US-UK TRANSATLANTIC WORKSHOP

TRANSFORMATION IN URBAN UNDERGROUND INFRASTRUCTURE

US-UK Workshop on Transformation in Urban Underground Infrastructure

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Final Report

April 12, 2024

DOI: 10.14324/000.rp.10190562

In the ground, pipes and cables reside,
Buried deep, from our view they do hide.
Though they’re hidden away,
They work night and day,
Bringing services we need, far and wide!

Limerick generated by ChatGPT3.5 on 29 September 2023 using prompt:
“Give me a limerick on buried infrastructure”

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Executive summary

With support from the United States (US) National Science Foundation (NSF) and the United Kingdom Research and Innovation (UKRI), a joint US-UK transatlantic workshop brought together internationally-leading infrastructure scholars and experts to consider the big questions, identify major gaps in knowledge and technology, and define opportunities for transformation in urban underground infrastructure systems. The outcomes are clustered in a sub-section of the report under headings that strongly reflect the future challenges and opportunities for underground infrastructure, as identified by workshop participants and interpreted by the organizers.

The major themes emerging from the evidence have been captured in an overarching narrative that seeks to inform researchers, practitioners, policymakers and regulators so that they can help improve our use of underground infrastructure and move us towards a more sustainable and resilient future. The narrative describes the ways in which we do not fully understand the subsurface, we do not work efficiently in the subsurface, and we do not use the subsurface to its full potential. In particular:

- The nature of what constitutes 'underground infrastructure' isn't agreed. Underground infrastructure can be at varying depths, include above ground components and interact with surface infrastructure.
- We do not fully understand interactions between co-located assets; between co-located assets and the surrounding ground; changing soil conditions; the impact subsurface works have on the underground; the wider natural underground environment; the effects of climate change; and the location, condition and deterioration of underground infrastructure assets.
- The appetite for building underground appears to vary as a function of population. As populations increase the delivery of services can require the burying of infrastructure.
- As a general rule nations do not pursue underground development due to the high cost and disruption it causes.
- Underground construction uses surface construction techniques despite the very different and inaccessible subsurface environment and not knowing how materials will behave over time when underground.
- Accessing the underground is usually achieved using disruptive trenching methods.
- Structured and strategic thinking about developing the subsurface will be key to the future services it provides.
- Climate change and population growth mean more efficient use of underground space is becoming a priority.
- Digital technologies and other innovations mean that it is increasingly possible to move things underground.
- Creating a value case for underground infrastructure is not straightforward.
- The potential benefits of moving services underground include improving public health, decreasing congestion, mitigating and adapting to climate change, improving environmental sustainability, and increasing the amount of productive land.
- Engineers need to prioritize co-benefits, co-location, multiple-purposes and closed-loop systems for underground infrastructure systems.
- Engineers need to consider the potential impacts of future changes and shocks.

The evidence is presented as a stand-alone section alongside a commentary on the interdependence of these enablers and solutions and how they can be aligned to produce positive outcomes. Seven categories of enablers and potential solutions were identified:

1. Data
    - Inventories of underground built asset locations and conditions, such as the UK's National Underground Asset Registry (NUAR), need to be created and maintained.
    - High quality data, and policies and mechanisms that encourage data curation and data sharing are necessary.
    - Issues of data privacy, security protection, and responsibility must be addressed.
    - Data in the immediate aftermath of extreme events must be captured.
2. Metrics, tools and models
    - Data, when available, can be exploited by metrics, tools and models to create deeper understandings.
    - Metrics for the underground are needed to create a value proposition and to assess the potential costs of taking or not taking action.
    - Tools and models designed specifically for the underground are needed.
3. Technological innovation
    - Identifying which technologies are worth developing can be expensive and time consuming and so must be underpinned by robust research and testing.
    - Faster construction and smart and proactive maintenance and retrofitting planning and implementation can address risks.
    - New materials that are self-aware, self-healing, self-maintaining, regenerative and report on their condition and function need to be developed for underground infrastructure.
    - An 'internet of things' for the subsurface could support a smart subsurface with self-aware and self-maintaining assets.
    - Subsurface observatories could test technologies and processes, devise and evaluate new tools and models, assess data provision and analytics approaches, assess and develop best practices, and demonstrate value.
4. Hazards
    - The subsurface is both a victim to and a creator of hazards.
    - Emerging risks for underground infrastructure are not well understood.
    - Techniques are needed to support hazard identification and characterization below (and above) ground.
    - A substantial contributor to risk reduction is the better understanding of subsurface and infrastructure conditions.
    - Hazard-driven design priorities would reduce the risk borne by future underground projects.

5. Ownership, governance, regulations, codes and standards
    - Underground ownership, governance, regulations, codes and standards lag behind their surface equivalents.
    - It is not always clear or established who owns and governs the subsurface, its contents and the rights of way through it.
    - Ownership requires capital investment and comes with the possibility of investment and profit, but also the possibility of legal liability.
    - Governance models, regulations, codes and standards for the underground should encourage innovation and investment and reduce risk.
    - Clear processes for educating future engineers and stakeholders in new codes and standards are necessary.
6. Systems of systems and collaboration
    - A collaborative, systems-of-systems approach to transforming underground infrastructure is needed.
    - No one industry, sector, profession or discipline can truly take a systems-of-systems approach; collaboration is needed.
    - Collaboration must be supported with processes and funding.
7. Sustainability, resilience and equity
    - The ability of the underground to positively contribute to sustainability, resilience and equity are evident but poorly understood.
    - Underground infrastructure should actively decrease societal disparities.
    - Sustainability, resilience, and equity do not always complement each other and trade-off must be fully understood.
    - Nations need to better understand the costs and benefits of centralized versus decentralized underground systems and to develop national strategies for underground systems.

The final section's concluding remarks note that the remarkably rich ideas, observations and reflections of the attendees captured here are only the first step in transforming underground infrastructure. The next step is already underway in the form of an academic paper that crystallizes the big research questions. Taken together, the paper and this report provide a firm base on which future research projects can build to advance our understanding and technology, and overcome the barriers to transforming our underground infrastructure systems.

Introduction

This pivotal transatlantic two-day workshop explored the state of the art in urban underground infrastructure research. The workshop was funded by the US National Science Foundation (NSF) and UK Research and Innovation (UKRI). The workshop brought together select, internationally-leading infrastructure scholars and experts to consider the big questions, identify major gaps in knowledge and technology, and define opportunities for transformation in urban underground infrastructure. The US and UK workshops were run concurrently, with a structure designed to enable some independent working in the host locations and online parallel sessions bringing both groups together for joint discussion. This report describes the background that led to the workshop gathering, workshop preparations and management, details of the event itself, workshop outcomes and suggestions for next steps.

Background and need for gathering

Cities across the world have been a major driver of economic growth, technological innovation, and cultural vitality. However, their infrastructure systems (whether above or below ground) are often patchworks of legacy and new components with incompatible standards, materials, and governance structures. As a result, the performance of such systems can be unpredictable under normal conditions and more so when subject to extreme events. Mega projects developed to address some of these issues are especially susceptible to cost overrun, delay, and public criticism. In the USA, for example, the Metropolitan Transportation Authority (MTA) Second Avenue Subway Extension in New York City cost $2.5 billion per mile, making it the world's most expensive subway line. The Gateway tunnel project to construct two new tunnels underneath New York's Hudson River and repair existing tunnels is currently three years behind schedule and is expected to cost $2 billion above original projected costs. In the UK, London's Elizabeth Line, formerly known as Crossrail, was first proposed in 1989. Once properly underway, project completion was repeatedly delayed: 2020, then 2021, 2022 and 2023. The project was also repeatedly re-costed. In 2013 the estimate for Crossrail was £14.8 billion. In the end, it cost £18.25 billion.

One by product of long lead times, delays and cost overruns is that the public is paying increasing amounts for services that are not delivered for decades. Additionally, long project delays create uncertainty about whether project services will be fit for purpose once delivered. It is extremely difficult to predict future service demand. For example, London's M25 ring road was proposed in 1944 and completed in 1986, by which time it had insufficient capacity to meet demand. This problem was the result of three factors: insufficient demand forecasting, the inability to be able to change the design to meet new demand projections, and, once opened, the M25 *induced* demand.

Without a paradigm shift in how infrastructure systems are engineered, constructed, and operated, significant cost overruns are likely to continue, and the gap between the services these systems are designed to deliver and the demand from citizens will continue to widen.

Our current socioeconomic paradigm requires seamless and continuous service delivery, supporting uninterrupted movement and commerce. The challenges to delivering such services that are faced by underground infrastructures such as water and wastewater, transportation, telecommunications, and power systems, are exacerbated by difficulties in access and the harsh environment in which these systems reside. Early success in building digital models at city scales through smart city and digital twin concepts offers a promising direction to help reduce such challenges, especially given new breakthroughs in sensing and computation. However, key knowledge gaps remain a barrier. As national governments invest trillions of dollars in infrastructure to combat climate change (e.g., US Inflation Reduction Act of 2022 and the UK Net Zero Strategy), there is a window of opportunity to mobilize scientific communities to create innovative, socially equitable, minimally disruptive and potentially transformative solutions to how we design, build and operate infrastructure systems, and in particular those that reside in the sub-surface. To that end, advances in fundamental theories and methods are needed for the questions that are considered too difficult to answer today. These include:

- How do we better design underground infrastructure systems to flex to long-term changes in demand, resource allocation and investment plans, as well as changing environmental and societal needs, user behavior, policies and incentives (including challenging the need for seamless and continuous service delivery)?
- How do we plan for and achieve the decarbonization goals by way of underground infrastructure systems?
- How do we characterize and explain the interaction between underground infrastructure systems and those residing above the surface within an urban ecosystem in a changing climate?
- How do we optimize cross-sector, day-to-day operations of underground infrastructures under normal, changing, and disaster conditions?
- How do we balance service reliability and operational cost?
- How do we discover and possibly resolve competing priorities among underground infrastructure owners and the public?
- How do we build unified digital models for systems that are made of spatially distributed, disparate components?
- How do we design and deploy sensors to reduce model uncertainty in predicting component condition state?
- How do we reduce risk and maximize productivity using innovative technologies such as human-computer interactions?
- How do we accurately map the location of existing systems with new processes and technologies?
- How do we incentivize open access and data sharing?

The workshop brought together experts in civil engineering, urban planning, computer science, operations engineering, public policy, sensing, energy, waste and other fields to identify gaps and opportunities for advancement relevant to underground infrastructure, and define a vision for supporting the transformation of underground urban infrastructure systems.

Organizing committee

Principal Investigators (PIs) Elise Miller-Hooks of George Mason University, serving as Co-chairperson for the NSF-side of the workshop, and Joanne Leach of the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC), serving as Co-chairperson for the UKRI-side of the workshop, worked together to design, plan and execute the workshop. The event was designed with feedback from members of the organizing committee, which consisted of the following.

United States

- Elise Miller-Hooks, Bill & Eleanor Hazel Endowed Chair in Infrastructure Engineering, Professor and Interim Department Chair, George Mason University
- Kenichi Soga, Donald H. McLaughlin Chair in Mineral Engineering Chancellor's Professor, University of California-Berkeley
- Priscilla Nelson, Professor, Colorado School of Mines

United Kingdom

- Joanne Leach, Executive Manager of UKCRIC
- Timothy Yate, Communications, Marketing and Events Manager, UKCRIC
- Members of the UKCRIC Executive Board

Members of the committees were chosen to ensure a breadth of expertise, perspective, geographic diversity, and interest relevant to the future of underground infrastructure and infrastructure systems. Committee members assisted with developing a list of potential attendees with broad, relevant expertise in the area of the workshop. They also assisted through follow-up with some of the invited experts. The committee members were consulted about the organization of the event, selection of keynote speakers, activities, activity leadership, themes and other elements of the program.

Workshop aims

The workshop aimed to support creative thought, development of new ideas, and knowledge exchange with the purpose of attaining several key outcomes:

1. A jointly-devised vision statement for the underground
2. Key questions associated with advancing underground infrastructure and what challenges stand in the way of answers
3. A list of relevant research areas, knowledge gaps, research opportunities, barriers, and fundamental research needs
4. Categorization of identified research needs in terms of difficulty and resource requirements to distinguish those that can be accomplished in the near-term with limited resources versus those requiring significant investment that might surpass NSF’s and UKRI’s resources
5. In-depth conversations and collaborations between experts from varying fields within and across the US and UK

6. New US-UK connections on underground infrastructure-related topics
7. Identification of relevant communities and listservs for outcome dissemination
8. Preparation of a report with ideas generated from the workshop for community-wide dissemination

Additional outcomes from post-workshop efforts include:

1. A co-authored perspectives paper on transformation in urban underground infrastructure for publication
2. Proposals for special issues in the area of underground infrastructure of one or more journals
3. Organization of special sessions at conferences

This effort aimed to develop a roadmap for future joint US-UK research in the area of transformation in urban underground infrastructure.

Dissemination of workshop outcomes

The report is posted on the UKCRIC website (ukcric.com), which will be supported for a minimum of two years, and has been placed in the NHERI DesignSafe Data Depo Repository. A link to the report and other outcomes will be shared across many communities, such as:

- NSF and its Civil, Mechanical and Manufacturing Innovation (CMMI) programs
- American Society of Civil Engineers (ASCE), its Geo-Institute, and its committees
- American Society of Civil Engineers (ASCE), its Geo-Institute, Committee on Sustainability, INSPIRE 2025 Conference, and other committees
- Association of Environmental Engineering and Science Professors (AEESP)
- United States Universities Council on Geotechnical Education and Research (USUCGER)
- National Academy of Engineering and the Committee on Geological and Geotechnical Engineering
- The American Water Works Association (AWWA)
- The Water Environment Federation
- Transportation Research Board via its relevant Committees
- UKCRIC
- UKRI
- Institution of Civil Engineers (ICE)
- Royal Academy of Engineering
- Institution of Engineering and Technology (IET)
- National Preparedness Commission
- The Alan Turing Institute
- British Geological Survey (BGS)
- National Underground Asset Register (NUAR)
- Energy, waste, environmental and other relevant communities

Workshop participants were asked to circulate the report to their networks. Post workshop, participants were invited to participate in the creation of the perspectives paper and in organizing and contributing to special issues of journals and special sessions at select conferences.

Logistics

This event was run in parallel in the US and UK on September 28 and 29, 2023, and included two four-hour joint hybrid sessions. The US portion of the proposed workshop was held at the NSF's headquarters in Alexandria, Virginia. The UK portion was held at the University of Birmingham in Birmingham, UK, and Zoom was used to facilitate hybrid participation in both the main and breakout sessions.

Participation was by invitation only. The goal was to include 25 attendees in each location plus NSF and UKRI representatives. Co-chairs Miller-Hooks and Leach worked with the organizing committees to develop the invitation list. Due to the small size of the event, registration was handled directly by the PI's institutions.

Meeting organization, conduct and program

To realize the workshop goals in the areas of disseminating technical achievements, developing new interdisciplinary ideas and interdisciplinary approaches, and building community, a variety of means for delivering and understanding technical content, along with networking and collaboration-building activities, were used.

Prior to the workshop, a Workshop Book of Participant Expertise was prepared and shared among participants (Appendix A). Participants were sent 'thought pieces' from opening keynote speakers plus one on systems of systems (Appendix B) to consider in advance of the workshop. The thought pieces were edited for publication and appear on the UKCRIC website as a short series on underground infrastructure.

The first half of the workshop focused upon identifying the big challenges, opportunities and barriers for the advancement of urban underground infrastructure. The second half focused upon identifying the big research questions and to determine what is needed to support research communities in answering these questions.

Chairs and co-chairs were identified for each breakout session. For joint US-UK breakout sessions, chairs alternated lead role over multiple sessions. Chairs were given instruction packages with a list of deeper questions/topics to aid in their discussion (Appendix C).

The program with the workshop logo as shared with the attendees is given next. Slides used to guide the meeting and keynote presentation slides are also provided (Appendices D and E).

Programme

28-29 September 2023

Alexandria, VA, USA and Birmingham, UK

US-UK TRANSATLANTIC WORKSHOP

TRANSFORMATION IN URBAN UNDERGROUND INFRASTRUCTURE

Message from the organisers

Welcome to this pivotal transatlantic two-day workshop exploring the state of the art in urban underground infrastructure research. The workshop has been funded by the US National Science Foundation (NSF) and UK Research and Innovation (UKRI).

This workshop brings together select, internationally-leading infrastructure scholars and experts to consider the big questions, identify major gaps in knowledge and technology, and define opportunities for transformation in urban underground infrastructure. The workshop's outcomes are to be captured in a single report co-authored and endorsed by the workshop participants and jointly published by NSF and UKRI.

The US and UK workshops run concurrently, with a structure enabling some independent working in the host locations and online parallel sessions bringing both groups together for joint discussion.

Session 1, Independent Session

UK only

Thursday 28 September

UK 9.30-12.00

UK 9.30	Registration and refreshments
UK 9.45	Welcome, purpose of the workshop and overview of the programme
UK 10.00	Introductions
UK 10.30	Tour of UKCRIC's National Buried Infrastructure Facility
UK 12.00	Lunch

Session 2, Joint Session

USA and UK, Thursday 28 September

USA 8.00-13.00

UK 13.00-18.00

USA 8.00 UK 13.00	Welcome, introductions, purpose of the workshop, programme overview, outputs and next steps • Welcome from the event organisers Elise Miller-Hooks of George Mason University and Joanne Leach of the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC) • Welcome from Daniel Linzell, Division Director, the National Science Foundation (NSF) • Welcome from Andy Lawrence, Head of Engineering, Engineering and Physical Sciences Research Council (EPSRC) • Programme overview, outputs and next steps
USA 8.30 UK 13.30	Keynotes from the US and UK present their perspectives on the underground infrastructure landscape, its big challenges and opportunities, the big research questions, and why they haven't yet been addressed. • Priscilla Nelson, Colorado School of Mines • Chris Rogers, University of Birmingham • Carlos Santamarina, Georgia Tech • Fleur Loveridge, University of Leeds
USA 10.30 UK 15.30	Break
USA 10.45 UK 15.45	Transatlantic breakout session: What points were you glad the keynotes raised? What wasn't covered in the keynotes that needs to be discussed at this workshop?
USA 11.45 UK 16.45	Break
USA 12.00 UK 17.00	Reporting back from the joint breakout session, witness snapshots and reflections on the day
USA 12.55 UK 17.55	Thank you and overview of what to expect next
USA 13.00 UK 18.00	Session closes
USA 13.00	Lunch
UK 19.00	Dinner, Edgbaston Park Hotel

Session 3, Independent Session

USA Thursday 28 September, 14.00-17.00

UK Friday 29 September, 9.00-12.00

USA 14.00 UK 9.00	Welcome and overview of yesterday's sessions
USA 14.15 UK 9.15	Independent breakout session: What services will underground infrastructure need to deliver in the future? What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure? What can and should be done better right now below ground and what savings can be made now when doing things underground?
USA 15.15 UK 10.15	Break
USA 15.30 UK 10.30	Reporting back from the independent breakout session
USA 16.00 UK 11.00	Plenary discussion: What research is needed to do underground infrastructure (much) better in the future? What are the big research questions? What is needed to answer those questions (e.g., policy/regulatory shift, equipment, training)?
USA 17.00 UK 12.00	Session closes
USA 18.15	Dinner, Old Town Alexandria
UK 12.00	Lunch

Session 4, Joint Session

USA and UK

Friday 29 September

USA 8.00-13.00

UK 13.00-18.00

USA 8.00 UK 13.00	Welcome
USA 8.05 UK 13.05	Keynotes from the US and UK present their reflections on the workshop discussions thus far and their perspective on the underground infrastructure landscape, its big challenges and opportunities, the big research questions, and why they haven't yet been addressed. • Kenichi Soga, University of California Berkeley • Holger Kessler, Government Office for Science
USA 8.55 UK 13.55	Reporting back from the independent breakout session
USA 9.25 UK 14.25	Transatlantic breakout session: Where are the synergies, tensions, gaps and opportunities between the 'big research questions' identified by the USA and UK in their independent sessions? What else is needed to support the two research communities, separately and collectively, in answering those questions?
USA 10.45 UK 15.45	Break
USA 11.00 UK 16.00	Reporting back from the joint breakout session, witness snapshots and reflections on the day
USA 11.45 UK 16.45	Organisers' summary and an opportunity to reflect upon the workshop outcomes and raise new and amplify existing points
USA 12.15 UK 17.15	Thank you, exit questionnaire and reminder of next steps
USA 12.30 UK 17.30	Networking
USA 13.00 UK 18.00	Workshop close

Workshop outcomes

The best is the enemy of the good

Italian proverb "il meglio è nemico del bene"

Opportunities for improving the utilisation of underground infrastructure

Over the two days of the workshop a clear overarching narrative emerged, the three components of which provide opportunities for improving the utilization of underground infrastructure: (1) we do not fully understand the subsurface, (2) we do not work efficiently in the subsurface, and (3) we do not use the subsurface to its full potential.

We do not fully understand the subsurface

The workshop delegates identified much about the subsurface and underground infrastructure that is not fully understood. These included the following, with more described in the section on cross-cutting themes.

- Interactions between co-located assets and between co-located assets and the surrounding ground
- Changing soil conditions and the impact subsurface works have on the underground
- The wider natural underground environment including the ecosystem services it provides
- How climate change and other stressors are affecting the subsurface
- The location, condition and deterioration of underground infrastructure assets

From built infrastructure elements to the ground itself, the delegates considered the meaning of infrastructure in the context of the underground. Underground infrastructure can be thought of as the buried assets that support service delivery (e.g., water pipes, electricity cables, subways). Their boundaries, however, are not always restricted to the subsurface. Underground assets may also exist above ground, may be inextricably linked to above ground infrastructure, or may be very shallowly buried. This gives rise to the question of how self-contained and deep does infrastructure need to be before it is considered 'underground infrastructure'?

The ground itself can be considered infrastructure (i.e., nature's infrastructure). Buried assets are frequently geographically co-located, connected together by the ground in which they sit. Soil has a temperature, nutrient value, infiltration capacity, strength and stiffness. When excavated, such as when installing new underground infrastructure, the soil is loosened and this can change its physical properties. This affects underground infrastructure, but also above-ground infrastructure and the surface of the ground itself. For example, the bearing capacity (the ability of the subsurface to support the surface) may be compromised, causing roads and their surroundings to sink.

In many locations around the world, including the US and UK, there exists considerable legacy infrastructure in the underground. A precise understanding of the location, condition and state of these assets (i.e., functioning, failing, decommissioned) is critical but remains out of reach because of a lack of investment, political will, knowledge, tools and techniques required to complete the task. In the UK this is changing with the introduction of the National Underground Asset Register (NUAR), which draws together third-party datasets to build a map of the geographical locations of buried utilities. However, NUAR does not include condition assessment of the assets or of the wider subsurface environment, it cannot predict subsurface conditions and vulnerabilities under hazard events (e.g., flooding) and it does not map the interdependencies of the systems. In other words, there is still much work to be done.

We do not work efficiently in the subsurface

The appetite for building underground appears to wax and wane as a function of population. As populations increase the delivery of services can require the burying of infrastructure. With decreasing populations (i.e., shrinking cities) this requirement diminishes and existing infrastructure may need to be decommissioned or repurposed. How to do this safely and sustainably requires research and testing. The gas sector could, for example, repurpose the network to support hydrogen (requiring additional safety considerations) or decommission the network (risking pipe collapse).

Motivations for building underground range from releasing functional space in densely populated areas to adapting to climate change. As a general rule (but with some notable exceptions, such as Singapore) nations do not pursue underground development due to the high cost and disruption it causes, and yet large cities are replete with underground infrastructure. This may be because when cities become very dense and there are barriers to (or lack of support for) sprawl they have no choice but to take development underground. This is especially the case in large, dense, wealthy cities like New York and London where basement living is not unusual. In places where excessive heat is an issue though, building residences underground can be a cost and energy efficient solution. In both cases, the wellbeing impacts of underground living are not well understood.

When underground construction is undertaken, especially in built-up areas, it is most often carried out using trenching methods (digging up the surface to reveal the subsurface). These methods are time consuming, damaging to the surface and the subsurface, and disruptive to society (think of all the traffic jams caused each year by roadworks). Trenchless methods are available, such as directional drilling and microtunnelling, but are underused because the location of existing buried assets is unknown and so the risk to damaging them using a trenchless technique is high.

Added to this, underground construction uses surface construction techniques despite the very different and inaccessible subsurface environment and not knowing how materials will behave over time when underground. For example, it is not well understood how concrete additives (increasingly used in low-carbon concrete mixes) impact the strength and deterioration of concrete when sited underground for long periods of time.

We do not use the subsurface to its full potential

Digital technologies and other innovations mean that it is increasingly possible to move things underground. Climate change and population growth mean more efficient use of underground space is becoming a priority. Underground transport for people and goods can be substantially expanded in densely populated areas as well as at regional and national scales. Underground farms and parks are of interest because they increase the amount of productive and recreation land respectively, but the need for sunlight means they are challenging to implement at scale. Underground data centres benefit from naturally cooler temperatures, and the same for underground living as climate change causes the Earth to heat up. They also benefit from the increased protection from some hazards and threats offered by the subsurface. Large underground data centres are now found worldwide but Earthscrapers (the underground equivalent of skyscrapers) remain the stuff of science fiction and we have not developed a clear understanding of why such differences in implementation exist.

