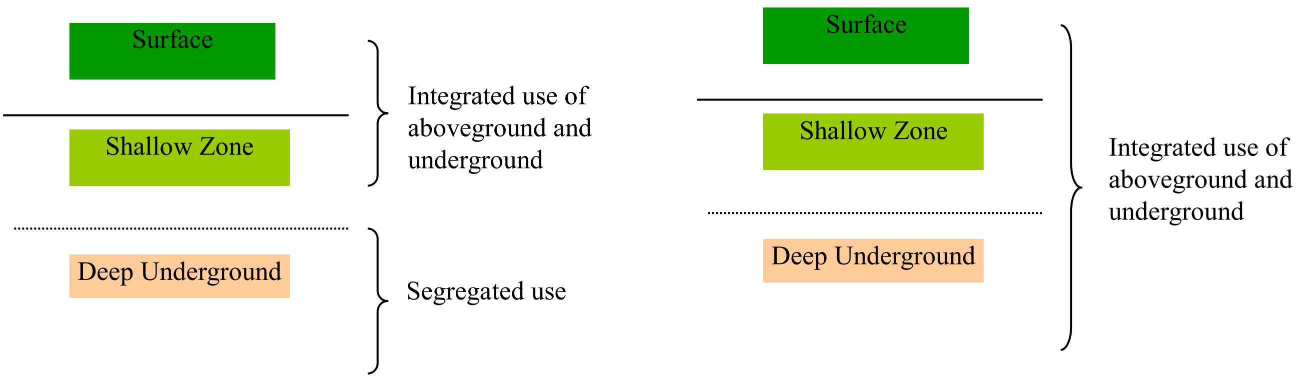


Figure 6. Schematic models for urban underground vertical use

4 Summary

Many considerations for underground vertical planning are briefly discussed in this paper, and the fundamental principles for urban underground vertical configuration identified herein provide a common frame of reference. Like any other new idea, the basic principles will require time for adjustment, further research (e.g., How to develop the applicable models for underground vertical configuration? how to figure out the quantitative indexes for underground vertical planning?), and application. Yet, the growing complications facing Chinese underground space with fast development will soon bring to light the necessity and urgency for some useful basic principles to the underground vertical planning.

The final goal is to design rational patterns leading to results that are solutions that address aspects of the urban challenges of the future. The key is for us to understand how to configure underground space use that can contribute to the sustainability of cities. For this, further study of this issue is warranted.

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Sustainability and Resilience of Underground Urban Infrastructure: New Approaches to Metrics and Formalism

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ABSTRACT

This paper argues for the importance to sustainability of establishing a system or framework for evaluation of resilience, and for the valuation of the underground as an urban space resource. The concept of resilience is a potentially fundamental characteristic of our sociotechnical urban communities, and the concept of performance response functions is a way to conceptually capture resilience characteristics of our communities and critical infrastructure systems (CIS). Convolution of performance response functions for different but interdependent systems informs the development of a new science of performance response analysis that can potentially and effectively be applied across sectors and systems. This work involves establishing generalizable metrics for characterizing infrastructure robustness and fragility, but the metrics must also be applicable to sociotechnical organizations (including government and business) to begin to capture and model community resilience as an inherently important and vital concept for our increasingly urban world. This work will lead to enhanced interpretations of the behavior of interdependent critical cyberphysical infrastructures, thus contributing to systems theory of integrated sociotechnical system behavior, particularly under conditions of increasing density and underground development. In this way, the importance of investment in the urban underground can be demonstrated as a key element of sustainable and life-cycle approaches to better planning and construction in our urban environments.

INTRODUCTION

Physical infrastructure systems are those distribution and transmission systems that deliver the services we rely on, and expect – they contribute public good, even though they are often managed by private entities. These systems include water, sewer, transportation, energy, and communications – the critical services that are in fact essence of our increasingly urban society. Since being initially designed and installed as simple, linear and uncoupled systems, they have been added to, repaired, and connected in new ways so that the decomposable systems of the past have become the tightly coupled, nonlinear and intractable complex systems of the present. They develop emergent behaviors that defy control in an absolute sense, particularly when these systems are asked to perform under conditions of crisis and disasters.

As these systems have become increasingly various and complex, they are now operated with increasing sophistication of control through dedicated information and communications technology (ICT) links. The interconnection of aging physical infrastructure systems into larger networks, and the loss of redundancy associated with high efficiency operations has led to reduced reliability and poorly understood interdependencies. Increasingly, equity and social issues become important in decisions about infrastructure supply, differentiation, and ICT deployment. Deregulation, mergers, consolidation of resources, and downsizing have resulted in reduced reserves and capacity. In addition, we realize that there are too few trained professionals for future needs in complex system management, and that decentralization and new concepts of design and control require recalibration of management judgment. Growing awareness of both the value and the vulnerability of critical infrastructure systems demands new, multidisciplinary, approaches focused on a long-term strategy toward the efficient, reliable, safe, secure, and sustainable planning, design, operation, and maintenance of these systems.

These physical and information systems are truly "critical," and research investments are needed to understand the complexity and interdependencies, leading to scalable systems of high reliability, decreased vulnerability to attack or interference, uncompromised and assured level of performance, and decreased life-cycle cost and environmental impact. Recent malevolent threats and extreme events (XE) have exposed the vulnerability of these systems and our limited understanding of their complexities. To lessen the vulnerability and increase our understanding requires a commitment to basic research. This research can only be accomplished through a multi-disciplinary approach focused on the normal, day-to-day operations as well as the response of these systems to the impact of extreme events of natural, technological, or human-initiated origin. The problem is multi-faceted and is embodied within the expertise of such disciplines as engineering, mathematics, natural sciences, information and computer science, decision and risk management, economics and other social and behavioral sciences.

The infrastructure systems of the US or any country are arguably the most fundamental and critical drivers of the economy. Our infrastructure systems also drive recovery after any natural or technological disaster. The resiliency of these systems has only increased in importance for planning and policy considerations of cities, regions and nations. But few think about underground space as a resource in itself – a resource that should have a defined VALUE so that it can considered when planning for urban planning decisions regarding sustainability (Sterling et al., 2011).

To the present, our society has viewed our infrastructure as a largely unseen benefit, and the service provided by our infrastructure systems we have come to expect as a fundamental right underpinning our quality of life. Our underground space was considered as a convenient sanctuary, a place to site facilities undesirable at the surface, and a resource for materials. However, as a nation and a world, we will become increasingly urban, with competition for surface space becoming ever more fierce. The underground must add to the desirability and vitality of the urban experience – and our underground designs design must uplift and inspire those who use and visit the urban environment. Therefore, it is important to make underground infrastructure systems reliable and resilient, and to make underground space desirable, so we need to understand why it is not. We need to:

- understand how underground space planning is best integrated with surface space planning, which depends on the subsurface geology, geographic constraints, past usage, society and culture.
- understand how to assess life-cycle performance, which requires that we are able to attach a value to underground space as a resource (separate from mineral rights and material resource development).
- understand how our complex systems, combinations of old and new with increasing interdependencies, perform under normal and stressed operations.
- understand how natural and technological hazards evolve into disasters, and how to make our communities and above and below-ground infrastructure systems more resilient to extreme events.

Our Nation's Infrastructure and Sustainable Urban Underground Development

Our national infrastructure may be valued at between $50 and $80 Trillion, perhaps more. This is equivalent to $200k to $300k for each U.S. citizen as his/her birthright, and this suggests that we are warranted to consider that the nation's infrastructure is a pre-investment upon which the economic engine runs, the quality of life is assured, and career developments of each individual are leveraged.

However, the US public and private infrastructure is aging. State-of-practice design and operation from the past has led to robust-enough systems for which we have sufficient experience to permit simplifying assumptions that enabled operation with minimal monitoring. There were sufficient reserves for acceptable service under known stress. But as we interconnect aging systems into larger networks, and observe decreasing performance levels, reductions in excess capacity and new stresses (e.g., poorly understood interdependencies, attack), our systems have lost robustness. As our system complexity has increased, many of the design simplifications are no longer acceptable, and new concepts of design and control provide an opportunity for new approaches of to system management.

Sustainable urban underground development must meet current human needs while conserving spatial resources and the natural and built environments for future generations to meet their needs. This requires a systems perspective for integrated above and below ground resource use and management, and must include consideration of cost effectiveness, longevity, functionality, safety, aesthetics and quality of life, upgradeability and adaptability, and minimization of negative impacts while maximizing environmental benefits, resilience, and reliability (Bobylev 2009).

Major infrastructure investment drivers include:

- Megacity and demographic growth demands which will require rehabilitation or repurposing of existing systems, extensions of existing systems, and creation of new systems in the developing world.
- The responsibility to address equity issues that include considering CIS service as a human right, and multicultural and societal issues are growing in importance globally.
- Increasing frequency and costs of disasters.
- CIS construction costs that only increase with time, and the fragility of the environment for building in the future that is not well understood.
- Resource crises that will expand in criticality, with foci on water and energy.

Much discussion has focused recently on the expectation for development of Compact Cities (Gordon and Richardson, 1997) responding to the need of society for co-existence and co-location. It is not yet clear whether this will be the choice for U.S. urban communities, but sustainability does suggest that compactness is a reasonable response to the demographic shifts and the growth of cities.

Sources of CIS interdependencies are varied and include technological, cyber, geographic and spatial, economics and business, social/human, political/policy/legal, organizational, resources and supply chains, and security. Figure 1 illustrates interdependencies that may be developed among six CIS sectors, and illustrates the complexity of performance and behavior of these systems.

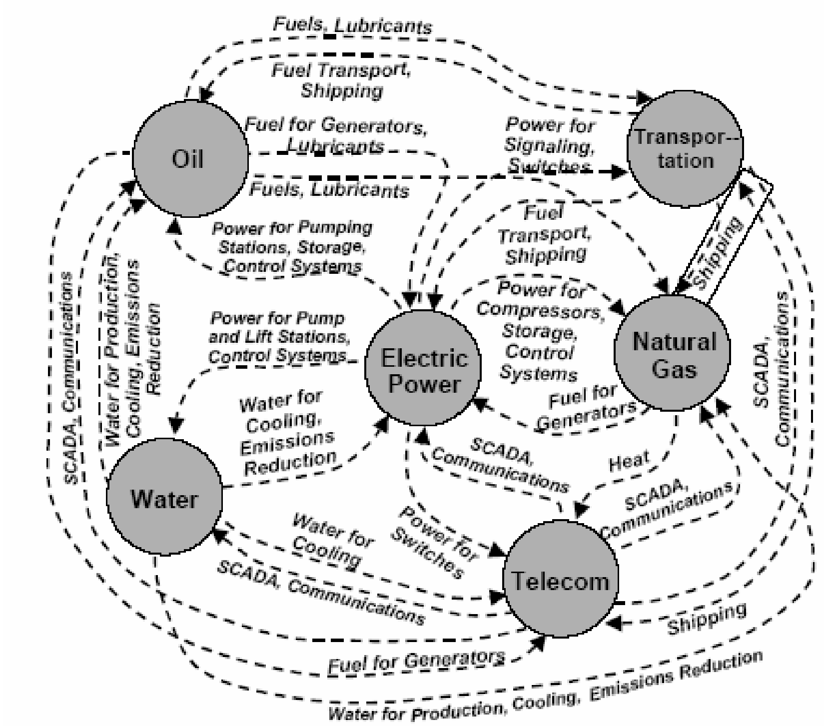

Figure 1. Interdependencies for six sectors of infrastructure (Rinaldi et al., 2001)

The key to sustainability and service for these systems is trustworthiness. However, recent events raise suspicion of emergent behavior not currently understood; these are CAS - complex adaptive systems. The complexity and interdependencies may introduce robustness or increase vulnerability, but current models do not help to recognize either outcome. In addition, for infrastructure system design, the goals for design are increasingly complex: they may be to optimize quantity, manage criticality, provide protection, minimize long- or short-term costs, provide a desired quality of service, or respond to equity of access and supply. Different goals have different stakeholders and will result in different design outcomes. To design systems for the future, we need tools to investigate interdependencies and complex system response (NRC, 2009; NRC, 2011), and to understand how goals compete and might be made synergistic.

