Muir Wood Lecture 2024

Underground Resources for a Sustainable Global Future

Professor Priscilla P. Nelson, PhD
Colorado School of Mines
Golden, Colorado, USA
pnelson@mines.edu

N° ISBN : 978-2-9701670-4-4

MARCH 2024

ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN
AITES
ITA
INTERNATIONAL TUNNELLING AND UNDERGROUND SPACE ASSOCIATION

Muir Wood lecture 2024 - **Underground Resources for a Sustainable Global Future** - N°ISBN : 978-2-9701670-4-4 / MARCH 2024
Layout : Shoot The Moon – Avignon – France – https://www.shoot-the-moon.fr

Muir Wood Lecture 2024

Underground Resources for a Sustainable Global Future

Professor Priscilla P. Nelson, PhD
Colorado School of Mines
Golden, Colorado, USA
pnelson@mines.edu

>> Abstract

Our world has changed in many ways over the past decade, in particular. The drivers for change includes our evolving comprehension of the finiteness of the carrying capacity of the earth. The growing population has led to urban densification and expansion, and to challenges in human and industrial waste management, disease control, ecology and habitat issues, and behavioral changes and social tensions related to food and water availability, social justice and equity. The fragility of the global supply chain and the realization of the impacts of climate change are driving the energy transition and the need for alternative sources of energy which will require utilization of critical metals and minerals.

What is the role of the underground as an earth resource in addressing these world changes ? This lecture will address the responsibilities and opportunities for the construction and mining industries to be leaders in the path towards a sustainable global future. We must be increasingly creative to deliver underground resources that support sustainability of earth's environmental systems and that provide positive outcomes for communities. The lecture will provide discussion on:

1. The global context for infrastructure
2. Limitations and opportunities for underground solutions
3. Approach to urban solutions, sustainability and resilience
4. Addressing underground risks

>> Introduction

Infrastructure demands will only grow in the future. The parameters and priorities for planning and decisions are changing and will continue to change. If underground space is to be appropriately considered in responding to demands for service – the gaps of data, knowledge, tools, governance, technology, workforce, and policy all need to be addressed so that underground infrastructure can make the contributions to society that are needed and warranted. We need to make compelling cases for putting infrastructure underground, and provide the advances in technology, methods, and legal ad contractual frameworks that will reduce the costs, and yield a more sustainable, accessible, equitable, and resilient integrated infrastructure systems.

The focus of this lecture is on the future and the role we (the underground construction industry) are needed to play. The first consideration introduced is the global context, and this is followed by discussions of the limitations and opportunities for underground solutions in the future, including comments on chronic issues for underground construction, and identification of areas in which mining and construction should be working together and sharing experience. The concepts of sustainability and resilience are then discussed underground urbanism and integrated solutions. The final topic addresses the risks for underground construction industry.

1 >> The Global Context for Infrastructure

The world population reached 8 Billion in 2023, and is expected to peak at 10.43 Billion in 2086 (http://ourworldindata.org). This increase is a major driver for increased demand for infrastructure systems and services. The population has also become increasingly urbanized, as reported by Hunt et al. (2016). The data for this urbanization is shown in Figure 1. The world is expected to have 41 megacities with more than 10 million inhabitants by 2030 (Lapenna, 2017).

Population increases means even more mega-cities, growing very fast as "compact cities" which grow up and down into the subsurface, serving high population densities, and reserving more surface space for social activities including environmental engagement. This creates a particular urgency to make the underground space of the future cheaper to construct, and more reliable in service and operational performance. The cost and performance of underground projects is intimately linked to the understanding and management of geologic risk for both construction and life-cycle performance of subsurface facilities. This includes not only expected and unexpected uncertainties, but also the anticipation that urban growth will extend into increasingly fragile and often difficult geotechnical environments, and that the projects will involve larger and deeper openings.

Increases in global population and urbanization, the global energy transition, climate change and carbon footprints, critical minerals and supply chain complexities, and expansion in the expectations for basic human rights equity and social justice, access to technology and services, and environmental quality – all of these drive our focused attention on the quality of life in urban environments of the future.

Quality of life is strongly correlated with power consumption (Pasten and Santamarina, 2012), and therefore, the ongoing global increase in the quality of life occurs at the expense of increased power consumption. Engineering a sustainable energy future must focus on reducing power consumption in energy-rich countries and improving the energy access for low-energy consumers. Pasten and Santamarina note that today's energy supply is predominantly based on fossil fuels (~83%). The energy transition will be energy-intensive and will actually result in a significant increase in fossil fuel consumption in the coming decades. Slow development of new mining operations and the rising demand for critical metals and minerals are bottlenecks for the material supply chains needed to support the energy transition, and mining itself is a high energy-demanding industry.

In addition, increased frequency and impacts from natural, technological, and societal extreme events (e.g., from weather, terrorism, economic stress, seismic activity), as indicated in Figure 2, make multi-hazard designs necessary (Ayyub, 2014), and engineered management of such low frequency/high consequence events remains a challenge, made more difficult by the power-grid stress in most countries, and the lack of redundancy in many systems. Design

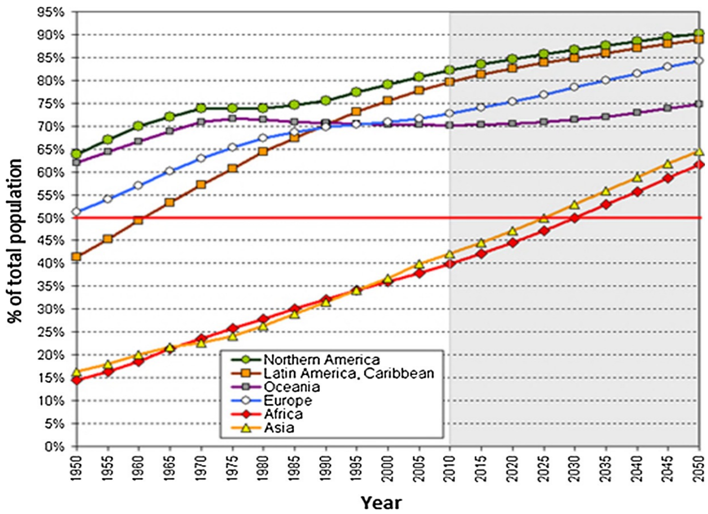

Figure 1: Urban Population Growth (Hunt et al., 2016).

for multi-hazards is "stacking the deck" in terms of risks, and will have high cost impacts on underground structures and systems that were already very expensive to construct.

We can also anticipate that underground space use will increase in spatial dimensions, depth, and architectural and life safety requirements, perhaps introducing additional fragility. It is imperative that underground planning be integrated with above-ground and at-grade urban developments, and that our urban infrastructure service systems be built and operated as networked and interdependent system of systems. Urban growth will also drive the extension of construction into increasingly fragile geologic and ecologic conditions, increasing the uncertainty and risk of significant problems when high-cost consequence events occur.

Design and professional codes have always incorporated factors of safety against failure by such individual (not multi-hazard) events, but the impacts of recent events have been more severe and complex with interdependent responses. Engineering professionals, construction contractors, urban planners and managers must work together to identify new ways to retrofit and bolster our infrastructure against extreme event impacts. Underground engineering can be a part of effective design and solution of problems because the underground structure designs inherently reduce exposure to some hazards. Therefore, the underground is an important resource to enhance urban resilience, and advantages and disadvantages are summarized in Table 1.

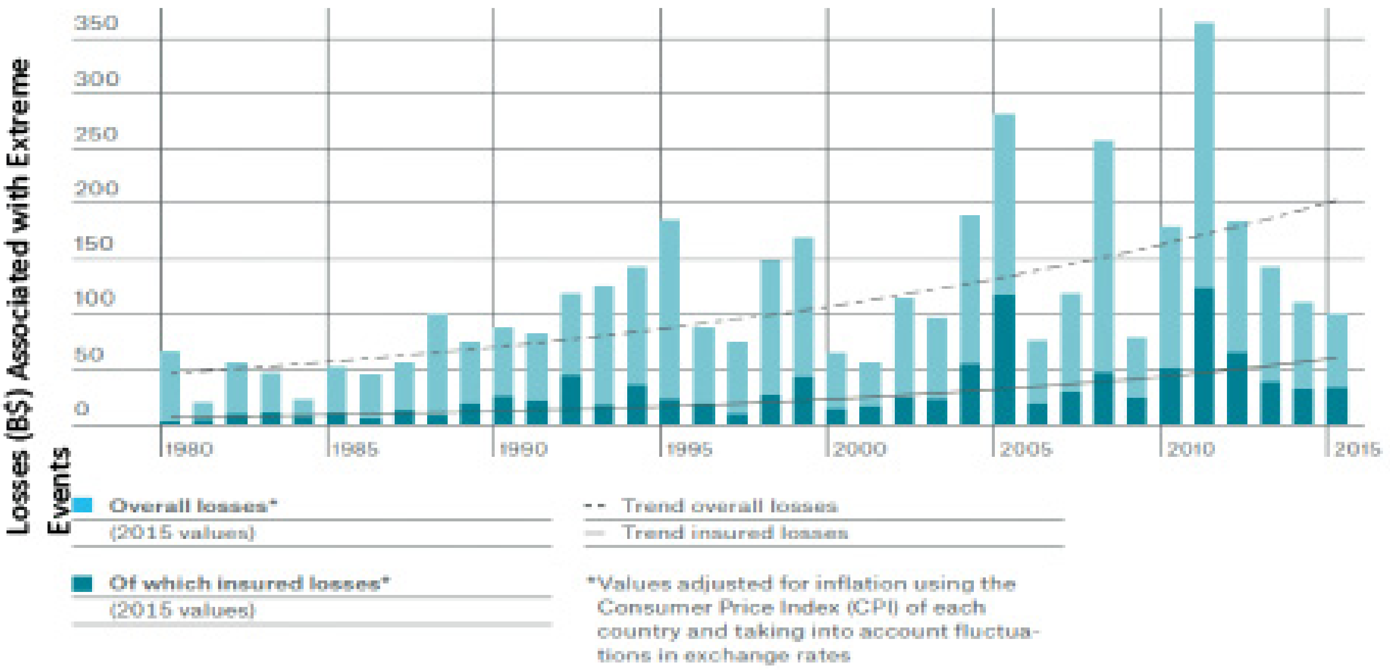

Figure 2: Escalation of Losses (B$) Associated with Extreme Events (Kunreuther et al. 2016).

TYPE OF EVENT	ADVANTAGES OR MITIGATIONS	DISADVANTAGES OR LIMITATIONS
Earthquake	Ground motions reduce rapidly below surface	Fault displacements must be accommodated
	Structures move with the soil.	Instability in weak materials or poor configurations.
Hurricane, tornado	Minimal impact on fully buried structures.	Damage to shallow utilities from toppling surface structures and trees.
Flood, tsunami	Protection from surge and debris flow	Extensive restoration time and cost if entrances are flooded.
Fire, blast	Stable ground (hard rock) provides effective protection (less true for softer soils and weak and/or weathered rock), limit damage by compartmentalization	Entrances and exposed surfaces are weaknesses, confined space risk. Point of safety and safe exit pathway must be identified and maintained.
External radiation, chemical/biological exposure	Ground provides additional protection	Appropriate ventilation and filtration system protections required.
Radiation, chemical/biological releases	Limited exposure with compartmentalization	Confined space may increase personnel risk

Table 1. Advantages and Disadvantages for Underground Infrastructure and Extreme Event Impacts (modified from Sterling and Nelson, 2013).

2.1 INFRASTRUCTURE SYSTEM RESILIENCE/ SUSTAINABILITY

The goals for having resilient infrastructure and resilient urban environments are really driving the implementation of emerging technologies. We must consider the speed of implementation, the redundancy, the robustness and how these emerging technologies can be implemented without being disruptive technologies. The focus on resiliency of an infrastructure system is on functionality and ability to adapt and restore functionality, including planned and spontaneous responses. To understand the evolution of a resilient response in an urban environment, an interdisciplinary approach is needed that captures attributes of the complex environmental, human and physical systems in a region.

System resilience functions have been investigated by many, including Chang et al. (2014) and Yang et al. (2023a and 2023b). According to the Resilience Alliance (https://www.resalliance.org/resilience) 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; and the ability to build and increase the capacity for learning and adaptation. The loss in function or performance, and the system recovery is schematically illustrated in Figure 3.

