Tunnelling and Underground Space Technology 55 (2016) 32–39

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

A framework for the future of urban underground engineering

Priscilla P. Nelson

Department of Mining Engineering, Colorado School of Mines, Golden, CO 80401, United States

ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 5 October 2015
Accepted 9 October 2015
Available online 6 November 2015

Keywords:
Infrastructure
Urban
Geologic risk
Underground construction
System performance
Resilience

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

---

E-mail address: pnelson@mines.edu

http://dx.doi.org/10.1016/j.tust.2015.10.023
0886-7798/© 2015 Elsevier Ltd. All rights reserved.

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.

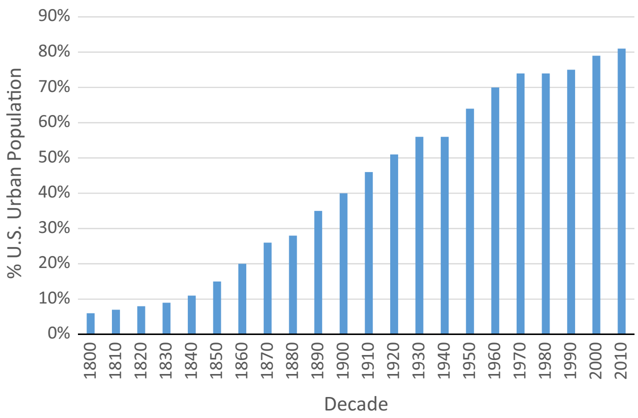

Fig. 1. Percent of the United States population living in Urban Areas (data from United States Census Bureau, https://www.census.gov/population/censusdata/table-4.pdf).

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