Big questions for these cyberphysical systems and networks include:

- Do we really understand how our interdependent infrastructure systems work well enough to model, validate, and trust them into the future?
- How vulnerable, reliable and resilient are our systems. What metrics (system-wide, distributed and local) should be developed for evaluation?
- How should we incorporate, deploy, and train for new technologies without increasing complexity and vulnerability in our systems?

We need a consistent framework and set of terms for study of interdependencies – terms that are meaningful and accepted across sectors, countries and cultures.

The Concept of Resilience

Resilience is a significant concept to many fields including psychology, materials science, economics, ecological, or even governance systems. According to the Resilience Alliance (http://www.resalliance.org/576.php) and as applied to ecosystems, metrics for resilience have three defining characteristics:

- The amount of change the system can undergo and still retain the same controls on function and structure.
- The degree to which the system is capable of self-organization.
- The ability to build and increase the capacity for learning and adaptation.

Bruneau et al. (2003) offered a conceptual definition of seismic resilience. In general, the loss in resilience can be illustrated as in Figure 2 for which the striped area is the loss in performance of system A with respect to a specific event (e.g., earthquake) measured as the expected degradation in quality from the pre-event "normal performance over time. The vertical scale for such a plot is some metric for system performance, and these curves are here referred to as Performance Response Functions (or PRFs). The system response will depend on system capacity relative to the event magnitude, how well the system has been maintained, how abrupt or intense the event is, the pre-preparation of the community for such an event, and the geography and social structure of the community and region. In the case of system

A, the impact of the event was minimized in intensity and duration, and the recovery was rapid reflective of a high level of resilience. In the case of system C, the system failed and recovery was not possible.

PRFs can also be viewed as a kind of metamodel outcome that reflects the functionality of the system(s) but without the sensitivity toward privacy and security that exists for some descriptive data sets. While we can construct PRFs for specific components of the infrastructure (Croope and McNeil 2011) and we can observe PRFs for regions or communities using data censored by time (Hallegatte 2008), constructing PRF's to assist decision makers and allocate resources requires us to understand scale, aggregation, interactions and interdependencies.

Conceptually, resilience is a very useful concept but its application has many challenges. The data for broad application of resilience is not often obtained, and the assessment of resilience is not yet widely recognized nor utilized by practitioners.

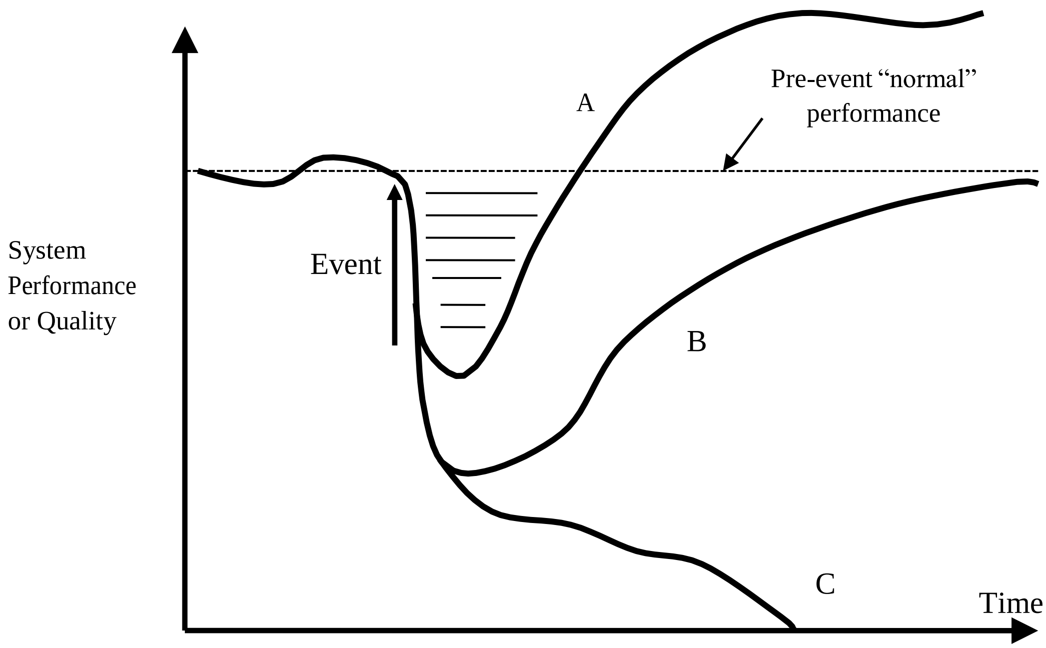

Figure 2. Conceptual Definition of Performance Response Functions

A – highly resilient system

B – less resilient system (may not fully recover)

C – loss of resiliency – system failure

The metrics for assessment of resilience from PRFs require investigation and none are yet accepted for wide usage, nor has the linkage between currently defined outcomes/metrics been made with standards or policy incentives an important aspect of implementation. Engineers and social scientists are not yet thinking in concert about representation of resilience, and planners and land use professionals are noticeably absent from discussions of resilience.

It is important that resilience be appreciated and characterized as a System Response representing the return to service or functionality, and the restoration of trust and well-being. As such, we need fundamental investigations into PRF metrics that include contributions from the social environment (human/organizational capital and capacity), the physical environment (infrastructural systems), and the natural environment (eco-systems). And any measurement of resilience will depend on the definition of the region being considered to include spatial and temporal scales, boundaries (and representation of boundary characteristics), and the model level of detail or granularity.

Examples of metrics for resiliency and/or PRFs include:

- Services – infrastructure function delivery (e.g., pressure, volume, rate, quality, reliability)
- Human activity (e.g., trips taken, tickets bought, calls made, population density, other demographics)
- Economics (e.g., income statistics, sales tax paid, targeted purchases)

Given a record of spatially distributed pertinent information over many time intervals, the geography and variation of a metric may yield understanding about how the region responds, where resources come from that aid in recovery – ultimately laying the bases for a prediction of comparative resiliency among different communities and societies. When integrated over space and time, the resulting character of the PRFs may indicate typical shape functions. If so, then a new science of complex system analysis of PRFs and resilience may be explored in which a fundamental understanding of how metric functions vary as a function of spatial, temporal and intensity effects and regional boundaries (and perhaps characteristics of boundaries) can be achieved. This would include building an understanding about how PRFs differ (or are the same) across scales, sectors, and systems. The prospect of a science of resilience and PRFs may actually have its own algebra for representing multi-system performance responses.

In order to investigate this possibility, we need to develop the computational <u>data resources</u> and <u>models</u> needed to investigate the behavior of complex adaptive and coupled infrastructure systems under conditions of routine operation, and under emergent behavior derived from complex system response to an extreme event. With this, we can develop and validate <u>performance response metrics and functions</u> that can be effectively applied across sectors and systems. We can develop computational and physical systems models and complex systems testbeds to analyze complex systems with interdependencies, and to anticipate performance and impacts of new technologies and methodologies.

With such an interdisciplinary approach that captures attributes of the complex systems in a region, we can begin to answer important questions including:

- What observations (evidence) can we make (identify) to indicate qualitatively whether a specific system or network will demonstrate resiliency?
- What metrics can be used to evaluate the capacity of a system or network for resilient response?

- How does resilience response develop, and what factors control or influence the development? Is it a process with thresholds, tipping points, state changes, or is it a continuous function?
- What can we understand about when investment or adaptive management is warranted to improve resiliency of a system or networks and interdependent systems?

Research for Sustainable and Resilient Underground Urban Development

The major elements of sustainability are increasingly a fundamental requirement to the successful undertaking of large capital construction programs – effectively constituting a social license for a "balanced solution." We need to create a methodology and the resources that will establish the value of subsurface space as a resource in urban environments – one that enhances sustainability and urban system resiliency [for example, see Allouche et al. (2008) for the impact of Hurricane Katrina on buried utility services].

- Create data, models, and methodologies to establish risk-informed approaches to project schedule and direct and indirect costs for construction and over long-term performance.
- Establish 3-D (spatial) guidance on urban subsurface geology and develop Geo and Infrastructure Information Modeling [GIM/IIM, not unlike the BIM or Building Information Modeling being developed and used today].
- These information resources are needed to support probabilistic modeling of life-cycle costs, uncertainty and risk/consequences for underground projects (including cost and schedule) and resources.
- Apply computational models that support investigation of coupled and interactive/interdependent performance of underground infrastructure systems needed to understand resiliency and sustainability of these systems.
- Integrate monitoring systems and data in real-time during construction and in operation.

Although no coherent program exists in the U.S. to date that would support these important resource developments and fundamental knowledge building, other countries have taken steps to begin this adventure. For example, citing the silos of disconnected data that result in a lack of technical interoperability and business interoperability, the U.K. has decided to establish a Digital National Framework in March 2010 (http://data.gov.uk) that will be the common platform to build *the "geographic spatial framework for the nation" to support information sharing and enable better decision making.*

In addition to developing the data and model resources needed for development of a resiliency methodology, research is also needed in other areas:

Decreasing the cost and risk of underground projects

- Site investigation and monitoring tools
  - Measurements while drilling, robotic probes
  - Expanded use and usefulness of geophysical technologies

- Expand applications for construction instrumentation and monitoring
- New methods for construction, ground improvement and remediation efforts
- Understand the long-term performance of installed support and waterproofing systems in underground facilities
- Quantitative risk assessment including deterministic and probabilistic approaches to scenario analyses, safety, uncertainty, vulnerability

Enhancing opportunities for innovation in underground construction and facilities management

- Advance understanding of time-dependent response and performance of underground structures that is key to understanding and predicting the long-term sustainability and functional resilience of underground infrastructure.
- Use new materials and technologies for the rehabilitation and life-extension of our existing underground infrastructure
- Remove contractual barriers to and create incentives for monitoring, and close the loop between observation, knowledge, design and action.