The potential benefits of moving services underground include improving public health, decreasing congestion, mitigating and adapting to climate change, improving environmental sustainability, and increasing the amount of productive land. This is further complicated by changing population needs over time. For example, some cities are shrinking, their land value is reducing and available productive land is increasing, which all impact the value case for sub-surface development. As is true above ground, where and how people live and where they work defines infrastructure service needs and affects underground land value.

Creating a value case is not straightforward but it is necessary if the subsurface is to be used to its full potential: water, heating, cooling, parking, energy, food, minerals, shipping, goods, telecoms, agriculture, transportation, sewage, waste, storage, commerce, living, and the movement of people and goods (the urban metabolism). Valuation of the underground can be given in the context of services, assets, and even potential for market creation; and climate change and new technologies are constantly changing the cost-benefit ratio. Governance, economic, business (ownership / responsibility / risk) and social cases all need to be made in order to fully realize the value of the subsurface.

Structured and strategic thinking about developing the subsurface will be key to the future services it provides. The underground is already home to an array of civil lifelines including sanitation, stormwater, power, telecoms and transportation. The subsurface provides regulating services (temperature, water flow, sewage), supporting services (strength, stiffness), and ecological services (natural groundwater flow, biota, ecological base). In the future the underground may need to deliver additional as well as increased services and to balance these across different spatial scales: stormwater control, water storage, protection from extreme heat and cold, goods movement, heat for above ground, carbon capture, and more.

Engineers need to prioritize co-benefits (multiple benefits rather than a single benefit), co-location (e.g., utilidors / multi-utility tunnels), multiple-purposes (e.g., streets carrying multiple utility services, parking garages serving as flood water reservoirs) and closed-loop systems (e.g., the earth's heat is used to treat and process water below ground). The future of energy, for example, might see the use of automated underground transport systems for goods and people, and combined underground EV charging and energy storage. Better use could be made of geothermal energy and underground storage (e.g., compressed air which itself stores potential energy), and existing infrastructure could be repurposed (e.g., using the gas distribution network to move more efficient fuels).

Engineers also need to respond to the potential impacts of future changes and shocks such as changing societal concerns and changes in climate, population, and demographics. Energy demand, for example, is affected by global events and so energy generation, storage and supply must be designed for shock events such as wars and pandemics. Energy demand affects energy costs, which in turn affect energy generation, storage and transmission. Tools such as scenario planning and horizon scanning are increasingly important skills for engineers.

Enablers and potential solutions

Spanning the three opportunities for improving our use of underground infrastructure were a set of seven enablers and potential solutions:

1. Data
2. Metrics, tools and models
3. Technological innovation
4. Hazards
5. Ownership, governance, regulations, codes and standards
6. Systems of systems and collaboration
7. Sustainability, resilience, and equity

Data

Data was a key topic of interest during the workshop. The following word cloud was generated from the bullets of the breakout sessions as given in Appendix F[1]. 'Data' appears 68 times, a frequency second only to 'infrastructure' (at 110 times). Considerations related to data include their role, needs, sharing and exchange, conversion to information, quality, security, durability and tools.

[1] Created using Pro Word Cloud in PowerPoint and showing the top 50 words. The larger the size, the more frequently the word appeared. Common words have been removed, as were "go," "allow," "can," "US," "UK," "will," "make," "identify," "can," "cannot" and "etc." "Needs" and "needed" were shortened to "need".

Substantial investments have been made to create and maintain an inventory of underground built asset locations and conditions, such as in the UK through the National Underground Asset Registry (NUAR). Expanding these inventories, particularly within the US, is important. The Minnesota Department of Transportation (DOT) may have the closest implementation to NUAR within the US. Such inventories must be kept up to date. One possibility is to require that all construction projects deposit data within a national inventory such as with the British Geological Survey (BGS) and that these data are made publicly available. New emerging sensor technologies can be used to provide new data as well as to keep existing datasets up to date.

High quality data on asset location and condition are fundamental, as are the impacts of data fragmentation, accuracy, and sparsity. Sensor data can be used to monitor the degradation or failure of underground infrastructure, to understand changing environmental conditions, to continuously track and update inventories, and to support automation and smart infrastructure. This information is critical for designing, building, managing, operating, expanding, and maintaining underground infrastructure systems and the surface systems built above them. Sensors can be used to detect hazardous underground conditions, such as where systems (running or abandoned) may leak or leach into the soil or groundwater. They can also provide improved understanding of surface-subsurface interactions. The data from sensors can be used to inform vulnerability and opportunity assessments, to identify potential cascading failures, and to identify how underground space can be used in the future. A truly 'smart subsurface' should integrate infrastructure and human activity data (such as through social media and web abstraction) to create understandings beyond the physical system and should include both legacy and new systems.

Technologies such as using Building Information Modeling (BIM), digital twinning and Artificial Intelligence (AI) can aid engineers in maintaining and exploiting data from the underground. Such technologies, however, rely on open and accurate data. BIM for the underground is advanced within industry but is siloed with users protecting their individual competitive advantages and investments to the detriment of data sharing.

The ultimate goal is to extract information from data for knowledge creation (i.e., the Data Information Knowledge Wisdom (DIKW) pyramid). Information about the underground can lead to understandings beyond the underground system. Consider, for example, the use of information about sewer flows for detecting disease outbreaks. Improved methods of visualization specific to underground systems and their spatial and temporal dynamics will aid data interpretation and information creation.

To support a data-rich, data-informed underground, policies that encourage data curation and data sharing are necessary. Data sharing requires data exchange protocols, a 'data commons', and data coordination and access. Data sharing does not need to be ubiquitous. It can involve various combinations of pairs or groups of stakeholders, including utility companies, the private sector, governmental agencies, local authorities, and researchers. It may also involve international agreements.

Even with agreements in place, there is a fundamental need for mechanisms to support data sharing and data exchange. Ideas raised during the workshop included requiring utility providers to share information, implementing policies that require sharing underground characteristics and build conditions when obtaining permits to work underground, and developing a global modern-day 'FDR New Deal for Data Infrastructure'. This New Deal would include the creation of national and international data backbones with public data commons and would support data literacy and education. A federated model was also suggested that uses distributed architecture, allowing data to be shared and accessed without the need for centralized control. This could be achieved through Secure Multi-party Computation (SMC), blockchain, and Distributed Ledger Technology (DLT). Building such a system requires data integration and common ontologies. Combining US and UK ontologies, map forms and model languages could drive a step change in US-UK data sharing.

Issues of data privacy, security protection, and responsibility must be addressed. Who is responsible if decisions taken based upon inaccurate data lead to costly outcomes? What if bad actors access sensitive data? Access protocols will need to be developed, with users only having access to the data they need. With the need to restrict data access, it may be useful to provide detailed, usable, copyright cleared, secure data for use in research and innovation.

Finally, society should be equipped to capture data in the immediate aftermath of extreme events. These include perishable damage, process, cost, timeline and recovery strategy data. This will require an immediate response as well as the capacity for long-term tracking. Such quick response data curation efforts can aid in developing case histories and improving the future resilience of infrastructure.

Metrics, tools and models

Data, when available, can be exploited by metrics, tools and models to create a deeper understanding of physical systems and processes, retrospective analyses, characterization, quantitative performance and state (deterioration) evaluation, prediction, and support for decision making.

Metrics for the underground are needed to create a value proposition for the underground and to assess the potential costs of taking or not taking action. Metrics provide quantitative evidence of the consequences of past poor monitoring of underground asset conditions and can be used to define and measure the impact underground infrastructure has or could have on quality of life. New metrics and infrastructure analytics should also be developed to support real-time, high-quality asset monitoring and evaluation. Performance metrics account for resiliency, adaptability, monetary value, social value, economic value, disruptions, and efficiency. They are important for the quantification of Environment, Social and Governance (ESG) propositions for using underground space. They can be designed to inform trade-offs, such as development and preservation (e.g., preserving historic and cultural resources), and short- and long-term investment goals, as well as to support continuous, integrated monitoring and maintenance. Metrics can also support an integrated planning approach. The workshop attendees supported the creation of universal metrics and computational methodologies to support consistent international evaluation.

Advancements in tools and models designed specifically for the underground will be important for future quantitative studies and to provide support for designing, building, monitoring, maintaining, interpreting and predicting conditions and performance in future underground infrastructure systems and components. A standardized methodology for developing an underground asset management system supported by research facilities such as those that form UKCRIC was discussed, as were tools and models making use of advances in digital twinning, uncertainty quantification, Artificial Intelligence (AI), machine learning, adaptive and iterative design, action learning, adaptive and performance-based design, and quantum technologies.

The workshop attendees agreed that there is a need to develop bespoke metrics, tools and models that are specific to the underground in order to address:

- Changes to underground infrastructure from climate change under both chronic (e.g., sea level rise) and acute (e.g., storms and flooding) events across geographies and hazards;
- Changing contexts (e.g., climate event, new technology, population growth, urbanization, migration, demographic changes), but also changing criteria (e.g., performance, resilience, sustainability);
- The impacts of overground processes on the underground;
- The nature and consequences of changing soil conditions;
- The performance of designed, as-built and as-used underground systems;
- Scalable, repeatable, robust buried infrastructure solutions (e.g., a BIM step wise approach);
- Making the subsurface smart (e.g., with sensors);
- Knowing with accuracy what is beneath the surface;
- Transforming subsurface engineering practices to protect and enhance the ground's properties for future exploitation;
- Valuing underground infrastructure, the subsurface and its contents;
- The integration of maintenance and adaptive design;
- The consequences of subsurface engineering;
- Understanding what has previously been done to and in the subsurface and what this means for future subsurface development;
- When underground development should be considered, where and how deep;
- Future subsurface requirements in order to make the best use of buried infrastructure; and
- Embedding sensor technology in legacy infrastructure.

These topics will need to be addressed through case studies, large-scale modeling efforts and digital twinning in order to demonstrate efficiency and convince stakeholders of their value. University campuses could be a good starting point for such studies. Cities, too, can serve as research platforms, testbeds and innovation beds allowing for the testing and study of, for example, green infrastructure, energy from waste, and climate islands. Governments and funding agencies have a crucial role to play in creating the capacity and capability to develop test beds and implementation pathways.

Technological innovation

Innovative new technologies include such things as nature-based solutions, biomimicry, trenchless technologies, quantum technologies, robotics, AI and smart materials. Identifying which technologies are worth developing can be expensive and time consuming and so must be underpinned by robust research and testing. Trenchless technologies, for example, have the potential to eliminate digging up roads and damaging the ground and the assets that are above or buried in close proximity, and to vastly reduce disruption to society and the economy (noting that those who are disrupted do not always see the benefit post-disruption); however, their development is hampered by a lack of knowledge of what is currently underground, a problem that requires considerable investment to solve.

Working underground poses unique challenges with regard to construction and the ability to undertake maintenance, repair and rehabilitation once in operation. Technological innovation and new construction and maintenance processes are key to overcoming these challenges. Trenchless technologies and robotics powered by machine learning promise improvements for both construction operations and maintenance only when accompanied by new system designs and operational processes that have been re-engineered to support them. Some innovations, such as utilidors / multi-utility tunnels (conduits that house multiple services) are underused not because of technical barriers, but because of process barriers.

Maintenance and retrofitting infrastructure located underground is challenging not least because of the reduced access when compared with surface infrastructure. It is not uncommon to delay maintenance, for example, until the symptoms of the problem can no longer be ignored. Leaking transportation tunnels and leaking water pipes are two such examples. Famously, the subsurface clay in London in which the city's water pipes lie seals the holes in the degrading Victorian pipe network and enables the system to continue working. This clay also supports London's many trees. It is said that if all the water pipes in London were fixed all its trees would suffer. It is this same stable, heavily over-consolidated clay that made it relatively easy to tunnel out the London underground transport system. London would be a very different place if it were not for London Clay, but its carefully balanced and heavily exploited subsurface system means the risks for further underground works are high. In the UK there is a 20% upcharge for working underground, which is applied to cover uncertainties.

Faster construction and smart and proactive maintenance and retrofitting planning and implementation can address these risks. Through-life asset management strategies including automated approaches support trading off lower-cost preventative maintenance and repairs against decommissioning and replacement. They also inform reactive repair and future planning. Such strategies require appropriate resourcing and should consider how they can contribute to wider priorities, such as the United Nation's Sustainable Development Goals, for example, by implementing circular economy practices.

New materials for underground construction that are self-aware, self-healing, self-maintaining, regenerative and report on their condition and function should be developed with consideration for execution, assessment and the repair needs and challenges of the subsurface. These new materials should have long design lives, require little human interaction and intervention, and could reduce both costs and damage to the ground and the infrastructures located in and on it. Such materials should be resistant to degradation, deterioration, and climate change. They should also be carbon light and environmentally sustainable, for example incorporating what otherwise might be considered waste as a material.

The workshop delegates discussed a possible future with ubiquitously monitored and instrumented smart infrastructure, requiring advancements in sensing technologies (currently sensors do not last long and wireless technology does not function well underground) and development of an 'internet of things' for the subsurface in order to create a smart subsurface with self-aware and self-maintaining assets. Robust research will help reduce the barriers to technology adoption by industries working in the subsurface, which was a particular concern.

Subsurface observatories (akin to urban observatories) were suggested that could test technologies and processes, devise and evaluate new tools and models, assess data provision and analytics approaches, assess and develop best practices, and demonstrate value. At scale, subsurface observatories could enable resource sharing across nations. Subsurface observatories could address:

- Mapping the impacts on the subsurface of stressors such as climate change and populations shifts;
- The ability of the subsurface to deliver and support ecosystem services;
- How subsurface properties are quantified and measured. For example, sensors placed underground face challenges related to signal strength, energy requirements, durability, and the capacity to measure the needed subsurface properties;
- The required spatial and temporal sensor measurement densities;
- The best structure for data lakes; and
- Utilizing above-surface (e.g., satellite) observations.

While several testbeds will be needed, a first pilot on a scale of 1km by 1km would provide proof of concept and could be implemented on a university campus. Ultimately, the delegates thought that a 'moonshot mission' would be needed to realize the technological transformation of underground infrastructure and to accelerate technology transfer to industry.

Hazards

The subsurface is both a victim to and a creator of hazards. Obvious hazards such as storms, floods, fire and earthquakes negatively impact the functioning of underground infrastructure, sometimes in unseen as well as unforeseen ways. Service disruption is frequently the symptom of damage, meaning damage that has not (yet) disrupted services can go unnoticed and unaddressed. Underground infrastructure systems exist in the harsh subsurface environment where hazards such as corrosion and ground movement are commonplace. With the ever-increasing reliance of society upon infrastructure, and the 'smartening' of that infrastructure, subsurface infrastructure must also be protected from physical- and cyber-based attacks.

Underground infrastructure can also be a hazard. As systems deteriorate they can create leaks, explosions, fire, subsidence of the ground, and other hazards. When legacy buried infrastructure systems are left in place or are not properly decommissioned or repurposed they can create unexpected hazards. For example, unused gas pipes can collapse and obsolete storage tanks may leak.

In recent years hazard research has adopted a systems-of-systems approach and has expanded beyond engineering to include the social sciences, emergency managers, economists, and others. Hazard research needs to be practically useful, requiring at the very least collaboration with the agency responsible for providing the service (e.g., the utility company). In circumstances involving homeland security or community resilience, collaborations will include government agencies.

Whether responding to an incident arising from within the underground or protecting underground assets from an external hazard, frontline works must operate in potentially harsh, difficult environments. Life safety and emergency response training should be provided.

Inevitably, a substantial contributor to risk reduction is the better understanding of subsurface and infrastructure conditions: recognizing deficient infrastructure condition, quantifying related uncertainties and completing risk evaluations. The workshop attendees noted that there is currently limited understanding of the emerging risks and recommended the development of techniques to support hazard identification and characterization not only below ground, but also above. Hazard-driven design priorities would reduce the risk borne by future underground projects.

Ownership, governance, regulations, codes and standards

In relation to the underground, ownership, governance, regulations, codes and standards lag behind their surface equivalents and contribute to the substantial uncertainties of working with existing and developing new sub-surface infrastructures.

In the US and the UK it is not always clear or established who owns or governs the subsurface, its contents (e.g., pipes and cables, items of archaeological interest) and the rights of way through it, at what depths ownership and governance change, what are the owner's responsibilities, and what are the responsibilities of those using the subsurface (such as utility companies). Additionally, who owns the data obtained from the underground? In the UK the Government Office for Science has commissioned the Foresight Future of the Subsurface project, which will provide some answers (see also Foresight of Cities: Development Underground).

Ownership requires capital investment and may involve collaboration, such as in developing a utilidor / multi-utility tunnel. It also may come with monetary returns. Considerations such as who pays, when, and over what timeframe are important, as are who is responsible for maintaining underground assets and who carries the risk from failures. Surface comparators can be useful. For example, bridge owners are responsible for the bridges on which utilities that are attached to the bridge rely. In the subsurface ownership is less clearly delineated and this can be a barrier to investment. For example, road owners may or may not own the land under a road depending upon the particular situation and location – and in some cases the ownership may never have been established.

With ownership comes the possibility of legal liability. In the subsurface liabilities can be unclear. For example, a leaking water pipe can cause damage to the surrounding subsurface, to the surface, to co-located utilities and to transport corridors (all of which may be separately owned). The repair of the water pipe by digging a trench will damage the subsurface and the surface and may damage co-located utilities and transport corridors. Who is responsible for ensuring: the water pipe did not leak in the first place, the leak caused minimal damage, the repair of the leak caused minimal damage, and that any damage is put right? How does this change if the leaky pipe was caused by ground movement?

With ownership also comes the possibility of investment and profit. Cost, contractual and other commercial barriers to investment are important considerations for sub-surface innovation. Appropriate business models are needed to attract public and private investment. Particularly true for infrastructure projects, there needs to be return on investment that links to government priorities, with public funding likely coming from multiple government departments. Public-private partnerships (P3s) might play a role here, but financing from the private sector is driven by shareholder priorities, which may not align with public priorities.

Governance models should encourage innovation and investment, reduce risk, and enable rapid repair, maintenance and deployment of new infrastructure. They should attend to areas of ownership and responsibility and how conflicts between owners, operators and other stakeholders are handled. They might also consider public priorities. For example, if the subsurface is used for one purpose (such as a train tunnel), it may preclude its use for another purpose (such as for buried water pipes). Moreover, attempts to avoid the congested shallow subsurface in urban areas might result in utility services being installed far deeper than would otherwise be the case, blighting the underground space in relation to other uses. Workshop attendees suggested identifying existing underground governance models, such as that found in Singapore.

Regulations, codes and standards for the underground have the potential to transform how organizations manage risks and opportunities related to environmental, social, and governance criteria (ESG) and to encourage innovation in underground infrastructure. They should address design, construction, operation, maintenance and end-of-life. For example, it may be a requirement to leave the subsurface in a usable state after the decommissioning of an underground infrastructure system. Research is needed to better understand what this looks like in practice. Currently, the London Underground will not allow some surface and subsurface works because the impact and stresses on the train tunnels are unknown.

Regulations, codes and standards should encourage the use of innovative and smart materials, equipment and processes, including in construction. They should address legacy buried infrastructure that may need to be safely decommissioned or removed to create space for new uses. They should also set out what a sustainable and resilient subsurface means (such as a 300-year design service life) and they should enable improving data and knowledge about the subsurface. Workshop attendees suggested a sector-based framework approach, as has been created in recent years for Connected and Autonomous Vehicles (CAVs).

Finally, processes for enforcing regulations and for educating future engineers and stakeholders in new codes and standards are needed, which will lead to improved best practices. Changes in service demand and climate change, amongst other drivers of change, are already influencing best practices. Research is needed to understand the full impacts of these changes.

Systems of systems and collaboration

The workshop delegates were unanimous in calling for a collaborative, systems of systems approach to transforming underground infrastructure.

Below ground, as above ground, few infrastructures act in complete isolation. Underground infrastructure systems such as electricity, water and sewer networks are not only frequently co-located, but they operate interdependently creating a system of systems: electricity is required to pump water; water and electricity are required to process sewerage; and electricity, water and sewer systems form part of the larger utility system. In a system of systems it is not possible to change one system (electricity) without affecting the others (water and sewer). Taking a systems-of-systems approach means that performance measurement of the different systems must be integrated, even those with different flows (e.g., electrons, water molecules and biological matter). The functionality of the components of one system must be considered in terms of their collective contributions to the entire system of systems. Understanding not just first-order effects but also second- and third- order effects is crucial. This is not to say that systems of systems are centralized *per se*, and the workshop attendees raised the need to investigate constructs of future systems that are more decentralized than is currently found in the US and UK.

No one industry, sector, profession or discipline can truly take a systems-of-systems approach; they must collaborate. The workshop attendees identified collaborations between industry, academia and policymakers as being especially important for underground infrastructure.

Traditional, deeply-rooted research and development in industry does not link as closely as it should with independent academic research. Innovation often emanates from industry, with academia creating multiplied benefits. Academics amplify, learn from and add value to industry-led innovation. However, academics can struggle to gain the ear of policymakers; whereas, industry is frequently in conversation with policymakers. Through industry and academia working together both the research itself and its influence on policy can be improved. Other desirable collaborations identified during the workshop were: between public and private utilities; between universities, cities and industry; between utilities, universities and Architecture, Engineering and Construction (AEC) entities; and between planners and industry to support urban planning.

The workshop attendees discussed at length how collaboration can be supported. One option was through the creation of an umbrella organization that creates a network of transdisciplinary professionals. UK national labs such as UKCRIC support coordination and foster collaboration between academia and industry. Innovate UK, part of UKRI, provides funding to academia and industry to work together on project-based solutions and use cases. Technology Readiness Levels (TRLs, a method for assessing the maturity of a technology) are used by governments, businesses, and other organizations to make decisions about funding, research, and development. Business incubators can address pressing infrastructure-related problems. Urban observatories can bring together multiple actors and disciplines. Secondments, placements (i.e., temporarily loaning a worker to another organization or department within the same organization) and initiatives like the UK Government's Chief Scientific Advisor scheme embed professionals, researchers and policymakers into other organizations or even government. No matter what the mechanism, the workshop attendees agreed that involving experts from nontraditional areas in underground infrastructure had value and that an interdisciplinary approach is necessary. Likewise, coordination across arenas in education is also needed. It is important to build skills and competencies across engineering, the social sciences and other disciplines (see The Turing's Data-centric Engineering Programme for skilling up engineers in AI).

Sustainability, resilience, and equity

The ability of the underground to reduce the negative impacts of the built environment on natural systems, to mitigate and adapt to climate change, to contribute to zero carbon targets, to improve environmental sustainability, and to increase infrastructure resilience and societal equity are evident but poorly understood. Research and testing are required at the project, system and system-of-system levels as well as in how to engineer for adaptability to changing physical, social, economic, and climate conditions.

It has been a past failing of infrastructure engineering that little consideration was given to how infrastructure can equitably support society (with equitable access to services). The workshop attendees advocated for underground infrastructure to actively decrease societal disparities. This begins with understanding the who, when, where and why of underground infrastructure transformation; with consideration of social acceptability and social value; and with building multi-disciplinary perspectives. Underground infrastructure must also contribute to a just transition in a world where not every country has the monetary resources to build underground.

Sustainability, resilience, and equity do not always complement each other. For example, utilidors / multi-utility tunnels provide an environmentally sustainable solution to utility placement and maintenance by facilitating access to multiple utilities. This increases the ability to monitor the pipeline and cables to prevent failure occurring, encourages proactive maintenance and allows for the easy placement of sensors. However, utilidors / multi-utility tunnels compromise resilience by placing all the utilities in the same geographical location, increasing the possibility of multiple failures if one fails or if the tunnel itself fails. They are also relatively expensive to implement and so are prevalent in wealthier areas. This example also speaks to the need to understand the costs and benefits of centralized versus decentralized underground systems. A national strategy for underground systems is needed to address these points.

Concluding remarks

The workshop uncovered a wide variety of challenges associated with constructing, operating, monitoring, maintaining and decommissioning subsurface infrastructure. It revealed a broad lack of understanding in many key areas, and thus a need for scientific and technological advancement associated with underground infrastructure elements and systems. It uncovered a need for the creation of a science and engineering discipline for the underground, suggesting a need for transformation in underground infrastructure to enable society's use of the underground to its full potential.

Through its bi-national delegation, the workshop uncovered commonalities across nations in their challenges and successes associated with constructing and operating their underground infrastructure, each nation gaining from knowledge of lessons learned from specific implementations and successful, on-going initiatives. Finally, ideas for combining aspects of approaches from each nation, such as combining ontologies, map forms and model languages in data sharing, arose that were noted as possible drivers of transformation.

This report is a first step toward identifying such ideas for driving transformation and advancement in underground infrastructure. The next step is already underway in the form of an academic paper that crystallizes the big research questions. Taken together, the paper and this report provide a firm base on which future research projects can build to advance our understanding and technology, and overcome the barriers to transforming our underground infrastructure systems.