In this figure, the green area represents the loss in performance of system A with respect to a specific event (e.g., storm, earthquake, terrorist act), measured as quality degradation from pre-event "normal" performance over time. The vertical scale is some metric for system performance, which could be based on service delivered, an econometric measure, etc. The response depends on system capacity relative to event magnitude and scale, how well the system has been maintained, how 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 was minimized in intensity and duration, and recovery was rapid reflective of a new high level of resilience (continuous improvement). In the case of system C, the system failed and recovery was not possible.

Rather than predicting and planning for a more sustainable future, resilience stresses uncertainty and building systems-based adaptive capacity to unexpected future changes. An under-explored question for system designers and operators who are focused on resilience remains: "Resilience for whom?" (Meerow and Newell, 2019). While maintaining a minimum level of service and rapidly restoring services to normal are key components of critical infrastructure (CI) resilience, who should and how to define these parameters remains under debate. "Rarely solicited in the debate, yet integral actors in Civil Infrastructure resilience, is the general public." (Petersen et al. 2020). An interesting probe into the "Who" and "How" issues is presented by Melo Zurita (2020) drawing on case studies in Australia, and offers

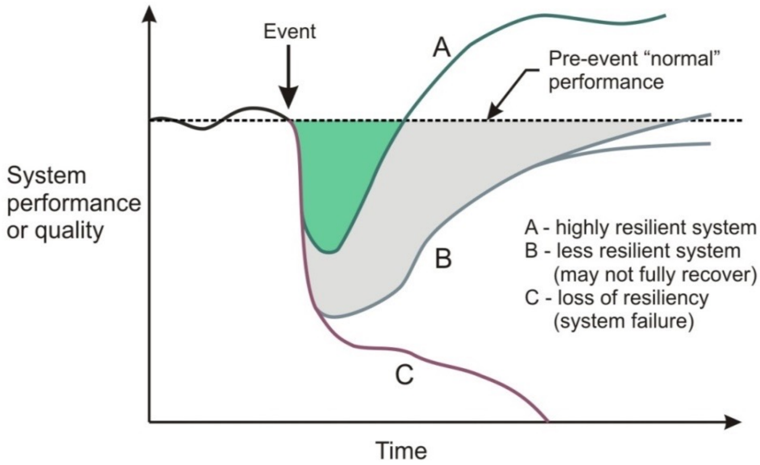

Figure 3 : Infrastructure System Resilience Function Schematic (Nelson and Sterling, 2012).

an approach "to move subterranean urban development away from a technoscientific tunnelling decision making process to one that engages with the social, political and economic implications of urban infrastructural projects."

A linked question is related to criteria for resilience, and the basis for design decisions. In fact, design could focus on any of the following criteria, and different criteria will result in different designs. There can be no such thing as an overall "optimized" design:

- Resilience (function)
- Sustainability (system performance over time)
- Reliability (instantaneous access)
- Equity
- Environmental
- Energy
- Climate Change
- Cost and schedule

For example, sustainability focuses on fulfilling today's need without affecting the need of future. In case of infrastructures, it focuses mainly on reducing the effect of such infrastructures in the natural environment. The strength of a sustainability approach is that it systematically examines future options, assigns values to those options via indicators, and customizes its strategies to attain those options. It rigorously integrates normative values and anticipatory thinking into a scientific framework (Clark and Dickson 2003, Swart et al. 2004).

In contrast, resilience focuses on developing the ability of a system to bounce back to normal operation after facing sudden external shock or disturbance. In the case of infrastructures, resilience focuses on enhancing the capacity of such infrastructures to respond to any possible hazards in an effective and efficient manner. The strength of a resilience approach is that it develops adaptive capacity and/or robustness into the system so that the system can gracefully weather system shocks and stressors (Redman, 2014). A resilience approach builds social and natural capital and adaptive capacity to cope with unknown futures (Carpenter and Folke, 2006; Folke et al. 2010).

There is no single effective systematic framework widely in use that is developed to simultaneously assess these two concepts while designing and constructing an infrastructure (Pandey and Sadri, 2022). However, Shadabfar et al. (2022) discuss the developing resilience-based design (RBD) approaches, and a methodology for underground infrastructure assessment has been developed by Makana et al. (2016). The Makana et al. approach, given the title "Sustainable Underground Use Resilience Evaluation" (SUURE) is suggested to be a systems approach to sustainability evaluation, which combines sustainability science and resilience theory. Martinez et al. (2018) used the Vulnerability Assessment Scoring Tool (VAST) for application to underground transportation systems, but they note that this tool does not provide information regarding indicators that should be used to assess sensitivity and adaptive capacity of such assets. Rodriguez-Nikl and Mazari (2019) used VAST and assessed the Envision (ISI, 2018) methodology for application to underground infrastructure. They noted that Envision's treatment of resilience focuses almost exclusively on the reduction of initial damage and ignores almost completely the speed of subsequent recovery.

Infrastructure systems enable increasing quality of life and human achievement. However, as is noted by Neuman (2020), underfunded and deteriorating infrastructure systems often make cities both less sustainable and resilient. Neuman suggests that designing urban infrastructure as small-scale and modular systems will endow flexibility, resilience and adaptability, but the question of whether such systems would be more sustainable may not follow.

In addition, regarding resilience vs sustainability for planning and design, Admiraal and Cornaro (2020) address the role that the subsurface and the use of underground spaces can play in achieving urban resilience. They suggest taking a "balanced" approach to apply both sustainable development principles and urban resilience objectives for integrated consideration of the best use of the subsurface geologic resources in urban planning. Furthermore, Hunt et al. (2016) note that regarding sustainability assessment, a range of knowledge gaps exist and need to be addressed, including:

- Lack of consideration for resilience in both design and assessment of geo-structures.
- Lack of consideration for long-term performance in a significantly changed future (i.e. will the geo-structure continue to deliver its intended function into the future, whatever that may be? (Rogers et al., 2012).
- Lack of consideration for complex geology, which greatly impacts the use and cost of underground space (ITA, 2002).
- Lack of support for decision making.
- Lack of consideration for spatial and temporal information.

How should the tunneling industry act to increase applications of the underground in the future? It needs to demonstrate the contribution of underground infrastructure to both resilience and sustainability. The priorities for planning and decisions will continue to change in the future, and for underground space to be appropriately used, the gaps all need to be addressed so that underground infrastructure can make the contributions to society that are needed and warranted.

Why should we be putting infrastructure underground? Can we make compelling cases and provide the advances in technology that will reduce the costs, and yield a more sustainable, accessible, equitable, and resilient system of systems?

2.2 URBAN INFRASTRUCTURE AS A SYSTEM OF SYSTEMS

In many of our urban environments, particularly in older cities, we have underground infrastructure 'chaos.' Knowledge of precise location and condition of utilities, subsurface structures and facilities, and obstructions is often not well known, and constitutes a major uncertainty for underground planning and system maintenance. In addition, city agencies themselves are often siloed into sectors, and maintenance is not often coordinated across sectors. Infrastructure construction is considered project by project rather than as an integrated and interdependent system of systems. Infrastructure owners who implement asset management and life cycle engineering (LCE) applications need data and widely accepted time-based metrics and methodologies for design and operational planning. These are still evolving. Furthermore, urban infrastructure responsibilities in many countries fall to a mix of public and private owners. This introduces more problems as information about public systems is often poorly organized, and information about private systems is generally not available.

Urban physical infrastructure systems are unique in every city, in terms of ages of components, types of construction, subsurface geology, etc. These large and interconnected networks exhibit poorly understood interdependencies and emergent behaviors particularly in conjunction with extreme events and other causes of system stress. Following 9/11 in the Unites States, much work was started on understanding interdependencies, and an example of such for a physical network is shown in Figure 4. Building and validating computational models of such composite systems requires algorithms to be developed for the interdependencies and event consequences across the systems. Following work has identified other urban systems beyond the physical systems shown in Figure 4 – including banking and finance, health care and emergency services, food supply and government that are important to include to understand sustainability and resilience in an urban region.

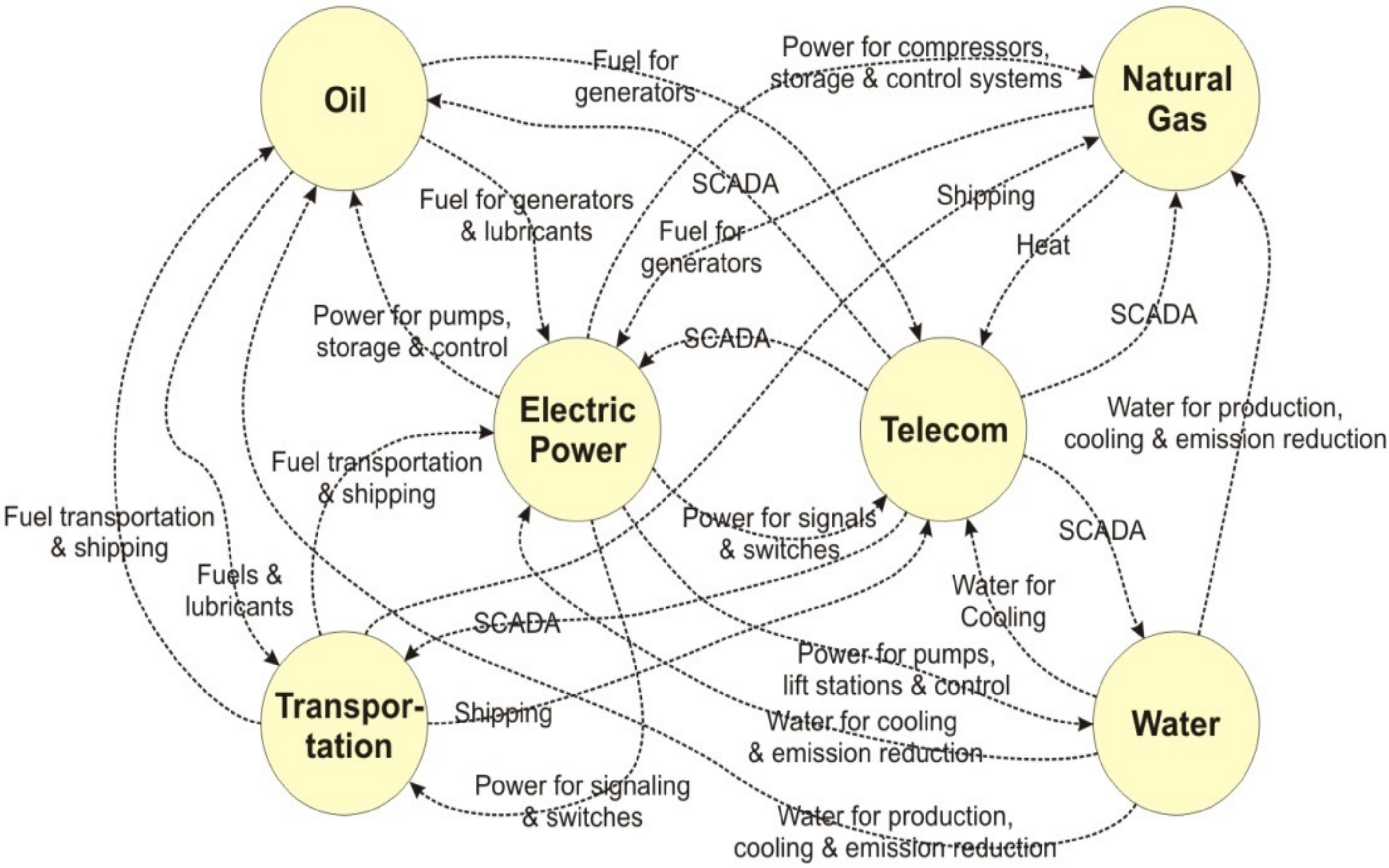

Figure 4: Interdependencies for Six Sectors of Physical Infrastructure (Rinaldi et al., 2001)

This expanding concept of what constitutes the integrated infrastructure in an urban environment complicates the development of an integrated model of urban system of systems function and makes difficult implementation of resilient design in the urban context. The possibility of studying the complexity is aided by the fact that many systems are in fact cyber-physical and cyber-social systems, and many of the emergent behaviors may be studied using social networks. Succes there will depend on whether we really understand how our interdependent infrastructure systems work well enough to model, validate, and trust them into the future? We need to understand what metrics (system-wide, distributed and local) should be developed for whole-city or regional evaluation? From an operational and continuous improvement standpoint, how should we incorporate, deploy, and train for new technologies without being disruptive and increasing complexity and vulnerability in our systems? We need a consistent framework and set of terms for study of the interdependencies of above- and below-ground integrated infrastructure systems – terms that are meaningful and accepted across sectors, countries and cultures (Nelson and Düzgün, 2018).