Developing new future uses with sustainability impact for underground space

- Re-use underground systems in future construction, e.g., the Rufus project in the EU
  http://www.skanska.co.uk/Services/Piling--foundations/About-us/Sustainability/RuFUS/
- Develop geothermal applications, e.g., integrate foundations, retention systems and tunnel linings with geothermal heat exchange system designs.
- Pursue possibilities for sequestration, new uses for underground space that address concerns arising from global climate change

However, a key element for enhancing the urban use of underground space is to develop a future cohort of engineers and planners who think about the underground in an integrated way, and view investment decisions with social perspectives. Perhaps we need to invent a new profession filled with people who:

- Hold a systems view that engages complexity within and across sectors.
- Approach issues from an interdisciplinary, integrative and holistic mindset.
- Understand how to frame issues and policies to be scalable over space (local, regional, national, global) and time.
- Communicate effectively across a wide spectrum of venues and audiences.
- Maintain a multicultural perspective, valuing the importance of diversity in setting priorities.
- Demonstrate effective leadership by seeking to address relevant and hard questions of importance to society.
- Manage uncertainty and risks with creativity and transparency.
- Are prepared to be an entrepreneur, to take chances and be agile in acting on innovation.

Who will make the curriculum? We will need faculty who are interested in career development opportunities that expand the traditional concepts of the role of engineering as a profession. We will need to engage public and private owners and industry including developing cross-sector people exchange (e.g., POP/professors in residence in industry), consulting and advising, co-ops and internships, opportunities to access cases/experience/observations, partnerships in research. We may invent new degree programs (e.g. planning, geosciences, environment, information systems, business, architecture, decision science, policy and social sciences), and new degrees including executive and clinical formats. And we need to expand our international connections into broad partnerships in education and research.

ACKNOWLEDGEMENTS

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A Framework for the Future of Urban Underground Engineering

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Abstract

A special and holistic approach is needed that captures aggregate attributes and emergent behaviors of the complex system of infrastructure systems in a region. Effective management of the impacts of future population growth, urbanization, and risks arising from continued evolution of our natural, physical and human/societal systems will require a systematic exploration and characterization of the urban subsurface, including much improved understanding and assessment of geologic risks. With recent cost escalations for underground construction projects, incentives are needed for the underground construction industry to develop and implement innovations in methods and technology, and smart integrated planning is needed to reduce costs both during construction and with life-cycle engineered design and operation of our subsurface facilities.

The needed framework requires investigation of potential metrics that reflect the performance of aggregate functions of an urban environment so that we can holistically study system performance response under "normal" and "stressed" operation. Such a metric can support a cross-disciplinary exploration of urban resilience, and build knowledge as we develop and test theory and models that explore resilience of complex socio-technical systems. Econometrics with spatial and temporal granularity will help to understand the integrated functionality of our cities and to establish appropriate policies that will drive continuous improvement in the quality of urban life while providing natural, human, and physical urban environmental resilience. The underground in urban regions can become an important component of managing the increasing complexity of our physical systems, and can also make more significant contributions to improving the robustness and resilience of our future cities.

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1. Introduction

Increases in global population and urbanization, economic and supply chain complexities, and expansion in the expectations for basic human rights and access to technology and services – all of these drive focused attention on the urban environments of the future. In addition, increased frequency and impacts from natural, technological, and societal extreme events (e.g., from weather, terrorism, economic stress, seismic activity) make multi-hazard designs necessary (Ayyub, 2014), and engineered management of such low frequency/high consequence events remain challenges. Underground space use will increase in spatial dimensions, depth, and architectural requirements. Underground planning must be integrated with above-ground and at-grade urban developments, and our urban infrastructure service systems must be built and operated as networked and interdependent systems of systems. Urban growth will also drive the extension of construction into increasingly difficult and fragile geologic and ecologic conditions, increasing the uncertainty and risk of significant problems with high cost consequences.

This paper develops a perspective that may be useful for future underground engineering developments. It starts by considering the current state-of-the-practice, and then suggests a path forward to better decisions about placement, design, construction, operation and analysis of our increasingly complex urban infrastructure. If done well, the functionality of our urban environments will be improved, and our urban natural, physical, and human/social environments will perform with resilience and provide the quality of life for all that will be demanded in the future.

2. Increasing Demands on Earth Resources

The Earth is finite and our earth resources (including ecology, energy, minerals and space) have limits. As noted by the World Population Balance, "Earth's resources are enough to sustain only about 2 billion people at a European standard of living…If all of the world's 7 billion people consumed as much as an average American, it would take the resources of over five Earths to sustainably support all of them." (http://www.worldpopulationbalance.org/3_times_sustainable). Considering the current rate of population and economic growth, and the current level of materials use and recycling, we would require the equivalent of eight Earths' worth of resources in order to provide expected quality of life for the people living on the earth in 2050. World population growth has exploded exponentially. Developed countries are growing more slowly and the developing countries are growing more quickly. These uneven growth rates create escalating stress on our political and societal structures.

In the United States, the population growth rate is shown in Figure 1. The United States' population was 5% urban in 1800, and the urban population has been increasing up to the present. Around the world, more people are living in the cities and moving to the cities, and there is where the infrastructure needs continue to grow. For urban construction, this means that the major building material that we use, and will use in the future, is concrete.

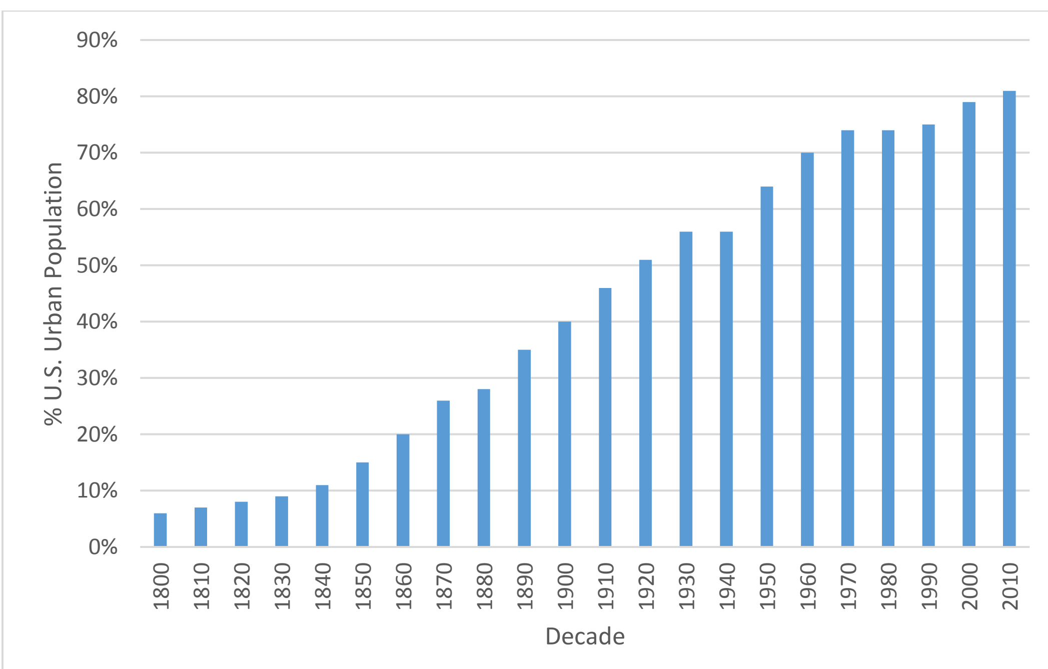

Figure 1. Percent of the United States Population Living in Urban Areas (Data from United States Census Bureau, https://www.census.gov/population/censusdata/table-4.pdf)

Figure 2 presents some U.S. data regarding raw materials usage in the last century. In 1900, use was fairly low, but from the 1940's, materials usage grew rapidly, particularly for the crushed stone, sand and gravel resources – reflecting the tremendous increase in use of concrete, particularly for highways in the U.S. Worldwide, about one cubic meter of concrete is being placed per person per year (http://inhabitat.com/is-it-green-concrete/), with little concrete reused as a recycled material.

The same is true for other industrial minerals as accelerated economic development has led to an overall rising demand for minerals that is unprecedented. Consider for example that Latin America has experienced a factor of four increase in mineral exports from 2000 to 2011 (Mandel, 2011). The region supplies more than 42% of the world's copper and silver but has only 8.5% of the world's population and 4.2% of the world's GDP. Such an imbalance is not fair, and fairness and equity have become extremely important in terms of how and where investments in mineral resources are made. Society needs to evolve a new way to think about earth resources. Organizations that resist mining and other resource extraction projects must be listened to from the fairness perspective, yet they must realize that because of the increasing world-wide demand for technology and resources, mining will be required into the future. Mining operations may be minimized if materials recycling approaches 100%, but even then population growth will require more materials, which means more mining.

This new and integrated, long- and short-term thinking may actually be a new profession: Earth Resource Engineering, a profession dedicated to stewardship of the earth's resources, including social, environmental, constructed, and mineral resources. For urban regions, Earth Resource Engineering must also include stewardship of underground space.

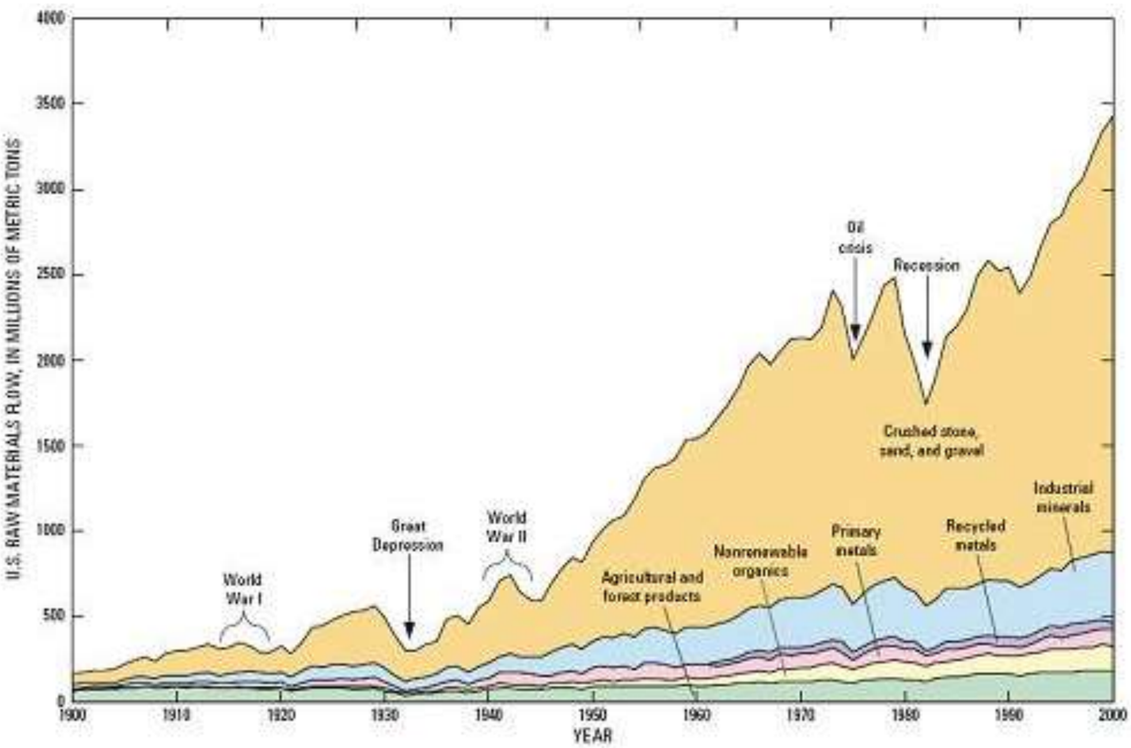

Figure 2. U.S. flow of raw materials by weight, 1900 – 1998. (Wagner et al, 2002).

that are acceptable, and cause things to be designed for efficient recycling, and then recycle them. Our economy, our society, and certainly our environment, needs people who have that frame of mind.