List of appendices

Appendix A: Book of participant expertise

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Dulcy M. Abraham is a Professor in the Lyles School of Civil Engineering, Purdue University, West Lafayette, IN. The main thrust of her research centers on the development of assessment technologies and decision-making methodologies for the rehabilitation of underground infrastructure. Her research initiatives in civil infrastructure systems include the development of: (1) an automated approach for analyzing and interpreting data regarding the status of wastewater pipelines; (2) a life-cycle based approach to infrastructure management; (3) an asset valuation methodology that incorporates deterioration modeling; (4) models for vulnerability analysis and disaster mitigation of pipelines infrastructures, and (5) evaluation of interdependencies/couplings between water/wastewater infrastructure systems and human interactions. Dulcy Abraham served on the ASCE Construction Research Council (CRC) Executive Committee (secretary, vice-chair and chair). She has also served on the ASCE Committee on Construction Equipment and Techniques Committee, the ASCE Water Infrastructure Security Enhancements (WISE) Committee, the ASTM Committee on Technology and Underground Utilities, and the WERF (Water Environment Research Foundation) Project Committee on the Examination of Innovative Methods Used in the Inspection of Wastewater Collection Systems. She has harnessed the benefits of engaging diverse stakeholders in infrastructure decision-making through her involvement in service-learning activities and multi-disciplinary global design teams for undergraduate and graduate students.

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Melissa Bedinger is a Research Associate in Future Infrastructure with interests across complex systems modelling, human factors and technology, transport and society, climate impacts, sustainable development, and making research useful and usable. Melissa’s research began through a BEng in Civil & Environmental Engineering and a PhD in Business Management & Human Factors with the Centre for Sustainable Road Freight, both at Heriot-Watt University. Melissa now leads the development of the Urban Systems Abstraction Hierarchy model which quantifies the interdependencies between physical resources across multiple sectors in cities, and demonstrates how they connect to resilience outcomes. This first-of-its-kind modelling approach uses qualitative and quantitative data across multiple sectors to better understand systemic risks and cascading impacts, related to different scenarios (e.g., flood hazards; pandemics; future technology transitions). As of June 2023, she has co-authored 12 peer-reviewed articles, 4 book chapters, and 2 open source software packages.

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Luís M. A. Bettencourt is the Pritzker Director of the Mansueto Institute for Urban Innovation at the University of Chicago. He is also a Professor of Ecology and Evolution at the University of Chicago and External Professor of Complex Systems at the Santa Fe Institute. He was trained as a theoretical physicist and obtained his Licenciatura from Instituto Superior Técnico (Lisbon, Portugal) in 1992, and his PhD from Imperial College (University of London, UK) in 1996 for research in statistical and high-energy physics models of the early Universe. He has held postdoctoral positions at the University of Heidelberg (Germany), Los Alamos National Laboratory (Director's Fellow and Slansky Fellow) and at MIT (Center for Theoretical Physics).

He has worked extensively on complex systems theory and on cities and urbanization, in particular. His research emphasizes the creation of new interdisciplinary synthesis to describe cities in quantitative and predictive ways, informed by classical theory from various disciplines and the growing availability of empirical data worldwide. He is the author of over 100 scientific papers and several edited books. His research has been featured in leading media venues, such as the New York Times, Nature, Wired, New Scientist, and the Smithsonian.

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Joby Boxall is Professor of Water Infrastructure Engineering at the University of Sheffield, was Head of Department of Civil and Structural Engineering 2017-21. He is a Chartered Engineer and Environmentalist and Fellow of the Chartered Institution of Water and Environmental Management. Joby's research interests are concerned with understanding and modelling hydraulic, water quality and infrastructure performance and interactions. He is focused on research addressing the grand challenges facing water and its wider interactions, including leading the EPSRC grand challenge consortium on sustainable clean water for all, TWENTY65.

John Bridgeman

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Civil and Environmental Engineering, University of Liverpool

John Bridgeman joined the University of Liverpool as JW Hughes Professor of Engineering and Head of the Department of Civil and Environmental Engineering in 2022, having previously been Deputy Vice-Chancellor (Research, Innovation & Engagement) at the University of Bradford (2017 - 2022), and Professor of Environmental Engineering at the University of Birmingham (2005 - 2017). The early part of John's career was spent in industry, working on the design and construction of water and wastewater infrastructure, before a planned move to academia in 2005. The focus of John's research is on experimental and numerical approaches to address the global challenges which we face in managing water security and resource efficiency. Current areas of interest include the numerical modelling of various water and wastewater treatment processes and pipe leakage using computational fluid dynamics and lattice Boltzmann modelling, and the development of novel optical water quality assessment tools. He has secured research funding from the Engineering and Physical Sciences Research Council, the Natural Environment Research Council and the European Union (FP7 and H2020), as well as fully funded industrial research contracts from a range of charities and industrial organisations.

Harvey J. Burd

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Department of Engineering Science, Oxford University

Harvey Burd is a Professor in the Department of Engineering Science, Oxford University and a Tutorial Fellow of Brasenose College. He is a Fellow of the Institution of Civil Engineers. His research is mainly concerned with the development of computational and analytical modelling techniques to predict and better understand the performance of civil engineering structures and systems. Burd has a particular interest in the development of computational techniques to understand the ground movements that occur due to underground construction (e.g., tunnels and deep excavations) and to make predictions on the ways in which these ground movements may interact with nearby existing infrastructure, with a particular focus on masonry buildings. Research in this area employs large-scale 3D finite element models as well as being concerned with the development of simplified modelling procedures that are suitable for routine assessment applications. He has a developing interest in the use of remote sensing techniques (e.g., laser scan point clouds) to monitor the response of buildings to nearby ground movements. Additionally, Burd has interests and expertise in the development of design models for foundation systems (e.g., monopiles) for offshore wind turbine support structures. These design models employ finite element analysis techniques coupled with machine learning methods.

Sergio Cavalaro

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School of Architecture, Building and Civil Engineering, Loughborough University

Professor Sergio Cavalaro is a civil engineer with 15 years of experience in building materials and structural engineering research and practice. His areas of research encompass innovative manufacturing processes for construction (Hybrid 3d printing), structural design, building materials (UHPC, FRC and other advanced cementitious composites), advanced modelling of cementitious materials performance and production processes (FEM, DEM, CFD), and durability (reinforced concrete corrosion and sulphate attack) applied to delivery and maintenance of infrastructure and buildings. He has led and worked in 14 publicly-funded, peer-reviewed research projects worth more than £5.3m to address urgent challenges in his field. He has published 80 refereed publications and supervised 16 PhD students to successful completion. He has a strong track record of collaboration with major stakeholders from the construction sector, equating to an enterprise income of more than £2.3 M. He has acted as an expert consultant in major infrastructure projects to solve challenging issues related to his research field. In 2018 He was awarded the RILEM Gustavo Colonnetti Medal for outstanding scientific contribution to the fields of construction materials and structures.

Ruchi Choudhary

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Department of Engineering, University of Cambridge

I work on energy use in buildings. My research concerns energy simulation models for decarbonisation of buildings; uncertainty quantification in simulation models; urban-scale energy system planning and optimization, including geothermal systems; and urban integrated agriculture. At Cambridge, I lead a multi-disciplinary research group called the Energy Efficient Cities initiative. I find the use of simulation modelling to investigate interactions among synergistic systems in cities especially exciting. For example, extracting waste heat from underground infrastructure synchronized with heating demand above ground, as well as with the hydrogeological conditions below ground. Prior to joining Cambridge in 2008, I was Assistant Professor of building technologies in the College of Architecture at Georgia Institute of Technology in Atlanta, USA (2004-08). From 2018-2022 I was Group Leader in the Data-centric Engineering Programme at the Alan Turing Institute, where I lead research on Digital Twins of Built Environments. I have also taught in the Sustainable and Environmental Design Unit at the Architecture Association in London (2007-09). I received my PhD in Architecture from the University of Michigan in 2004. I am Fellow of the International Building Performance and Simulation Association since 2019 and chaired its England chapter from 2018-2023.

Patricia Culligan

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Patricia Culligan is the Matthew H. McCloskey Dean of the University of Notre Dame's College of Engineering. Culligan previously was Department Chair and Carleton Professor of Civil Engineering and Engineering Mechanics at Columbia University. While at Columbia, she was the founding associate director of Columbia's Data Science Institute; a member of the Executive Committee of the Earth Institute; and Co-Founder of the Collaboratory @Columbia, which supports the development of cross-cutting curricula for a data-rich world. She also served as the vice dean of academic affairs for Columbia Engineering. Culligan is a Chartered Engineer registered with the UK Engineering Council and a Fellow of both the American Society of Civil Engineers and the British Institution of Civil Engineers. She is internationally recognized for her expertise in water resources and geo-environmental engineering. Her research focuses on the application of advanced measurement, sensing and modeling techniques to improve water, energy, and environmental management. Some of her most recent work examines the role of green infrastructure in supporting urban sustainability and human health and well-being in the face of environmental stressors. Culligan earned her doctorate and master's degrees in engineering from the University of Cambridge. She holds a bachelor's degree in civil engineering from the University of Leeds. She also earned a diploma in language, literature, and civilization from the Université d'Aix-Marseille III. She is the author or co-author of seven books, seven book chapters, and more than 175 technical articles. In 2021, she was awarded the H. Bolton Seed Medal from the American Society of Civil Engineers for expanding the boundaries of geo-environmental and sustainability engineering.

Cliff Davidson

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Department of Civil and Environmental Engineering at Syracuse University in Syracuse, NY

Cliff Davidson is the Thomas and Colleen Wilmot Professor of Engineering in the Department of Civil and Environmental Engineering at Syracuse University in Syracuse, NY. He also serves as SU Director of Environmental Engineering Programs. He received his B.S. in Electrical Engineering from Carnegie Mellon University, and his M.S. and Ph.D. degrees in Environmental Engineering Science from California Institute of Technology. Following his PhD, he was a member of the Carnegie Mellon faculty for 33 years before moving to Syracuse University in 2010. Davidson's research background is in the area of air quality, especially aerosol interaction with surfaces. He has also worked on environmental sustainability in other areas, such as the design of sustainable cities, the effectiveness of green roofs in reducing urban stormwater runoff, educational innovations for teaching sustainable engineering, and identifying the preferences of individuals and organizations for strategies to adapt to climate change. He has published over 150 papers in refereed journals and another 100 papers in peer-reviewed conference proceedings and book chapters. He is a past president of American Association for Aerosol Research (AAAR), and he served as the Distinguished Lecturer for 2022-2023 for the Association of Environmental Engineering and Science Professors (AEESP). He is a Fellow of AAAR, AEESP, and the American Society of Civil Engineers.

Craig A. Davis

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C. A. Davis Engineering

Craig A. Davis, Ph.D., PE, GE is a professional consultant with C A Davis Engineering on geotechnical, earthquake, and lifeline infrastructure system resilience engineering. During his 32-year career at the Los Angeles Department of Water and Power, Water System (LADWP) he worked as the Departmental Chief Resilience Officer, Resilience Program Manager, Seismic Manager, Geotechnical Engineering Manager and Trunk Line Design Manager. Dr. Davis developed a comprehensive LA Water System resilience program and is involved in creating policy for improving infrastructure systems to threats and hazards. He has worked on the development of numerous underground structures including large tanks, reservoirs, tunnels, and pipelines, and buried concrete structures. He is involved in the utilization of hazard resilient pipes, instigating development of a resilient pipe industry, and applications to create resilient networks using performance-based methodologies. He is a California licensed Civil and Geotechnical Engineer and received a Ph.D. in Civil Engineering with emphasis in geotechnical earthquake engineering from the University of Southern California in 2000. Dr. Davis has served on many national advisory boards and councils, national and international professional committees, received several prestigious awards, and published 180 papers, books and contributions.

Jason T. DeJong

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Civil & Environmental Engineering, University of California

Professor Jason T. DeJong is the Director of the UC Davis Center for Geotechnical Modeling and the UC Davis lead for the NSF ERC Center for Bio-mediated and Bio-inspired Geotechnics. Prof. DeJong's major technical contributions have been in the areas soil and subsurface characterization, earthquake engineering, bio-mediated and bio-inspired geotechnics, and geotechnical sustainability. Jason has developed several in situ and laboratory tools as well as associated analysis and interpretation techniques to guide characterization of challenging soils and decision making in engineering practice. In compliment, he has worked at incorporating variability and uncertainties in subsurface conditions into engineering analyses using geostatistical modeling. Jason is one of the pioneers of biogeotechnics, leading the development of novel technologies and helping guide the maturation of this emerging field. He has also worked to incorporate life-cycle sustainability analysis into prioritizing research opportunities and design alternatives evaluation. Results from his research program have been disseminated through 250 publications and he is currently chair of the ISSMGE TC102 In situ Testing committee. Prof. DeJong has served as a reviewer or technical advisor on several civil infrastructure projects.

Flavia De Luca

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School of Civil, Aerospace and Design Engineering, University of Bristol

Dr De Luca is a structural and earthquake engineer with expertise on soil-structure interaction, structural reliability, performance-based design and disaster risk reduction related associated to natural hazards. Her current focus are sustainable infrastructures in the context of UN SDG. Flavia awarded her PhD in Seismic Risk at the University of Naples Federico II in 2012 and, after an experience as post-doctoral researcher at the same institution, she joined the University of Bristol in 2014 as lecturer. Dr De Luca has more than ten years' experience in structural engineering with expertise of experimental campaigns delivered within international projects such as Horizon2020 and EPSRC. She is an active consultant as earthquake engineer for the structural and nuclear industry I the UK. She was part of the delivery team of the national Soil-Structure interaction facility at the University of Bristol and she has long-term experience with post-earthquake reconnaissance missions in Europe (Italy and Spain) and Asia (Nepal). Flavia is currently Associate Professor and Faculty PGR Director for Engineering at the University of Bristol.

Juliano Denicol

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Dr Juliano Denicol is the Director of the Megaproject Delivery Centre at UCL and the founding Programme Director of the MBA Major Infrastructure Delivery. Before joining UCL, Juliano has worked as a supply chain management consultant at High Speed 2, the largest infrastructure project in Europe, and advisor to the European Commission on public procurement policies. As Global Head of the IPMA Megaprojects SIG, Juliano coordinates a global platform with more than 70 countries to advance our understanding of megaproject delivery. He is the founder and director of the IPMA-UCL The Megaproject CEO and IPMA Megaprojects Book Club, two global platforms to discuss concepts and practices with leading megaproject authors and CEOs. He was Co-Investigator of Project X, a major research network that aims to improve major project delivery in the UK, established by nine universities in collaboration with the Infrastructure and Projects Authority (IPA), and the Cabinet Office. Juliano's work on megaprojects has been regarded of high global impact receiving multiple research awards, including the prestigious: PMI Young Researcher Award - Project Management Institute (PMI) (2023), Project Management Research Paper of the Year Award - Association for Project Management (APM) (2022), and the Global Young Researcher Award - International Project Management Association (IPMA) (2019).

Irem Dikmen

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School of Construction Management and Engineering, University of Reading

Irem Dikmen is a professor of construction engineering and management in the University of Reading. She carries out research at the interface of engineering, management, and decision sciences. Her research interests relate to construction project management, mainly risk modelling and management. She combines theories and methods from various disciplines to analyse complexity, risk and resilience in construction projects. She uses systems thinking to model project systems and explore engineering project organizations. She conducts research to explore actuality of projects and develop decision-support systems/tools in collaboration with industrial partners. She has hands-on practical experience in the construction industry as a consultant, expert witness and DAB member in resolution of disputes. Her recent research and development projects include risk information modelling and visualisation in mega infrastructure projects, managing project risk and complexity with digital twins and assessment of social value in infrastructure projects.

Tom Dolan

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Dept of Civil, Environmental & Geomatic Engineering, University College London

Holistic, ecologically minded, systems thinking researcher, with a penchant for asking awkward questions. Simultaneously a Senior Research Fellow for UKCRIC and Postgraduate Fellow for C-DICE, Tom's research is focused on:

- The Climate Emergency as a Wicked Problem of problems comprising 3 deeply interdependent wicked problems i) achieving global net zero by 2050, ii) enhancing systemic and societal resilience to the disruptive impacts of at least 1.5^0C and iii) enhancing global sustainability.
- The potential role that infrastructure system transformation can play as globally replicable leverage points at the heart of a transformative climate emergency strategy.
- The importance of outcome-oriented infrastructure governance frameworks and decision-making processes closely aligned with current social priorities.
- the societal and economic value of establishing a Net Resilience Gain culture across the infrastructure industry

Tom is a passionate advocate for UKCRIC's Scientific Missions, and believes that Infrastructure systems can, and must be: Systemic enablers of equitable, inclusive, fair, affordable societally beneficial outcomes; Systemically resilient systems that enhance overall societal resilience; Sustainable Net Zero pollution systems that enable the emergence of sustainable, net zero pollution, societies; underpinned by Fit for Purpose Governance +++structures and business models purposefully aligned with the outcomes and qualities specified above.

Colin Eddie

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School of Engineering, University of Warwick

Colin is an expert in the design and construction of tunnels and underground space. He has 38 years' experience in the tunnelling industry and has an intimate working knowledge of current best practice in both the design and construction of tunnels. This includes a detailed knowledge of all forms of temporary and permanent construction methodologies in use today. Colin actively manages a research and development program, and has personally introduced numerous innovations that have improved safety, efficiency and quality in recent major projects. In recognition of his expertise, Colin was invited to become a Fellow of the Royal Academy of Engineering in 2005 and in 2015, he was appointed as Royal Academy Visiting Professor of Innovation and Tunnelling at the University of Warwick. He was awarded the John Mitchell Gold Medal by The UK Institution of Civil Engineers in 2014 for his significant contribution to tunnelling. Until recently Colin was engineering director of one of the UK's largest tunnelling firms and managing director of the in-house design consultancy business. In 2017 Colin formed his own consultancy business, and has been responsible for the management of a specialist underground engineering department, which has designed some of the largest underground projects in the UK. Over the past two decades, he has managed the implementation of over £2.5bn of tunnelling work.

Amanda Elioff

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Amanda Elioff's background is in planning, design development, and delivery, for light and heavy rail subway systems. She has served as Deputy Project Director, Project Manager, and Engineering Manager for multiple phases of Los Angeles Metro's system development: Her responsibilities have included conducting geotechnical investigations and feasibility studies; developing specifications; preparation of geotechnical baseline reports; and providing design support during construction. Amanda's design and construction experience also includes water and wastewater tunnels and an underground physics research facility. She has worked on design criteria for underground structures, and design/testing of mitigation measures for construction in gassy underground conditions. Currently, she is WSP's Manager for Section 1 of the Purple Line Extension project under construction in Los Angeles, and Engineering Manager for San Francisco Bay Area's Link21 Planning and Engineering Team (ARUP/WSP JV), studying a second Bay Tunnel Crossing and Megaregional transportation. Amanda has been active in professional associations: American Society of Civil Engineers (ASCE- Past President, LA Branch), Director - American Underground Construction Association, and VP, International Tunneling Association. Recently, she was a member of the committee preparing the ASCE publication "Geotechnical Baseline Reports: Suggested Guidelines." (3rd edition 2022). This Manual of Practice explains the role of GBRs in allocating and managing risks associated with subsurface construction. Amanda holds MS and BS degrees from the University of Texas, Austin.

David Garner

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Cadent Gas

Dave Garner is the Head of Engineering (2 Bar and Below) for Cadent Gas, the largest gas distribution network in the UK. Dave joined Cadent's predecessor company in 1998, and has worked in many engineering and IT roles across the organisation. His current role sees him as custodian of Cadent's engineering framework for the distribution network with responsibility for engineering policies, procedures and definition of competence ensuring legislative compliance, asset integrity and practicable application. Through his role at Cadent, he plays a significant part across the industry, leading strategically on sensitive matters and shaping industry policy and standards. He leads Cadent's engineering relationship with HSE, having managed the response to the Multi Occupancy Building issues following the Grenfell Tower incident and leads on our adaption to extreme weather resilience and the increased risk of theft of gas. Dave plays a central role in agreeing Cadent approved programme for iron mains decommissioning and replacement, along with other risk controls associated with Cadent's underground plant such as a range of enhancements to plant protection processes.

Lizan Gilbert

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Kiewit Infrastructure Co.

Lizan has been in the underground industry for over 23 years. She is a Geotechnical Engineer by trade and started her career as a design consultant. For 11 years as a designer, she worked primarily in Central Texas on infrastructure projects including water transmission and wastewater interceptors, highway expansions, foundation design for residential to high-rise buildings, and waterways stabilization. Throughout, her career favored the underground components of each project. For the past 12 years, Lizan has worked in the underground construction industry. She has built projects around the country primarily for municipalities and regional communities. Her projects were typically small- to medium- diameter, TBM tunnels. Her design experience allowed her the opportunity to bring a unique perspective to the projects in the form of innovations and efficiencies, creating a focus on Alternative Delivery. Currently, Lizan works for Kiewit Infrastructure in the Underground District helping to deliver complicated infrastructure projects around the country. She specializes in hard rock TBM, conventional excavations, and hand-mining projects. Her notable projects include infrastructure improvements in the water and transportation sectors. Lizan was elected by her peers to The Moles class of 2021, heavy civil industry's most prestigious fraternal organization, for her leadership, dedication to promoting the industry, and passion for encouraging young people to pursue a career in heavy civil construction.

Kazi Hasan

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National Highways

Chartered Civil Engineer and Head of Drainage at Safety, Engineering and Standard Division, National Highways. Custodian and author of DMRBs and MCHW on highway drainage, responsible for reviewing and updating standards and approving departures from standards. Responsible for setting up drainage asset management strategies and implementation plan at national level. Previous experience included managing drainage design projects for residential and commercial developments, peer review of drainage design and abnormal cost, hydraulic modelling and flood risk assessment. Extensive experience in highway and railway drainage design. Over 17 years' experience of works in different sectors in the UK Construction Industry.Research and consultancy experience in monitoring and measuring methane potential from landfill sites and modelling of gas simulation from landfill sites. Experience gathered in contaminated land including site investigations, risk assessments and remediation.

Youssef Hashash

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The Grainger College of Engineering, University of Illinois Urbana-Champaign

Professor Hashash joined the faculty of the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign in 1998. His research focus includes deep excavations and tunneling in urban areas, earthquake engineering, continuum and discrete element modeling and soil-structure interaction as well as resiliency and sustainability of the built infrastructure. He also works on geotechnical engineering applications of deep learning, artificial intelligence, visualization, augmented reality, imaging and drone technologies. He has published numerous journal articles and is co-inventor on four patents. His research group developed the software program DEEPSOIL that is used worldwide for evaluation of soil response to earthquake shaking. His work on seismic design of underground structures is extensively used in engineering practice. He is the geotechnical co-leader of the NIST (National Institute of Standards and Technology) led investigation into the Champlain Towers South Collapse in Surfside, Florida. Professor Hashash is a Fellow of the American Society of Civil Engineers (ASCE), a past president of the Geo-institute of ASCE and has received a number of teaching, university and professional awards including the Presidential Early Career Award for Scientists and Engineers and the ASCE 2014 Peck medal. He was elected to the National Academy of Engineering in 2022.

Arun Jaganathan

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Civil Engineering, Construction Engineering Technology, Molecular Science and Nanotechnology, Louisiana Tech University

Dr. Arun Jaganathan is an Associate Professor of Civil Engineering at the Louisiana Tech University. He is associated with the Trenchless Technology Center (TTC) of the Louisiana Tech. His research is focused on the development of advanced sensors for non-destructive testing and imaging of buried infrastructure. He has strong multi-disciplinary research experience, and has been involved in the development of electromagnetic radar and elastic wave based sensors the imaging and condition assessment of buried pipes. He is also involved in developing “see-ahead” sensors for the Horizontal Directional Drilling (HDD) equipment to prevent mechanical damage during underground drilling operations. He is actively involved in collaborating with industrial partners and technology commercialization activities. The Ultra-wideband (UWB) radar he helped develop for pipeline inspection has been licensed to an industrial partner and commercialized in the past. He holds 7 patents in the area of pipeline inspections.

Holger Kessler

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British Geological Survey

25 years' experience in developing scientific, technical, operational and policy solutions to geoscience issues at local, regional and national scales. My broad knowledge of the geoscience sector has been generated by listening to real world requirements of schools, universities, town and county halls, contractors, consultants, asset owners, utility companies, international partners, regulators and government. I focus my energy on making geoscience data, information and knowledge available and accessible to improve planning and decision making particularly in the environmental, water resource, engineering and infrastructure sectors. From 2018-2023 I led on the research phase and stakeholder engagement during the build phase of the UK National Underground Asset Register. I am currently on secondment to the Government Office for Science where I lead a Foresight project 'Future of the Subsurface' identifying gaps in knowledge, policy, regulations and coordination related to subsurface resources.

Debra Laefer

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Tandon School of Engineering, New York University

Dr. Debra Laefer is a Professor of Urban Informatics at New York University in the Center for Urban Science and the Department of Civil and Urban Engineering. She holds undergraduate degrees in Art History and Civil Engineering from Columbia University, a masters' degree in Civil Engineering from New York University, and her doctorate from the University of Illinois at Urbana-Champaign looking at the impact of excavation on adjacent structures. Prof. Laefer's work often stands at the cross-roads of technology creation and community values such as devising technical solutions for protecting architecturally significant buildings from sub-surface construction. Her current research interests focus on subsurface utility and geotechnical data integration with high density above ground laser scanning, hyperspectral imagery and historical data about the built environment and its forgotten remnants as a way to both understand urban spaces and to manage them. She is the 2022 recipient of the ASCE Harry Schnabel award for contributions in the area of earth retaining systems. Her work has been funded by the National Science Foundation, the US Department of Defense, and the European Research Council.