In a 2016 paper, Nelson introduced an analogy between complex urban infrastructure and the systems of the human body, considering New York City as an example. Both New York City and the human body systems are complicated, and in either case we may pretend that our systems are independent but, in fact, they are not. Integrated modeling of all systems together as a system of systems is too complicated at this time, but may be possible in the future. However, as noted by Yusta et al. (2011) and shown in Figure 5, different infrastructure sectors have used different modeling methods which will be very difficult to mesh into a composite system of systems model for an urban region. The application of Artificial Intelligence (AI) may well help in this integrated modeling.

Neither is an optimization of these systems of systems a clear construct. However, in a reductionist way, we have come to realize that a human body temperature of 37 degrees centigrade indicates that the human body system of systems was operating well, that the human was healthy, and likely to be resilient regarding disease.

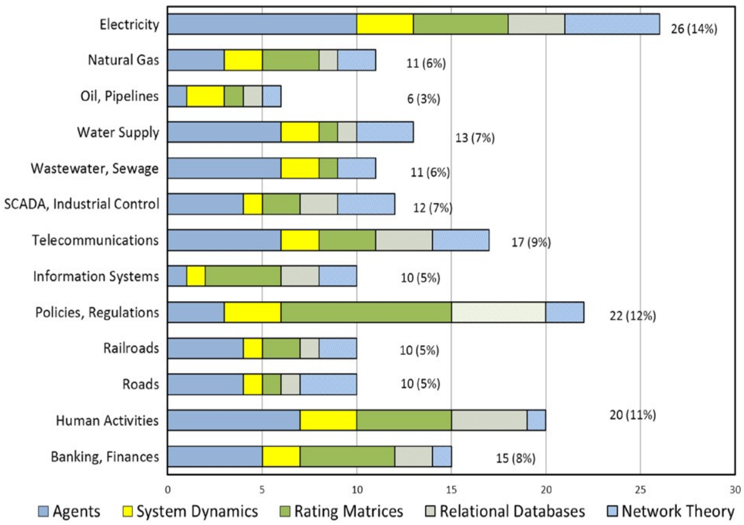

Figure 5: Variety of Modeling Approaches Taken for Infrastructure System Modeling (Yusta et al., 2011)

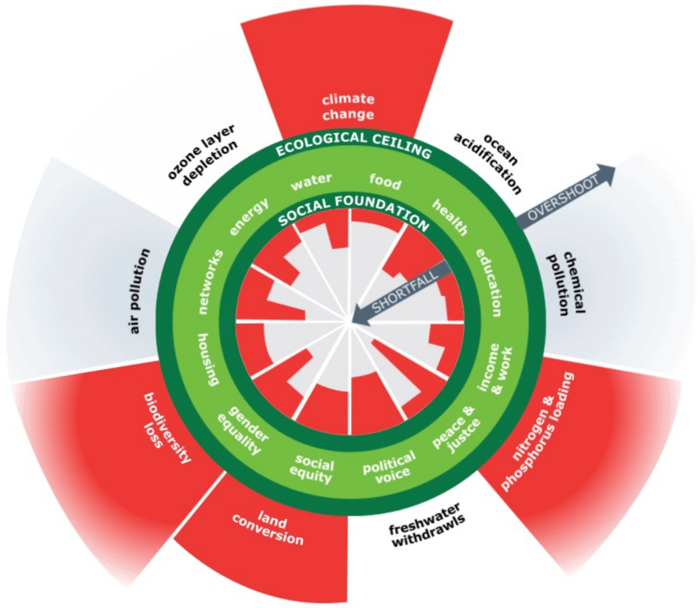

Figure 6: The Doughnut Economics Model (Raworth, 2017) from https://www.weforum.org/agenda/2017/04/the-new-economic-model-that-could-end-inequality-doughnut/ (image developed by Kate Raworth and Christian Guthier/The Lancet Planetary Health)

Can an analogous metric be defined for urban systems of systems performance be identified that tells us if our urban environment is healthy regarding its infrastructure. If so, can that metric be interrogated to guide future designs and urban response to threats from climate change impacts, including flooding, urban heat, sea level, etc.?

This suggests that research is needed to explore urban response to chronic and acute (extreme) stressors, and to identify models and metrics for aggregate urban system of systems response. With metrics and methods, we can demonstrate how underground infrastructure contributes to resilient response. Climate change impacts will be important as well. For example, Rotta Loria (2023) reports on "The Silent Impact of Underground Climate Change on Civil Infrastructure." He studied the underground thermal changes causing a "subsurface heat island" effect in Chicago. The predicted thermally-caused deformations could be sufficient to cause building foundation settlement and tilting, and damage to underground physical infrastructure. Such underground heat island effects have also been documented in London (Greenham et al., 2023) and in Osaka, Japan (Benz et al., 2018).

2.3 DOUGHNUT ECONOMICS

The Doughnut Economics model was introduced in a book by Raworth (2017). Doughnut Economics essentially models the donut as the place where people live on the surface of the earth, schematically demonstrated in Figure 6.

The Doughnut is bounded by the internal hole in the doughnut. The hole bounds the safe zone (the social foundation) where people have access to all human needs and rights (e.g., life's essentials, such as food, water, healthcare and political freedom of expression); in the hole itself, human needs and rights are not accessible. The concept is to have people NOT fall into the hole, and no one is harmed.

The external boundary of the donut is the planetary boundary (the ecological ceiling) where the concern is for harming the planet and the planetary systems. In Figure 6, the red planetary boundaries can be defined – we know that because we have already over-shot them); the grey and white boundaries are not yet quantified.

Paraskevopoulou et al. (2019) used models of a circular economy and a Doughnut Economy and identified principles that should be embedded to achieve resilience and sustainability during construction and operation of underground urban infrastructure. To achieve sustainability and resilience, they note that planning and organization of the underground development is required "not only in terms of spatial organization or overcoming the engineering challenges but also in regards to the establishments of policies, regulations and social factors consideration."

Another example of the application of this Doughnut thinking comes from Amsterdam. Immediately after the start of the pandemic, the city announced its own strategy for recovering from that crisis, and all crises (https://www.c40knowledgehub.org/s/article/Amsterdam-s-City-Doughnut-as-a-tool-for-meeting-circular-ambitions-following-COVID-19?language=en_US).

By embracing the Doughnut Economy, the model was used to inform city wide strategies and developments in support of the overarching ideas, providing a good quality of life for all without putting additional pressure on the planet. Other cities are following this path.

Doughnut Economics implies that success in life and work in the dough must have two mandates. The design must be regenerative (designing for reuse) and distributive design (providing equitable access and sharing). How does this Doughnut concept tie into urban and underground infrastructure? How can infrastructure planning, construction and operation honor the constraints of the Doughnut? How should we be thinking about underground infrastructure to be regenerative and distributive, with the value of the infrastructure investment distributed to everybody, not just to the rich and famous. In considering sharing, concepts such as shared enterprise, ownership, ethical supply chain, community empowerment and open-source design must be considered.

The urban underground infrastructure industry and operators do not bear the sole responsibility for addressing the climate change and Doughnut Economics challenge, but the industry does need to ensure that opportunities to contribute meaningfully to aversion of the crisis are capitalized on. This means minimizing all future carbon emissions. This could imply that we do not build any more infrastructure or maintain existing assets. However, that is not a responsive solution since infrastructure is the lifeblood of society, with the social value of infrastructure being increasingly included in decision making to enable improvements in, or at least sustaining the level of, quality of life.

2.4 THE VALUE OF THE URBAN UNDERGROUND

The value of underground urban comes in many forms, in terms of water as a resource, in terms of valuable space which may also be seen to preserve surface space for people to access, in terms of geo-energy and the energy balance and thermal considerations, and the stewardship in use of subsurface geomaterials. For the underground construction industry to get to the point that society respects the underground urbanism assertions, the industry needs to provide a framework that addresses the following very broad issues.

If we assert that the quality of urban life is improved, we need established metrics and data to measure the improvement in urban life quality. In addition, we need to use these metrics to demonstrate how underground space can improve resilience and sustainability of urban systems of systems. If we establish the metrics and framework, we will be providing planners and decision makers with the basis for making different decisions. If no metrics or methodology exist, we cannot demonstrate how underground space proof improves quality of life and resilience, and the assertions will stay assertions.

What research needs to be done in this context, what data needs to be collected and organized into information and further developed into knowledge? We need answers that will inform, not just ourselves, but inform professionals, planners and the public. What technical and analytical advances are required for all of these stakeholders to value the contributions of underground urban resources? What social, economic, political, and policy advances are needed to support the integrated and holistic decisions about underground investments?

A basic metric needed to address the assertions is the established value of underground space. There are markets for that establish values for surface acreage and for air rights in urban environments. But there is no market for underground space. So how should that underground space market (as an urban resource) be established?

The absence of an accepted methodology for underground space valuation likely results in sub-optimal decisions and an under-usage of underground space. Pasqual and Reira (2005) noted that underground land values were a missing factor in land economics and planning, and that ignoring such a potentially valuable resource may seriously delay any underground land policy to be undertaken. Considering subsurface land values in economic studies of underground projects increases their reliability for the decision-making process. They developed a theoretical and empirical way to estimate underground land values. Mavrikos and Kaliampakos (2021) presented an integrated methodology for estimating the value of underground space, depending on the land-use, on the ground of a modified real estate appraisal approach that also includes the appraisal of the environmental advantages of underground structures through the use of environmental economics. As of yet, neither approach has been significantly utilized.

The underground construction industry needs to pay attention to this and to support the development of underground space value methodology. This has been done in some cities. For example, Venvik (2018) reported on how Oslo has estimated values for its underground space usage, and noted that more underground installations are planned which will continue to increase the value. Rotterdam City has development plans to 2035 that use its subsurface in a wise manner to give urban development a new dimension to explore. Venvik also noted that Glasgow, a city underlain by many mine openings which are not well accounted for, has additional complexity for underground planning in subsurface uncertainty – it is important to know where the negatives (and positives) are in planning to use underground space. Additional major efforts to establish resources that can lead to subsurface valuation have been done in the UK and China, in particular.

Other issues that affect the valuation of the subsurface for urban quality of life include the right of way (ROW) access and land ownership. The 2001 Deep Underground (Daishindo) Utilization Law established that land ownership rights in populated areas (e.g., Tokyo, Osaka) only extend to 40 meters below ground, or 10 m below a deep foundation (Li, 2013 and Figure 7) The act is focused on metropolitan areas of Tokyo and Osaka, and ensures the right of developers.

to use deep underground space regardless of surface ownership. In the case of public use of the underground space, no compensation to the landowner is required. In 2015 Singapore adopted a similar approach by limiting ownership to 30m below the Singapore Height Datum (SHD) (Stones and Heng, 2016).

This issue of urban subspace subsurface space ownership needs to be addressed globally, and the industry, academia and municipal and state agencies should pay attention to it.

2.5 ISSUES IN COMMON FOR THE UNDERGROUND CONSTRUCTION AND MINING INDUSTRIES

The underground construction and mining industries certainly have differences, but they also have common causes. The issues of ESG, climate change and the energy transition, work hazards, deeper (e.g., hotter, higher stress, more water) future work, and geological uncertainty and risk certainly are common causes for the two industries. But in many areas, information and experience exchanges could be low-hanging fruit for improvements. For example, geologic material failure and the time-dependent response of geologic materials are far more likely to be observed in an underground mine than in a civil works project. Mining engineers develop a strong geologic perspective on risk that would benefit in application to underground construction projects. Such a partnership or collaboration across industries brings an enhanced potential for real spatial understanding of rock mass and water inflow and pressure variability, and for better understanding of time effects, presenting the possibility to develop performance information needed to understand and assess sustainability. The two industries also have many environmental issues in common, as do they have a mutually beneficial potential for application of automation, robotics, and big data/information systems.