3. Urban Implications and Questions of Resilience

With the above discussion in mind, we must now reconsider the inexorable drives towards urbanization, and the consequences in placing tremendous pressures on performance of existing infrastructure. We have to rehabilitate and repurpose existing infrastructure, particularly in the developed world. We have to extend existing systems to places where they are needed, and we have to do this with equity and social justice. We need new systems in developing countries, and Earth Resource Engineers will need to be aware and capable of effectively serving different cultures and societies in the future.

We also have an increasingly aging population. We have to understand and provide for the infrastructure needs of older people. During and in the aftermath of Superstorm Sandy in the New York region, many elderly people living in high rises in Manhattan lost utility service and could not get out of the buildings. The infrastructure did not work for them. Our infrastructure must serve the entire population.

Resource crises are only going to become more acute, with elevated focus on water and on energy, both of which involve the underground. Compounding the problem is that we have experienced recent increases in frequency and intensity of major "extreme events." These natural or man-made events are major drivers of change, and are opportunities for improvement. Preparations for extreme events should include identification of advances in design and analytical frameworks, including integrated multi-hazard engineering. People who work in extreme event response and recovery need to create databases, tools and knowledge that will integrate engineering, economics, society, natural sciences, and risk assessment and management to support better decisions and even better designs in the future. This framework needs to include the evolving design constraints associated with sustainability, terrorism, and security. Engineers did not design most urban infrastructure and facilities considering such priorities.

For healthy urban environments in the future, engineers and planners have to think in an integrated way about how to use the underground for improved space utilization and urban quality of life, including integrated planning of above-ground and below-ground space resources, and to include all of the networked infrastructure sectors (e.g., water, sewer, power, transportation, information) under conditions of normal service and also under stress. A city planning a subway needs to be thinking about the next water line, and ten years from now where should a new gas line be placed. Uninformed decisions about placement may lead to restrictions on future opportunity. Therefore, the concept of stewardship also comes into urban sustainable space utilization, a kind of "Urban Infrastructure Stewardship." Engineers need to provide decision makers (e.g., politicians and city planners) with trusted information and tools so that stewardship-guided plans can be implemented.

If we accept that increasing urban growth and density (e.g., compact cities) will happen, we also need to appreciate that for many cities, the easiest construction sites have already been developed. This means that new infrastructure needs to be placed in poorer and perhaps more fragile ground conditions, meaning more expensive construction. Fragile environments are harder to deal with whether placement is above ground, at grade, or below ground. In addition, infrastructure construction costs have only increased with time, and engineers should not tolerate this cost escalation.

Consider how costs could be reduced. First there is risk avoidance, including subsurface zoning and reserved flexibility in alignment selection. Each city has its own unique subsurface geology, with some materials better for low permeability, and with some materials of strength sufficient to support large excavations. Planning and zoning should support intelligent decisions about alignments and the locations for underground facilities.

A partner to risk avoidance is new technology and its successful implementation, something perhaps best considered through public-private-academic entrepreneurship in which the flow of ideas, development and demonstration of products and methods, and assessed and successful introduction to the market leads to improved and longer-term performance and reduced costs. For some areas of excavation technology, for example blasting in the urban underground, contractors are doing substantially the same thing that was being done fifty years ago. This has to change, because blasting is an important part of making the underground space for the future.

Costs can also be reduced by engineering for sustainability. In order to apply cost-benefit design approaches for decisions about above-ground vs below-ground placement, a value for the underground space needs to be determined, even as the value of surface acreage and air rights has been established for years. Underground space has a value beyond potential mineral rights, but a market has not been created for this resource. Integrated urban planning will drive creation of a market for the underground space, and then it will be appropriately valued. For sustainable design in engineering, we also need to create and maintain databases on system performance, construction costs, indirect costs, rehabilitation costs, and operations impacts. If we understand how our systems operate, then we will understand how to introduce new technology without disruption, perhaps with improvement of performance and reliability.

Increased risk awareness permits better risk management. For the underground, the biggest risk is often geologic risk. Characterization of subsurface risk can be done much more effectively than the current state-of-the-practice. This means much more than application of geostatistics, because exploration data without a geologic framework can lead to wrong interpretations and predictions. Engineers need to engage more effectively with geologists and geologic knowledge to build improved models for geologic risk that are more reliable and allow us to manage the risk in an intelligent fashion. Included in such thinking is continuous assessment of new technology in the long-term, including costs and performance. Engineers should support introduction of a new technology when it solves one problem, but they should also be committed to perform long-term performance assessment to determine if unanticipated and emerging complications arise in the future.

4. The Role of Engineers

The complexity of our future urban environments reaffirms the responsibility of engineering as a profession to continue to learn from each project - engineering forensics. In the current contracting environment, design is often outsourced to consulting firms, so that owners retain much less engineering control than in the past. The consultants complete the design and are often assigned to other projects, losing the opportunity to learn from the past project, to validate assumptions, and to better understand the behavior of ground and impact of the variability of geology experienced in the project they left. If the owner organization has very few engineers, the owner may well try to control risk by contract and legal means. This often does not bode well for risk sharing that is mandatory for best management of geologic risk. Contractors need to know that risk is being shared before they are receptive to innovation.

Engineers need to be skilled in communicating risks in a way that results in a willingness to share risks. If risks are identified, risk across projects can be pooled. This is a better way to manage risk for owners that have many projects. Engineers will then be more effective and trusted in communicating both opportunities and risks to the public.

Engineers also need to develop metrics that are meaningful to the public regarding the value of infrastructure and underground space. For example, several approaches can be taken to establish the value of our infrastructure systems in the United States. Arguably, that value probably lies between $50 and $80 trillion. If this huge number is divided by the population of the U.S., a number around $250K is identified. This is the birthright of each U.S. citizen: the amount that has been pre-invested on their behalf and provides a platform upon which each person can build their career. Such a metric has a meaningful value which is about the cost of a first home.

Moreover, in the developed world, public and private infrastructure is aging. Pipe breaks and power outages are more common in older systems. The reduced system reliability has broad economic consequences. Urban infrastructure systems have become huge interconnected networks with poorly understood spatial and functional interdependencies (Heller 2001; Rinaldi et al., 2001). The key for our infrastructure is trustworthiness, and having owners and engineers who are prepared to act as stewards. These are very complex systems and, under stress or crisis, they behave in ways that we might not anticipate.

Engineers and planners have been working to develop computational models for each of our individual systems (e.g., water, sewer, transit, rail, highway, power, information, etc.), but we have not yet been successful in developing validated models that simulate system interconnectedness and interdependencies. We can build complex models but we honestly do not know whether they are right or whether we should trust them. Beyond the models, we need to develop interdependency linkage elements to apply across sectors. We need real data that can be applied for model calibration and validation to include service level and functionality; common spatial and temporal registration for different systems, real time and rates of processes, and regional definition of model boundaries that are correlated with the magnitude (geography and intensity) of a triggering extreme event.

Alternatively (and complementarily), high-level and intuitive models of appropriate complexity may more quickly help us to understand how the system of systems in the city's network will behave under extreme stress from an extreme event (e.g., Yusta et al., 2011). Our models need to consider system function and performance in the case of widely diverse design criteria beyond imagined extreme events, including system capacity, reliability, security, equity, etc. Different criteria have different stakeholders, and engineers need to understand all aspects of design consideration, not just those easiest to implement. The systems involved in a holistic and organic consideration of an urban region also extend beyond the physical infrastructure that engineers are familiar with. Urban analyses need to include other systems including business and finance, food supply, governmental agencies, and first response and emergency systems.

However, we do not really understand how our complex infrastructure systems operate interdependently. We do not know how resilient or vulnerable our systems or models are, and we are usually surprised by what happens when an extreme event occurs. We do not know what metrics will help us to investigate and describe resilience and interdependent vulnerability.

5. Development of useful metrics

The term "resilience," was first introduced in the field of ecology, in the study of plant/animal life and understanding how biotic systems work together. It is a significant concept to many fields including psychology, materials science, economics, ecological, and even governance systems. According to the Resilience Alliance (http://www.resalliance.org/576.php), and as applied to ecosystems, resilience has defining characteristics that include the amount of change the system can undergo and still retain the same controls on function and structure, and the degree to which the system is capable of self-organization. The focus is on functionality, and systems exist to provide certain functions: to reduce the delay between loss of function and restoration of supply and trust in the system is to be more resilient. The resilient ecosystem is one which can lose species and still survive and flourish. Resilience must also consider spatial and temporal issues as it is necessarily scale-dependent – the boundaries of the system under consideration must be established.

Resilience can be used to look at human response as well. Figure 3 provides data on human feelings of fear following a terrorism event, using different techniques to try to track what people were thinking. At the time this event happened, 90% were fearful. In time they became less fearful. A very resilient community would lose fear and regain trust in their world quickly. Such a plot of response versus time is here referred to as a PRF or Performance Response Function.

The concept of resilience can also be applied to physical infrastructure system recovery after an extreme event. Consider Katrina, a major hurricane that hit the U.S. in 2005. The electrical power system in the region was studied by Reed et al. (2011) in terms of the percent of clients experiencing power loss.

Immediately following the event, only 20% of people had power. They found that recovery rates (restoration of service) were significantly different between earthquakes and hurricanes – with the recovery rates being slower for hurricanes. Recovery after Katrina was slow, and 45 days were required before all clients had power restored. The importance of duration and intensity on the recovery of a system is shown in Figure 4. In this figure, the normalized time is the time in days for a given level of restoration divided by the total duration of the event.

Data for Louisiana are from the records of Entergy New Orleans (ENOI) and other suppliers, and that for Florida and Mississippi is from regional companies. The data for the Hanukkah Eve winter storm of 2006 data was from a significant wind extreme event in the Pacific Northwest. The character of the PRFs (or recovery functions) for all cases is similar, but it is clear that for Florida, which was not hit directly by Katrina, the recovery was much faster.