Andy Lawrence

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Engineering and Physical Sciences Research Council, UK Research and Innovation

Andy Lawrence is the Head of Engineering at the Engineering and Physical Sciences Research Council (EPSRC) as part of UKRI, and has been responsible for strategy and delivery of EPSRC's investment in engineering research across UK academia since September 2016. The theme covers a diverse portfolio of civil, mechanical, chemical and materials engineering disciplines, in addition to enabling technologies and systems, such as robotics, and parts of biomedical and electrical engineering. He has led numerous impactful schemes such as the Engineering Engagement Champions and the National Fellowships in Fluid Dynamics, and most recently initiated the Tomorrow's Engineering Research Challenges activity. Andy joined EPSRC in 2007 and has held roles in EPSRC's Strategy and Planning team providing support to the Executive Leadership team and in senior portfolio manager positions in the Manufacturing the Future and ICT themes. Prior to his career at EPSRC, Andy gained a PhD in Atmospheric dynamics from the University of Cambridge and held academic research posts at the British Antarctic Survey, Massachusetts Institute of Technology and the European Centre for Medium-Range Weather Forecasts.

Joanne Leach

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UK Collaboratorium for Research on Infrastructure and Cities

Joanne's research interests can be found at the intersection of liveability, sustainability and resilience, with an emphasis upon research integration, transdisciplinary working practices and the science of team science. Her research focuses upon the link between the built environment, infrastructure and wellbeing and in translating research outcomes to influence how people think about infrastructure and cities. Joanne is currently the Executive Manager of the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC), which is creating a world-class national cities and infrastructure research capability.

Mosi London

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Arlington County Department of Environmental Services

Dr. Mosi London, Principal Planner at the Arlington County Department of Environmental Services, leverages his diverse expertise in civil engineering, transportation, infrastructure, and emergency management to create sustainable and efficient transportation systems. He boasts extensive experience in project management, planning, research, and instruction, focusing on areas like performance evaluation, transportation-environment interactions, and local/national policy development. Dr. London's passion lies in using his expertise to create sustainable and efficient transportation systems that benefit both communities and the environment. He achieves this through a combination of diverse skills, extensive experience, and a commitment to collaboration and public engagement.

Fleur Loveridge

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School of Civil Engineering, University of Leeds

Fleur is a civil engineer who has worked in practice and academia and is accustomed to working across disciplines on problems related to infrastructure resilience and the energy transition. Her work, united by the pressing nature of the climate crisis, has two main themes. The first considers understanding the vulnerability of our geotechnical infrastructure to climate change and what we can do to improve resilience. She has a track record in understanding soil-atmosphere-vegetation interactions, their consequences, and translating learnings for a practical audience. The second theme relates to how we can use the ground and underground infrastructure to provide low carbon heating and cooling solutions for society, and how we can integrate between different infrastructure types. She has worked on heat transfer analysis around buried structures, heat pump system performance, district heating integration and policy translation for heating decarbonisation. Fleur is a Chartered Engineer and a Chartered Geologist and is often found at the intersection between civil and mechanical engineering, and applied geoscience.

Alec Marshall

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Alec's main interests relate to the built underground environment, with specific expertise relating to tunnelling, pipelines, foundations, and the interaction between these systems during construction within congested urban areas. He has been actively involved in research and consulting relating to a wide variety of civil/geotechnical engineering topics for over 20 years. He completed his Bachelor's and Master's degrees at the University of Waterloo in Canada and then worked as a consulting engineer with Mott MacDonald in London, UK, before returning to research to obtain his PhD from the University of Cambridge in 2009. Alec is now Head of Group for the University of Nottingham Centre for Geomechanics (NCG) and has authored over 100 Scopus indexed papers on the topics of physical, numerical, and analytical modelling of geotechnical problems, including the 2016 British Geotechnical Association Medal winning paper. Much of Alec's research makes use of experimental methods, in particular geotechnical centrifuge testing, and he pioneered the use of hybrid centrifuge-numerical modelling for tunnel-structure interaction analyses, with the aim of acquiring more accurate/realistic models of the global interaction behaviour. He has managed several large, multi-partner research projects within the UK and Europe and has supervised or co-supervised 15 completed PhDs.

Nicole Metje

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School of Engineering, University of Birmingham

Nicole Metje is Professor of Infrastructure Monitoring and Head of Enterprise, Engagement and Impact within the School of Engineering at the University of Birmingham, UK. She is also the Director of the National Buried Infrastructure Facility (NBIF) part of the UK Collaboratorium for Research on Infrastructure and Cities and the co-Director of Birmingham's Institute of Quantum Technologies. Nicole leads the Geophysics research of the Birmingham-led Quantum Technologies Hub for Sensors and Timing and works closely with industry to develop sensors and novel processing methods to see through the ground to ensure that any excavation is safer and results in fewer delays. Nicole is also involved in several utility committees both in the UK and internationally developing standards and working on best practice and training. Her paper on assessing the impact of PAS128 in the UK has won the ICE's James Hill prize in 2021. Nicole's involvement in the Underground Service Protection (USP) Competency Framework (https://uspcompetency.co.uk) was recognised by the team winning LSBUD's 'Best Safe Working Campaign' in 2023 which aims to overcome the inconsistency related to competency in duties relating to underground services with gaps in training, knowledge and experience being the norm, and not the exception.

Ana Mijic

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Ana is a Reader in Water Systems Integration and Director of the Centre for Systems Engineering and Innovation with >15 years' experience in water systems modelling and water infrastructure planning. Her expertise in development of novel simulation tools focused on quantifying interactions between the water cycle and human activities will be crucial for improved evaluation of carbon, environmental and service provisioning targets of water systems. She has published >50 papers, with >1,450 citations since 2017 (h-index=19). Ana has extensive research projects experience – she has been a PI/Co-I on multiple UK and international research projects with a total value of >£18M, including NERC RISE £4M CAMELLIA programme, in which she is leads the Systems Theme Lead and development of a state-of-the- art whole-water system model that will underpin our new integrated analysis and assessments of decarbonisation pathways. Ana is the PI of the £810k EPSRC VENTURA project, which develops virtual decision rooms for water neutral planning, and she is leading the £340k DAFNI STFC Resilience scenarios for integrated water systems project. In 2022, Ana was awarded prestigious Satish Dhawan Visiting Chair Professorship at the Indian Institute of Science in Bangalore.

Elise Miller-Hooks

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Sid & Reva Dewberry Department of Civil, Environmental, and Infrastructure Engineering, *George Mason University*

Professor Elise Miller-Hooks holds the Bill and Eleanor Hazel Endowed Chair in Infrastructure Engineering and is the Interim Department Chair of the Sid & Reva Dewberry Department of Civil, Environmental, and Infrastrucure Engineering at George Mason University. She has served as an advisor to the World Bank Group and is the founding Editor-in-Chief of Elsevier's Sustainability Analytics and Modeling journal. Prior to her appointment at Mason, Dr. Miller-Hooks served as a program director at the US National Science Foundation and on the faculties of the University of Maryland, Pennsylvania State University and Duke University. Dr. Miller-Hooks received her Ph.D. (1997) and M.S. (1994) degrees in Civil Engineering from the University of Texas – Austin and B.S. in Civil Engineering from Lafayette College (1992). She has expertise in: disaster planning and response; multi-hazard civil infrastructure resilience quantification and infrastructure protection investment; sustainability; intermodal freight transport, including maritime transport, port operations, and supply chains; real-time routing and fleet management, e.g., paratransit, ridesharing, bikes and delivery; hazmat transport; stochastic and dynamic network algorithms; and collaborative and multi-objective decision-making.

Priscilla Nelson

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Colorado School of Mines

Dr. Priscilla P. Nelson came to the Colorado School of Mines in 2014 as Professor and Department Head of Mining Engineering. She has an international reputation in geological, civil and tailings engineering. Dr. Nelson has published more than 180 technical and scientific publications, and she is a Distinguished Member of the American Society of Civil Engineers (ASCE), former president of the Geo-Institute of ASCE, a lifetime member and first president and Fellow of the American Rock Mechanics Association. Dr. Nelson is a Mole, Tau Beta Pi Eminent Engineer, and she received the Kenneth Andrew Roe Award from the AAES, and the Henry L. Michel Award from ASCE. In 2016 she was identified as a Global Inspirational Women in Mining (by WIM/UK), and in 2018 she received the Outstanding Educator award from UCA of SME. In 2020, she founded the Tailings Center as a collaboration with Colorado School of Mines, Colorado State University, and the University of Arizona. She received her BS degree in geology from the University of Rochester (1970) and two master's degrees in geology (Indiana University, 1976) and structural engineering (University of Oklahoma, 1979). In 1983, she received her PhD degree from Cornell University.

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Dr Jelena Ninić is Associate Professor of Digital Engineering at the School of Engineering, University of Birmingham, since 2022. Before, she was Assistant Professor in Structural Engineering at the University of Nottingham from 2018, where she also held a Marie Curie Individual Fellowship from 2016 to 2018. In 2015, she obtained her PhD at Ruhr University Bochum, Germany. Her research combines intelligent computing, computer vision and machine learning, computational mechanics, and Building Information Modelling (BIM) with application to structural and geotechnical problems. Her two main research areas are i) the integration of design and analysis through a unified platform combining BIM and numerical simulations, and ii) intelligent computing strategies for the holistic prognosis of soil-structure interaction and steering of construction to minimise environmental impacts. Jelena has published more than 70 research papers, including over 32 refereed articles in high-impact journals, and three book chapters. She has (co)organised three international conferences (EG-ICE 2017, CTTU 2020 and UKACM 2022), is associate editor of "Tunnelling and Underground Space Technology" (TUST), a high-impact journal in the field. She is core member of ISSMGE TC222 for Geotechnical BIM and Digital Twins and UKACM EC member. She was PI for three European research projects totalling €2M. She (co-)supervised seven PhDs to completion and is currently involved in the supervision of 8 PhD students (5 as first supervisor) in structural and geotechnical engineering.

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Esdras is an Assistant Professor in Geotechnical Engineering at the Department of Civil Engineering, School of Engineering, University of Birmingham, UK. His research interests include ground engineering, sustainability, infrastructure resilience and adaptability, erodibility and deformation characteristics of geomaterials, buried infrastructure and facilities, linear transport (road and railway) infrastructure and asset management. Please liaise with Esdras if you are interested in any of these research areas for a PhD, postdoctoral or research collaboration programme.

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Tom O’Rourke is the Thomas R. Briggs Professor of Engineering Emeritus in the School of Civil and Environmental Engineering at Cornell University. He is a member of the US National Academy of Engineering, Distinguished Member of ASCE, International Fellow of the Royal Academy of Engineering, Member of the Mexican Academy of Engineering, and a Fellow of the American Association for the Advancement of Science. He received a number of distinctions for his research and teaching. He gave the 2009 Rankine and 2016 Terzaghi Lectures. He served as President of the Earthquake Engineering Research Institute (EERI) and as the chair or member of many professional society committees. He authored or co-authored over 430 technical publications. His research interests cover geotechnical engineering, earthquake engineering, underground construction technologies, engineering for large, geographically distributed systems, and geographic information technologies and database management. He served on government advisory boards, as well as the consulting boards or peer reviews for many projects associated with highway, rapid transit, water supply, and energy distribution systems.

Robert E. Paaswell

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Dr. Robert Paaswell is a Distinguished Professor of Civil Engineering at the City College of New York, the flagship institution of The City University of New York (CUNY). He served as its Interim President from 2009-2010. He is the emeritus Director of the College’s University Transportation Research Center, Region II, which he led for 19 years and the founding Director (2001-present) of the CUNY Institute for Urban Systems (CIUS). He served as Site Director of the new NSF sponsored Industry/University Cooperative Research Center: Sustainably Integrated Buildings and Sites Center. He is a founder of the Rangel infrastructure Workforce Initiative (2020) – concerned with training a 21st C. workforce for the Infrastructure industry.

Prior to his roles at CCNY, Paaswell served as the CEO (President) of the Chicago Transit Authority – the nation’s second largest transit system (1986-1989). Dr. Paaswell is an internationally recognized expert in public transportation issues and consulting. He has reported on governance structures for US transit organizations, public-private issues in New York and Chicago, and labor union/management issues. He served as an advisor to the Israeli government concerning restructuring of their bus companies, and issues of competition. He was a charter member of the (National Academies) Transit Cooperative Research Program and served as a member of its Board for 6 years. Full Biography

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Dr Debra Phillips has 25^{+} years experience in Environmental Engineering and Soil Science. Before joining Civil Engineering at Queen's University Belfast, she worked in the Environmental Sciences Division at Oak Ridge National Laboratory, Tennessee, USA. Her research focuses on fate and transport of contaminants in the subsurface, site characterisation, remediation of contaminants in the environment, ecological restoration, and drinking water treatment. She has a broad range of field and laboratory expertise which include, morphological, chemical, physical and mineralogical analysis of soil/rock material, water analysis/monitoring, and use of geographical information systems.

Mark Reiner

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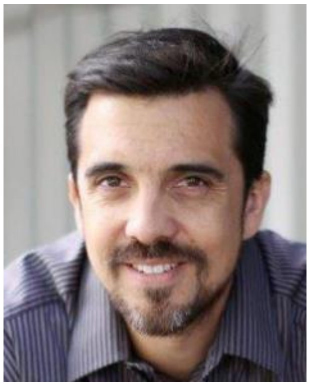
25 years of experience as a professional engineer, and geologist. Served as project engineer for dams and tunnels, co-lead infrastructure sustainability for Kigali, Rwanda before leaving Tetra Tech in 2005. The next 16 years were focused on implementing innovative geospatial solutions for engineering and utility related issues from aging infrastructure to monthly city carbon footprint updates. During this time, I founded two geospatial application focused companies that were acquired by AEC firms; Symbiotic Engineering – energy/water/carbon intensities at a meter level – acquired by ICF in 2012, and WISRD – identifies cross-sector vulnerabilities for cities/campuses/installations – acquired by Jacobs in April 2021.

My current position as Director of Resilient Infrastructure at Jacobs allows for refining applications for WISRD (now called Kaleidoscope) for Capital Expenditure prioritization for campuses and military installations. The intended purpose of Kaleidoscope is to engage in more proactive subsurface infrastructure planning and identify what limits and barriers prevent the adaptive flexibility and innovation of our utility systems, that results in chronic vulnerabilities. This work and interest led to my inclusion in the NYC's DDC Town and Gown "Utilidor Working Group" since 2018. The remains of WISRD is now my blog site www.wisrd.com



Tonatiuh Rodriguez-Nikl

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Dr. Rodriguez-Nikl earned a Ph.D. in Structural Engineering. His research projects have investigated the response of structures to explosive blasts and earthquakes using experimental, analytical, and computational approaches. During the last seven years Dr. Rodriguez-Nikl served on the leadership team of the University Transportation Center for Underground Transportation Infrastructure and conducted related research (resilience and sustainability, advanced liner materials, automated damage detection, and prediction of in-situ conditions). His recent research interests have grown to include a wider range of interdisciplinary topics related to the broader impacts of technological development. Topics he has explored include systems thinking, the role of engineering in addressing contemporary challenges, and engineering ethics, including a textbook on the subject. His professional service activities have included terms on sustainability committees of the Structural Engineering Institute (SEI) and the American Concrete Institute and the Engineering Philosophy Committee of the SEI. Dr. Rodriguez-Nikl is an associate editor for the journal Civil Engineering and Environmental Systems. As part of the editorial board, he led a special issue, published in 2022, on systems approaches to the use of underground space in urban environments. Dr. Rodriguez-Nikl is also an active contributor to the Planetary Limits Academic Network.

David Richards

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David is a Professor in Ground Engineering and Head of the School of Engineering, Faculty of Engineering and Physical Sciences at the University of Southampton. Technical interests include the geotechnical aspects of ageing infrastructure, large-scale field monitoring, the engineering behaviour and characterisation (pre and post processed) of landfill wastes, and the mechanical characterization of chalk using CT imaging techniques and cyclic simple shear tests. He has undertaken extensive studies into the rate loading effects of electricity transmission tower (shallow) footing systems involving both scaled physical modelling techniques in a geotechnical centrifuge and through field monitoring. He is PI for the £26M BEIS/EPSRC funded UKCRIC National Infrastructure Laboratory on the Boldrewood Campus and UKCRIC Coordination Node (CN) Director of Strategy – the CN is working to deliver a networked suite of national research test facilities. Working with industrial collaborators and recent graduates, he leads the Civil Engineering Part 1 Constructionarium located at the National Construction College, Norfolk. David was awarded a Gledden Senior Visiting Fellowship by the University of Western Australia, Centre for Offshore Foundation Systems in 2001. He is a co-recipient of the IMechE Thomas Hawksley Gold Medal and the John F Alcock Memorial Prize, 2007, an ICE Telford Premium, 2009 and the ICE Curtin Medal, 2016. David is also Head of UKCRIC Test Facilities.

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Chris’ research interests cover the sustainability, resilience and liveability of cities, infrastructure and urban systems, and how systemic changes can be designed and implemented to realize greatest value. He focusses on buried infrastructure, utility services, urban metabolism, structural performance of roads, use of underground space and infrastructure systems’ interdependencies. Recent research includes robots for streetworks, swarms of small robots for pipeline condition assessment, Net Zero roadworks & streetworks, and the advancement of trenchless technologies. Chair of the Institution of Civil Engineers’ Research, Development & Innovation Panel from 2011-2021, a member of the Lead Expert Group of the UK Government Foresight Future of Cities project and founder member and Executive Committee member of the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC), he has been appointed to the Department for Transport College of Experts. He led the bid for the £27.6m National Buried Infrastructure Facility that followed a £10m, 10-year research programme using remote sensing technologies to locate, map and assess the condition of buried pipelines and cables – the Mapping and Assessing the Underworld projects. His recently-published Theory of Change embraces: stakeholder identification, synthesis of stakeholders’ aspirations, system mapping, problem diagnostics, baseline functional performance, sustainability and far-future resilience assessment, business models and governance.

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J. Carlos Santamarina (Professor, Georgia Tech) graduated from Universidad Nacional de Córdoba and completed graduate studies at the Universities of Maryland and Purdue. His research team combines experimental and numerical methods to study geomaterials in the context of energy geo-science and engineering, with contributions from resource recovery to energy and waste geostorage. He delivered the 50th Terzaghi Lecture on Energy Geotechnology, was a British Geotechnical Association Touring Lecturer and is member of both Argentinean National Academies.

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Dr. Sinha is director of the Sustainable Water Infrastructure Management (SWIM) Center. Dr. Sinha's research, teaching, and consulting are in the areas of infrastructure management, sustainability, resilience, pattern recognition, sensor informatics, and artificial intelligence. He has a total of seven years of practical experience in the infrastructure industry. Dr. Sinha was the seed behind a Public Broadcasting Service (PBS) multimedia documentary titled "Liquid Assets: The Story of Our Water Infrastructure," that throws light on a long-buried problem ~~ America's aging water systems. The film is a startling look at water services that Americans use every day, but rarely consider. He has given many NPR interviews and featured as a water expert in a History Channel documentary titled "The Crumbling of America". Dr. Sinha is working on a documentary that will show how we can empower new approaches, and inspire the next generation, to better meet our water needs and challenges.

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Dr. Janille Smith-Colin is the J. Lindsay Embrey Trustee Assistant Professor of Civil and Environmental Engineering at Southern Methodist University. Janille’s research advances the cross-cutting themes of equity, sustainability, and resilience in civil infrastructure management, with a specific focus on multi-modal transportation systems. The Smith-Colin Research Group focuses on (1) planning and designing socially sustainable and resilient infrastructure (2) equity-based analysis of emerging transportation technologies, (3) transportation as social-determinant of health, and (4) community-engaged civil engineering education and research. Prior to her doctoral studies, Dr. Smith-Colin worked for a state Department of Transportation and in civil engineering consulting. At the DOT, she worked in Intermodal Systems Planning. Dr. Smith-Colin is a member of the Transportation Research Board Standing Committee on Transportation Planning Analysis and Application (AEP15) and co-chair of the Megaregions joint subcommittee. She is also a member of the American Society of Civil Engineers, Infrastructure Resilience Division Committee on Social Science, Policy, Economics, Education and Decision (SPEED). Dr. Smith-Colin received her M.S. and Ph.D. from the University of Wisconsin-Madison and the Georgia Institute of Technology respectively. Her research has been funded by the National Academies of Sciences, Medicine and Engineering and the National Science Foundation. She is a licensed professional engineer.

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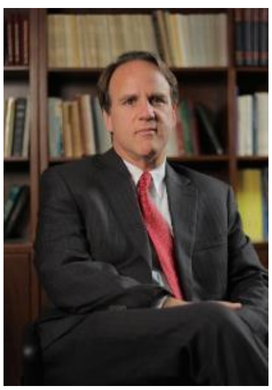
Kenichi Soga is the Donald H. McLaughlin Professor in Mineral Engineering and a Chancellor’s Professor at UC Berkeley. Soga is also the Director of the Berkeley Center for Smart Infrastructure, a faculty scientist at Lawrence Berkeley National Laboratory, and serves as a Special Advisor to the Dean of the College of Engineering for Resilient and Sustainable Systems. He has published more than 450 journal and conference papers and is the co-author of "Fundamentals of Soil Behavior, 3rd edition" with Professor James K Mitchell. Soga’s research focuses on infrastructure sensing and modeling, performance-based design and maintenance of infrastructure, energy geotechnics, and computational geomechanics. He is also a member of several professional organizations, including the National Academy of Engineering, a fellow for the UK Royal Academy of Engineering, the Institution of Civil Engineers (ICE), the American Society of Civil Engineers (ASCE), and the Engineering Academy of Japan. He is the chair of the ISSMGE TC105 Geomechanics from Micro to Macro and of the ASCE Infrastructure Resilience Division’s Emerging Technologies Committee.



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Professor Soibelman is the Fred Champion Estate Chair in Engineering Professor at USC. He obtained his BS and MS Degrees from UFRGS, Brazil and worked as a construction manager for 10 years before he obtained his PhD in Civil Engineering Systems from MIT. During the last 25 years as a professor at University of Illinois, Carnegie Mellon University and now at USC he focused his research on advanced data acquisition, management, visualization, and mining for construction and operations of advanced infrastructure systems. He published over 250 books, books chapters, journal papers, and conference articles and performed research with funding from NSF (NSF career award and several other NSF grants), NASA, DOE, US Army, NIST, IBM, Bosch, IDOT, RedZone Robotics among many others funding agencies. His areas of interest are: Use of information technology for economic development, information technology support for construction management, process integration during the development of large-scale engineering systems, information logistics, artificial intelligence, data mining, knowledge discovery, image reasoning, text mining, machine learning, advanced infrastructure systems, sensors, streaming data, construction robotics, Multi-reasoning Mechanisms and advanced modeling and digital twins.

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Jamie Standing is Professor of Ground Engineering in the Department of Civil and Environmental Engineering at Imperial College London. Full-scale field monitoring, tunnelling and soil-structure interaction are three of his key research interests. He has always worked closely with industry and has run major tunnelling research projects associated with: Jubilee Line Extension (greenfield sites and numerous building interactions); CTRL (effect of tunnelling on piled foundations) and Crossrail (effect on existing cast iron lined tunnels). He is a chartered Civil Engineer, Fellow of the Geological Society, Associate of the Geotechnical Consulting Group and a member of three ISSMGE technical committees: TC204 (Underground Construction in Soft Ground); TC220 (Field Monitoring in Geotechnical Engineering) and TC301 (Preservation of Monuments and Historic Sites). He has served on the BGA and BTS committees and been an editorial board member for Géotechnique and QJEGH. He has delivered numerous invited lectures, including the Géotechnique lecture in 2009.

Liz Varga

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Professor Liz Varga, FCABE, FAcSS, has a chair in Complex Systems in the Civil, Environmental, and Geomatics Engineering Department, University College London (UCL). She leads the Infrastructure Systems Institute and was principal investigator for the coordination node of UK Collaboratorium for Research in Infrastructure and Cities (https://www.ukcric.com/) and co-investigator for the Data and Analytics Facility for National Infrastructure (https://dafni.ac.uk/). She teaches, writes, and advises globally on energy, transport, digital communications, water, and waste. Her key research themes are infrastructure resilience, sustainable innovation, circular engineering, and decarbonisation, using digital twins, hybrid models, and self-healing systems. Given that linear infrastructure networks are often buried (electricity lines, water pipes, telecommunications cables) and that transport infrastructure in urban areas is often underground (or involves tunnels), it is vital that the networks are not disrupted by construction works and hazards, whether of a natural origin or man-made. Her work on intelligent excavation concerns the real-time sensing and detection of buried networks on construction sites matching to digitalised records of buried assets, for the purpose of construction site safety. This has spun out into Connected Autonomous Plant work. Other work on fire resilience also considers the socio-technical intersections but in buried transport metro stations.

Graeme West

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The Alan Turing Institute and University of Strathclyde

Dr Graeme West (he/him) is a Reader in the Department of Electronic and Electrical Engineering at the University of Strathclyde and has recently joined the Alan Turing Institute as Theme Lead for Critical Infrastructure in the Data Centric Engineering Programme. His research is focussed on the application of AI and data science to develop intelligent decision support systems for through-life asset management, particularly applied to nuclear power generation. Common challenges in these applications include a) legacy physical infrastructure which pre-dates modern computing capabilities, though augmented with retrofitted modern monitoring devices and data storage, b) the need for transparent and justifiable decision making in safety critical environments and the role AI can play in this process, and c) a limited, ageing workforce with vast experiential knowledge relating to complex assets and processes. Dr West has had over 20 years' experience developing and deploying applications to industry across areas such as data visualisation, anomaly detection, diagnostics and prognostics.