There are three additional areas of interest to both industries that are discussed below: workforce, automation and robotics, and engagement of zero waste and the circular economy

2.5.1. Workforce

In many countries, developed countries in particular, young talent is not interested in building a career in either mining or underground construction. In a recent survey conducted by McKinsey (https://www.mckinsey.com/industries/metals-and-mining/our-insights/has-mining-lost-its-luster-why-talent-is-moving-elsewhere-and-how-to-bring-them-back#/) the majority of respondents aged 15 to 30 indicated that they either definitely or probably would not consider working in mining (70%) or civil construction (57%). At the other end of the workforce, the size of workforce retirement numbers indicates that a crisis is brewing.

In the United States, there has been a steady decline in the number of mining and mineral engineering programs at U.S. colleges and

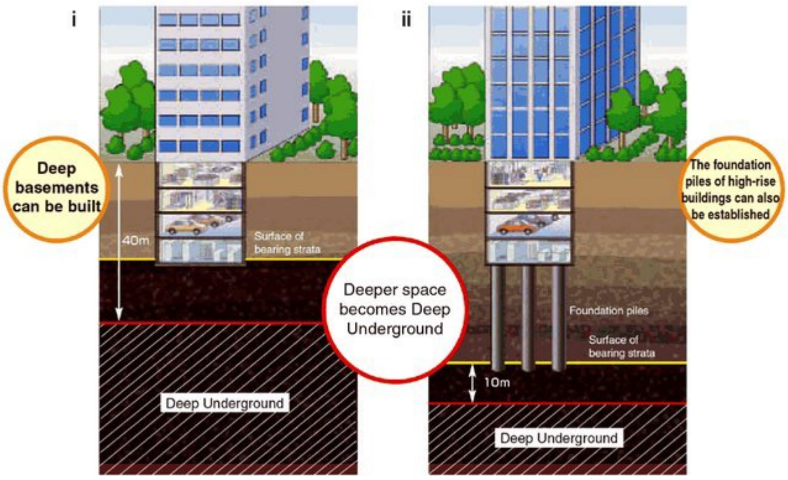

Figure 7: Schematic of Impacts of the 2001 Deep Underground Utilization Law in Japan (Li, 2013).

universities from a high of 25 in 1982 to 14 in 2014. There has also been a corresponding decline in the number of U.S. faculty (~120 in 1984 to ~70 in 2014) in these programs, at a time when there is also a shortage of qualified candidates to fill faculty vacancies.

Turning to consider the university student's choice of degree programs, Figure 8 presents data from the United States and from one of the many universities in China (data from SME, https://www.smenet.org/What-We-Do/Technical-Briefings/Maintaining-the-Viability-of-U-S-Mining-Education).

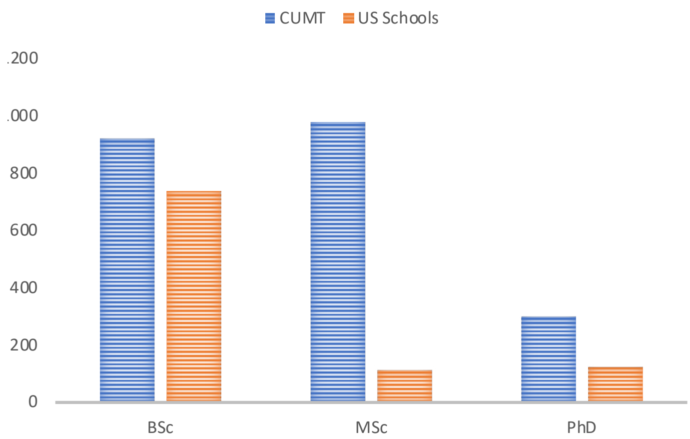

Figure 8: Total Number of BSc, MSc and PhD students in all US Mining Engineering Programs vs China University of Mining and Technology

The entire United States had 736 students enrolled in undergraduate mining engineering programs in 2023, compared to 920 undergraduate students enrolled in similar programs at the China University of Mining and Technology.

The low enrollment trend (low and decreasing still) also affects programs in Canada and Australia, and perhaps other developed countries as well.

A sustainable workforce pipeline is a major issue for both industries, made even more important by the drive for critical minerals.

2.5.2 Automation and Robotics

Applications for automation and robotics in mining are being pursued by most mining companies, with the dual main drivers of increased production and reduced worker hazard exposure. Many opportunities for future development exist, and many applications are as pertinent for underground construction as they are for mining. Some needs and applications are summarized below:

Geology and exploration

- Measurements while operating include drilling and geophysics borehole measurements.
- Automated deployment of geologic imaging and spectroscopic systems.
- Robotic deployment of assay systems for rapid ore grade assessment.
- Robotically deployed mine-to-surface geophysics during exploration and mine operations.
- Expanded application of airborne geophysics and remote sensing.

Ground characterization and response

- Robotic mine rovers with instrumentation to include LiDAR, thermal imaging, radar, photogrammetry, spectroscopy, and multi- and hyper-spectral imaging.
- Geophysics robots (electrical and seismic) to operate in boreholes and on surface exposures.
- Mobile and self-organizing sensor networks.

Excavation

- New approaches to automated excavation (e.g., mechanical, drill/blast, dragline, continuous miners and drum shearers).
- Advanced tool designs and automated tool replacement.
- Focus on automation applied to shaft sinking – little has changed in most such operations for many decades.
- Automated/robotic load/haul muck equipment and systems.

Productivity

- Robotic applications for on-site maintenance of all equipment decreasing downtime.
- Integrated and self-aware communicating and fully automated mine equipment.
- Autonomous sensing of geologic conditions during mining, and automated ground support design and installation.
- Real time tracking of ore quality.
- Automated control of mineral processing and filtration circuits.
- Automated and robotic shaft sinking.

Worker health and safety

- Autonomous equipment for excavation and ground support installation.
- Remote and continuous spatial tracking of workers and their work environment.
- Health monitoring stations accessible to non-tethered robots to provide immediate health-related support.
- Wearable networked technologies to monitor and anticipate problems.
- Robots to explore abandoned mines to assess accessibility and hazards.
- Robotics used to conduct mine search and rescue, supply and extract.

Hazards detection and avoidance

- UAVs and ground-based robots developed for uses including:
  - Automatic dusting, and dust scrubber robots for high dust concentration.
  - Ventilation management, e.g., on-demand systems
  - Gas concentration monitoring/warn of approach to explosive limits
- Smarter interference detection (beyond proximity sensing).
- Worker fatigue monitoring.
- Mobile acoustic sensing systems to detect precursors/incidents of rock failure.

Disaster response

- Robots to support incident management – e.g., reconnaissance, post-event environment assessment, communications, delivery of supplies.
- Robots for search, rescue and treatment (robomedics) of workers.
- Robots for assessment and execution of mined opening recovery or closure.

Communications, sensing and data management

- Coordinate spatial and temporal registration and communications through IOT applications.
- Self-organizing and autonomous fixed and mobile communication agent networks.
- Integrated 3D information visualization of ground conditions.
- Independent network-enabled multi-sensor communication systems for monitoring and interpreting changes in the mine environment.

In this section, discussion will focus on the intersection of underground urban infrastructure and the United Nation's Sustainable Development Goals (SDGs), the rising Environmental, Social and Governance (ESG) framework, construction funding gaps and financing, resilience and sustainability of urban regions, and Doughnut Economics.

3.1 THE SDGS AND EQUITY

The United Nations (UN) established the 17 Sustainable Development Goals (SDGs) (https://www.undp.org/sustainable-development-goals; UN, 2015 and UN, 2023) to transform our world by targeting achievement, or at least strong advances, to a sustainable planet by 2030. Qiao et al. (2019) mapped nine of the SDG goals to underground assets, including physical systems, groundwater, geomaterials, and groundwater resources. This mapping is shown in Figure 9.

Most countries are developing policies that explicitly consider sustainability, particularly in the context of equity. In the USA, The American Society of Civil Engineers has addressed the needs for future infrastructure as a major focus (https://www.asce.org/topics/equity-infrastructure), producing a variety of reports focused on infrastructure and equity, social justice, and climate change. Historical infrastructure placements have created injustices to communities of color and communities put at economic disadvantages. The infrastructure that civil engineers design and build in the future must be rethought to ensure the social, economic, and environmental well-being of all communities that might be affected. The European Union has committed to ensuring inclusive growth, with equality and non-discrimination ensured in its policies (European Commission, 2023). A study by ETH Zurich University (Klaassen and Steffen, 2023) concluded that investments in infrastructure in Europe need to increase to €302 Billion annually until 2025 for net-zero targets to be reached. And in China, Cui et al. (2022) report on approaches to incorporate social equity in decisions and designs for solving urbanization problems, and Rodenbiker (2022) reports on social justice and justice-oriented planning in China's cities. Governmental agencies are also responding. Michael Regan (USEPA) has noted that one of the most important things that [governments] can do to advance environmental [and social] justice is to ensure that the infrastructure in these communities is resilient to the impacts of climate change, so that our already overburdened communities aren't continuing to bear the brunt and cumulative impacts of climate change (https://www.epa.gov/newsreleases/statement-administrator-regan-bipartisan-infrastructure-deal.

And cities are responding as well. As cities grow and urban populations continue to rise, ensuring the equitable distribution of essential services becomes an increasingly complex challenge. Access to services such as water, electricity, and transportation is essential for the well-being and development of urban communities. However, traditional and aging infrastructure systems often fall short in providing equal access to these services for all residents. Li and Gao (2022) note the presence of "infrastructure deserts" in Dallas, Texas, defining the desert areas as low-income neighborhoods with significantly more deficient infrastructure. Cao and Hickman (2019) addressed the relationship of urban transport and social equity in London, and found statistically significant differences in terms of accessibility across the socio-demographic characteristics of individuals, and also across different neighborhoods – effectively causing a transportation infrastructure desert in the close vicinity of the underground stations along the Jubilee Line Extension. Many cities have recently established policies that address the infrastructure desert phenomenon. For example, in Los Angeles, the Public Works agency has a strategic focus area of Equity, creating an environment where all communities receive the services they need (https://equity.pw.lacounty.gov/). The agency expects that investing with equity will drive infrastructure funding and improve services to communities with historical disadvantage.

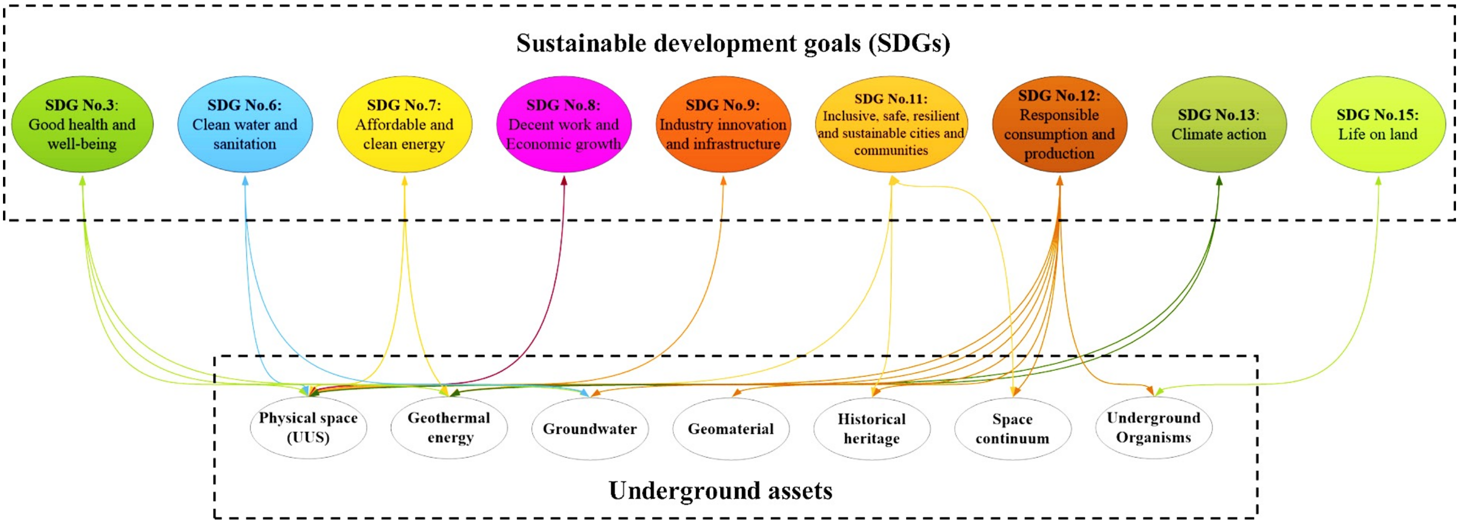

Figure 9:The United Nations' SDGs and the Underground (Qiao et al., 2019)

In Shanghai, Qing et al. (2018) report on a project to bring the Deep Underground Space (DUS) to Shanghai, benchmarking from projects in Finland and Japan. And Luo et al. (2020) report results from an interesting survey on the use of Multipurpose Utility Tunnels (MUTs) that integrate all utilities in one tunnel and can be easily accessed for inspection and maintenance activities. They note that China is currently leading the development of MUTs in the world on a large scale because of the central government initiatives, and they also note that many of the new MUT projects are in the Middle East oil countries. These projects not only improve service reliability, but also revitalize public spaces above the ground, promoting community engagement. Such projects respond to the mandate that the infrastructure that engineers design and build in the future must be rethought to ensure the social, economic, and environmental well-being of all communities that might be affected.