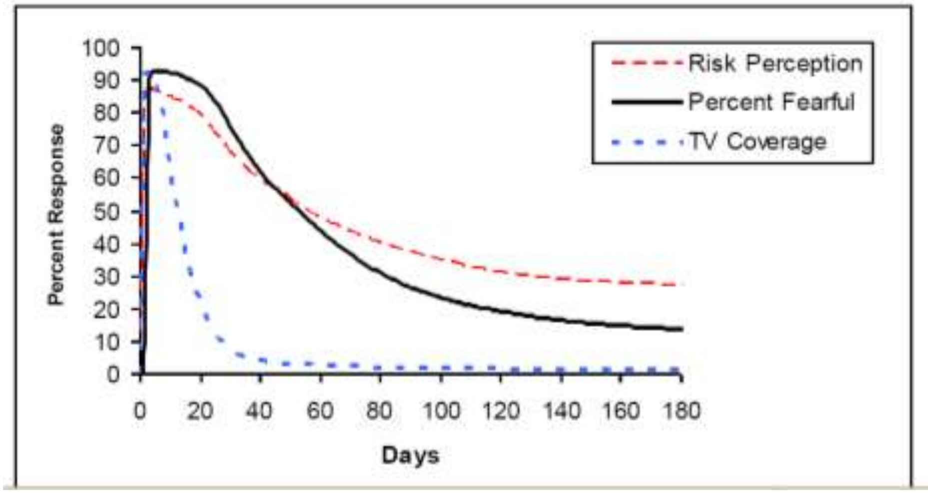

Figure 3. Resilience and diffusion of fear following a terrorism event. (Rose, 2009)

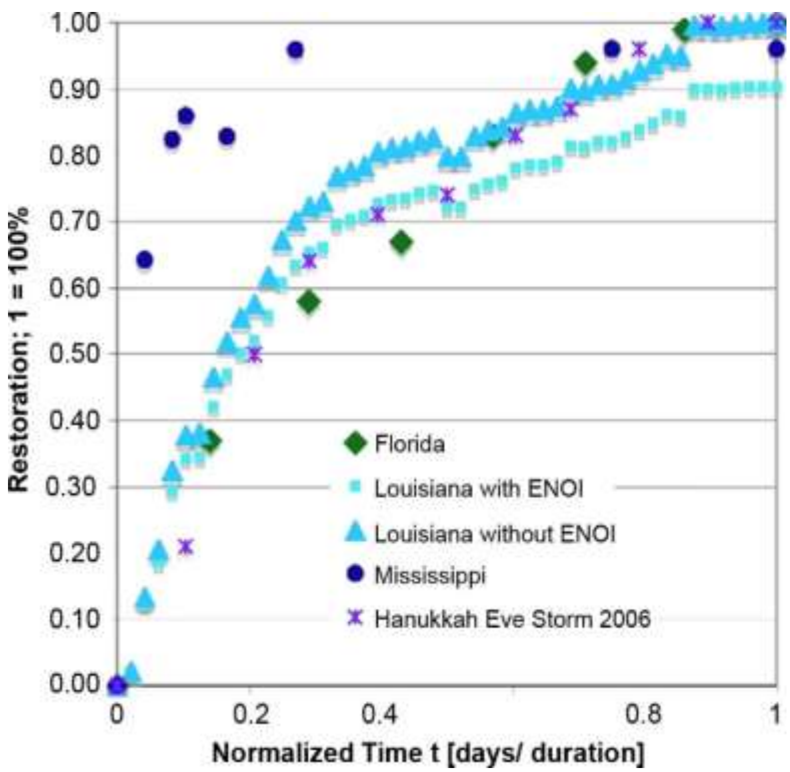

Figure 4 Recovery PRF analyses for wind extreme events in the U.S., presenting a comparison of restoration curves for various data sets using a normalized time scale. (Reed et al., 2011)

A similar analysis can be applied to water supply systems. Tabucci et al. (2008) analyzed the PRF for the Los Angeles water supply system after the Northridge earthquake in 1994, with the results shown in Figure 5. They developed a simulation model for the system, and validated the model with observations made during recovery.

Similar analyses have been conducted for recovery of highway and train systems following the Kobe earthquake in 1995 in Japan (Chang and Nojima, 2001). In Figure 6a, the same recovery process is identified in the PRF analysis, showing an initial severe loss of performance followed by gradual recovery over a seven month period. In Figure 6b, summary period of recovery data is presented for different infrastructure sectors, clearly indicating that different systems recover at different rates. Following many events, electric power receives high attention and comes back very quickly. Different infrastructure systems have different time constants for how fast they can be brought back to full function. All of this indicates that it may be possible to model system response using PRFs in a systematic way for all systems, and such a common basis offers the possibility for building an urban infrastructure system model from the ground up.

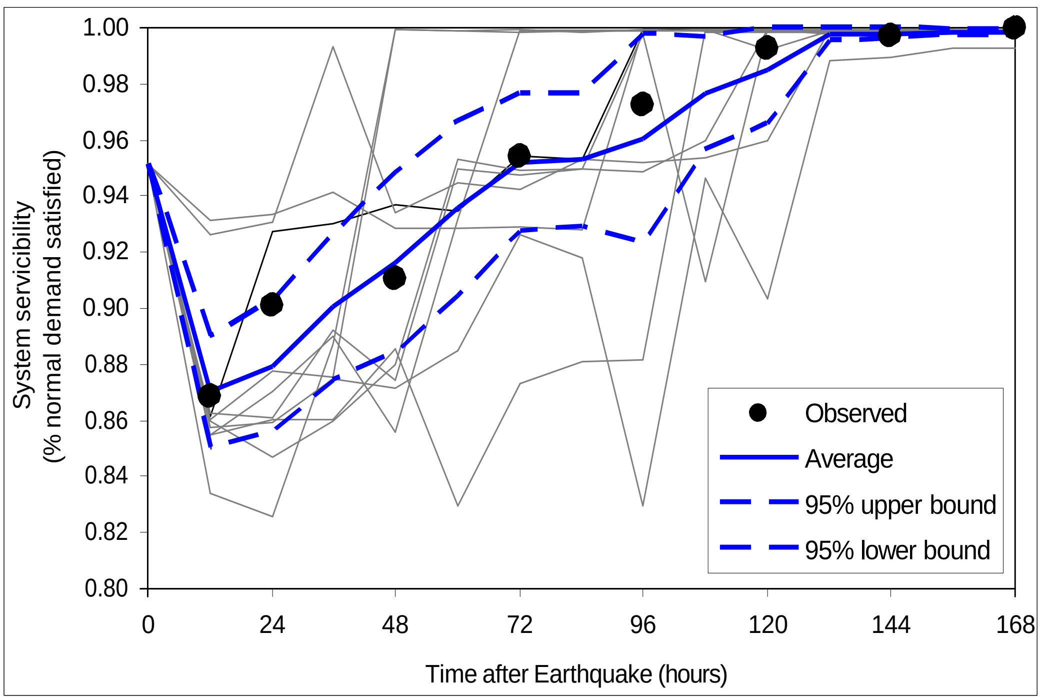

Figure 5 1994 Northridge earthquake water supply PRF analysis with observed data and simulation model curves. (Tabucci et al., 2008)

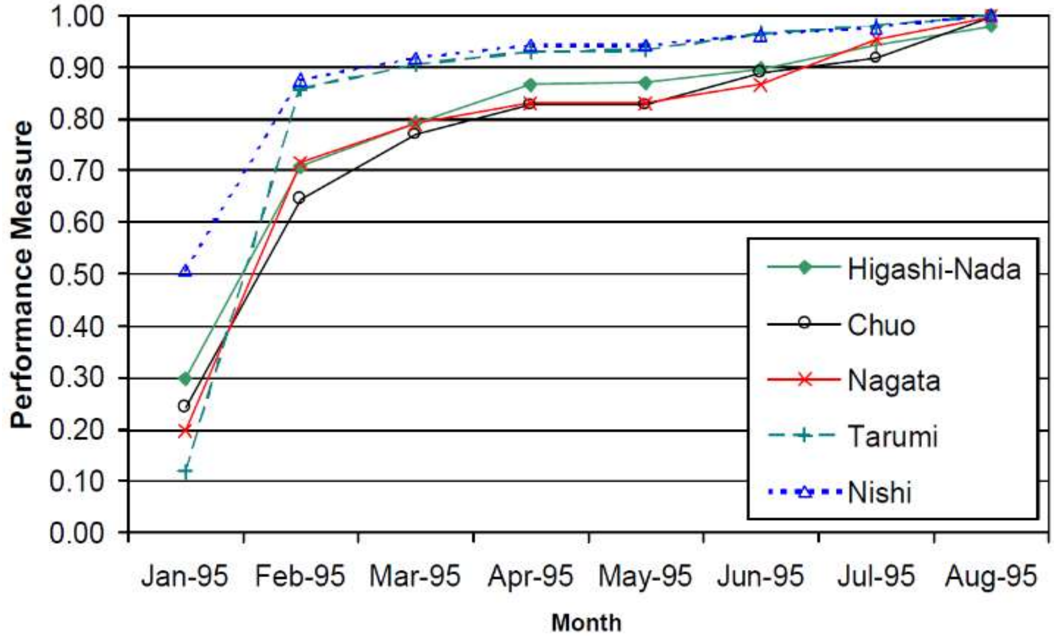

Figure 6a) Rail Performance Restoration, Selected Kobe City Wards (Chang and Nojima, 2001)

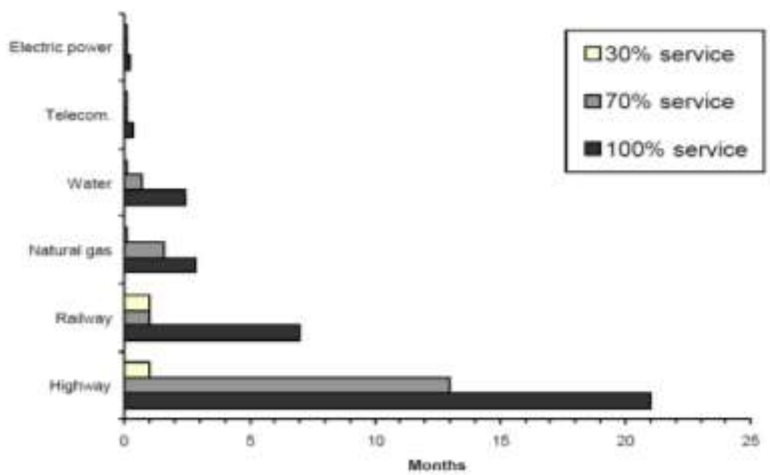

Figure 6b) Timeframes for recovery of different infrastructure sectors (Chang and Nojima, 2001).

This approach also offers potential to analyze different service providers in terms of their management and effectiveness of their response plans. For Superstorm Sandy, data from 13 different power supply companies were pulled together by the New York Times, and the data is plotted in Figure 7. For the affected New York region, the general trend of recovery is clear and in common among service providers, but the PRFs for different companies have different shapes and different sizes, indicating that there is something about the way these systems were managed in preparation and response that demonstrates higher or lower resilience. Observations such as this can serve as the basis of study for how power systems may be managed differently to enhance resilience.