Appendix B: Thought pieces

Priscilla P. Nelson

Subsurface Space and Underground Urbanism

Tsunamis for Urban Infrastructure Investment
- Climate change
- Energy transition
- Circular economy
- Critical minerals
- Concrete and GHG
- Outsourced construction management, data, and experiential learning by public owners
- Aging population

Drivers for an Urban Infrastructure Focus
- Global population and our cities are growing, and the expectations for access to infrastructure services are increasing and considered as fundamental human right.
- The location and condition of infrastructure is largely unknown, and information is largely not shared.
- Natural and man-made disasters are increasing in frequency and social and economic consequences.
- Escalating infrastructure failures are often driven by the interdependencies of our systems.
- Aging systems in older urban areas are a growing risk: The average age of NYC water mains and sewers is 68 years; about 1/3 of the systems are over 100 years old - not considered a hazard by FEMA.

The Assertions of Underground Urbanism
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 mega-cities, and
2. The use of urban underground resources can contribute to sustainability and resilience, maintaining quality of life, and preparing the world for the impact of climate change.

Main Topics in the Presentation
1. ESG
2. Donuts
3. System of Systems
4. Chronic issues for underground space
5. Gaps and Research TBD
6. Back to ESG
7. Summary

1. What is ESG?

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?
ESG is becoming more important, and we must do the work that will ensure that the underground is fully considered in decisions regarding future investments in existing infrastructure or new projects.

- What does ESG Imply for Infrastructure? QII (Quality Infrastructure Investment) Principles (G20, 2019
  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

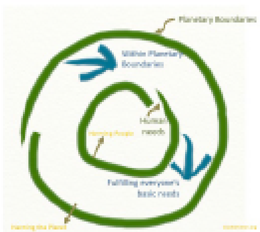
  The goal: countries pursue infrastructure investments that maximize the economic, social, environmental, and development impact of infrastructure—the foundation for achieving sustainable, resilient, and inclusive growth

- What does ESG imply for investment in infrastructure? From PRI (Principals for Responsible Investment) https://www.unpri.org/download?ac=4141 As institutional investors, we have a duty to act in the best long-term interests of our beneficiaries. In this fiduciary role, we believe that environmental, social, and governance (ESG) issues can affect the performance of investment portfolios (to varying degrees across companies, sectors, regions, asset classes and through time). We also recognize that applying these Principles may better align investors with broader objectives of society. Therefore, where consistent with our fiduciary responsibilities, we commit to the following:
  1. We will incorporate ESG issues into investment analysis and decision-making processes.
  2. We will be active owners and incorporate ESG issues into our ownership policies and practices.
  3. We will seek appropriate disclosure on ESG issues by the entities in which we invest.
  4. We will promote acceptance and implementation of the Principles within the investment industry.
  5. We will work together to enhance our effectiveness in implementing the Principles.
  6. We will each report on our activities and progress towards implementing the Principles.

- What does ESG imply for Infrastructure and Financing
  The role of infrastructure as a catalyst for sustainable growth and as an enabler of the transition to a low-carbon economy has become increasingly clear. But the global infrastructure financing gap – the difference between infrastructure needs and investment

– is anticipated to reach US$15 trillion by 2040. This gap cannot be reconciled by public funding alone; mobilizing private capital and public-private partnerships will also be essential.

2. Doughnut Economics https://www.youtube.com/watch?v=J_WPzDVpKvw



The Doughnut Model, introduced with the book "Doughnut Economics" by Kate Raworth in 2017, essentially represents the "safe zone" between social equity and environmental/planetary system boundaries that we must acknowledge in all decisions. https://stephenhinton.org/2019/04/17/why-the-doughnut-needs-the-bathtub-economic-models-for-real-change. The outer boundary defines environmental/planetary limits that should not be crossed. The inner boundary defines social standards that need to be met. We live and work in the dough. https://whatsyour2040.com/worksheets/doughnut-economics-case- studies-years-9-10-student-worksheet/

The Doughnut and Infrastructure - How Amsterdam Uses the Doughnut Economics Model to Create a Balanced Strategy for Both the People and the Environment. https://www.archdaily.com/997291/how-amsterdam-uses-the-doughnut-economics-model-to-create-a-balanced-strategy-for-both-the-people-and-the-environment

Success in life and work in the Dough must respect two mandates:

- Regenerative design and decisions – engage the circular economy. To be regenerative we must be cyclical and restorative. This goes for businesses and for infrastructure as well. The model of take, make, use, and lose. Regenerative design follows a circular path – take, make, use, regenerate, restore, reuse.
- Distributive (not centralized) by design – equitable access and sharing. To be distributive we must share value equitably. The fact that 1% of the population owns half of the world's wealth, indicates how un-distributive the global economy currently is. Enterprise ownership, ethical supply chains, community empowerment, and open source design are favored as methods of refocusing on distribution.

3. Urban Infrastructure as a Systems of Systems

Underground Spatial Chaos

- City infrastructure agencies are often siloed in sectors
- Infrastructure management is often considered by project, rather than as an integrated and interdependent systems of systems.
- Life Cycle Engineering (LCE) exists as a concept, but the data and widely accepted time-based metrics and methodology needed for design are still evolving.
- The mix of public and private systems introduces more problems – Information about public systems is poorly organized, and information about private systems is generally not available (especially since 9/11).

Basis for Planning and Design: Choose criteria for decisions ("optimization")

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

Note: Different criteria will yield different system designs.

Human Body Analogy

- Consider New York City infrastructure and the human body. Both NYC infrastructure and the human body systems are complicated. In both cases, We often pretend our systems are independent (but they are not). Modeling all systems together is too complicated for now, and "optimization" of the system of systems is not a clear construct, but maybe some day…
- However, Someone in the past realized that a 37$_o$C body temperature indicated that the human body system of systems was operating well, that the human was healthy, and if healthy, likely to be resilient regarding disease. Can we carry this analogy over into an urban system of systems?
- Modeling our integrated urban infrastructure SYSTEMS OF SYSEMS together is also not possible as of now. Can we find an analogous integrative metric to understand the health (and resilience) of an urban region – analogous to 37$_o$C body temperature? We need to explore urban response chronic and acute (extreme) events, and 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.

Other issues:

ROW and Fee Simple Land Ownership – need access to the urban subsurface without undo legal constraints (e.g., Japan experience - 2001 Deep Underground Space Utilization Law after Kyoto EQ).

Need to establish a rational basis for the value of underground space. There is a market that establishes values for surface acreage and for air rights. There is no market for underground space. How should the value of space itself (as an underground resource) be established?

4. Chronic Issues for Underground Space • High costs of UG construction – equipment, materials, labor, risks

- Contractual issues (low bid vs PPP vs Alliance)
- Planning project by project and year by year rather than long-term integrated planning
- Local connections/access – "the last mile"
- Spatial referencing
- Systems of different ages and performance (many quite "dumb")
- Uncoordinated maintenance (# of pavement cuts)
- Material deterioration (and the use of cement/concrete)

- Water - Impact on construction and long term infiltration and performance of waterproofing?
- Reactive replacement and little thought to repurposing
- Lack of environment and social/equity metrics in planning
- Geologic risks - unanticipated conditions and unmanaged conditions
- Policy and politics

5. Gaps and Research TBD

We need answers that will inform professionals, politicians, and the public:

- What technical and analytical advances are required for governmental organizations, planners, architects, the public, and other stakeholder groups to value the contributions of the underground urban resources?
- What social, economic, political, and policy advances are needed for integrated and holistic decisions about underground investments?

We need to provide a framework that addresses the following research questions:

- How can the quality of urban life be measured? What are the metrics – we need these to demonstrate how underground space can improve the quality of urban life.
- How can resilience and sustainability be modelled in a way that can be used to quantify the benefits of urban underground space.

If no metrics or methodology exist, we cannot demonstrate how underground space improves quality of life and resilience.

Where are the “Gaps”?

1. Data gaps (including smart systems and digital twins)
2. Model gaps (infrastructure sectors often uses different models that are difficult to mesh into a system of systems model)
3. Knowledge gaps
4. Technology/equipment gaps
5. Decision tools and planning gaps
6. Workforce and skills gaps
7. Governance gaps
8. Financing gaps
9. Policy gaps, regulations

We need to develop clarified structures, methodologies and metrics to achieve planning and performance goals – costs (first and LCC), equity, environmental, and resilience, sustainability, reliability…

What does “optimization mean? Planning for whom, to what, when, where, why…And we need to understand the answer soon because the current global pipeline for infrastructure projects is estimated at $9 trillion.

6. Back to ESG

Governments have long been the traditional drivers of social and economic development in our communities — particularly through infrastructure and construction - but they are now increasingly embracing innovation and environmental sustainability as new dimensions into this mix.

Private sector infrastructure players (including private finance) are also connecting into this movement — there is an increasing awareness of the linkages between ESG-enhanced infrastructure assets and positive community impacts at scale - potentially generating stronger levels of stakeholder support and business opportunities as a result.

GWU Program – School of Business, Institute for Corporate Responsibility – the ESG & Infrastructure Initiative. Vision: 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.

ESG is becoming more important, and we must do the work that will ensure that the underground is fully considered in decisions regarding future investments in existing infrastructure or new projects. Making the urban system of infrastructure systems more resilient and sustainable is a genuine ‘wicked’ problem with the themes within the ‘E’, ‘S’ and ‘G’ all strongly interrelated. Working on ESG requires a systems approach.

- Governments are trying to encourage greater innovation around ESG in infrastructure.
- Infrastructure capital projects can provide opportunities to support innovation.
- Maintaining innovation requires inflows of new capabilities, supportive investment frameworks and strong pipelines of opportunities.

This trend is also being driven by the shift in government procurement away from more direct, taxpayer forms of investment and towards other types of alternative contracts like Build-Operate-Transfer (BOT), Alliancing and PPPs. 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.

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 involving the community and addressing their concerns.
- Encouraging innovation and advancements in technology that align with environmental/social goals.

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.

7. Summary

Infrastructure demands will only grow. 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.

Where 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? Should we seek adaptation or transformation?

Should the aim be sustainability or resilience?

- 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, 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 the inevitable, but unspecified, system shocks and stressors. Resilience approach does not require predicting outcomes. Instead, it builds social and natural capital and enhances adaptive capacity to cope with unknown futures (Carpenter and Folke 2006, Folke et al. 2010).

Simply put, sustainability prioritizes outcomes; resilience prioritizes process. Is underground urbanism more responsive pr differently responsive to sustainability or resilience goals?

Adaptation Incremental change Respond to shock Maintain previous order Build adaptive capacity Emergent properties guide trajectory	**Transformation** Major, potentially fundamental, change Action in anticipation of major stresses Create new order, open ended Reorder system dynamics Build agency, leadership, change agents
Resilience Theory Approach Change is normal, and there are multiple stable states Experience adaptive cycle gracefully Origin in ecology, maintain ecosystem services Result of change is open-ended, emergent Concern with maintaining system dynamics Stakeholder focus is on desirable dynamics	**Sustainability Science Approach** Envision the future and act to make it happen Utilize transition management approach Origin in social sciences, society is flawed Desired results of change are specified in advance Focus is on interventions that lead to sustainability Stakeholder input focused on desirable outcomes

Addendum: ESG in Public Infrastructure Thoughts

E: ESG in public infrastructure often emphasizes environmentally sustainable practices, such as building and maintaining 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 engaging with and considering the needs and concerns of the communities impacted by infrastructure projects. It aims for 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. This can include measures to minimize public health risks and enhance safety features.

G: ESG promotes transparent decision-making processes and the active involvement of stakeholders in governance. 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.

Chris Rogers

Dealing with the Complexity of the Underworld

The underworld has two formally-defined connotations – a place under the Earth where the spirits of the dead go, and the part of society consisting of criminal organisations and activities. My interest (bear with me) lies only in the former, a term that evokes something poorly defined, something complex in nature; it therefore serves as a useful metaphor for those who study (interrogate, understand, map) the ground and what is buried in it, and then use this information for some purpose (exploitation, harvesting its ecosystem services, protecting something). When defining a major EPSRC-funded programme of research to address one of the essential challenges of installing or maintaining utility service pipelines and cables – understanding what is there before carrying out engineering works in this space, noting the common argument that we know more about the surface of the moon than we do about the top 2 metres of the ground beneath our urban places – we used the term 'underworld'.

The programme was called *Mapping the Underworld* and researched several different technological and organisational approaches to detecting, identifying and mapping in 3-D the shallow-buried infrastructure beneath urban streets. This was followed by a complementary programme, *Assessing the Underworld*, which sought to use similar approaches to determine the condition of both what was buried and the ground that supported it, recognising that a pipeline system performs structurally due to a combination of the competencies of both the pipe and the ground in which it is buried. This research led to and was complemented by a sequence of practical and Government developments, including the creation of industry guidance (e.g., the PAS 128 utility surveying standard), the *National Underground Asset Register* and the formation of the Geospatial Commission based in the UK Government Cabinet Office. Indeed, this activity has become further recognised as an issue of national importance by the establishment of a UK Government Foresight *Future of the Subsurface* project (GoFS, 2023). Unsurprisingly, the British Geological Survey has been at the heart of all of this work, firstly as a project partner to the multi-university, multidisciplinary research programme, then a direct research collaborator, and now providing leadership on behalf of the Government by Holger Kessler, who is part of this workshop.

One of the many profound outcomes from this research was the conceptualisation of three interdependent infrastructures in the street corridor: the buried infrastructure (of whatever type), the surface transport infrastructure (typically a road structure) and the ground as the third infrastructure that connects and supports them both. Affording the status of 'an infrastructure' to the ground introduces the notion of initial structural competence, a change in structural competence as the context changes, and 'deterioration' models to define amended structural performance due to ageing if adverse physical or environmental conditions develop (noting also that consolidation and compression can improve performance – think shakedown theory). While geotechnical engineers readily understand the role of the ground, such terminology elevates the importance of it to the less initiated – it removes all notion that the ground is an innocent bystander in the functioning of two important infrastructure systems from any professional conversation.

Sticking with the shallow subsurface and its relationship to the urban landscape, it can be argued that it underlies three broad categories of the surface: the built environment, the natural environment (the blue and green spaces that house the flora and fauna that make up urban biodiversity), and the street corridors that largely accommodate the arteries of our villages, towns and cities. The street corridors are the communally-owned, shared spaces in places where the urban metabolism operates most intensively – the flow of people, goods, resources and ideas, both above and below the surface. Engineers have a responsibility to make this urban metabolism, via the many different physical infrastructure systems that support it, operate both efficiently and effectively. This responsibility is complicated by the fact that these infrastructure systems are highly interdependent – their construction, maintenance and operation both affects and are affected by the other systems and, while working on one system there is a need to maintain the services the other systems provide. Factoring in the seemingly infinitely variable nature and properties of the ground and we soon arrive at a situation of considerable complexity.

Referring back to the underworld, and to paraphrase from Robert Macfarlane (2019) when referring to our relationship with the subsurface, the same three tasks recur across cultures and epoques: to shelter what is precious or vulnerable, to yield what is valuable, and to dispose of what is harmful or unwanted. He, like others, refer to our nature, and our description even, as being connected to the ground – the word human deriving from the Latin *humanus*, said to be a hybrid relative of *homo*, meaning man, and *humus*, meaning earth. Whether you agree with this or not, it is undoubtedly true that we rely upon the ground for both our survival and the successful operation of our society. We acknowledge its ability to grow the food we eat, and as engineers we would perhaps focus more on the trees and green infrastructure that we need to weave into our urban designs in some way to ensure that the ecological, health and well-being benefits they offer are not lost in the extensive constructed environment. We need to take account of, and make space for, tree roots. Moreover, we need to acknowledge the pervasive biological activity that occurs in the ground from the scale of bacteria upwards. As engineers, we often stop at simply acknowledgement, though with a slightly uneasy feeling that we (or at least I) ought to take greater account of this biological dimension in some way.

The concept of ecosystem services perhaps provides a more helpful perspective. Ecosystem services are defined as the goods and services provided by ecosystems to humans and are commonly grouped into four broad categories: provisioning services, regulating services, supporting services and cultural services (Sadler *et al*., 2018). Provisioning (minerals, water, heat), regulating (temperature, enabling / limiting or preventing the flow of water) and supporting (strength, stiffness) are straightforward to interpret from a geotechnical engineering perspective, while cultural demands a little more reflection – 'we bury our history' is a starting point, yet there is a human connection with the ground that enhances our wellbeing. Such conceptions are particularly useful for three reasons: they reinforce the idea that engineering should seek to augment what the planet provides rather than replace it, that there are many forms of value that can be realized alongside the particular engineering requirements that we seek from our designs if we are aware of the full range of opportunities, and that when harnessing ecosystem services for our immediate needs we should recognise that (other and/or additional) future needs might need to be met from this same source (the ground with which we are working). It is in recognition of this that Price *et al*. (2016) describe "a methodology that combines subsurface characterisation, ecosystem service classification and future scenario analysis".

Extending the notion that 'we bury our history', it is widely appreciated that construction in a built-up area might reveal unknown and/or unanticipated archaeological remains of some type. These include what previous generations have either left at the surface and then covered or consciously buried. They might be of cultural value at the time of burial or simply functional, reflecting societies and practices of their time. It is incumbent upon us to record, and perhaps retrieve or rebury, what we find so that the archaeological value is not lost. This dimension of the underworld adds both to the value equation that we should compile when creating and presenting the case for our designs and to the many dimensions of the context in which our work is carried out and to which our designs must speak.

One of the primary forms of value offered by the subsurface is underground space. As alluded to earlier, we bury things for several different reasons. Burial for protection and aesthetics combine in the form of pipelines – a partnership between structural elements and the ground to provide a stable and resilient conduit through which some resource can pass. By avoiding this activity on the surface or above the ground, it also serves to make places more sustainable and liveable (and what about 'waste by pipeline'?). As also alluded to earlier, monitoring the condition of the pipe and ground, and carrying out maintenance when required, add to the pipeline's sustainability and resilience credentials. A proactive approach applied to all infrastructure ensures continuation of functionality and protects the initial investment; put another way, maintenance itself is an investment and not simply a cost as many perceive it.

One prime example from the current UK research portfolio concerns Pipebots – the creation of swarms of small robots that will ultimately live within a pipe network and traverse it periodically to carry out a longitudinal programme of assessment of its condition. In this way, incipient failure – for example, the formation of blockages in sewers, formation of misaligned joints, cracks or other forms of progressive deterioration that might result in leakage – can be identified and dealt with economically before failure occurs. One reason why this programme is particularly important is that it has been suggested that there are more than 300 UK projects that have focused, or are focusing, on leakage detection from pipelines (i.e., once failure has already occurred and, importantly, once the ground has been affected by whatever has leaked). By adopting such routine monitoring, the industry would become proactive in terms of pipeline maintenance and thereby avoid the many adverse consequences, or negative value if you wish, associated with failures and emergency repairs. The business models, and hence business case, for such proactive action should surely be compelling.

None of this is a surprise, of course, to those of us who own buildings, gardens, vehicles, other mechanical equipment or, in fact, pretty well anything – we know we need to monitor, assess and maintain where necessary. Taking gardens as an obvious parallel, it is well known that growing and harvesting without ploughing back in organic matter and fertiliser of some sort results in steadily reducing productivity, quality and value of the outcome – maintaining the health of the ground is a necessary action, and arguably a responsibility if we do not wish to leave things in a poorer state than we found them. The thinking should equally apply to engineering soils.

In a slightly roundabout way, this leads to UKCRIC – the UK Collaboratorium for Research on Infrastructure and Cities. Both the business case and the science case for UKCRIC were founded on the need for maintaining and upgrading our infrastructures and systems to sit alongside the need for innovation when creating new infrastructures and systems. UKCRIC is underpinned by investments in three stands of activity – its laboratories, its urban observatories and its modelling and simulation facility. The laboratories of most direct relevance to this gathering are the National Buried Infrastructure Facility at Birmingham, the National Soil-Foundation-Structure Facility at Bristol and the National Infrastructure Laboratory at Southampton, although the sensing, materials, water engineering and green infrastructure laboratories naturally all provide important complementary capabilities.

UKCRIC's approach to the wide range of challenges of engineering in the infrastructure and cities space is founded on an appreciation that what we are dealing with is inherently complex and needs a systems approach: it requires all involved to think and act systemically and to work seamlessly across silos wherever they exist (academic, professional, governance and so on). The UKCRIC partnership has come together specifically to tackle these challenges and has compiled a theory of change for infrastructure and cities to help guide this process (Rogers *et al*., 2023). Underpinned by a process of system mapping to make transparent the full reach of consequences of bringing about a change in the system-of-systems that make up our places, it starts by identifying all of those who either influence, or are influenced by, the proposed system change and establishing these stakeholders' aspirations. Combining them into a design brief for the system change, the methodologies thereafter recommend processes of establishing both the baseline performance of the system of interest and the current context in which the system change is to operate. This information is then used in a process of rigorous problem diagnostics.

Only once these processes have been carried out is it then appropriate to apply engineering (ingenuity) to solve the problems and bring about beneficial change. This will lead to a number of alternative design options, all having alternative combinations of benefits associated with them. The system maps can be used to identify, for each of these design options in turn, where value is gained, and equally where value is lost, in all other infrastructure and urban systems with which the system of interest is dependent or interdependent. Summation of this value, positive and negative, *de facto* provides the basis for the alternative business models associated with the system change. The designs must be tested both in the current context, which is straightforward since we will understand both the context and existing system performance, and in the future. Moreover, UKCRIC offers a suite of laboratories, urban observatories and a modelling and simulation capability to trial the proposed system changes and hence de-risk their application if they were to be implemented today.

When considering the resilience and sustainability of the designs, we need to consider the efficacy of the proposed system change(s) in the future. For the types of design for which civil engineers are responsible it is the far future that matters, and the future context becomes progressively more uncertain the farther into the future we look. Therefore, it is essential to use scenario analysis alongside models that deliver predictions and projections (which are of the greatest benefit for the near future). The recommended approach in the UKCRIC Theory of Change is to use extreme-yet-plausible futures in which to trial the system changes, since these will illustrate both where, and why, a particular design might be vulnerable to inefficiency or ineffectiveness, and hence limit or compromise fully the intended beneficial outcomes, if the future context changes.

Once the likely immediate and future benefits, and any risks associated with their delivery, have been established, then the alternative business models can be finalised, the most appropriate design option chosen and the case for change made. However, woven into all of this work from the very early stages, and brought into sharp focus at the final stage, is the role of governance. There are both formal and informal systems of governance, and both exert a powerful control over the success or otherwise of a system change. The formal forms of governance include legislation, regulation, codes & standards, taxation and incentives – the formal leavers of government that are applied 'top down'. The informal forms of governance include individual attitudes and behaviours, societal attitudes and behaviours, societal norms, (professional) practice norms and so on. These might be viewed as the 'bottom up' forms of governance. Consideration of governance is where both culture and politics comes into play, since those who govern are generally elected or appointed to serve on the behalf of individuals and society, and therefore the 'bottom up' views can strongly influence those responsible for shaping the 'top down' levers of government. These forms of governance need to align with the engineering designs if the full suite of intended outcomes is to be realized, i.e., if the systems are to function and be used as intended.

Once all of these processes have been completed, the traditional approach would be then either to implement and expect the users of the system to put into operation or comply with the system change, or to 'sell' it to the user community. However, by following the UKCRC Theory of Change's processes the users will have been identified at the very start of the process, they will have been given a voice to articulate their aspirations, and these aspirations will have been taken into consideration, possibly by active participation (co-creation), in the design processes. This means that the process of 'selling the system change' becomes largely unnecessary and more of a process of explanation as to why the system change is the way it is and how it meets the combined aspirations. The final point to make in all this is that every stage of the Theory of Change process is iterative and, because we are dealing with a complex context and a complex set of systems, it is important to be flexible in the design and implementation of system changes so that we learn while we are advancing, and in turn advance in response to the learning.

Now that we have broached the subject of contextual change, a set of major uncertainties that best all infrastructure and urban systems designs, it is worth quoting Macfarlane (2019) again: "We are presently living through the Anthropocene, an epoque of immense and often frightening change at a planetary scale, in which 'crisis' exists not as an ever-deferred future apocalypse but rather as an ongoing occurrence experienced most severely by the most vulnerable. Time is profoundly out of joint – and so is place. Things that should have stayed buried are rising up unbidden." I find this useful because it deals in geological time and cuts through arguments about whether what we are experiencing is a natural perturbation of the weather and social systems or a profound human-induced phenomenon. One convincing argument when dealing with climate change is that directing our actions towards decarbonisation without adversely affecting their functional and societal outcomes, or even delivering a suite of additional benefits, negates the argument that a move towards net zero is simply a drain on resources. This is further proof of the need for understanding and making transparent all of the consequences of engineering system changes and creating innovative designs in the light of this information. It is here that the geotechnical engineer has an enormous amount to offer, and where geotechnical engineering researchers have a well-defined research brief, either as an addition to the work or as a central focus. There can be no excuses for overlooking the long-term consequences of our designs.

