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.

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 Fig. 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.

Fig. 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 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

![Fig. 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).](image-url)
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 $250 K 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 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. Fig. 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. (2010) 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 Fig. 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.

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 Fig. 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 Fig. 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 Fig. 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.

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 Fig. 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.

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 Fig. 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 labeled B is a more typical response experienced by our current cities, with time to recovery of a significant duration. The system labeled 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.
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, and 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.

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 °C indicates a state of health. Deviations from 37 °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.

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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