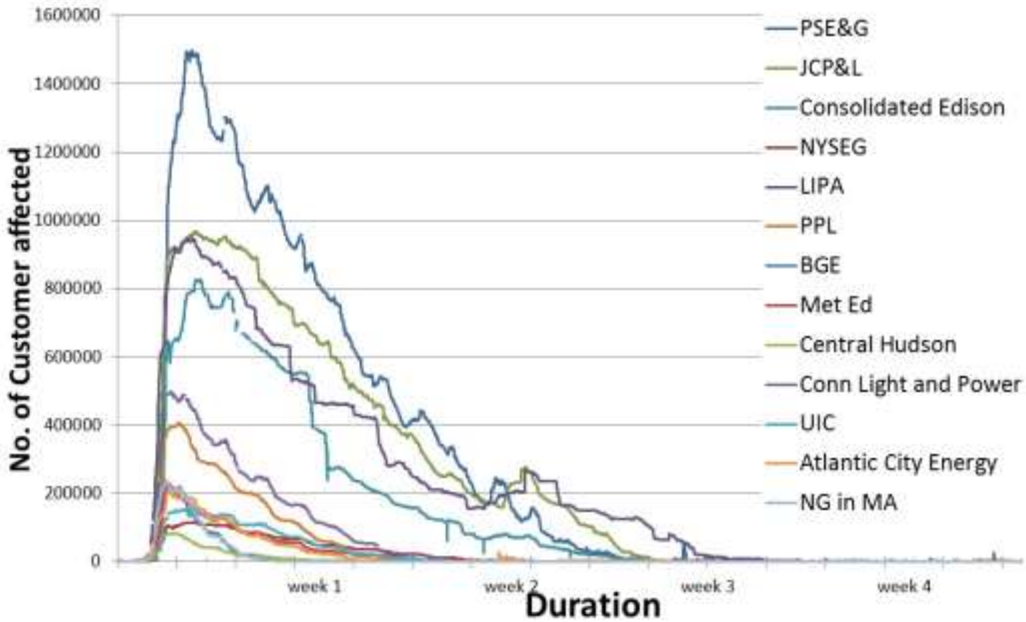

Figure 7 Outage data for regional power suppliers following Superstorm Sandy (Data from New York Times, http://www.nytimes.com/interactive/2012/10/30/nyregion/new-york-power-outages.html?ref=us, accessed August 30, 2015).

Performance Response Function (PRF) analysis is clearly very interesting for understanding behaviors of individual systems and sectors. The shape and dimensions of PRFs reflect event intensity, system capacity, and plans for recovery. A schematic example of such an analysis is shown in Figure 8, in which the performance of a system or network is plotted over time. The system response identified as curve C is a non-resilient response, with loss of functionality that is not recovered. The PRF labelled B is a more typical response experienced by our current cities, with time to recovery of a significant duration. The system labelled A, however, is highly resilient, with functionality recovered quickly, and an actual improvement in performance achieved because of pre-prepared response plans that used the extreme event as an opportunity to better the urban environment. It may be anticipated that the shapes of PRFs may well vary with geography, spatial distribution of infrastructure, and social, political, and cultural systems in which the city is developed.

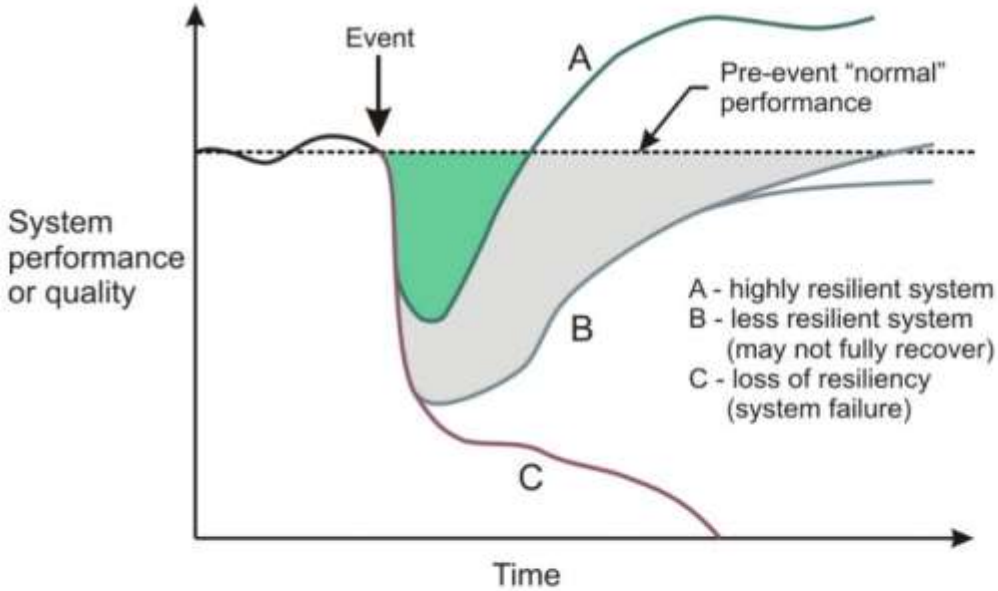

Figure 8 Schematic plot of Performance Response Functions (PRFs) for infrastructure systems and networks with different resilience. (Nelson and Sterling, 2012)

Urban resilience depends upon many factors – how big is the city, where does it extend, what is the geography, what is the intensity and duration of the extreme event, and what are the operating characteristics and designs of the physical, natural and social systems themselves. The PRF approach can also be used to understand the response of a whole city the integrated systems of infrastructure systems in an entire urban region if the correct metrics that are applicable for the variety of systems can be established. Pertinent metrics could be focused on service provision (e.g., infrastructure functional parameters such as pressure, volume, rate, quality, reliability, outages), human activity (e.g., trips taken, tickets bought, calls made, population density, other demographics), economics (e.g., income statistics, sales tax paid, targeted purchases), or ecologic system health (population dynamics and environmental restoration). But since the main purpose of a city is for enterprise, perhaps an economic metric of sufficient spatial and temporal granularity will be most insightful for urban region analysis.

In any event, delving into this complexity is daunting, but the goal of urban quality of life and resilience is compelling. We have an urgent need for improved understanding of the genesis and evolution of resilience, in particular in urban and coastal regions. We need to build and enhance social and ecological capital and community resilience, as well as to increase system adaptive capacity (including self-organization) and improve the cost-effectiveness of investments in sociotechnical (human, cyber and physical) infrastructure systems.

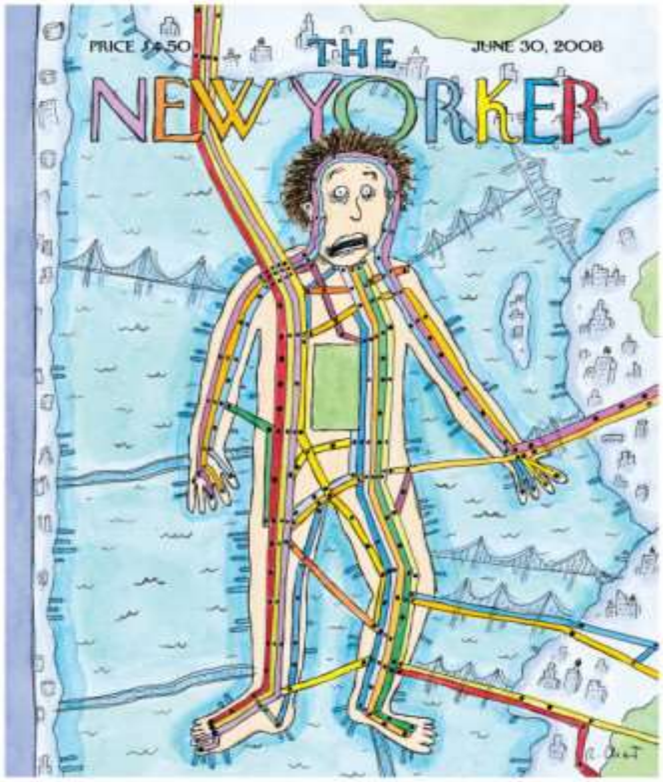

Figure 9. Schematic analogy between urban infrastructure and human biologic systems. ("A man is the shape of a transit map, Chast, R., artist, June 30, 2008 New Yorker magazine cover).

The complexity of the many systems in the human body is a good analogy for the complexity of urban infrastructure networks. The human body has many systems with different and interdependent functions that we do not fully understand. Yet we have come to know that a human body temperature of 37 ^{o}C indicates a state of health. Deviations from 37 ^{o}C indicate that the body is under stress, whether for hypothermia, a low-grade infection or a high fever. While there are many other detailed diagnostics that can be applied for different body systems, body temperature is an aggregate reflection of health. Perhaps there some metric that can provide a similar insight into urban system health and its evolving response to an "attack," with the ability to respond and evolution of the response related to resiliency (reflected in the cartoon shown in Figure 9).

This suggestion is both naïve and intimidating, but such an investigation is nonetheless warranted because of the potential benefits. If the function of a city can be related to the economic engine that drives the dynamics of urban life and careers, then perhaps spatially (geographically) and temporally registered economic metrics can be used to investigate the aggregate functional performance of an urban area. Since data frequencies with acquisition intervals on the order of hours, days or perhaps week intervals are needed, this problem cannot be addressed by the US Census data which is only gathered every 10 years. Fine-scaled geographic control is needed as well.

Consider the following scenario: The aggregate function of the New York City region may be represented by a parameter such as sales tax receipts which might provide sufficient spatial granularity and reporting frequency to allow the data to be mapped and periodic "topographic maps" of sales tax receipts to be prepared. Where commerce is occurring, a "mountain" would be indicated by the topographic map. Bedroom suburbs would have much less commerce and would appear as valleys in the map. The map would change during the seasons, with the mountain of Manhattan perhaps rising to a peak at Christmas, and the shore of New Jersey rising to high hills during summer months (perhaps with a peak on the 4th of July).

The topology of the map could be integrated and the area below presented radially or as a total area corresponding to some measure of the total commerce in the region. The total area could be plotted over time to obtain a "performance response function" indicating general performance of the aggregate city systems. In addition, the topographic map would provide information guiding selection of the boundaries of the region influenced by the New York City core.

Now consider how the map would change in the event of a crisis (terrorist, natural, technological). Such a crisis could stretch from a snowstorm to hurricane to the 9/11 World Trade Center incident. In other areas, earthquakes and other types of disasters could be considered, including the way a city responds, what happens to commerce and where do resources come from to support recovery. In what way and how fast is aggregate urban system functionality restored?

For example, consider the 9/11 terrorism event in New York City. What happened to the map for Manhattan? The mountain of commerce suddenly turned into a well. As people and industry relocated, there were ripples in the following weeks and months as commerce moved into New Jersey, Long Island, Connecticut and upstate New York. How far and fast did the ripples extend, and when did they start to come back into Manhattan, building the mountain again? The area under the sales tax topography could be integrated to create PRFs for the city, defining how the city responds as a function of direction and overall.