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J. Carlos Santamarina

Transformation in Urban Underground Infrastructure: An Energy-centered Perspective

Life and Energy Demand

- Quality of life is strongly correlated with power consumption. 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 quality of life among low-energy consumers.
- Today's energy supply is predominantly based on fossil fuels (~83%). The energy transition will be energy-intensive and will be fueled by fossil fuels.
- Population growth, improved quality of life, and the energy transition will result in a significant increase in fossil fuel consumption in the coming decades.
- Mining is the bottleneck for the energy transition and it is high energy demanding.

Economy ↔ Energy ↔ Climate

- The economy, energy and climate are intimately coupled; as a first order approximation, 1$ = 2kWh = 0.5 kg CO_2. The cost for carbon capture and storage is projected to exceed 50$/kg CO_2.
- All our systems are "open systems". Where do we draw the boundaries for true life cycle analyses?
- Caution with misnomers, e.g.: "circular carbon economy", "net-zero", "carbon-neutral <cities>", "zero emission <vehicle>", "electric vehicle". *Fake news hinders democracies…. Fake technologies derail our children's future.*
- Conundrum: if we conserve energy and increase efficiencies, what will affluent societies do with resulting savings?

The Reimagined Urban

- The urban population continues to grow. With approximately 60-to-80% of the total population residing in cities, they are the primary consumers of global resources, significant contributors to climate change, and most vulnerable to its effects.
- Urban developments in the XX century where shaped by the low cost of transportation, which is based on fossil fuels (90%). Reimagined urban life and pronounced changes in transportation must take place as part of the energy transition in the XXI century.
- Coastal cities house 40% of the population and are particularly vulnerable to climate change. How can the underground be integrated into the reimagining of coastal cities to enhance their resilience?
- *Trees = solar-fueled C-capture*. Burying the infrastructure allows for increased tree density within cities.
- The development of the underground will benefit from enhanced construction efficiency (Bio-inspiration: ants).

Fleur Loveridge

Underground Infrastructure in the time of a climate crisis. What can we do to help?

The most pressing challenge facing humanity is the climate crisis. How can we ensure that everyone has the ability to live comfortable and meaningful lives, while preventing further damage to the planet and atmosphere, and also starting to reverse negative impacts? Those stewarding the creation, use, maintenance, and (if appropriate) end of life of urban underground infrastructure do not bear the sole responsibility for addressing this challenge, but we do need to ensure that opportunities to contribute meaningfully to aversion of the crisis are capitalised on. This means minimising all future carbon emissions. In the simplest sense that could mean that we do not build any more infrastructure or maintain existing assets. However, we know that is not the 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 metrics.

Given the urgency of the climate crisis, carbon emitted now and in the near future also bears greater cost. This is in synergy with UK governmental budgeting rules, where the "discount rate" effectively makes money cheaper in the future, discouraging spending now and giving lesser value to benefits (financial or otherwise) that are accrued a long time in the future. Again, this could encourage us to do less now and more in the future. But at what cost? Some climate change impacts are already locked in. Urbanisation is increasing and more and more people live in cities, increasing the demands on infrastructure. Combined these effects have the potential to reduce resilience of infrastructure, risking them not delivering on their purpose, and hence providing declining social value. Hence there is arguably a conflict between embedding and improving essential resilience and minimising the accumulation of further embodied carbon through capital works and maintenance.

Or is there? Often the costs of developing or maintaining infrastructure are discussed, but rarely the costs of inaction. Not investing in infrastructure can ultimately lead to catastrophic failure. But even if that is avoided, fixing problems in a pro-active way is more efficient in both cost and carbon terms than being reactive. Underground infrastructure in particular can have high construction and maintenance costs due to the specialist nature of the environment, and the inability to divert services (be they rail, road, water, wastewater) elsewhere. Therefore, allowing a recovery situation to arise will inevitably result in greater financial, carbon and social costs. There is therefore a "sweet spot" for intervening in existing infrastructure to take action to increase their resilience and prevent loss of service. Some research work is happening to understand when this should be, but there remain uncertainties. How, and how fast, underground structures will deteriorate in current and future climate conditions still needs to be better understood. We routinely think about quantifying design life for steel through corrosion rates, but concrete and soil aged in aggressive conditions remains active areas of research. In addition, the cost and benefits in both purely financial, but also carbon and social terms still needs to be quantified. Overall, methodologies for all these aspects are not necessarily available.

Making the correct decisions to maintain cost, carbon and social value is also hampered by the lack of frameworks for taking those decisions. This makes the case to invest in resilience of infrastructure, including underground infrastructure, difficult. Firstly, the "Green Book" approach in the UK does not allow for accounting of value outside of the project being assessed. This neglects the inherent connectedness of all infrastructure and urban systems. Secondly, the approach is designed primarily for new projects and does not have a method for giving value to resilience improvements of existing underground infrastructure. Coupled with current demands for cost constraint in public spending this often means that action will be taken to reduce costs (and with it resilience) rather than to increase it.

The first conclusion of this piece is therefore that we need 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.

However, looking fully at benefits in multiple areas and timescales is not enough. We can also seek to actively minimise those carbon costs and maximise those social benefits. Lean design and low carbon materials have important roles to play, but I will look here at my special interest in maximising social and carbon benefit by increasing the connectivity of infrastructure by making it dual use. The Stormwater Management and Road Tunnel (SMART) in Kuala Lumpur's central business district is one example of financial and carbon costs being deployed to achieve two purposes and hence offer better value. It cost 515 million US $ to construct, which can be compared with benefits accrued over 30 years comprising: 1.58 billion US $ flood damage prevention, and up to 1.26 billion US $ savings due to non-realized traffic congestion.

However, in times of climate crisis it would be desirable for our buried infrastructure to positively help reduce future carbon emissions. The most obvious way for this to occur is via use of buried structures for heat exchange and storage as well as for their original function. Heat decarbonisation is a massive issue in the UK. Heating still accounts for almost one quarter of national carbon emissions, and is particularly hard to tackle due to the need to enter and retrofit around 28 million buildings as well as make changes in national infrastructure. Use of foundations and retaining walls or basements related to buildings for heat exchange, and their connection to local ground source heat pumps is well established. However, despite trials of using buried infrastructure in the same way, the solution has not become popular. Recent work has tried to uncover the reasons for this difficulty in implementing buried infrastructure heat sources.

Several transport infrastructure projects in the UK (Crossarail, Northern Line extension, HS2 Phase 1) have discussed, commissioned studies and even commenced design of dual use new tunnels for thermal energy exploitation, but none have implemented the solutions. Consultations with parties involved in these projects suggests this is due to a combination of high capital costs that make it hard to meet government affordability tests and the challenges of interfacing with various heat users outside of the specific infrastructure project so that a return on investment can be both generated and guaranteed. There can also be reluctance for a transport infrastructure provider to also work as an energy supply company.

The first of these reasons speaks to the earlier discussion about the absence of methodologies to fully consider benefits of infrastructure beyond the specific project. This is further compounded by the nature of government. Different departments have responsibility for the budget for transport, buildings and energy security and supply. While the costs for new transportation tunnels are borne by the department for transport, if the tunnels become energy tunnels they also give benefit to other government departments which are not sharing in the costs. At the same time, in the UK, the Department for Energy Security and Net Zero is leading on the development of heat network zones, where heat networks are expected to be the lowest cost answer to heating decarbonisation. However, the methodology for developing these zones takes is relatively unsophisticated in how it takes account of the availability of heat sources. In particular, the potential to use heat from underground sources is not well integrated into the zoning models. The presence of, for example, transportation tunnels or buried water and waste water pipes which could be exploited for thermal resources are not considered at all. This disconnect at the heart of government and in major infrastructure projects leads to significant missed opportunities, e.g., for the low carbon heating of around 1,000 homes per tunnel kilometre.

The examples above which considered use of tunnel heat exchange for thermal energy were all new build projects. But the opportunities to make a different would be much greater if existing buried assets could be retrofitted for energy exploitation. For some old tunnels, e.g., London Underground, this will prove challenging due to the tight train-tunnel envelope, but there may still be opportunities in e.g., the track drainage which is accessed for periodic maintenance. Heat pumps have already been connected to hot air coming from tunnel ventilation shafts in London and this opportunity could be utilised further. The waste water network in particular offers substantial opportunities for retrofit. Previous conservative estimates suggest that between 80 and 140GWh/day of thermal energy could be harvested, or enough to heat over 4 million homes. Flooded historical and abandoned mine adits and shafts also offer excellent opportunities for re-use in various regions of the UK, with the Coal Authority estimating that one quarter of the UK population lives in an area that could access mine heat.

Again, why do we not adopt these solutions? Some of the same challenges arise about accounting for benefits over a large system size. But in the case of retrofitting existing underground infrastructure for heat there are also technical challenges to be overcome. How can the retrofit be carried out in a cost effective way that does not effect existing service levels? All structures require maintenance for their resilience and taking advantage of these works to also implement the additional capacity for heat capture must be at the heart of any solutions. For example, water and waste water networks already suffer unacceptable performance levels in terms of leaks. Combining the lining or repair of these networks with adapting for heat transfer makes sense. There is also the possibility for additional benefit to be drawn from heat capture, for example in lowering the temperature of sewerage and reducing the rate of harmful processes than can lead to corrosion of components within the network.

Finally, how we account for and allocate the carbon benefit from dual use infrastructure needs careful consideration. In the same way as the costs of dual use infrastructure should be split between the benefiting organisation, the carbon benefits need to also be shared. But how much of the benefit should an infrastructure company take compared to the energy company which distributes the heat? Again, the answer will lie in considering our systems over wider boundaries. Artificial divisions are of course useful for planning and budgeting, but can otherwise give rise to artificial barriers for adoption of new solutions.

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 their resilience also becomes, and developing the methods needed to value that resilience and balance carbon costs and benefits will be more important in the future.

Tom Dolan

A Systems-of-Systems Approach to Underground Infrastructure

Introduction

The Infrastructure that enables all aspects of life in modern societies and economies is a deeply interdependent system of systems, components of which are located:

- Terrestrially, overground, at the subsurface, and underground
- Aquatically, below the sea/riverbed, on the sea/riverbed, on or immediately above, the sea/riverbed
- Atmospherically, in the tropo, strato, meso, thermo and exo spheres

All of the above locations provide a unique set of context specific technical, scientific, economic, societal challenges for infrastructure provision. Nevertheless, interdependencies exists between infrastructure components.

Regardless of the sector that owns and operates them, and regardless of whether they are located above ground, in the subsurface, underground, the skies immediately above our heads or in orbit, all infrastructure assets and systems are part of deeply interdependent system of systems with a shared common purpose.

This workshop provides an opportunity to focus on the unique challenges faced by underground infrastructure across all stages of the infrastructure asset, and infrastructure system, lifecycle. Whilst remaining mindful of the wider systemic context within which underground infrastructure is embedded and the interdependencies between underground, subsurface, and overground infrastructure.

A Systemic Context

All modern societies, economies and places in which we live are enabled by a deeply interdependent system of economic infrastructure sectors and associated governance structures (henceforth, infrastructure systems). More specifically, the flow 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 an infrastructure systems enables, 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 the climate emergency , whilst simultaneously seeking to transform infrastructure systems from a passive driver of the climate emergency into a system that:

- is able to mitigate the causes of the climate crisis by:
    - reducing its own GHG emissions to net zero (a net zero system)

    - reducing the GHG emissions from the activities, supply chains, households, communities, places, societies and economies it enables (a net zero enabling system),
- is resilient to the disruptive impacts of global warming of between 1.5^{o}C-4^{o}C (a resilient system)
- is capable of protecting the activities, supply chains, households, communities, places, societies and economies it enables from those same disruptive impacts (a resilience enhancing system)
- is significantly harder.

Particularly given that the climate emergency is a wicked problem - an unintended emergent property of modern life, neither wholly caused, nor wholly resolvable, by a single party acting in isolation. A wicked problem is neither a technical problem awaiting the right technical fix nor a political problem awaiting the right policy initiative. Rather, it is a type of problem in need of a mission-oriented approach focused on the transformation of the systems (including mindsets and governance structures) from which it has emerged.

It is, nevertheless, driven by the knowledge that infrastructure systems are societally significant, globally replicable leverage points that can either catalyse or impede the type of societal transformation needed to have a chance of successfully tackling the climate emergency, and that infrastructural inaction is a luxury we can no longer afford. These are the challenges on which the UK Collaboratorium for Research on Infrastructure and Cities' (UKCRIC's) Scientific Missions are broadly focused and I believe they offer an invaluable systemic perspective.

UKCRIC Scientific Missions: A Brief Summary

UKCRIC's scientific missions capture the collective belief of its members that Infrastructure systems can, and must be,

- Mission 1: Systemic enablers of equitable, inclusive, fair, affordable societally beneficial outcomes.
- Mission 2: Systemically resilient systems that enhance overall societal resilience.
- Mission 3: Sustainable, net zero pollution systems that enable the emergence of sustainable, net zero pollution, societies.
- Mission 4: Underpinned by fit-for-purpose governance +++ structures and business models purposefully aligned with Missions 1-3.

Mission 1 is focused on the purpose of infrastructure and the catalytic role it can play in supporting realisation of the type and quality of outcomes we expect infrastructure systems to enable. Missions 2 and 3 focus on two critical long-term qualities infrastructure systems must possess to support the long-term sustainable realisation of Mission 1. Mission 4 focuses on the governance, regulation and management structures required to enhance the feasibility of Missions 1-3 being realized.

UKCRIC Scientific Missions: Some Key Reflections

1. Remove Infrastructural Barriers and Unlock Systemic Potential

The UKCRIC Scientific Missions aim to remove infrastructural barriers to progress, and unlock the catalytic potential of infrastructure systems as leverage points by:

> (I) establishing an enabling role for infrastructure systems at the heart of net zero, sustainability, resilience, levelling up strategies;
>
> (II) integrating the qualities sustainable, net zero and resilient into the societal and economic outcomes infrastructure systems are expected to enable;
>
> (III) ensuring all infrastructure governance +++ structures align with the type and quality of outcomes infrastructure systems are expected to enable (i.e., are fit for purpose).

2. Catalyse Wider Collaborative Action, Don't Provide a Magic Bullet

Whilst transforming infrastructure systems into net zero-enabling, sustainability-supporting, resilience-enhancing systems is a pre-requisite for a successful transformative response to the climate emergency, it is not a guarantor of success.

It must be supported by a wider collaborative portfolio of systemically targeted actions, performed by a diverse array of mission actors, utilising a range of different types of action, supported by a government committed to removing all impediments to action, and implemented (and funded) by a diverse network of communities of interest/mission actors/stakeholders.

For example, a society cannot be resilient if the infrastructure system upon which it depends is not resilient, but resilient infrastructure systems do not guarantee a resilient society. Likewise, a society cannot achieve net zero unless the infrastructure system upon which it depends aspires to achieve net zero, but net zero infrastructure systems do not guarantee a net zero society.

Therefore, whilst resilient, net zero, infrastructure systems do not guarantee a resilient, net zero, society they can have a significant influence on the feasibility of a society achieving resilience and net zero targets.

To put it another way, if infrastructure system priorities are aligned with societal priorities, a successful response is possible. If they not, a successful response becomes highly improbable.

3. Infrastructure Governance Must be Fit for Purpose

The type and quality of societal, environmental and economic outcomes enabled by current infrastructure systems are a legacy of design and procurement decisions and governance structures aligned with past societal, environmental and economic priorities.

The climate emergency and other global trends[2] have begun to shift perceptions of societal, environmental and economic priorities. This is a process that will no doubt accelerate in the future. However, whilst net zero targets are an encouraging sign that a new mindset is slowly

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[2] https://nationalpreparednesscommission.uk/wp-content/uploads/2023/06/2020_11-NPC-CollinsStrategicIssues-Final-WEB.pdf

beginning to emerge, systemic transformation of infrastructure systems requires a shove not a timid nudge.

The way infrastructure systems are perceived, designed, procured, governed, regulated, financed, and owned and the objectives used to inform infrastructure policy priorities, performance metrics needs assessments, and decision-making processes have not evolved at the same pace and are in urgent need of review. The result is a misalignment between legacy governance structures and current climate crisis necessities, which impedes infrastructural action to address societal priorities.

If infrastructure systems are to make possible the type of society, the quality of life outcomes, and economic prosperity expected by the citizens they serve and the places they enable, fit-for-purpose governance structures closely aligned with new societal priorities will be essential.

Final thought

Systemic transformation will follow, albeit slowly, given the long asset life of incumbent infrastructure assets. To remove infrastructural impediments and avoid undermining progress, misalignment between priorities must be sought out and addressed. Misalignment, if allowed to persist, will lead to infrastructure systems that deliver outcomes that are inconsistent with, and potentially detrimental to, the realisation of societal priorities.

Appendix C: Breakout session example instructions with questions

Graeme West and Patricia Culligan

As given for Patricia Culligan (mirror image given for Graeme West)

Thursday

Transatlantic Breakout Session

Room 3320
10.45-11.45
Followed by 15-minute break

Reporting Session

Room 3450
12.00-12.55
10 minutes

Purpose

To answer the following two questions.
Your breakout room will be linked to a breakout room in the USA via Zoom.

You are the chair
Graeme West, Turing Institute, is the session co-chair and will be in the UK room
(this will be flipped tomorrow)

Please ask for a volunteer or two to keep notes. Please take your own notes for the feedback session.

Post it notes are available in the room for those who wish to write down their thoughts. Delegates are to leave these on the table for the home team to collect.

You may wish to use a slide to present the feedback. If so, please use the template slide provided.

The questions are:

1. **What points were you glad the keynotes raised?**
2. **What wasn't covered in the keynotes that needs to be discussed at this workshop?**

The chair's/co-chair's brief is to ensure the session runs smoothly and to try to involve everyone in the UK and US rooms.

Friday

Transatlantic Breakout Session
Room 3320
9.25-10.45
Followed by 15-minute break

Reporting Session
Room 3450
11.00-11.45
10 minutes

Purpose

To bring together the UK and US independent sessions by answering the following two questions.

Your breakout room will be linked to a breakout room in the UK via Zoom.

You are the co-chair
Graeme West, Turing Institute, is the chair and will be in the UK room

Please ask for a volunteer or two to keep notes. Please take your own notes for the feedback session.

Post it notes are available in the room for those who wish to write down their thoughts. Delegates are to leave these on the table for the home team to collect.

You may wish to use a slide to present the feedback. If so, please use the template slide provided.

The questions are:

1. **Where are the synergies, tensions, gaps and opportunities between the ‘big research questions’ identified by the USA and UK in their independent sessions?**
2. **What else is needed to support the two research communities, separately and collectively, in answering those questions?**

The chair’s/co-chair's brief is to ensure the session runs smoothly, to steer the discussions towards consensus and to try to involve everyone in the UK and US rooms.

Jelena Ninic and Cliff Davidson

As given for Cliff Davidson (mirror image given for Jelena Ninic)

Thursday

Transatlantic Breakout Session
Room 3330
10.45-11.45
Followed by 15-minute break

Reporting Session
Room 3450
12.00-12.55
10 minutes

Purpose

To answer the following two questions.
Your breakout room will be linked to a breakout room in the USA via Zoom.

You are the co-chair
Jelena Ninic, U of Birmingham, is the session chair and will be in the UK room
(this will be flipped tomorrow)

Please ask for a volunteer or two to keep notes. Please take your own notes for the feedback session.

Post it notes are available in the room for those who wish to write down their thoughts. Delegates are to leave these on the table for the home team to collect.

You may wish to use a slide to present the feedback. If so, please use the template slide provided.

The questions are:

3. **What points were you glad the keynotes raised?**
4. **What wasn't covered in the keynotes that needs to be discussed at this workshop?**

The chair's/co-chair's brief is to ensure the session runs smoothly and to try to involve everyone in the UK and US rooms.

Friday

Transatlantic Breakout Session
Room 3330
9.25-10.45
Followed by 15-minute break

Reporting Session
Room 3450
11.00-11.45
10 minutes

Purpose

To bring together the UK and US independent sessions by answering the following two questions.

Your breakout room will be linked to a breakout room in the UK via Zoom.

You are the chair
Jelena Ninic, U of Birmingham, is the co-chair and will be in the UK room

Please ask for a volunteer or two to keep notes. Please take your own notes for the feedback session.

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The chair's/co-chair's brief is to ensure the session runs smoothly, to steer the discussions towards consensus and to try to involve everyone in the UK and US rooms.

Melissa Bedinger and Lucio Soibelman

As given for Lucio Soibelman (mirror image given for Melissa Bedinger)

Thursday

Transatlantic Breakout Session
Room 3340
10.45-11.45
Followed by 15-minute break

Reporting Session
Room 3450
12.00-12.55
10 minutes

Purpose

To answer the following two questions.
Your breakout room will be linked to a breakout room in the USA via Zoom.

You are the co-chair
Melissa Bedinger, U of Edinburgh, is the session chair and will be in the UK room
(this will be flipped tomorrow)

Please ask for a volunteer or two to keep notes. Please take your own notes for the feedback session.

Post it notes are available in the room for those who wish to write down their thoughts. Delegates are to leave these on the table for the home team to collect.

You may wish to use a slide to present the feedback. If so, please use the template slide provided.

The questions are:

5. **What points were you glad the keynotes raised?**
6. **What wasn't covered in the keynotes that needs to be discussed at this workshop?**

The chair's/co-chair's brief is to ensure the session runs smoothly and to try to involve everyone in the UK and US rooms.

Friday

Transatlantic Breakout Session
Room 3340
9.25-10.45
Followed by 15-minute break

Reporting Session
Room 3450
11.00-11.45
10 minutes

Purpose

To bring together the UK and US independent sessions by answering the following two questions.

Your breakout room will be linked to a breakout room in the UK via Zoom.

You are the chair
Melissa Bedinger, U of Edinburgh, is the co-chair and will be in the UK room

Please ask for a volunteer or two to keep notes. Please take your own notes for the feedback session.

Post it notes are available in the room for those who wish to write down their thoughts. Delegates are to leave these on the table for the home team to collect.

You may wish to use a slide to present the feedback. If so, please use the template slide provided.

The questions are:

5. **Where are the synergies, tensions, gaps and opportunities between the 'big research questions' identified by the USA and UK in their independent sessions?**
6. **What else is needed to support the two research communities, separately and collectively, in answering those questions?**

The chair's/co-chair's brief is to ensure the session runs smoothly, to steer the discussions towards consensus and to try to involve everyone in the UK and US rooms.

Dulcy Abraham / Amanda Elioff, Jason DeLong / Youssef Hashash, Janille Smith-Colins / Sunil Sinha

Thursday

Independent Breakout Session

Dulcy/Amanda – Room 3320
Jason/Youssef – Room 3330
Janille/Sunil – Room 3340
14.15-15.15
Followed by 15-minute break

Reporting Session

Room 3450
15.30-16.00
10 minutes each

Purpose

To answer the following three questions.
The UK will be running a similar session asynchronously.

A member of the home team will be present to assist with technical issues and to take notes for the workshop report. Please take your own notes for the feedback session.

Post it notes are available in the room for those who wish to write down their thoughts. Delegates are to leave these on the table for the home team to collect.

You may wish to use a slide to present the feedback. If so, please use the template slide provided.

The questions are:

7. **What services will underground infrastructure need to deliver in the future?**
8. **What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?**
9. **What can and should be done better right now below ground and what savings can be made now when doing things underground?**

The chair’s/co-chair's brief is to ensure the session runs smoothly and to steer the discussions towards consensus.

Additional prompts

- Q1: What services will underground infrastructure need to deliver in the future?
    - E.g., resilience, sustainability, climate change, circularity, equity, etc.
    - How does underground infrastructure fit with other systems in the systems of systems?
    - How might these things change over time?
    - The underground is a resource. For what could it be a resource? What are the demands on the underground 50 years from now?
- Q2: What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?
    - Where should we put infrastructure where we are not currently putting it?
    - What about decentralised systems that don't require pipelines?
    - What is beyond the state-of-the-practice in terms of what people are thinking of doing in the future with regard to new uses?
    - Is there a role for underground infrastructure to help with climate change and hazard events?
    - What are the barriers and enablers?
        - E.g., climate change, financing, coordination across sectors, valuing the underground space / market creation, uncertainty, doing things the way they've always been done (why?), safety, regulation, capabilities of Local Authorities (outsourcing), ownership (In America if you own the surface you own the subsurface), equity, decision-making.
- Q3: What can and should be done better right now below ground and what savings can be made now when doing things underground?
    - Doing things underground is expensive. How can this barrier be overcome?
    - What is / do we know the current state of practice?
    - What is / do we know the current state of research?
    - What is / do we know the desired future performance?
    - What does underground infrastructure look like when 'done well'?
    - What are the essential elements of underground infrastructure?
    - What are the embodied values of underground infrastructure?
    - What are the economic, societal and environmental outcomes underground infrastructure aspires / should aspire to achieve?

Friday

Independent Breakout Session

Jaime – room 308
Irem – room 326
Sergio – room 327
9.15-10.15
Followed by 15-minute break

Reporting Session

Main room
10.30-11.00
10 minutes each

Purpose

To answer the following three questions.
The USA will be running a similar session asynchronously.

A member of the home team will be present to assist with technical issues and to take notes for the workshop report. Please take your own notes for the feedback session.

Post it notes are available in the room for those who wish to write down their thoughts. Delegates are to leave these on the table for the home team to collect.