3.2 THE ENVIRONMENTAL, SOCIAL AND GOVERNANCE (ESG) FRAMEWORK

The Environmental, Social and Governance (ESG) framework provides guidance that targets investors, banks, insurers, governments, and customers to assess risks. ESG issues are generally aligned with SDG goals, as is indicated in Figure 10. Corporate offices are expected to respond to ESG mandates by measuring and disclosing how non-financial risks and opportunities related to the planet and its people are managed. ESG reporting is risk-focused using specific and measurable metrics, and ESG information is assessed by multiple ratings organizations. The ESG framework is closely linked with the United Nations Global Compact (https://unglobalcompact.org/) which includes signatories (businesses and organizations) that are committed to adopt sustainable and socially responsible policies as defined through the Ten Principles (https://unglobalcompact.org/what-is-gc/mission/principles) and the UN's SDGs, and to report on their implementation.

What does ESG mean for civil infrastructure? Questions for infrastructure owners might include: Environmental: How does an infrastructure owner act as an environmental steward? Social: How does an infrastructure owner engage and serve employees and stakeholders (e.g., customers and communities)? Governance: How does an infrastructure owner make policy and communicate decisions?

In response to changing citizen demands, government leaders are increasingly making ESG a priority. In fact, 70% of public sector organizations are already responding to ESG expectations, and 61% indicate sustainability is the top priority over the next 5 years. https://www.globalprivatecapital.org/app/uploads/2017/10/EMPEA-Brief_ESG-in-Infrastructure.pdf

Additional thoughts about the relationship of infrastructure construction and ESG follow:

E: ESG in public infrastructure emphasizes environmentally sustainable practices, such as constructing and operating infrastructure with a reduced environmental footprint, utilizing renewable energy sources, and implementing waste reduction and recycling programs. ESG encourages the incorporation of climate change considerations into infrastructure planning and development, ensuring that projects are resilient to climate-related challenges like extreme weather events and rising sea levels.

S: ESG in public infrastructure emphasizes engagement with and responding to the needs and concerns of the communities impacted by infrastructure projects. This means equitable distribution of benefits and opportunities across diverse demographic groups, addressing issues like access to services and economic opportunities. Ensuring the health and safety of the public during the construction, operation, and maintenance of infrastructure is a critical social aspect of ESG.

G: ESG promotes transparent decision-making processes and the active involvement of stakeholders in governance. There are both formal and informal systems of governance, and both exert a powerful control over the success of a system change. Formal governance includes legislation, regulation, codes and standards, taxation and incentives, and inclusion of fair labor and fair contracting practices. Public infrastructure projects should be developed and managed with clear accountability structures, community engagement, ethical practices, and financial transparency. Adherence to laws and regulations concerning public infrastructure, along with ensuring compliance with international standards and best practices, is a key aspect of governance within the ESG framework. Forms of governance need to align with planning, design, construction, operation and maintenance including life cycle asset management if the infrastructure systems are to function and be used as intended.

Figure 10: Schematic of ESG Targets Linkages to the UN SDGs (from https://www.berenberg.de/fileadmin/web/asset_management/news/esgnews/SDG_understanding_SDGs_in_sustainable_investing.pdf)

It should be clear that the underground construction industry must work ensure that the underground is fully considered in ESG-driven decisions regarding future investments in existing infrastructure or new projects. This is made very clear in the QII (Quality Infrastructure Investment) Principles, developed by the G-20 with the goal that countries pursue infrastructure investments that maximize the economic, social, environmental, and development impact of infrastructure—the foundation for achieving sustainable, resilient, and inclusive growth (https://www.worldbank.org/en/programs/quality-infrastructure-investment-partnership/qii-principles).

The Principles call for owners, constructors, designers, financiers to achieve the following:

1. Maximizing the positive impact of infrastructure to achieve sustainable growth and development
2. Raising economic efficiency in view of life-cycle cost
3. Integrating environmental considerations in infrastructure
4. Building resilience against natural disasters
5. Integrating social considerations in infrastructure investment
6. Strengthening infrastructure governance

One example is the work of Thomas (2022) who indicates that tunnels could be soon be built with carbon footprints which are substantially lower than today and in line with the overall goals of reducing Green House Gas (GHG) emissions by 30 to 40%. Accounting for embodied carbon creates a baseline – a budget – which can be driven downwards in the same way that project teams seek to drive down the financial costs of projects.

ESG reporting is becoming more important, and the underground construction industry must do the work that will ensure that the underground is fully considered in decisions regarding future investments in existing infrastructure or new projects. Many consultant have developed formats for reporting (e.g., Deloitte, Position Green, Ernst and Young). As of 2023, 29 countries and territories maintain some degree of mandatory ESG disclosure regulation (https://www.azeusconvene.com/esg/articles/the-global-state-of-mandatory-esg-disclosures). At the end of 2023, the European Commission adopted ESG mandatory standard reporting requirements, and enactment of that law applies to all 27 member countries with the first report produced in 2025. The U.S. Securities and Exchange Commission recently announced that ESG accountability will be an important requirement and that its conditions should be monitored (https://www.sec.gov/securities-topics/enforcement-task-force-focused-climate-esg-issues). To mitigate ESG risks, there is a call for additional regulatory governance of infrastructure projects, and mandatory reporting, to test that declarations of sustainability are accurate. Full and consistent infrastructure project disclosure of ESG performance will be mandated for any project implementation that purports to be ESG compliant. This means that tangible project environmental impacts are identifiable and auditable.

Making the urban infrastructure systems more resilient and sustainable is a genuine ‘wicked problem’ (https://www.stonybrook.edu/commcms/wicked-problem/about/What-is-a-wicked-problem) with the themes within the ‘E’, ‘S’ and ‘G’ all strongly interrelated. Working on ESG requires a systems approach, with governments encouraging greater innovation around ESG in infrastructure.

Public infrastructure projects and governance need to strike a balance among environmental, social, and governance factors to create infrastructure that is sustainable, beneficial for the community, and well-managed in the long term. Incorporating ESG principles into public infrastructure governance can have several benefits:

- Enhancing long-term sustainability and resilience of public infrastructure.
- Attracting responsible investments by demonstrating a commitment to sustainability and social responsibility.
- Improving public perception and trust by actively involving the community and addressing their concerns.
- Encouraging innovation and advancements in technology that align with environmental and social goals.

3.3 Contracting and Finance for Infrastructure

What does ESG Imply for underground resources and infrastructure financing? The role of infrastructure as a catalyst for sustainable growth and as an enabler of the energy transition is increasingly clear. But the global infrastructure financing gap – the difference between infrastructure needs and investment – is anticipated to reach US$15 trillion by 2040 (https://outlook.gihub.org/). This gap cannot be reconciled by public funding alone.

The World Economic Forum (WEF) has produced a white paper (WEF, 2024) acknowledging this, and that public-private partnerships (PPPs) are needed to address project challenges that no one party can tackle alone. This includes developing new financing and insurance mechanisms to de-risk resilience, and setting up the PPP organization to promote collaborations.

An interesting McKinsey web article ((McKinsey, 2024) notes that: “Rapid technology advances, growing stakeholder complexities, and evolving societal and environmental issues are just some of the factors reshaping the infrastructure industry. With traditional approaches now outdated, infrastructure CEOs have to adapt—and fast. What made infrastructure CEOs successful in the past will no longer suffice: communication skills outweigh construction skills, public credibility is more important than ever, and ambition must be balanced with strategy.” They also note the increased scrutiny of the public and media, and that the increased flow of private capital has led to bigger and more complicated projects that can only be accomplished by joint ventures (JVs) and other contracting mechanisms.

A new academic program at George Washington University pertains – the program is titled "ESG & Infrastructure" and it is housed in the School of Business in the Institute for Corporate Responsibility (https://business.gwu.edu/esg-infrastructure-initiative). The vision states "Our vision is the transformation of infrastructure development where sustainable infrastructure is the norm, promoting environmental leadership, social well-being, and strong governance. Through innovation, collaboration, and a relentless commitment to sustainability, we strive to create a resilient and inclusive infrastructure landscape that meets the needs of present and future generations, while safeguarding the planet and fostering prosperous communities."

Once the likely immediate and future benefits, and any risks associated with their delivery, have been established, alternative business models can be considered. Governments have long been the traditional drivers of social and economic development in our communities — particularly through infrastructure and construction - but ESG is now driving innovation and environmental sustainability in infrastructure system design, construction and operation. Private sector infrastructure players (including private finance) are also connecting into this movement — and alternative contracting methods like Build-Operate-Transfer (BOT), Alliancing and PPPs are becoming the norms. These approaches encourage longer-term thinking at the outset of projects — helping to build stronger business cases and strategies — all linked to the desired ESG impacts a project can have on its communities.

3.4 THE ENERGY TRANSITION AND ENERGY STORAGE

The use of renewable energies will be increasingly necessary to reduce carbon dioxide emissions. As noted by Barlo and Insana (2023), an important contribution can be provided by energy tunnels, citing the example work at Politecnico di Torino which led to the development of an innovative energy segment of an energy tunnel. In an urban region, there is a clear possibility of integration with district heating systems and the possible creation of local heat distribution networks directly connected to the underground infrastructure.

Climate change impacts will be important as well. For example, Rotta Loria (2023) reports on "The Silent Impact of Underground Climate Change on Civil Infrastructure." He studied the underground thermal changes causing a "subsurface heat island" effect in Chicago. The predicted thermally-caused deformations could be sufficient to cause building foundation settlement and tilting, and damage to underground physical infrastructure. Such underground heat island effects have also been documented in London (Greenham et al., 2023) and in Osaka, Japan (Benz et al., 2018).

There is certainly continued consideration of underground placement of hydroelectric or pump-storage facilities, whether at small scale or at large scale (e.g., Sarmast et al., 2023). Of particular interest could be community-scale compressed air energy storage (CAES, or CAEG for Geostorage). The schematic in Figure 11 was developed by Maurice Dusseault (U. of Waterloo) in Canada to provide >10 MWh energy storage systems for larger cities and grid applications. The Canadian concept (undergoing patenting) is to use oil drilling technology to make about 12 in. ID steel-cased wells. The process can also be made adiabatic with capture of the heat during compression and using the heat to increase the temperature of the intake to the turbines. However, such a system could be used for off-grid distributed energy storage for single users (perhaps in remote locations) or towns. Such CAES storage could be incorporated into renewable schemes, e.g., the foundations of wind turbines or with distributed solar farms.

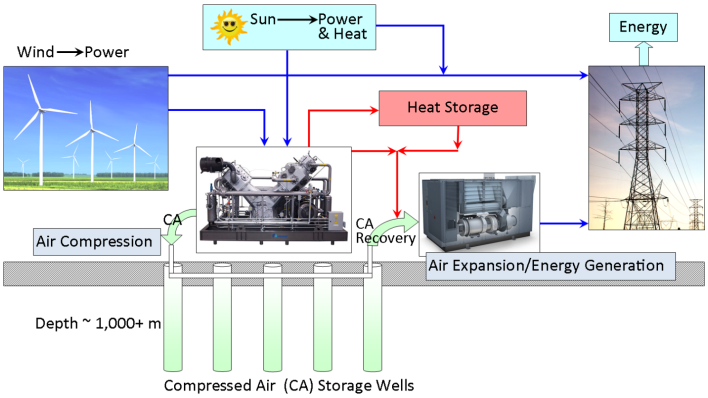

Figure 11: Schematic for Vision of CAES Wells as Flexible Energy Geobatteries for Renewable Energy.