This is an interesting intellectual question that deserves investigation: For an extreme event, how does resilience develop for a spatially distributed urban system including human/social, physical and information systems? Does resilience behave like a 3-D wave form that spreads out over time? Do the PRF shapes and trends vary for different types and scales of extreme event, and how do they vary from city to city and from country to country? Some cities might be more resilient than others. Can we tell which, and why?

Many challenges need to be met before achieving any level of success in this inquiry. Engineers need to learn how to engage and communicate with social scientists and planners. The language and ideas for communication need to be developed, and planners, land-use people, architects, have not been trained to understand geologic materials and the underground. We have a poor linkage between the outcomes and metrics we think might work and the standards to be implemented with policy incentives. Certainly the assessment of resilience is not standardized but maybe an approach like the one presented here might work.

6. Conclusions and the Path Forward

In final conclusion, what do we have to do as engineers? We need to develop cyber-environments in which we have rich data and from which we gain understanding how to present the data to the stakeholders so they understand can make effective decisions and investments. We have to develop those computational models that actually work across systems and give the appropriate interdependencies. We have to develop the information for model validation, and we have to establish a market for underground space so we can appropriately consider its value. We have to develop life cycle decision models, and we need to determine if this concept of resilience is important and works. Finally, we have to be aware of new technologies that can help us do an ever better job – such as tracking social network data during an extreme event, following the level of text traffic, tracking key words and who is receiving the texts – from which we may be able to understand more about when trustworthiness is reestablished.

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New Approaches to Metrics and Methods for Resilience of Underground Urban Infrastructure

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ABSTRACT

In order to make better decisions concerning the use of underground space, particularly in urban environments, the functions and operations of the human and physical infrastructure systems must be understood in an integrated framework with common and meaningful metrics and representations. Considering the importance of economics, sustainability and vulnerability to extreme events, decision makers need an understanding of the valuation for underground space as a resource in order to consider life-cycle engineering and trade-offs and pros and cons of above- and below-ground infrastructure investments. This paper discusses an appropriate framework and metrics for infrastructure analysis that can include complex systems representations for all sectors – physical, social and environmental.

1 INTRODUCTION

Physical infrastructure systems are those distribution and transmission systems that deliver the services we rely on, and expect – they contribute public good, even though they are often managed by private entities. These systems include water, sewer, transportation, energy, and communications – the critical services that are in fact essence of our increasingly urban society. Since being initially designed and installed as simple, linear and uncoupled systems, they have been added to, repaired, and connected in new ways so that the decomposable systems of the past have become the tightly coupled, nonlinear and intractable complex systems of the present. They develop emergent behaviors that defy control in an absolute sense, particularly when these systems are asked to perform under conditions of crisis and disasters.

Over the past century, we have experienced dramatic changes in demographics, and existing sociotechnical systems have become more complex and increasingly networked. As these systems have become increasingly various and complex, they are now operated with increasing sophistication of control through dedicated information and communications technology (ICT) links, making effectively cyberphysical systems. The interconnection of aging physical infrastructure systems into larger networks, and the loss of redundancy associated with high efficiency operations has led to reduced reliability and poorly understood interdependencies. To complicate matters, our cyberphysical infrastructure has not been maintained, causing unexpected vulnerabilities and cascading failures (ASCE, 2009; AWWA, 2001). As extreme events frequency and magnitude of resulting disasters have increased, unexpected performance response, and lack of resilience have been noted (Sanford Bernhardt and McNeil, 2008). While there has been success in modelling complex response and predicting behaviors of our urban sociotechnical networks under stress, the models have grown so complex that data is not available to validate the model predictions (NRC, 2009).

It is clear that we need to understand our sociotechnical system dynamics and resilience at a fundamental level or we will learn the wrong lessons from the past. Resilience is a significant concept to many fields including psychology, economics, ecology, or even governance systems. According to the Resilience Alliance (http://www.resalliance.org/576.php) and as applied to ecosystems, metrics for resilience have three defining characteristics:

- The amount of change the system can undergo and still retain the same controls on function and structure.
- The degree to which the system is capable of self-organization.
- The ability to build and increase the capacity for learning and adaptation.

Here, resilience is defined as the ability (sufficient capacity and/or flexibility) of a system to experience unexpected shocks or perturbations, and to respond and recover functionality at some acceptable level of performance or action. We have an urgent need for improved understanding of the genesis and evolution of resilience, in particular in urban and coastal regions. We need to build and enhance social and ecological capital and community resilience, as well as to increase system adaptive capacity (including self-organization) and improve the cost-effectiveness of investments in sociotechnical (human, cyber and physical) infrastructure systems.

2 RESILIENCE FRAMEWORK

2.1 Need for Holism and Interdisciplinarity

The focus for resiliency is on functionality and apparent ability to adapt and restore functionality, including planned and spontaneous responses. To understand the evolution of a resilient response in an urban environment, it is clear that an interdisciplinary approach is needed that captures attributes of the complex environmental, human and physical systems in a region. In addition, the concept of what is an appropriate responding region itself needs to be investigated through development of complex layered and registered data resources. More complex models are needed that require assembling varied and deep information reflecting current and future conditions, response and usage so that we can expand our knowledge and validate our discoveries and predictions for system performance response. With these assembled information and modelling resources, we can develop a framework of variables and relationships that will support a cross-disciplinary exploration of resilience, and build knowledge as we develop and test theory and models about the resilience of complex socio-technical systems. Only then can we answer important questions including:

- What observations (evidence) can we make (identify) to indicate qualitatively whether a specific system or network will demonstrate resiliency?
- What metrics can be used to evaluate the capacity of a system or network for resilient response?
- How does resiliency develop or evolve in response, and what factors control or influence the development? Is it a process with thresholds, tipping points, state changes, or is it a continuous function?
- What can we understand about when investment or adaptive management is warranted to improve resiliency of a system of systems, networks, and interdependent systems?

A number of sector-specific models (e.g., telecom, electric power) of system performance are currently available (Lee et al., 2007) that are more comprehensive in terms of both their geographical scope and the level of detail they capture, and more sophisticated in terms of how effectively they represent, to operational personnel, the information they can produce. But not all sectors have been addressed, and the models are relatively primitive (e.g. employing disparate, ad-hoc implementations, and not interoperable across geographical service areas) for other sectors. A close analogy between physical infrastructure systems

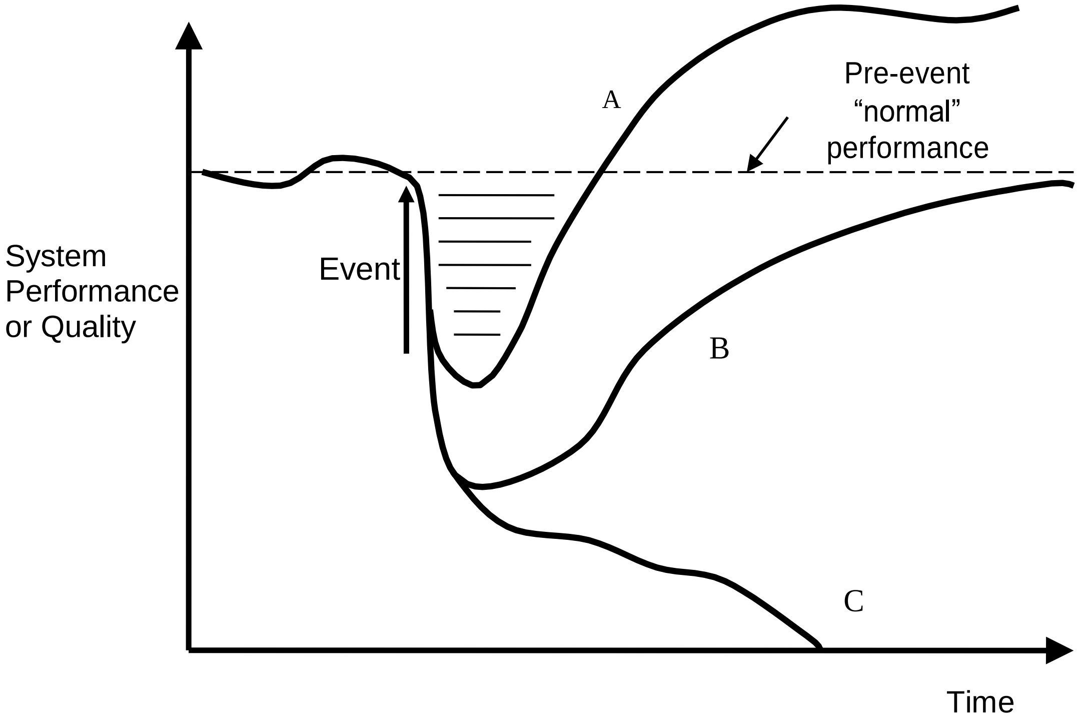

Figure 1. Conceptual Definition of Performance Response Functions
A – highly resilient system
B – less resilient system (may not fully recover)
C – loss of resiliency – system failure

(the focus here) and social systems (e.g., disease) and virtual systems (e.g., Internet) is notable, as is the observation that many of the solution methods in complex systems science are common to all applications. Lacking is a consistent methodology for modeling cross-sector behaviors of critical infrastructures under stress.

2.2 Performance Response and Resilience

As a foundation for integrated study of complex system resilience, it will be important to develop Performance Response Functions (PRFs) that serve as the backbone curves for system response. Performance response concepts have been introduced before (e.g., Bruneau et al., 2003; Silverman, 2004; Fwa, 2005; Rose, 2009; Reed et al., 2010), but PRFs have a greater potential for breakthrough insights in evaluating what performance means, establishing cross-sector performance metrics and variables (the resilience framework), and understanding how system performance response functions (PRFs) record or reflect important aspects of system behavior at different temporal and spatial scales.

As an example, consider Figure 1, which shows PRFs for socio-technical system performance. The striped area is the loss in performance of system A with respect to a specific event (e.g., storm, earthquake, terrorist act) measured as the experienced degradation in quality from the pre-event "normal" performance over time. The vertical scale for such a plot is some metric for system performance, which could be based on service delivered, an econometric measure, etc. The system response will depend on system capacity relative to the event magnitude, how well the system has been maintained, how abrupt or intense the event is, the pre-preparation of the community for such an event, and the geography and social structure of the community and region. In the case of system A, the impact of the event was minimized in intensity and duration, and the recovery was rapid reflective of a high level of resilience. In the case of system C, the system failed and recovery was not possible.

Conceptually, resilience is a very useful concept but the data required for its application is not often obtained, and the assessment of resilience is not yet widely recognized nor utilized by practitioners. Neither has the linkage between currently defined outcomes/metrics been made with standards or policy incentives an important aspect of implementation.