Flip chart pads and pens are available in the room should you wish to utilise them.

You may wish to use a slide to present the feedback. If so, please use the template slide.

The questions are:

10. **What services will underground infrastructure need to deliver in the future?**
11. **What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?**
12. **What can and should be done better right now below ground and what savings can be made now when doing things underground?**

The chair's/co-chair's brief is to ensure the session runs smoothly and to steer the discussions towards consensus.

Additional prompts

- Q1: What services will underground infrastructure need to deliver in the future?
    - E.g., resilience, sustainability, climate change, circularity, equity, etc.
    - How does underground infrastructure fit with other systems in the systems of systems?
    - How might these things change over time?
    - The underground is a resource. For what could it be a resource? What are the demands on the underground 50 years from now?
- Q2: What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?
    - Where should we put infrastructure where we are not currently putting it?
    - What about decentralised systems that don't require pipelines?
    - What is beyond the state-of-the-practice in terms of what people are thinking of doing in the future with regard to new uses?
    - Is there a role for underground infrastructure to help with climate change and hazard events?
    - What are the barriers and enablers?
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- Q3: What can and should be done better right now below ground and what savings can be made now when doing things underground?
    - Doing things underground is expensive. How can this barrier be overcome?
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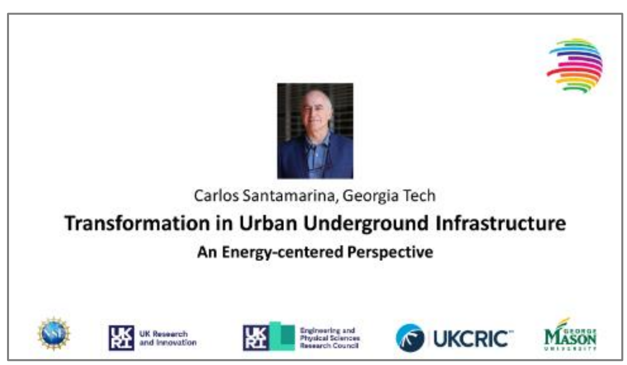
    - What does underground infrastructure look like when 'done well'?
    - What are the essential elements of underground infrastructure?
    - What are the embodied values of underground infrastructure?
    - What are the economic, societal and environmental outcomes underground infrastructure aspires / should aspire to achieve?

Appendix D. Presentation to guide the workshop

The following slides were used to guide the meeting.



Fleur Loveridge, University of Leeds

Underground Infrastructure in the time of a climate crisis

What can we do to help?

Transatlantic breakout session

- What points were you glad the keynotes raised?
- What wasn't covered in the keynotes that needs to be discussed at this workshop?

Chairs* and Co-chairs

	UK	USA
Room 1	Graeme West, Turing Institute	*Patricia Culligan, U of Notre Dame
Room 2	*Jelena Ninic, U of Birmingham	Cliff Davidson, Syracuse Univ.
Room 3	*Melissa Bedinger, U of Edinburgh	Lucio Soibelman, USC

Reporting back

- Room 1: Patricia Culligan & Graeme West
- Room 2: Jelena Ninic & Cliff Davidson
- Room 3: Melissa Bedinger & Lucio Soibelman

Witness snapshots

- David Garner, National Preparedness Commission
- Luis Bettencourt, University of Chicago-Mansuetto Institute
- Debra Phillips, Queen's University Belfast
- Ruchi Choudhary, University of Cambridge

What to expect next...

USA Lunch

Room 3450 and breakout rooms at NSF

UK – Dinner

7:00pm at the Edgbaston Park Hotel in the Composers Suite

What to expect next...

USA Lunch

Room 3450 and breakout rooms at NSF

UK – Dinner

7:00pm at the Edgbaston Park Hotel in the Composers Suite

Session 3, Independent Session

USA Thursday 28 September, 14.00-17.00 | UK Friday 29 September, 9.00-12.00

Welcome back

- Instructions
  - Elise Miller-Hooks | Joanne Leach

Independent breakout session

- What services will underground infrastructure need to deliver in the future?
- What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?
- What can and should be done better right now below ground and what savings can be made now when doing things underground?
- Session chairs and co-chairs

Independent breakout session - USA

	Chair	Co-chair
Room 3320	Dulcy Abraham, Purdue Univ.	Amanda Elioff, WSP
Room 3330	Jason DeLong, UC-Davis	Youssef Hashash, UIUC
Room 3340	Janille Smith-Colins, Southern Methodist Univ.	Sunil Sinha, VA Tech

Independent breakout session - UK

	Chair
Room 308	Jamie Standing, Imperial College London
Room 326	Irem Dikman, University of Reading
Room 327	Sergio Cavalaro, Loughborough University

Reporting back - USA

- Group 1: Dulcy Abraham and Amanda Elioff
- Group 2: Jason DeLong and Youssef Hashash
- Group 3: Janille Smith-Colins and Sunil Sinha

Reporting back - UK

- Room 308: Jamie Standing
- Room 326: Irem Dikman
- Room 327: Sergio Cavalaro

Plenary Discussion - USA

- What research is needed to do underground infrastructure (much) better in the future?
- What are the big research questions?
- What is needed to answer those questions (e.g., policy/regulatory shift, equipment, training)?Session chairs and co-chairs
  - **Chair**: Thomas O'Rourke, Cornell University
  - **Co-chair**: Mark Reiner, Jacobs Engineering

Plenary Discussion - UK

- What research is needed to do underground infrastructure (much) better in the future?
- What are the big research questions?
- What is needed to answer those questions (e.g., policy/regulatory shift, equipment, training)?Session chairs and co-chairs
  - **Chair**: Liz Varga, University College London
  - **Co-chair**: Esdras Ngezahayo, University of Birmingham

What to expect next... - USA

- Dinner at the Hummingbird Bar & Kitchen
  - In the Indigo Hotel
  - 220 S. Union Street
  - Old Town Alexandria

Session 4, Joint Session

USA and UK, Friday 29 September. USA 8.00-13.00 | UK 13.00-18.00

- Welcome
- Keynote lectures
  - Reflections on workshop discussions thus far
  - Perspectives on
    - ✓Underground infrastructure landscape, its big challenges and opportunities
    - ✓The big research questions
    - ✓Why they haven't yet been addressed.

Kenichi Soga, UC - Berkeley
Holger Kessler, Government Office for Science

Kenichi Soga, UC - Berkeley

Holger Kessler, Government Office for Science

Reporting back – USA & UK

- UK: Liz Varga & Esdras Ngezahayo
- USA: Thomas O'Rourke & Mark Reiner

Transatlantic breakout session

- Where are the synergies, tensions, gaps and opportunities between the 'big research questions'?
- What else is needed to support the two research communities, separately and collectively, in answering those questions?

Chairs* and Co-chairs

	UK	USA
Room 1	*Graeme West, Turing Institute	Patricia Culligan, U - Notre Dame
Room 2	Jelena Ninic, U of Birmingham	*Cliff Davidson, Syracuse Univ.
Room 3	Melissa Bedinger, U of Edinburgh	*Lucio Soibelman, USC

Reporting back

- Group 1: Graeme West & Patricia Culligan
- Group 2: Cliff Davidson & Jelena Ninic
- Group 3: Lucio Soibelman & Melissa Bedinger

Witness snapshots

- Ruchi Choudhary, University of Cambridge
- Debra Phillips, Queen's University Belfast
- Luis Bettencourt, University of Chicago-Mansuetto Institute
- David Garner, National Preparedness Commission

Organisers' summary

- Co-chairs Elise Miller-Hooks & Joanne Leach
- Agencies: NSF & UKRI/EPSRC

Closing remarks

- Exit questionnaire
- Thank you!

Appendix E. Keynote presentation slides

Pricilla Nelson

NSF US-UK Workshop on Transformation in Urban Underground Infrastructure

Subsurface space and Underground Urbanism

September 28, 2023

Priscilla P. Nelson, PhD
Professor of Civil, Geological, Mining and Tailings Engineering
Colorado School of Mines
pnelson@mines.edu

Tsunamis for an Urban Infrastructure Focus

- Climate change
- Energy transition
- Circular economy
- Critical minerals
- Concrete and GHG
- Outsourced construction management, data, and experiential learning by public owners
- Aging population

Drivers for an Urban Infrastructure Focus

- Global population and our cities are growing, and the expectations for service is increasing as a human right.
- The location and condition of infrastructure is largely unknown and information is largely not shared.
- Natural and man-made disasters are increasing in frequency and social and economic consequences.
- Escalating infrastructure failures are often driven by the complexity and interdependencies of our systems.
- Aging systems in older urban areas are a growing risk:
  - The average age of NYC water mains and sewers is 68 years; about 1/3 of the systems are over 100 years old.
  - Not considered a hazard by FEMA.

The Assertions of Underground Urbanism

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 mega-cities, and
2. The use of urban underground resources can contribute to sustainability and resilience, maintaining quality of life, and preparing the world for the impact of climate change.

Drivers for an Urban Infrastructure Focus

- Global population and our cities are growing, and the expectations for service is increasing as a human right.
- The location and condition of infrastructure is largely unknown and information is largely not shared.
- Natural and man-made disasters are increasing in frequency and social and economic consequences.
- Escalating infrastructure failures are often driven by the complexity and interdependencies of our systems.
- Aging systems in older urban areas are a growing risk:
  - The average age of NYC water mains and sewers is 68 years; about 1/3 of the systems are over 100 years old.
  - Not considered a hazard by FEMA.

Main Topics

1. ESG
2. Donuts
3. System of Systems
4. Chronic issues for underground space
5. Gaps and Research TBD
6. Back to ESG
7. Summary

1. What is ESG?

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?

ESG is becoming more important, and we must do the work that will ensure that the underground is fully considered in decisions regarding future investments in existing infrastructure or new projects.

What does ESG Imply for Infrastructure?
The QII (Quality Infrastructure Investment) Principles (G20, 2019)

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

The goal: countries pursue infrastructure investments that maximize the economic, social, environmental, and development impact of infrastructure—the foundation for achieving sustainable, resilient, and inclusive growth.

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What does ESG Imply for Infrastructure and Financing?

The role of infrastructure as a catalyst for sustainable growth and as an enabler of the transition to a low-carbon economy has become increasingly clear. But the global infrastructure financing gap – the difference between infrastructure needs and investment – is anticipated to reach US$15 trillion by 2040. This gap cannot be reconciled by public funding alone; mobilizing private capital and public-private partnerships will also be essential.

COLORADO SCHOOL OF MINES https://outlook.gihub.org/

ESG is Becoming more important

...and we must do the work that will ensure that the underground is fully considered in decisions regarding future investments in existing infrastructure or new projects. Making the urban system of infrastructure systems more resilient and sustainable is a genuine 'wicked' problem with the themes within the 'E', 'S' and 'G' all strongly interrelated. Working on ESG requires a systems approach.

- Governments are trying to encourage greater innovation around ESG in infrastructure.
- Infrastructure capital projects can provide opportunities to support innovation.
- Maintaining innovation requires inflows of new capabilities, supportive investment frameworks and strong pipelines of opportunities.

This trend is also being driven by the shift in government procurement away from more direct, taxpayer forms of investment and towards other types of alternative contracts like Build-Operate-Transfer (BOT), Alliancing and PPPs. 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.

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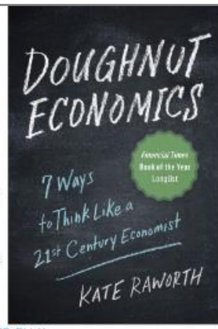
2. Doughnuts

The Doughnut Model, introduced with the book "Doughnut Economics" by Kate Raworth in 2017, essentially represents the "safe zone" between social equity and environmental/planetary system boundaries that we must acknowledge in all decisions.

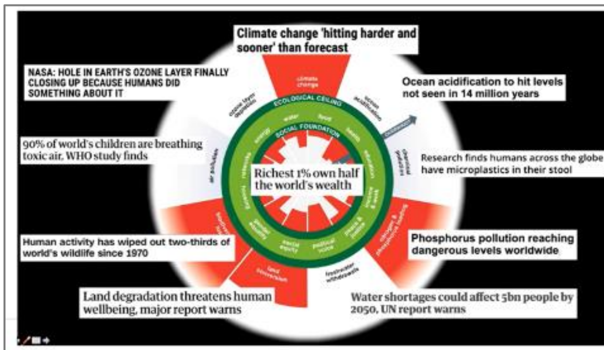


- https://www.youtube.com/watch?v=J_WPzDVpKvw

The Doughnut

The infrastructure desert?

https://stephenhinton.org/2019/04/17/why-the-doughnut-needs-the-bathtub-economic-models-for-real-change/



The Doughnut and Infrastructure

https://whatsyour2040.com/worksheets/doughnut-economics-case-studies-years-9-10-student-worksheet/

How Amsterdam Uses the Doughnut Economics Model to Create a Balanced Strategy for Both the People and the Environment

- In 2020, in the midst of the first wave of lockdowns due to the pandemic, the municipality of Amsterdam announced its strategy for recovering from this crisis by embracing the concept of the "Doughnut Economy."
- The model is now used to inform city-wide strategies and developments in support of this overarching idea: providing a good quality of life for all without putting additional pressure on the planet. Other cities are following this example.

COLORADO SCHOOL OF MINES https://www.archdaily.com/997291/how-amsterdam-uses-the-doughnut-economics-model-to-create-a-balanced-strategy-for-both-the-people-and-the-environment

The Energy Bagel

https://www.whatdesigncando.com/stories/have-your-doughnut-and-eat-it-too/

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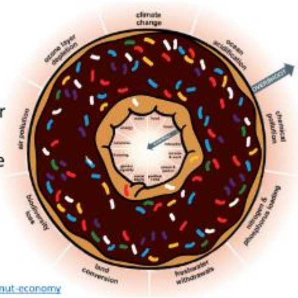
Success in life and work in the Dough must respect two mandates:

1. Regenerative design and decisions – engage the circular economy
2. Distributive design – equitable access and sharing

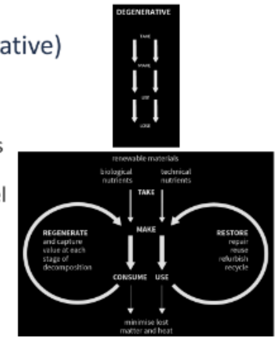
How does infrastructure fit into regenerative and distributed design?



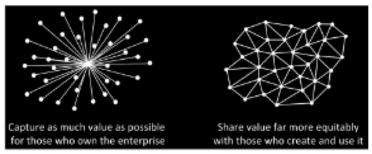
https://www.greenbiz.com/article/can-we-do-business-doughnut-economy

Regenerative (not Degenerative) by Design

To be regenerative we must be cyclical and restorative. This goes for businesses and for infrastructure as well. The model of take, make, use, and lose. Regenerative design follows a circular path – take, make, use, regenerate, restore, reuse.



Distributed (not centralized) by design



Centralized Distributed

- To be distributive we must share value equitably.
- The fact that 1% of the population owns half of the world's wealth, indicates how *un*-distributive the global economy currently is.
- Enterprise ownership, ethical supply chains, community empowerment, and open-source design are methods of refocusing on distribution. nHow does Infrastructure fit in?

3. Systems of Systems

Underground Spatial Chaos

- City agencies are often siloed in sectors
- Infrastructure management is often considered by project rather than as an integrated and interdependent systems of systems.
- Life Cycle Engineering (LCE) exists as a concept, but the data and widely accepted time-based metrics and methodology needed for design are still evolving.
- The mix of public and private systems introduces more problems – Information about public systems is poorly organized, and information about private systems is generally not available (especially since 9/11).

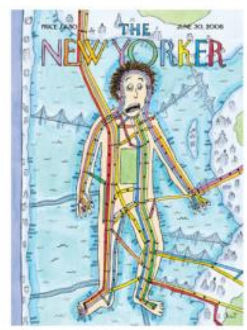
Basis for Planning and Design

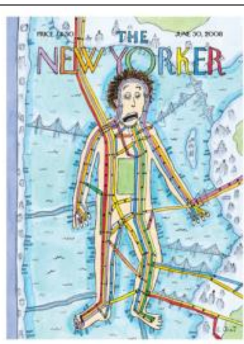
Choose criteria for decisions ("optimization")

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

Different criteria will yield different system designs

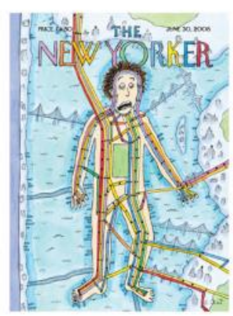
Consider New York City infrastructure and the human body





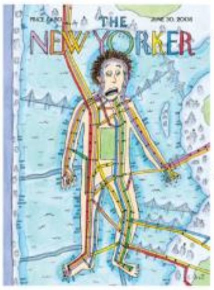
Both NYC and the human body systems are complicated. In both cases,

- We often pretend our systems are independent (but they are not).
- Modeling all systems together is too complicated for now, and "optimization" of the system of systems is not a clear construct, but maybe some day…



However:

- Someone in the past realized that a 37°C body temperature indicated that the human body system of systems was operating well, that the human was healthy, and if healthy, likely to be resilient regarding disease.
- Can we carry this analogy over into an urban system of systems?

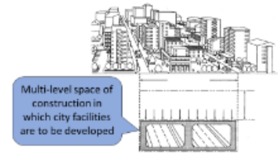


- We need to explore urban response chronic and acute (extreme) events, and identify models and metrics for aggregate urban system of systems response.
- With metrics and methods, we can demonstrate how underground infrastructure contributes to resilient response.

Other Issues: ROW and Fee Simple Land Ownership

Japan experience

- 2001 Deep Underground Utilization Law: land ownership rights in populated areas (e.g., Tokyo, Osaka) only extend to 40 meters below ground, or 10 m below a deep foundation.
- In the case of public use, no compensation to the land owner is required.
- 1st projects using the law: Underground water mains in Kobe, and the Tokyo Gaikan Expressway.



What is the value of Underground Space?

There is a market that establishes values for surface acreage and for air rights.

There is no market for underground space.

How should the value of space itself (as an underground resource) be established?

4. Chronic issues for underground space

a. High costs of UG construction – equipment, materials, labor, risks
b. Contractual issues (low bid vs PPP vs Alliance)
c. Planning project by project and year by year rather than long-term integrated planning
d. Local connections/access – "the last mile"
e. Spatial referencing/locating
f. Systems of different ages and performance (many quite "dumb")
g. Uncoordinated maintenance (# of pavement cuts)

4. Chronic issues for underground space

h. Material deterioration (and the use of cement/concrete)
i. Water
   i. Impact on construction
   ii. Long term infiltration and performance of waterproofing?
j. Reactive replacement and little thought to repurposing
k. Lack of environment and social/equity metrics in planning
l. Geologic risks
   i. Unanticipated conditions
   ii. Unmanaged conditions
m. Policy and politics

5. Gaps and Research TBD

We need answers that will inform professionals, politicians, and the public:

- What technical and analytical advances are required for governmental organizations, planners, architects, the public, and other stakeholder groups to value the contributions of the underground urban resources?
- What social, economic, political, and policy advances are needed for integrated and holistic decisions about underground investments?

The Research Agenda for Underground Urbanism

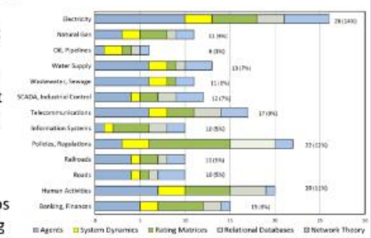
We need to provide a framework that addresses the following research questions:

- How can the quality of urban life be measured? What are the metrics – we need these to demonstrate how underground space can improve the quality of urban life.
- How can resilience and sustainability be modelled in a way that can be used to quantify the benefits of urban underground space.

If no metrics or methodology exist, we cannot demonstrate how underground space improves quality of life and resilience.

Where are the Gaps?

1. Data gaps (including smart systems and digital twins)
2. Model gaps (infrastructure sectors often uses different models that are difficult to mesh into a system of systems model)
3. Knowledge gaps
4. Technology/equipment gaps
5. Decision tools and planning gaps



From J.M. Yusta et al. / Energy Policy 39 (2011) 6100–6119

Where are the Gaps?

6. Workforce and skills gaps
7. Governance gaps
8. Financing gaps
9. Policy gaps, regulations

We need to develop clarified structures, methodologies and metrics to achieve planning and performance goals – costs (first and LCC), equity, environmental, and resilience, sustainability, reliability…

What does "optimization mean? Planning for whom, to what, when, where, why…

6. Back to ESG

Governments have long been the traditional drivers of social and economic development in our communities — particularly through infrastructure and construction - but they are now increasingly embracing innovation and environmental sustainability as new dimensions into this mix.

Private sector infrastructure players (including private finance) are also connecting into this movement — there is an increasing awareness of the linkages between ESG-enhanced infrastructure assets and positive community impacts at scale - potentially generating stronger levels of stakeholder support and business opportunities as a result.

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GWU Program – School of Business, Institute for Corporate Responsibility

ESG & Infrastructure Initiative

Vision

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.

COLORADO SCHOOL OF MINES https://business.gwu.edu/esg-infrastructure-initiative

7. Summary

- Infrastructure demands will only grow. 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.
- 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? Should we seek adaptation or transformation?

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7. Summary

Adaptation	Transformation
Incremental change	Major, potentially fundamental, change
Respond to shock	Action in anticipation of major stresses
Maintain previous order	Create new order, open ended
Build adaptive capacity	Reorder system dynamics
Emergent properties guide trajectory	Build agency, leadership, change agents

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7. Summary

Should the aim be sustainability or resilience?

- 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, 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 the inevitable, but unspecified, system shocks and stressors. Resilience approach does not require predicting outcomes. Instead, it builds social and natural capital and enhances adaptive capacity to cope with unknown futures (Carpenter and Folke 2006, Folke et al. 2010).

Simply put, sustainability prioritizes outcomes; resilience prioritizes process.

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7. Summary

Resilience Theory Approach	Sustainability Science Approach
Change is normal, and there are multiple stable states	Envision the future and act to make it happen
Experience adaptive cycle gracefully	Utilize transition management approach
Origin in ecology, maintain ecosystem services	Origin in social sciences, society is flawed
Result of change is open-ended, emergent	Desired results of change are specified in advance
Concern with maintaining system dynamics	Focus is on interventions that lead to sustainability
Stakeholder focus is on desirable dynamics	Stakeholder input focused on desirable outcomes

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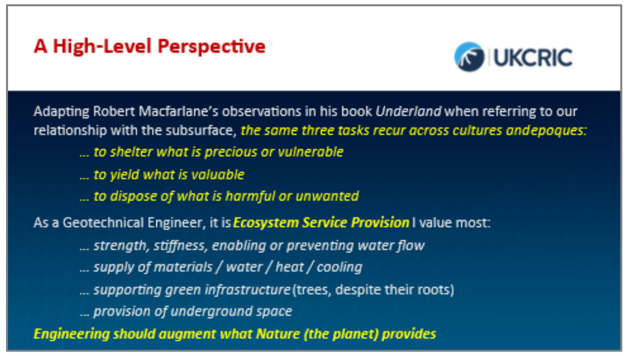
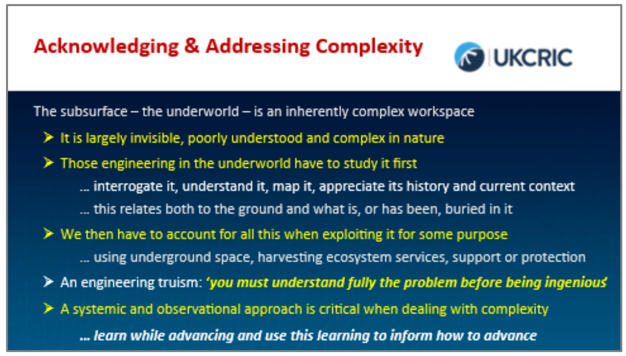
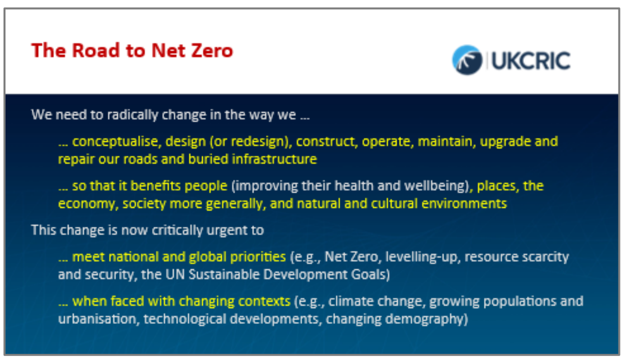
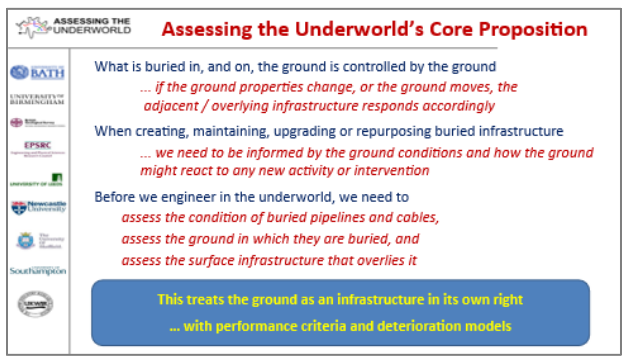
UK COLLABORATORIUM FOR RESEARCH ON INFRASTRUCTURE & CITIES
Inspired infrastructure for better living
Urban Futures
GG TOP
Liveable Cities
urban living Birmingham
Resilience Through Innovation Critical Local Transport and Utility Infrastructure
ASSESSING THE UNDERWORLD
Pipebots
EPSRC
Pioneering research and skills
The Challenges and Opportunities of Engineering the Underworld
Professor Chris Rogers
University of Birmingham
28th September 2023

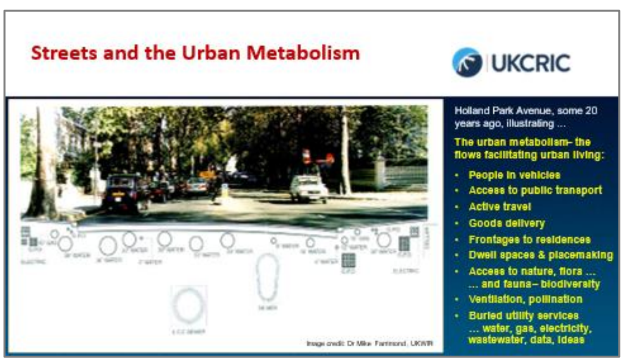

A High-Level Perspective
UKCRIC
Adapting Robert Macfarlane's observations in his book Underland when referring to our relationship with the subsurface, the same three tasks recur across cultures and epoques:
… to shelter what is precious or vulnerable
… to yield what is valuable
… to dispose of what is harmful or unwanted
As a Geotechnical Engineer, it is Ecosystem Service Provision I value most:
… strength, stiffness, enabling or preventing water flow
… supply of materials / water / heat / cooling
… supporting green infrastructure (trees, despite their roots)
… provision of underground space
Engineering should augment what Nature (the planet) provides

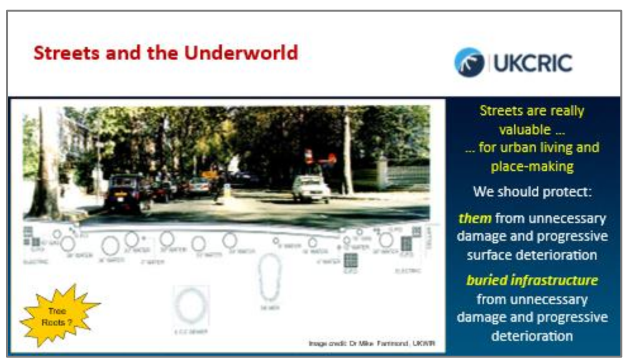

Priscilla's Reflections
UKCRIC
Should the aim be sustainability or resilience?
More generally, what criteria should influence design decisions?
… different design criteria will yield different system 'design options'
What does "optimization" mean?
We need a rational basis for the value of underground space
… I would talk about 'business models', or accounting for all forms of value
A non-siloed approach is essential
… I would talk of the need to move towards transdisciplinarity
A systems approach is essential
… considering planetary boundaries – what does doughnut engineering look like?