There are also current discussions about converting closed mines into larger capacity geostorage for energy (Schmidt et al., 2020). This would require consideration for the effects of cyclic loading on the geomechanical performance of underground compressed air energy storage systems. A broad consideration of the types of underground energy storage chamber being considered include the following (King et al. 2021):

- Aquifer storage, the air is injected into a permeable rock displacing water and capped by a cap rock
- Lined rock cavern, a specifically excavated chamber then lined with a material to ensure hermeticity
- Depleted gas reservoir, reservoir previously used for gas tapping or storage, can be permeable or semi-permeable rock type.

As early as 2008, another concept has being developed at the University of Nottingham in the UK (https://web.archive.org/web/20110203142906/http:/www.nottingham.ac.uk/news/pressreleases/2008/june/energybagsandsuperbatteries.aspx). This work involves the futuristic perspective of using nanotechnology to develop an electrical energy storage system based on power electronics and a new energy storage device called a "supercapattery," which combines the benefits of a supercapacitor and a battery. It would be constructed from carbon nanotubes chemically engineered with traditional battery materials. Another idea being pursued is using renewable power to compress and pump air into underwater bags anchored to the seabed. The possibility of using such a system in any flooded underground opening (including an abandoned or closed mine) is an apparent addition to their thinking. A start-up company (Hydrostor) is developing and deploying systems that use a similar concept https://hydrostor.ca/.

3.5 ZERO WASTE AND THE CIRCULAR ECONOMY

Mining is a dynamic industry, constantly subject to market forces, supply and demand trends, regulatory changes and stakeholder expectations. These present collaborative economic transformation options that are separate from the mine site. Mining companies are considering how all aspects of operation including closure can add value for the community, including research into how to leave the land and associated natural resources suitable for repurposing.

For the mining industry, perhaps the biggest risk identified by many mining companies is the management of water and solid mining wastes (tailings and waste rock). The estimated worldwide generation of solid mining wastes (tailings and waste rock) is > 100 billion tonnes each year. These huge volumes of tailings will increase in the future due to lower-grade ores and rising societal demand. The world has more than 30,000 existing active, inactive, and legacy tailings storage facilities (TSFs). Despite improvements in safe design for TSFs, there have been reported failures every year for the past 30 years.

The world is moving away from the linear economy of the past (take, make, use, dispose, and waste). But in most discussion of the circular economy, the mining industry and its operations are placed outside of the circular economy, kicking in raw materials as is needed. Most mining companies are really not engaged in the circular economy, or thinking about taking responsibility for design, manufacture, consumption, reuse and recycling. Circular economic principles can be applied to mining operations (mine to mill) and to downstream waste management in a way that considers the geometallurgical flow of materials (Nelson and Spiller, 2021; Nelson, 2023). We can modify the wastes waste stream to actually produce high-value products (Nelson, 2022).

Green mining is avoiding/preventing preventing the generation of any extractive waste. As is summarized by the NEMO project, there are many benefits of reduced waste volumes and downstream production of new materials (https://h2020-nemo.eu/), including value recovery, avoiding future environmental problems, enhanced social license, ability to get projects permitted, and lower reclamation costs and increased likelihood of successful closure. In the discussion that follows, only the development of new materials from tailings and mine waste will be considered.

Traditional construction is commonly cement-based, such as concrete and some mortars. Concrete is the second most-consumed substance on Earth, after water, and the manufacture of concrete involves billions of tons of feedstock, with a use rate at >5 tons of concrete per person per year globally. By 2050, concrete production is expected to be four times higher than in 1990.

The manufacture of cement is a major cause of greenhouse gas emissions (Balaji et al., 2017), and about 10% of the global emissions of CO2 are due to construction materials production (Kappel et al., 2017). By 2025, around 3.5 billion tons of carbon dioxide is anticipated to be released into the atmosphere during cement production. Cement contents and raw materials could be fully or partially replaced by eco-friendly secondary resources with lower embodied energy. Experience indicates that such substitutions should be taken with caution as mining wastes may contain harmful compounds, such as heavy metals that may leach (Candeis et al., 2013). Strategies to remove or neutralize these elements are also important to optimize the use of mining residues with different compositions.

Silica and alumina are relevant elements for the production of construction products, and pozzolanic activity of the natural pozzolans is closely interrelated with their content of reactive silica. When submitted to a relatively low thermal treatment, silica and alumina state may change to an amorphous form and acquire pozzolanic reactivity, enabling the development of different construction products by partial conventional binder replacement. Geopolymers are a class of inorganic polymers which have an amorphous structure of [SiO4] and [AlO4], generally produced by mixing a raw aluminosilicate source in the form of a powder with an alkaline silicate solution followed by curing. Geopolymerization may be a key factor to stabilize hazardous compounds in mixtures with mining residues, avoiding leaching problems. Lightweight geopolymers (aka geofoams) have been developed that can be 3D-printed, and/or marketed for facility insulation.

Naturally formed geologic melts abound, in their cooled form as igneous rocks such as basalt. Re-melting of rocks, and subsequent controlled cooling for forming a solid with desired properties, is a relatively recent concept. For example, the recorded history of melting basalt rock and manufacturing glass fiber from the melt dates back to 1922 (US Patent US1438428), and additional development occurred during and after World War II. Much of the activity during the Cold War period occurred in the Soviet Union, with fibers pulled from basalt melts being investigated for aerospace and military purposes, including insulation and textile applications (Acar et al., 2017). After the dissolution of the Soviet Union, basalt fibers began to be produced and used on a commercial scale as the research was declassified, with the primary locus of fiber production being in Ukraine. Several research groups are focused on using mine tailings as the feed to be melted and turned into glass fibers, reinforcing bars as a no-corrosion substitute for steel in concrete, reinforcing fibers for shotcrete, and rock wool (Nelson et al., 2021). By this and many other processes under investigation, the goal of zero waste from mining, and the by-production of useful and valuable materials is not beyond the bounds of reality.

4 >> Addressing Underground Risks

4.1 OVERVIEW OF EXISTING AND FUTURE RISKS (AND OPPORTUNITIES)

There are many risks associated with underground construction, and with the operation of underground facilities. Many of these are chronic, meaning that they have been encountered for many years to the present, and implying that the industry needs to address them.

These sources of risk include many dealing with planning, policy and financing/contracting. The lack of the availability of uniform planning, design and reporting guidelines including environment and social/equity metrics in planning will impact on ESG issues, and the need to consider carbon footprints in design and construction will become an increasing risk in the future. The general rising costs of underground construction, including equipment costs incurred in trying to avoid or minimize risks, and the rising costs of materials (and their carbon footprints) and labor are potential problems that need to be handled differently in the future.

Regarding rising costs, Goldwyn et al. (2023) report on major drivers on the high costs for transit projects in the US, in particular:

- Standardization reduces design and soft costs. Agencies that follow consistent national or international standards for design and construction build projects cheaper and quicker than agencies that turn to bespoke solutions for every project element.
- Cities should be willing to tolerate somewhat more surface disruption to get construction done more quickly.
- Agencies that prioritize value engineering and in particular build right-size stations using conventional techniques have lower station construction costs than those that mine palatial stations with plenty of excess space.

Risks in the future will extend beyond design and construction methods. As one example of ESG risks, cement production and concrete use alone is estimated to account for 4 – 8% of global GHG emissions. On the social impact side, large infrastructure projects often involve disputes over rights of way or land use conversion that give rise to environmental justice concerns (e.g., pipeline or transmission projects across native lands; easements or eminent domain actions in disadvantaged urban neighborhoods). An organization undertaking large construction projects may perceive unique ESG risks associated with materials supply, focusing on everything from conflict-free sourcing and fair labor practices to use of sustainable materials.

There are also chronic problems associated with spatial referencing and location of existing infrastructure components, widely varying age and conditions of parts of systems, uncoordinated maintenance scheduling and costs, and the "last mile" – connections between the main infrastructure lines and those serviced that are largely charged to the individual public and that are a significant reason for stakeholder dissatisfaction. It is likely that digitalization and production of digital twins will be of use for this in the future.

In terms of future performance over the long-term, increasing introduction of automation and robotics should be expected, perhaps bringing new and different risks. Alternatives to the continued use of cementitious materials (e.g., shotcrete, concrete) with a significant carbon footprint need to be developed. Deterioration of materials over time must be monitored for "old" and "new" materials, and the rates of performance loss with time in service need to be quantified and integrated into performance assessment and asset management systems. The industry also has the opportunity to consider methods for more efficient replacement of aging infrastructure, and potential repurposing options for previous infrastructure investments.

There are cyber-opportunities as well. Virtual reality (VR) simulations provide training environments for gaining experience under realistic conditions without being exposed to any real hazard. In addition, VY can serve as a tool to expedite the decision-making process where quick decisions and actions are necessary for a safe operation. A typical example in tunneling is assessing hazards in a newly blasted tunnel face. Ground support systems must be installed based on stability as embodied in the stand-up time to ensure the safe access of personnel and equipment to the working area. A VR environment can be designed for improving the decision-making skills and enhancing communication with experienced people not present regarding failure types and support measures in real-world situations under several constraints such as time, visibility and proximity (Isleyen et al., 2019).

4.2 CHRONIC GEOTECHNICAL RISKS

A majority of the risk associated with underground infrastructure construction and performance is derived from the spatial variability and uncertainty associated with geologic conditions, including soil, rock and water. Design in the underground is best accomplished by anticipating materials, behavior and properties needed for intelligent analysis and construction in the underground. The greatest risk for most underground project success is derived from lack of geologic knowledge or improper interpretation, including uncertainty about groundwater, and about spatial material and property distributions. The greatest risk for long-term performance is uncertainty about as-built construction, and uncertainty concerning time-dependent behavior. What is warranted is a "Grand Campaign" to provide the knowledge base to address these risks. Four areas of focus are discussed below.

4.2.1 New technologies and methods

The underground industry has many methods that can be applied including Tunnel Boring Machines (TBMs) and shields, and the newer slurry, earth pressure balance and hybrid pressure-face equipment. The excavation and support of shafts has not seen such a benefit from new technology, and the risks of shaft excavation remain unacceptably high (and perhaps increasing). More developments are needed to decrease costs, and improve safety (e.g., avoid hyperbaric cutter replacements and other interventions). The seemingly inexorable trend is for larger and larger diameters, and this by itself drives up project costs and expands project schedule.

Many of our infrastructure projects are designed for low first cost and to comply with right-of-way limitations. Such systems are not necessarily designed for long-term sustainability and maintainability. Engineers must seek new materials and technologies to reduce construction risks and to enhance performance and durability of our infrastructure systems, new and old. In addition, new technologies must not be just implemented – they must be assessed for short and long-term performance. Sober assessment of long-term performance is very often forgotten in the cycle of innovation we seek for the underground industries.

4.2.2. Better subsurface characterization

Spatial and temporal variations in subsurface materials and conditions continue to be a risk. Knowledge of the underground conditions has been improving over past decades, but the combination of continuing sore points and arising new difficulties must be considered in planning. In many urban environments, previous underground works have demonstrated spatial and material property distributions that should be acknowledged and respected by wise and experienced owners, so that our conventional site investigations should become confirmatory rather than exploratory.

Many geologic issues continue to be encountered and have problematic impacts like a thorn in the side, such as shallow cover and weathered rock, progressive deterioration, piping, and caving. Ground loss consequences include construction settlement, subsidence, impact on structures, consolidation with water table changes, and differential settlement associated with a varying depth to top of rock. These are perhaps the “low-grade infections” in comparison to the “high fever” of geoproblems that cause extensive stoppages. In addition, there is a growing overreliance on (and misuse of) rock mass ratings - RQD on steroids. The industry should take a fresh look at integrating geophysical and remote sensing methods. Engineers should also rethink materials and methods in use. For example, engineers and contractors should revisit and dramatically improve our “old” or “conventional” technologies such as drill/blast operations.

Geological and Geotechnical Engineers still wrestle with scale effects as well, extrapolating from lab behavior to full scale in the field. Many rock mass rating systems have been developed. On a large number of projects, ratings applications have been uninformed and inconsistent, and there have been only limited attempts to validate their inference, or the use of a large number of empirical correlations. This observation also can be applied to the plethora of computational models available for subsurface design. We must make opportunities to validate design assumptions and performance prediction. This is the era of information: with an expansion in sensing and measurement capabilities, how should the entire site investigation and construction process be re-thought, not to mention real-time data flows and their importance to effective management for resilience of urban infrastructure systems.