3 PRF ANALYSIS AS A METAMODEL FRAMEWORK FOR RESILIENCE

PRFs can also be viewed as a kind of metamodel outcome that reflects the functionality of the system(s) but without the sensitivity toward privacy and security that exists for some descriptive data sets. Convolution of performance response functions for different but interdependent above- and below-ground systems informs the development of a new science of resiliency that can effectively be applied across sectors and systems. This work involves establishing metrics for characterizing infrastructure robustness and fragility, but the metrics must also be applicable to sociotechnical organizations to begin to capture and model community resilience as an integrative and vital concept for our increasingly urban world. This work will lead to enhanced interpretations of the behavior of interdependent infrastructures, thus contributing to systems theory of integrated sociotechnical system behavior, particularly under conditions of increasing density and underground development. In this way, the importance of investment in the urban underground can be demonstrated as a key element of sustainable and life-cycle approaches to better planning and construction in our urban environments.

While we can construct PRFs for specific components of the infrastructure (Croope and McNeil 2011) and we can observe PRFs for regions or communities using data censored by time (Hallegatte 2008), constructing PRF's to assist decision makers and allocate resources requires us to understand scale, aggregation, interactions and interdependencies. PRFs can also serve as a framework to consider use of new technologies, evaluate strategic investments, or introduce stresses to systems. PRA may be applied to individual systems, or all systems in a region. With coupled models, PRA can be used to explore how the performance/behavior changes as a function of degree and type of interconnectivity of systems in a sector and across sectors, and across temporal and spatial scales.

It is important that resilience be appreciated and characterized as a System Response representing the return to service or functionality, and the restoration of trust and well-being. As such, we need fundamental investigations into PRF metrics that include contributions from the social environment (human/organizational capital and capacity), the physical environment (infrastructural systems), and the natural environment (eco-systems). And any measurement of resilience will depend on the definition of the region being considered to include spatial and temporal scales, boundaries (and representation of boundary characteristics), and the model level of detail or granularity.

Models and metrics for resilience have been the subject of much recent work (Gilbert, 2010), and examples of metrics for resiliency and/or PRFs include:

- Services – infrastructure function delivery (e.g., pressure, volume, rate, quality, reliability)
- Human activity (e.g., trips taken, tickets bought, calls made, population density, other demographics)
- Economics (e.g., income statistics, sales tax paid, targeted purchases)

Given a record of spatially distributed pertinent information over many time intervals, the geography and variation of a metric may yield understanding about how the region responds, where resources come from that aid in recovery – ultimately laying the bases for a prediction of comparative resiliency among different communities and societies. When integrated over space and time, the resulting character of the PRFs may indicate typical shape functions. If so, then a new science of complex system analysis of PRFs and resilience may be explored in which a fundamental understanding of how metric functions vary as a function of spatial, temporal and intensity effects and regional boundaries (and perhaps characteristics of boundaries) can be achieved. This would include building an understanding about how PRFs differ (or are the same) across scales, sectors, and systems. The prospect of a science of resilience and PRFs may actually have its own algebra for representing multi-system performance responses.

Demands for infrastructure service vary over time but have typically been assumed constant (Tierney and Trainor, 2004). This assumption must be carefully examined, e.g., the supply side of transportation systems can be measured by metrics such as accessibility, travel time and capacity using risk assessment methods, but the supply-demand relationship has not been captured. PRFs can be used to explore individual system vulnerability, develop summary indicators of net resilience of all systems providing satisfaction to this demand, and to assess topological properties of a networked infrastructure as well as interactions between network structures when subjected to disturbance. These properties include the shortest path distance, clustering coefficients, network density, vertex degree, node and link betweenness centralities, network connectivity loss and efficiency.

By keeping track of the history of the system through a memory kernel as dictated by data and microscale event modelling, it is possible to develop new quantitative performance models of infrastructure systems (Lee et al., 2007). Currently, there are no standards or universal methods of developing and analyzing the resilience indices of the networked infrastructure. The challenge is to define more specific measures, which will integrate across resilience computations in economics or social sciences.

4 INTERDEPENDENCIES AND RESILIENCE

The major elements of sustainability are increasingly a fundamental requirement to the successful undertaking of large capital construction programs – effectively constituting a social license for a "balanced solution." We need to create a methodology and the resources that will establish the value of subsurface space as a resource in urban environments – one that enhances sustainability and urban system resiliency (for example, see Allouche et al., 2008 for the impact of Hurricane Katrina on buried utility services]. Our sociotechnical systems are interdependent, so that disruption of one infrastructure system can impact the operation of other systems. Sources of interdependencies are varied and include technological, cyber, geographic and spatial, economics and business, social/human, political/policy/legal, organizational, resources and supply chains, and security.

Figure 2 illustrates interdependencies that may be developed among six physical infrastructure sectors, and illustrates the complexity of performance and behavior of these systems. In some cases, geospatial mining tools for data-rich sectors have been used to explore the interdependencies, e.g., among transportation and energy systems by merging geospatial and nonspatial data (Shih et al., 2009). Such compound system resiliency analysis will likely lead to new understandings of compound system performance and sources of vulnerabilities.

The resilience of our urban communities depends on many factors that extend beyond the physical system complexities and interdependencies. Therefore, social network research is needed to provide linked and registered metrics for event impacts, yielding change trajectories over time (Anex, Realff and Wallace, 2006). Social networks in use now

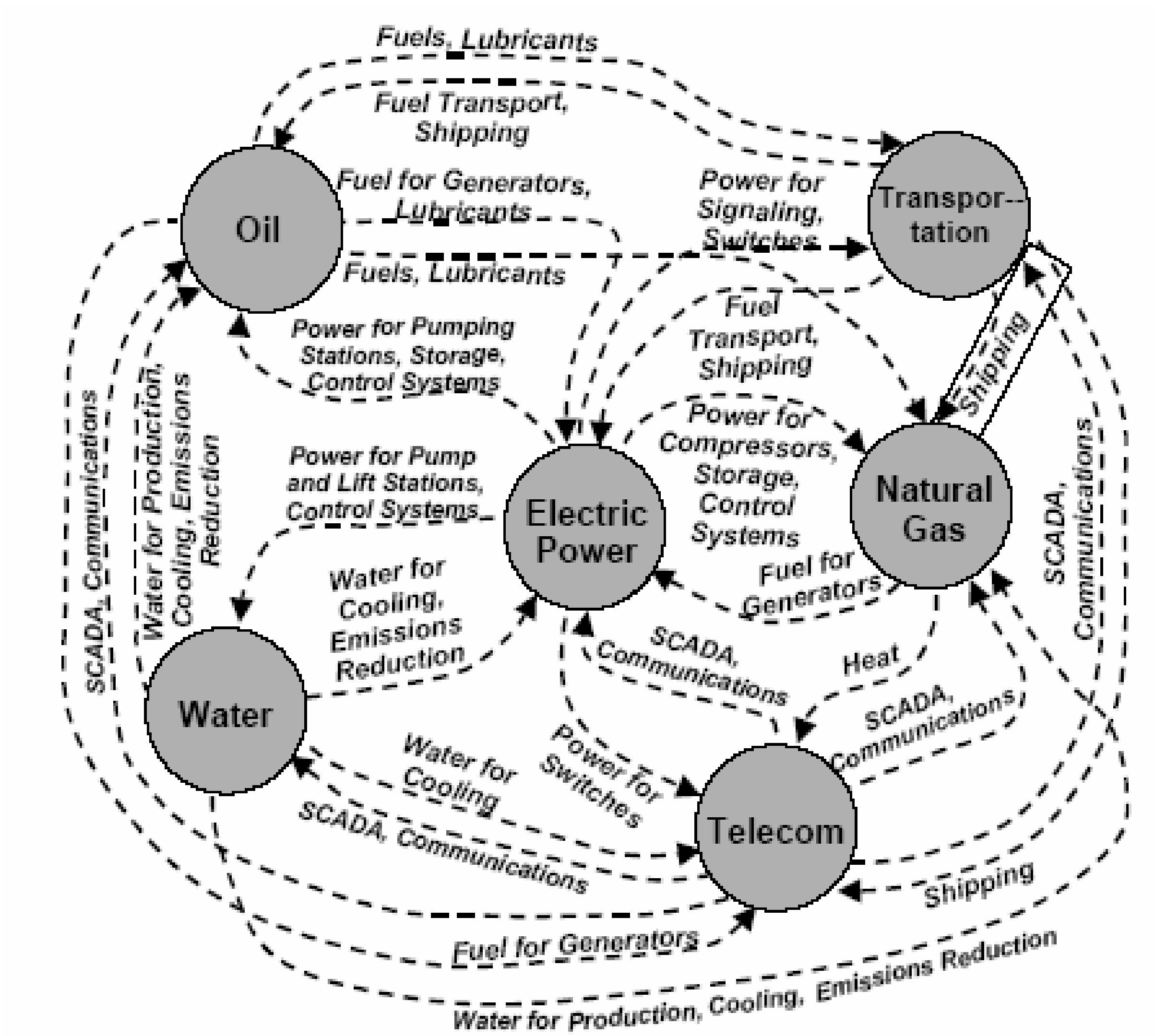

Figure 2. Interdependencies for Six Sectors of Infrastructure (Rinaldi et al., 2001)

represent a new resource that allows researchers access to social data quickly, and software designed to analyze word function and content on social media (such as blogs) and on-line information sources can be used to capture and analyze the public's acute reactions to extreme events (Sherrieb et al., 2010), providing an exciting window into social resilience.

5. CONCLUSIONS

It is important to tackle one of the principal questions that has perplexed scholars in the natural, social, and engineering sciences as well as the humanities—what are the elements of survival of social and built systems? Such questions have engaged scholars since antiquity, and emerge in both classical descriptions and more modern studies of the growth trajectory, and decline of great civilizations. Scholars, political leaders, and attentive citizens want to know if what we build is going to last, or if there is a clause in our creations that might limit their longevity. Are human creations durable enough to stand up to time? Can we measure their strength and adaptive capability? What is the value of underground space and how can it be best used to improve urban infrastructure service and resilience.

The complexities of technical and architectural development on an increasingly urbanized planet raise the salience of such concerns as people and resources are increasingly concentrated. Critics such as Perrow (2007) argue that these characteristics of modernity are just the advance guard of more and greater catastrophes. Recent cataclysms support his views: the collapse of the Twin Towers of the World Trade Center fatally damaged even very large buildings in their environs, while more recently, the Japan Tohoku earthquake and tsunami wrecked habitation, industry, and commerce on a broad scale and forced unprecedented multiple simultaneous nuclear emergencies. These events emerged as surprises that, though envisioned (Mitchell, 1996), surpassed the scale of extant planning and demanded solutions that were as expedient as they were inventive. The burgeoning growth of resilience studies offers an advanced and scientifically valid approach to understanding capacities for system survival. Wildavsky (1988) suggested that in a dilemma between anticipation and resilience, resilience was to be preferred in most cases because many threats cannot be anticipated. Others (e.g., Kendra and Wachtendorf, 2003) argued that the distinction between anticipation and resilience is not so absolute, because resilience owes much to anticipating needs as well as to creativity and improvisation. What to plan for, how durable our creations need to be, what we must look forward to, and how we can improvise in crisis comprise the basic knowledge of resilience—survival—that we will study as we address questions that build a science of resilience – one that includes both above- and below-ground resources as an integrated environment for the urban quality of life.

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