More urban infrastructure will necessarily be placed deeper, and the in situ stress state will likely become more important on more projects. Estimation of an in situ stress field is challenging without a clear geologic framework for interpretation, and most stress assessments are made as point measurements (interpretation of deformation measurements at a point). This can only be addressed by obtaining a better understanding of the spatial variability of rock mass structured which introduces uncertainty. The variety of excavation shapes and dimensions can be expected to vary in the future, with more gallery space rather than plane strain tunnels needed, making the predictions of displacements, strains and stress redistribution around an underground opening increasingly important. We also need to understand spatial and temporal variations that affect performance of existing facilities for sustainable design and operations.

4.2.3 Better management of water

The presence of water in the subsurface changes the behavior of many materials, and strongly influences the long-term performance of underground facilities. Full consideration of the influence of water includes knowledge and understanding of volume, flow rate, quality, pressure, and changes over time. On many tunnel projects, water is encountered but few of these parameters are assessed or evaluated for spatial variability unless a claim is anticipated. Such observations and measurements are required if we are to significantly reduce the impact of water. Research is also needed on the relationship between fracture mechanical aperture and hydraulic aperture with consideration for rock type and geologic regime, diagenesis, discontinuity fillings, normal stress and shear stress along and across fractures.

Some of the most active areas of new technology implementation have been related to the introduction of waterproofing into tunnel linings. The long-term performance of such installations needs to be assessed on a continuing basis. Operational impacts of seepage and inflows are incredibly important since water drives long term deterioration in the underground, and inflows can cause piping and ground loss that affects lining performance and also structures nearby. The long-term performance of waterproofing or drainage management technologies is not well documented.

4.2.4 Risk awareness, assessment and management

Many underground construction projects in the US now use the three-legged stool of a Disputes Review Board (DRB) requirement for bid documents to be escrowed, and the development of a Geotechnical Baseline Report (GBR) as a part of the contract documents explicitly developed for subsurface risk management. A good GBR is thoughtfully written to present a baseline of expected subsurface conditions, and or “geoproblem event” frequency (temporally and spatially) to be assumed during a project. The project data collected informs designers and contractors as to behaviors and properties of geologic materials, but a statistical assessment of the probability and consequences of encountering major geotechnically-driven stoppages in underground excavations is difficult – and yet such events are the main causes of major problems on underground construction projects. In addition, thoughtful owners should be encouraged to invoke methods of a priori (preconstruction) ground improvement, instead of leaving known or suspected risks to be encountered and managed (or mismanaged) by the contractor.

The industry as a whole should commit to building a geologically-framed data base that includes spatial information about soil and rock mass variability and impacts in a geologic context. Such a data resource can inform regarding likelihood of major "geoproblems" being encountered and how, for different construction means and methods, the problem conditions may be best managed. The data and information needed include:

- Type of geoproblem event
- Means and methods of excavation and equipment
- Ground and water control
- Spatial frequency: length of each encountered problem, and distance between events
- Temporal frequency: hours to handle, and time between events
- Agility and performance of the contractor in responding to each geoproblem event

The framework of geologic inference and analysis opens the prospect for real predictability of geotechnical event with extreme impact on a project.

4.2.5 Summary of Actions for Risk Reduction in Underground Construction

A brief listing that summarizes thoughts expressed in this paper regarding actions to be taken for risk reduction in underground construction includes the following as a summary:

- Rethink materials and methods.
- Advance methods and expand budgets for subsurface characterization.
- Extend applications for pre-construction ground improvement methods.
- Improve framework for understanding risk and spatial variability of geologic conditions.
- Improve understanding of assessment and redistribution of in situ stress.
- Focus on validation of computational models.
- Manage underground risks by construction operations rather than by "bullet-proof" equipment that is more expensive.
- Improve "old" excavation methods including drill/blast.
- Advance and incentivize new innovative technologies and methods.
- Advance knowledge about how the underground can minimize risks from extreme events.
- Develop and communicate a new understanding of urban underground design (and architecture) for the public.

5 >> Closure

The assertions of underground urbanism (Nelson, 2020) may be summarized as: 1) the effective and integrated use of underground space is vital in a world where the majority of the population lives in urban areas, including in increasing numbers of megacities, and 2), the use of urban underground resources can contribute to the sustainability and resilience of the urban environment. maintaining the quality of life and preparing the world for the impact of climate change.

The future will bring great innovation in the way infrastructure and its associated land uses are planned, the objective being to deliver social, equity and economic impacts through innovative construction and sustainable and just land use. The underground construction industry needs to equip decisions makers with the tools needed to value the costs and benefits associated with existing and new buried infrastructure that properly takes account of financial resources, carbon resources and social value across longer time scales and over as wide as possible system boundaries.

Planning and making decisions about urban infrastructure is complicated by their scale, expense, and long-lasting nature and by the multiple stakeholders and criteria that must be addressed. Infrastructure's long-time horizon exceeds the length of election cycles, and city managers are often working with outdated or inaccurate data. Designing sustainable infrastructure requires consideration of technical expertise, project and budget planning, equity and the level of community disruption, environmental impacts, and engagement and governance. Making decisions about infrastructure projects is, therefore, difficult both technically and politically.

Decision making is further complicated by the multiple stakeholders affected by infrastructure projects and the environmental, economic, and social impacts that must be considered. The results of past decisions, which did not adequately consider these factors, have often exacerbated the very problems they had sought to solve.

The flows of goods and services produced by infrastructure systems enable all other forms of economic and societal activity, create multiplier effects and ultimately enable the emergence of outcomes that simply would not occur in their absence. Ensuring that the type of outcomes enabled by infrastructure systems, and the qualities these outcomes possess are closely aligned with long term societal priorities (i.e. are equitable, inclusive, fair, affordable, healthy, secure, resilient), is a profoundly significant challenge. Attempting to do so in the context of climate change will drive the industry to reduce its own GHG emissions to net zero (a net zero system), and to reduce the GHG emissions from the activities, supply chains, households, communities, places, societies and economies it enables (a net zero enabling system).

In summary, while the construction and maintenance of buried urban infrastructure is associated with significant carbon emissions there is also the potential to use that infrastructure to help reduce carbon emissions in other sectors as long as we take a broad enough and long enough view of the both the costs and the benefits and we fully account for social value outside of any individual projects. The more value we take from infrastructure, the more important the system resilience becomes, and developing the methods needed to value that resilience and balance carbon costs and benefits will be only more important in the future.

>> Acknowledgements & References

The author thanks the leadership of ITA for review of this article during preparation. In particular Ms. Sanja Zlatanic, ITA Executive Council, provided very useful input and her contributions are appreciated.

Acar, V., F. Cakir, E. Alyamac, and M. O. Seydibeyoglu. 2017. "Basalt Fibers." Chapter 8 in Fiber Technology for Fiber-Reinforced Composites. Elsevier http://dx.doi.org/10.1016/B978-0-08-101871-2.00008-4

Admiraal, H. and A. Cornaro. 2020. "Future cities, resilient cities – The role of underground space in achieving urban resilience." Underground Space 5, 223–228. https://doi.org/10.1016/j.undsp.2019.02.001

Ayyub, B. M. 2014. "Systems resilience for multihazard environments: definition, metrics and valuation for decision making." Risk Anal. 34 (2), 340–355. https://doi.org/10.1111/risa.12093

Balaji, M., S. Dillip Sharma, A. Vigneshwaran, and K. Fayaz Ahamed. 2017. "Experimental study on the behavior of self compacting self cured concrete using chemical admixtures and metakaolin." International Conference on Emerging Trends in Engineering, Science and Sustainable Technology (ICETSST-2017).

Barlo, M. and A. Insana. 2023. "Energy tunnels as an opportunity for sustainable development of urban areas." Tunnelling and Underground Space Technology 132. https://doi.org/10.1016/j.tust.2022.104902

Benz, S., P. Bayer, P. Blum, H. Hamamoto, H. Arimoto, and M. Taniguchi. 2018. "Comparing anthropogenic heat input and heat accumulation in the subsurface of Osaka, Japan." The Science of the Total Environment. DOI:10.1016/j.scitotenv.2018.06.253

Candeias, C., R. Melo, and P. F. Avila. 2013. "Heavy metal pollution in mine-soil-plant system in S. Francisco de Assis - Panasqueira mine (Portugal)." Appl. Geochem. 44 (2013) 12–26, https://doi.org/10.1016/j. apgeochem.2013.07.009

Cao, M. and R. Hickman. 2019. "Urban transport and social inequities in neighborhoods near underground stations in greater London." Transportation Planning and Technology, , 42:5, 419-441, DOI: 10.1080/03081060.2019.1609215

Carpenter, S. R., and C. Folke. 2006. Ecology for transformation. Trends in Ecology & Evolution 21(6):309-315. doi. org/10.1016/j.tree.2006.02.007

Chang, S. E., T. McDaniels, J. Fox, R. Dhariwal, and H. Longstaff. 2014. " Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments." Risk Analysis, Vol. 34, No. 3. DOI: 10.1111/risa.12133

Clark, W. C., and N. M. Dickson. 2003. Sustainability science: the emerging research program. Proceedings of the National Academy of Sciences of the United States of America 100 (14):8059-8061. http://dx.doi.org/10.1073/pnas.1231333100

Cui, X. et al. 2022. "Construction and optimization of ecological security patterns based on social equity perspective: A case study in Wuhan, China." Ecological Indicators. 136. https://doi.org/10.1016/j.ecolind.2022.108714

European Commission. 2023. "How the EU delivers on a social Europe that is fair, inclusive and full of opportunity." https://ec.europa.eu/regional_policy/whats-new/panorama/2023/01/01-04-2023-how-the-eu-delivers-on-a-social-europe-that-is-fair-inclusive-and-full-of-opportunity_en retrieved February 16, 2024.

Folke, C. S. R., R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockstrom. 2010. "Resilience thinking: integrating resilience, adaptability and transformability." Ecology and Society 15(4):20. http://www.ecologyandsociety.org/vol15/iss4/art20

Goldwyn, E., A. Levy, E. Ensari and M. Chitti. 2023. "Transit Costs Project: Understanding transit infrastructure costs in American cities." Final Project Report, New York University, Marron Institute of Urban Management. https://transitcosts.com/Final-Report/ retrieved February 16, 2024.

Greenham, S., E. Ferranti, R. Powell, K. Drayson, and A. Quinn. 2023. "The impact of heat on London Underground infrastructure in a changing climate." Weather. June 2023, Vol. 78, No. 6.

Hunt, D. V. L., L. O. Makana, I. Jefferson, and C. D. F. Rogers. 2016. "Liveable cities and urban underground space." Tunnelling and Underground Space Technology 55 (2016) 8–20. http://dx.doi.org/10.1016/j.tust.2015.11.015

Institute for Sustainable Infrastructure (ISI). 2018. "Envision: Sustainable Infrastructure Framework Guidance Manual." Institute for Sustainable Infrastructure, Washington, D.C. https://sustainableinfrastructure.org/wp-content/uploads/EnvisionV3.9.7.2018.pdf

Isleyen, E., S. Düzgün, and P. P. Nelson. 2019. "Virtual Reality Models for Hazard Assessment and Risk Mitigation in Tunneling", 2019, Proceedings, World Tunnelling Conference, Naples, Italy,

ITA. 2002. "Why Go Underground?" A booklet produced by ITA. https://tunnel.ita-aites.org/en/why-go-underground, retrieved February 16, 2024.

ITA. 2023. "Urban Problems, Underground Solutions. Underground Urban Space for Resilient Cities." Working Group 20, ITA Report No. 32, April. ISBN:978-2-9701670-1-3

King, M., A. Jain, R. Bhakar, J. Mathur, and J. Wang. 2021. "Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK." Renewable and Sustainable Energy Reviews 139. https://doi.org/10.1016/j.rser.2021.110705

Klaassen, L. and B. Steffen. 2023. "Meta-analysis on necessary investment shifts to reach net zero pathways in Europe. Nat. Clim. Chang. 13, 58–66 (2023). https://doi.org/10.1038/s41558-022-01549-5

Kunreuther, H., E. Michel-Kerjan, and G. Tonn. 2016. "Insurance, Economic Incentives and other Policy Tools for Strengthening Critical Infrastructure Resilience: 20 Proposals for Action." Center for Risk Management and Decision Processes, The Wharton School, University of Pennsylvania.

Lapenna, V. 2017. "Resilient and sustainable cities of tomorrow: the role of applied geophysics." Bollettino di Geofisica Teorica ed Applicata Vol. 58, n. 4, pp. 237-251; December. DOI 10.4430/bgta0204

Li, R. and Y. Gao. 2022. "On the component resilience importance measures for infrastructure systems." international journal of critical infrastructure protection 36. https://doi.org/10.1016/j.ijcip.2021.100481

Li, H.-Q., A Parriaux, P. Thalmann, and X.-Z. Li. 2013. "An integrated planning concept for the emerging underground urbanism: Deep City Method Part 1 concept, process and application." Tunnelling and Underground Space Technology 38 (2013) 559–568. http://dx.doi.org/10.1016/j.tust.2013.04.010

Luo, Y., A. Alaghbandrad, T. K. Genger, and A. Hammad. 2020. "History and recent development of multi-purpose utility tunnels." Tunnelling and Underground Space Technology 103. https://doi.org/10.1016/j.tust.2020.103511

Makana, L. O., I. Jefferson, D. V. L. Hunt and C. D. F. Rogers. 2016. "Assessment of the future resilience of sustainable sub-surface environments." Tunnelling and Underground Space Technology 55, pp. 21-31. http://dx.doi.org/10.1016/j.tust.2015.11.016

Martinez, E., J. Hernandez, T. Rodriguez-Nikl, and M. Mazari. 2018. "Resilience of Underground transportation infrastructure in coastal regions: A case study." Chapter in the proceedings of the International Conference on Transportation and Development, ASCE. https://ascelibrary.org/doi/10.1061/9780784481561.022

Mavrikos, A. and D. Kaliampakos. 2021. "An integrated methodology for estimating the value of underground space." Tunnelling and Underground Space Technology 109. https://doi.org/10.1016/j.tust.2020.103770

McKinsey. 2024. "The Changing Role of the infrastructure CEO." https://www.mckinsey.com/capabilities/operations/our-insights/global-infrastructure-initiative/voices/the-changing-role-of-the-infrastructure-ceo?cid=eml-web retrieved February 16, 2024.

Meerow, S. and J. P. Newell. 2019. "Urban resilience for whom, what, when, where, and why?" Urban Geography, 40:3, 309-329. https://doi.org/10.1080/02723638.2016.1206395

Melo Zurita, M. de L. 2020. "Challenging sub terra nullius: a critical underground urbanism project, Australian Geographer. https://doi.org/10.1080/00049182.2020.1723829

Nelson, P. P. 2022. «The Future of Tailings Management,» Chapter 17 in the Tailings Management Handbook: A Life-Cycle Approach, SME, pp. 277-316, Society for Mining, Metallurgy and Exploration, Inc.

Nelson, P. P. 2016. "A framework for the future of urban underground engineering." Tunnelling and Underground Space Technology 55 (2016) 32–39. http://dx.doi.org/10.1016/j.tust.2015.10.023

Nelson, P. P. 2020. "Underground Urbanism in the U.S." Proceedings of the Associated Research Centers for the Urban Underground Space (ACUUS) 2020 Virtual Conference.

Nelson, P. P. 2023. "New Directions for Tailings Management." Tailings and Mine Waste Conference Proceedings, Victoria, British Columbia.

Nelson, P. P. and S. Düzgün. 2018. "Assessing Resilience Impacts from Integrated Above-and Blow-Ground Urban Infrastructure," Proceedings, World Tunnel Congress, International Tunnelling Association, Dubai.

Nelson, P. P. and D. E. Spiller. 2021. "Future of Tailings Management.» Tailings and Mine Waste Conference, Banff, Canada.

Nelson, P. P. and R. L. Sterling. 2012. "City Resiliency and Underground Space," Associated Centers for the Use of Underground Space (ACUUS) Conference, November 2012, Singapore.

Nelson, P. P., Sridhar, S. and K. Pfaff, K. 2021. "Glass from Mine Waste and Tailings," Proceedings of the American Rock Mechanics Symposium. ARMA 21-1299.

Neuman, M. 2020. "Infrastructure is key to make cities sustainable." Sustainability 2020, 12, 8308; https://doi.org/10.3390/su12208308

Pandey, S. J. and A. M. Sadri. 2022. "Critical Review of Sustainability, Resilience, and Their Unifying Assessments for Civil Infrastructure Systems." ASCE Construction Research Congress. Infrastructure Sustainability and Resilience (288 - 298).

Paraskevopoulou, C., A. Cornaro, H. Admiraal and A. Paraskevopoulou. 2019. "Underground space and urban sustainability: An integrated approach to the city of the future." Proceedings of the International Conference on Changing Cities IV: Spatial, Design, Landscape & Socio-economic Dimensions. ISBN 978-960-99226-9-2

Pasqual, J., and P. Reira. 2005. "Underground land values." Land Use Policy 22, 322–330. doi:10.1016/j.landusepol.2004.03.005

Pasten, C., and J. C. Santamarina. 2012. "Energy and quality of life." Energy Policy 49 (2012) 468–476. http://dx.doi.org/10.1016/j.enpol.2012.06.051

Petersen, L., E. Lundin, L. Fallou, J. Sjostrom, D. Lange, R. Teixeirs, and A. Bonavita. 2020. " Resilience for whom? The general public's tolerance levels as CI resilience criteria." International Journal of Critical Infrastructure Protection 28. https://doi.org/10.1016/j.ijcip.2020.100340

Price S. R., J. R. Ford, S. D. G. Campbell, and I. Jefferson. 2016. Urban Futures: The Sustainable Management of the Ground Beneath Cities. In Eggers MJ, Griffiths JS, Parry S & Culshaw MG (eds) Developments in Engineering Geology. Geological Society, London. Engineering Geology Special Publication 27, 19–33.

Qiao, Y.-K., F.-L. Peng, S. Sabri, and A. Rajabifard. 2019. "Socio-environmental costs of underground space use for urban sustainability." Sustainable Cities and Society 51. https://doi.org/10.1016/j.scs.2019.101757

Qing, L. H., F Y. Qun, and Y. M. Jian. 2018. "Deep Shanghai project – A strategy of infrastructure integration for Megacities." Tunnelling and Underground Space Technology 81, 547–567. https://doi.org/10.1016/j.tust.2018.08.008

Raworth, K. 2017 Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist. Chelsea Green Publishing. 320 p.

Redman, C. L. 2014. "Should sustainability and resilience be combined or remain distinct pursuits?" Ecology and Society 19(2): 37. http://dx.doi.org/10.5751/ES-06390-190237

Rinaldi, S. M., J. P. Peerenboom and T. K. Kelly. 2001. "Identifying, understanding, and analyzing critical infrastructure interdependencies." in IEEE Control Systems Magazine, vol. 21, no. 6, pp. 11-25. doi:10.1109/37.969131.11–25.

Rodenbiker, J. 2022. "Social justice in China's cities: Urban-rural restructuring and justice-oriented planning." Transactions in Planning and Urban Research 2022, Vol. 1(1–2) 184 –198. DOI: 10.1177/27541223221111799

Rodriguez-Nikl, T. and M. Mazari. 2019. "Resilience and sustainability in underground transportation infrastructure: Literature review and assessment of Envision rating system." Proceedings of the International Conference on Sustainable Infrastructure, ASCE.

Rogers C. D. F., L. O. Makana, J. M. Leach, and the UKCRIC Community. 2023. The Little Book of Theory of Change for Infrastructure and Cities. University of Birmingham, UK. ISBN 978-0-70442-981-9

Rogers, C. D. F., C. J. Bouch, S. Williams, A. r. G. Barber, C. J. Baker, J. R. Bryson, D. N. Chapman, J. Coaffee, I. Jefferson, and A. D. Quinn. 2012. "Resistance and resilience – paradigms for critical local infrastructure." Proc. Inst. Civ. Eng. Munic. Eng., 165 (2) (2012), pp. 73-84.

Rotta Loria, A. F. 2023. "The silent impact of underground climate change on civil infrastructure." Communications Engineering, 2:44. https://doi.org/10.1038/s44172-023-00092-1

Sadler J.P, N. Grayson, J. D. Hale, M. G. Locret-Collet, D. V. L. Hunt, C. J. Bouch, and C. D. F. Rogers. 2018. "The Little Book of Ecosystem Services in the City." ISBN: 978-0-70442-956-7

Sarmast, S., K. Rouindej, R. A. Fraser, and M. B. Dusseault. 2023. "Sizing-design method for compressed air energy storage (CAES) systems: A case study based on power grid in Ontario." Energy Conversion and Management 277. https://doi.org/10.1016/j.enconman.2023.116656

Schmidt, F., J. Menendez, H. Konietsky, P. Pascual-Munoz, J. Castro, J. Loredo, and A. B. Sanchez. 2020. "Converting closed mines into giant batteries: Effects of cyclic loading on the geomechanical performance of underground compressed air energy storage systems." Journal of Energy Storage 32. https://doi.org/10.1016/j.est.2020.101882

Shadabfar, M. et al. 2022. "Resilience-based design of infrastructure" Review of models, methodologies, and computational tools." ASCE-ASME J. Risk Uncertainty Eng. Syst., Part A: Civ. Eng., 8(1). DOI: 10.1061/AJRUA6.0001184.

Sterling, R. L and P. P. Nelson. 2013. "City Resiliency and Underground Space Use." Keynote lecture at the 2012 ACUUS Conference, Advances in Underground Space Development, pp. 45 – 57.

Stones, P., and T. Y. Heng. 2016. "Underground Space Development Key Planning Factors." Procedia Engineering 165, 343 – 354. 15th International conference Underground Urbanisation as a Prerequisite for Sustainable Development. doi: 10.1016/j.proeng.2016.11.709

Swart, R. J., P. Raskin, and J. Robinson. 2004. "The problem of the future: sustainability science and scenario analysis." Global Environmental Change 14(2):137-146. http://dx.doi.org/10.1016/j.gloenvcha.2003.10.002

Thomas, A. H. 2022. "Achieving sustainability in tunnelling through innovation." https://www.tunnels-infrastructures.com/achieving-sustainability-in-tunnelling-through-innovation/

United Nations. 2015. Transforming our world: the 2030 Agenda for Sustainable Development. https://sustainabledevelopment.un.org/post2015/transformingourworld

United Nations. 2023. "The Sustainable Development Goals Report: Special Edition - Towards a Rescue Plan for People and Planet." https://unstats.un.org/sdgs/report/2023/

Venvik, G. 2018. "The Ground Beneath our Cities." Proceedings, The Ground Beneath Our Cities 54th ISOCARP Congress.

World Economic Forum (in collaboration with McKinsey & Company). 2024. "Building a resilient tomorrow: Concrete Actions for Global leaders." https://www.mckinsey.com/capabilities/risk-and-resilience/our-insights/building-a-resilient-tomorrow-concrete-actions-for-global-leaders?stcr=46FCDB4F43BF4B17A2CCE62818ADA40D&cid=other-eml-alt-mip-mck&hlkid=23596e964336441ba3e466856c3be4d2&hctky=12593305&hdpid=b3e8ab01-077d-4510-bc6d-d9ce0ee08017#/ retriever February 16, 2024.

Yang, Z., B. Barroca, K. Laffrechine, A. Weppe, A. Bony-Dandrieux, and N. Daclin. 2023a. "A multi-criteria framework for critical infrastructure systems resilience." international journal of critical infrastructure protection 42. https://doi.org/10.1016/j.ijcip.2023.100616

Yang, Z., B. Barroca, A. Weppe, A. Bony-Dandrieux, K. Laffrechine, N. Daclin, V. November, K. Omrane, D. Kamissoko, F. Benaben, H. Dolidon, J. Tixier, and V. Chapurlat. 2023b. "Indicator-based resilience assessment for critical infrastructures – A review." Safety Science 160. https://doi.org/10.1016/j.ssci.2022.106049

Yusta, J.M., G. J. Correa-Henao, G.J., and R. Lacal-Arántegui. 2011. "Methodologies and applications for critical infrastructure protection." Energy Policy 39, 6100–6119. doi.org/10.1016/j.enpol.2011.07.010

Layout : Shoot The Moon - 04 90 14 48 48 - (30767 - 03/2024

ITA Secretariat - c/o MIE2 – Chemin de Balexert 9 - CH-1219 Châtelaine (GE) - Switzerland
Tel. : + 41 22 547 74 41 - Email : secretariat@ita-aites.org - Web : www.ita-aites.org