Acknowledging & Addressing Complexity
UKCRIC
The subsurface – the underworld – is an inherently complex workspace
It is largely invisible, poorly understood and complex in nature
Those engineering in the underworld have to study it first
… interrogate it, understand it, map it, appreciate its history and current context
… this relates both to the ground and what is, or has been, buried in it
We then have to account for all this when exploiting it for some purpose
… using underground space, harvesting ecosystem services, support or protection
An engineering truism: 'you must understand fully the problem before being ingenious'
A systemic and observational approach is critical when dealing with complexity
… learn while advancing and use this learning to inform how to advance

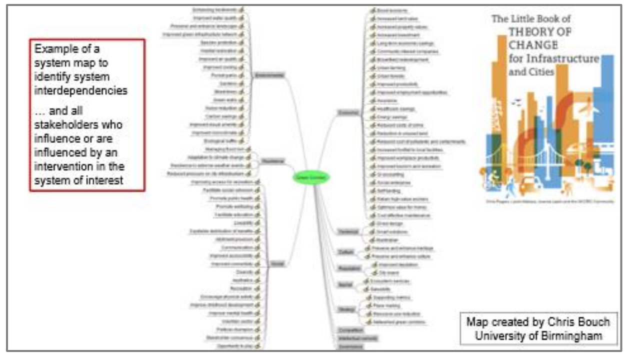

The Road to Net Zero
UKCRIC
We need to radically change in the way we …
… conceptualise, design (or redesign), construct, operate, maintain, upgrade and repair our roads and buried infrastructure
… so that it benefits people (improving their health and wellbeing), places, the economy, society more generally, and natural and cultural environments
This change is now critically urgent to
… meet national and global priorities (e.g., Net Zero, levelling-up, resource scarcity and security, the UN Sustainable Development Goals)
… when faced with changing contexts (e.g., climate change, growing populations and urbanisation, technological developments, changing demography)

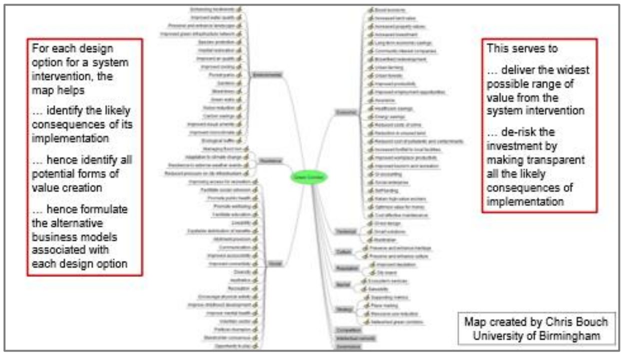

ASSESSING THE UNDERWORLD
Assessing the Underworld's Core Proposition
BATH
EPSRC
Southampton
What is buried in, and on, the ground is controlled by the ground
… if the ground properties change, or the ground moves, the adjacent / overlying infrastructure responds accordingly
When creating, maintaining, upgrading or repurposing buried infrastructure
… we need to be informed by the ground conditions and how the ground might react to any new activity or intervention
Before we engineer in the underworld, we need to
assess the condition of buried pipelines and cables,
assess the ground in which they are buried, and
assess the surface infrastructure that overlies it
This treats the ground as an infrastructure in its own right
… with performance criteria and deterioration models


Streets and the Urban Metabolism
UKCRIC
Holland Park Avenue, some 20 years ago, illustrating …
The urban metabolism – the flows facilitating urban living:
People in vehicles
Access to public transport
Active travel
Goods delivery
Frontages to residences
Dwell spaces & placemaking
Access to nature, flora … and fauna – biodiversity
Ventilation, pollination
Buried utility services … water, gas, electricity, wastewater, data, ideas
Image credit: Dr Mike Farrimond, UKWIR

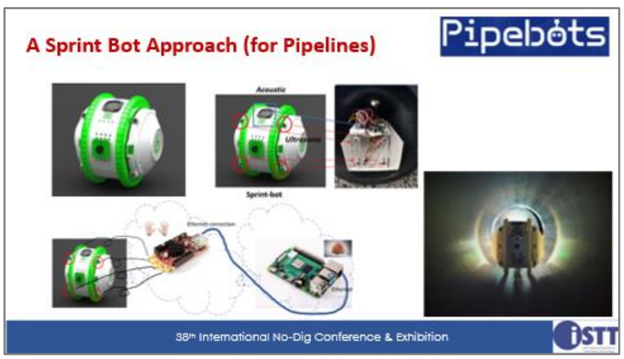

Streets and the Underworld
UKCRIC
Tree Roots ?
Image credit: Dr Mike Farrimond, UKWIR
Streets are really valuable …
… for urban living and place-making
We should protect:
them from unnecessary damage and progressive surface deterioration
buried infrastructure from unnecessary damage and progressive deterioration


Visions of the Urban Subsurface
UKCRIC
Urban Futures
ASSESSING THE UNDERWORLD

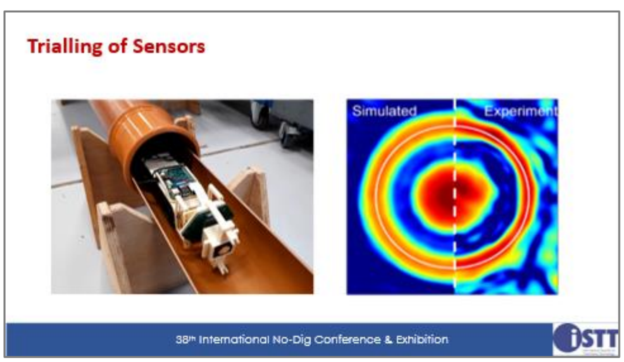

Example of a system map to identify system interdependencies
… and all stakeholders who influence or are influenced by an intervention in the system of interest
The Little Book of THEORY OF CHANGE for Infrastructure and Cities
Map created by Chris Bouch University of Birmingham


For each design option for a system intervention, the map helps
… identify the likely consequences of its implementation
… hence identify all potential forms of value creation
… hence formulate the alternative business models associated with each design option
This serves to
… deliver the widest possible range of value from the system intervention
… de-risk the investment by making transparent all the likely consequences of implementation
Map created by Chris Bouch University of Birmingham


Robotics for Streets (and Bridges)
UKCRIC
FHWA, USA. Gucunski, et al. (2013)


A Sprint Bot Approach (for Pipelines)
Pipebots
Acoustic
Ultrasound
Sprint-bot
38th International No-Dig Conference & Exhibition
ISTT


Trialling of Sensors
38th International No-Dig Conference & Exhibition
ISTT


Trialling of Sensors
Simulated
Experiment
38th International No-Dig Conference & Exhibition
ISTT

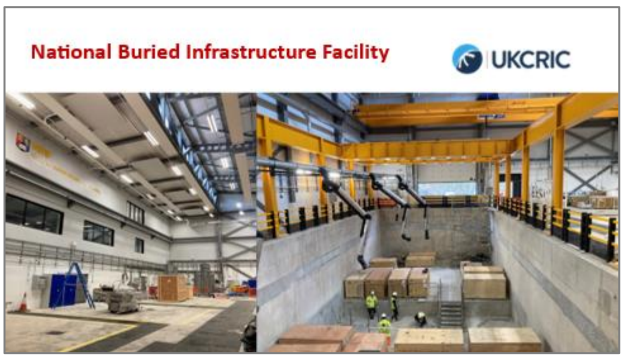

Trialling of Sensors
38th International No-Dig Conference & Exhibition
ISTT


Whegged Robots
38th International No-Dig Conference & Exhibition
ISTT


A Possible Means of Deployment
38th International No-Dig Conference & Exhibition
ISTT


A Possible Means of Deployment
38th International No-Dig Conference & Exhibition
ISTT


National Buried Infrastructure Facility
UKCRIC
The host facility for two of Pipebots' proving trials
NATIONAL BURIED INFRASTRUCTURE FACILITY
NBIF


National Buried Infrastructure Facility
UKCRIC

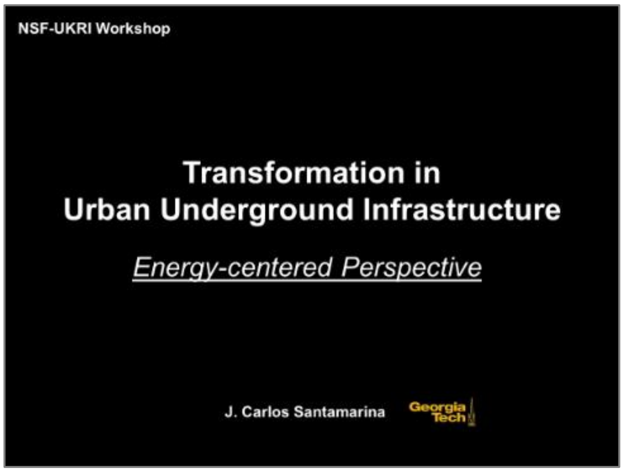

National Buried Infrastructure Facility
UKCRIC
National Buried Infrastructure Facility

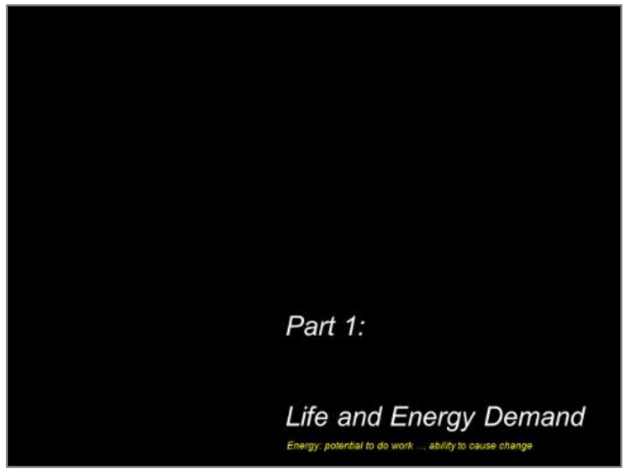

National Infrastructure Laboratory
UKCRIC
• £46m investment in state -of-the-art teaching and research facilities
• Focusing on infrastructure, rail and maritime sectors

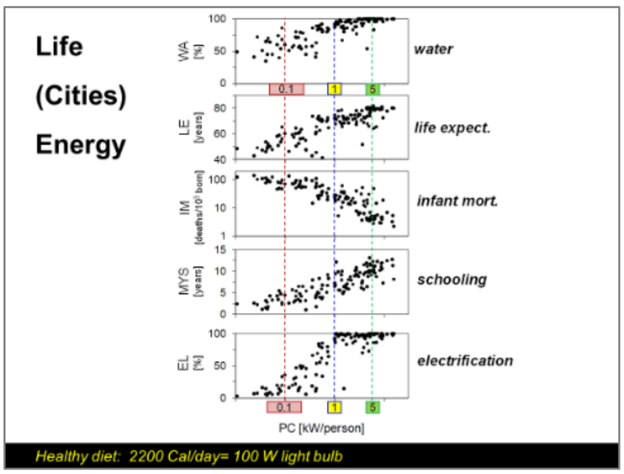

National Infrastructure Laboratory, Southampton
National Green Infrastructure Facility, Newcastle
National Water & Wastewater Treatment Test Facility, Cranfi
National Distributed Water Infrastructure Facility, Sheffield
National Centre for Smart Infrastructure & Construction, Cambridge

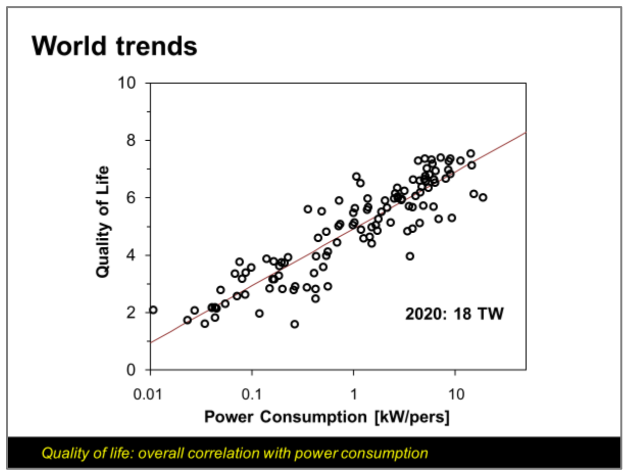

UK Research Facilities and Programmes
UKCRIC
c.d.f.rogers@bham.ac.uk

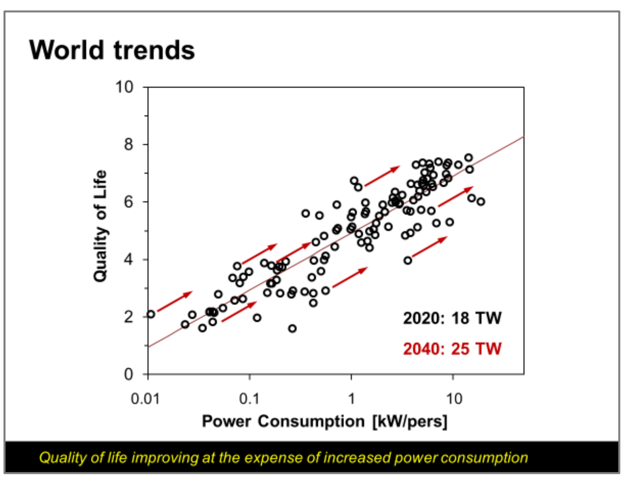
Carlos Santamarina

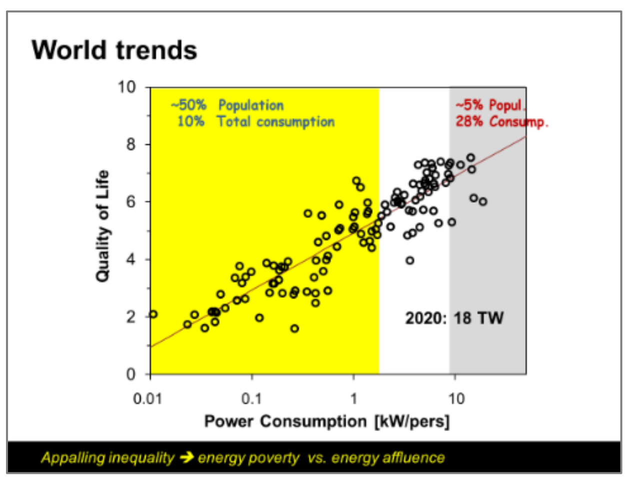


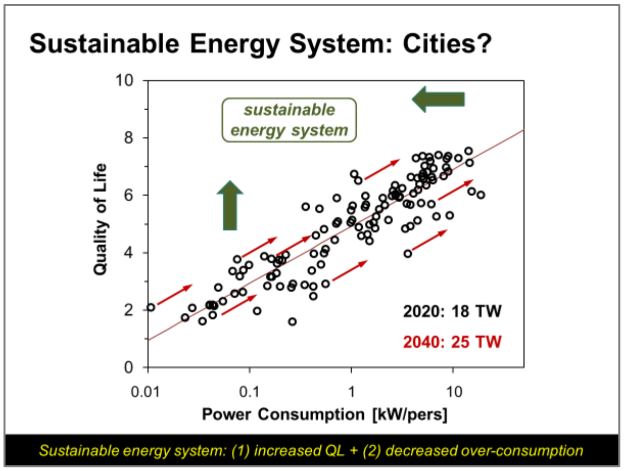


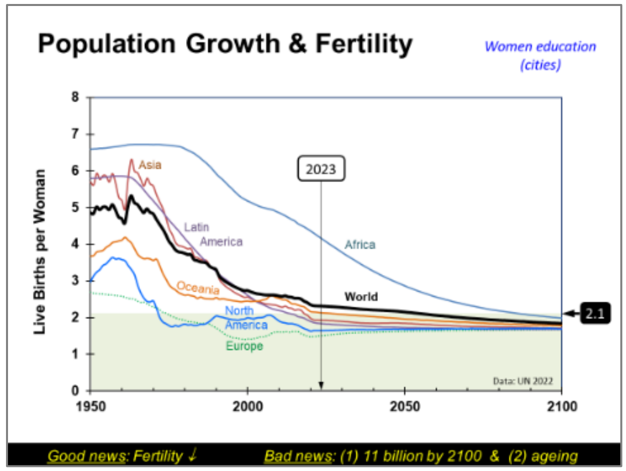


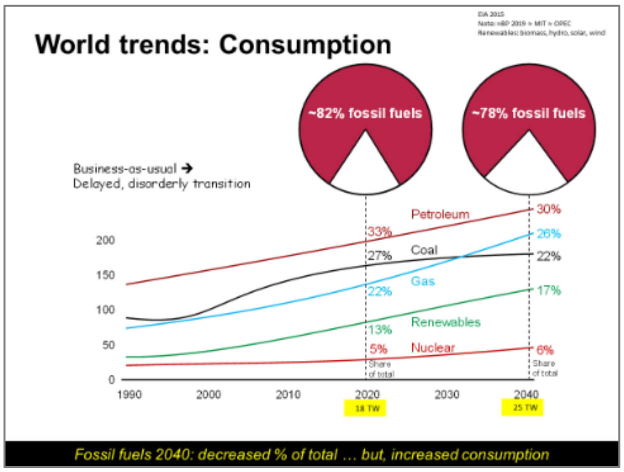






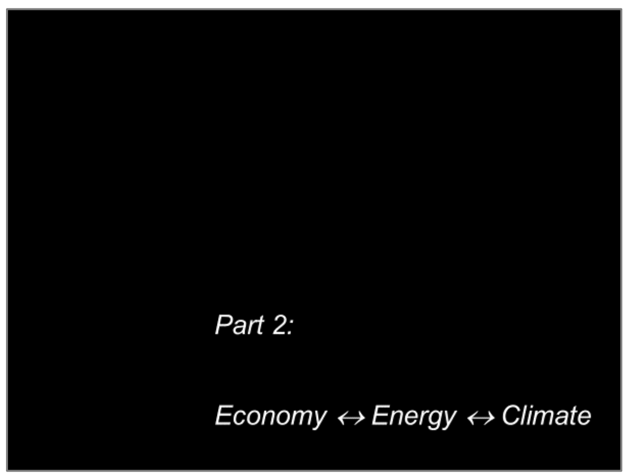

Sustainable Energy System: Cities?
sustainable energy system
Quality of Life
Power Consumption [kW/pers]
2020: 18 TW
2040: 25 TW
Sustainable energy system: (1) increased QL + (2) decreased over-consumption

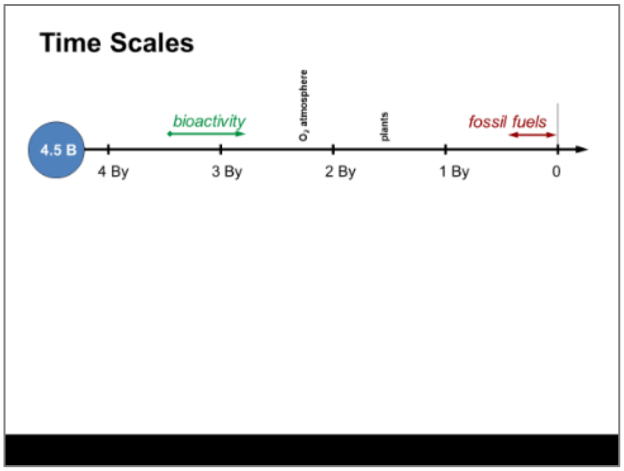

Population Growth & Fertility
Women education (cities)
Live Births per Woman
Asia
Latin America
Africa
2023
Oceania
World
North America
Europe
2.1
Data: UN 2022
Good news: Fertility ↓
Bad news: (1) 11 billion by 2100 & (2) ageing

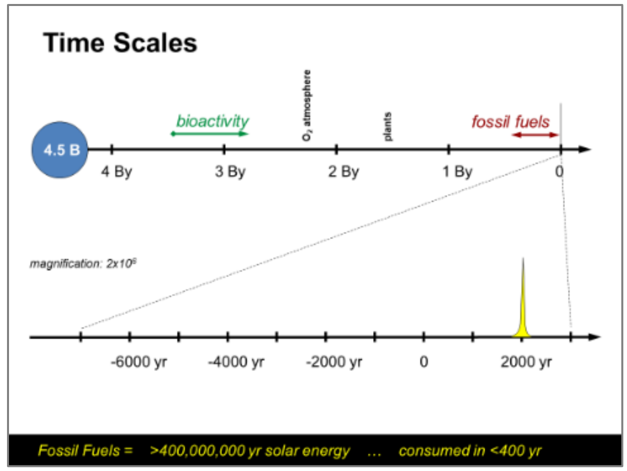

World trends: Consumption
~82% fossil fuels
~78% fossil fuels
Business-as-usual →
Delayed, disorderly transition
Petroleum
Coal
Gas
Renewables
Nuclear
Share of total
18 TW
25 TW
Fossil fuels 2040: decreased % of total … but, increased consumption

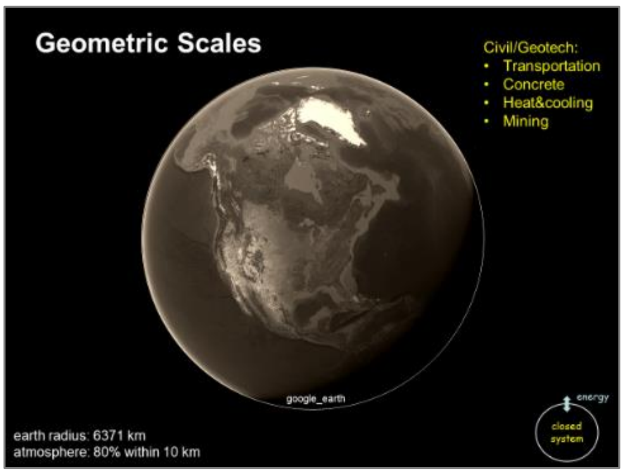

World trends: Consumption
BBC 10/20/2021
Fossil fuel production set to soar in next decade
Government plans to extract coal, oil and gas are incompatible with safe temperatures, says the UN.
SCIENCE & ENVIRONMENT
Transition to net-zero: fueled by fossil fuels!


Mining needed for Net Zero 2050
Copper (grid, solar, wind)
• Needed: 20·10⁶ ton copper to satisfy Net zero 2050
• Equivalent: one Escondida/year discovered & into production
Lithium and Nickel (batteries): 40 times increase in demand (by 2040)
Rare earth elements (wind turbines): 3 times increase (by 2040)
Time: >20-30 years from discovery to full production
Environmental/social restrictions may stop project
Mining-limited transition to "net zero 2050"

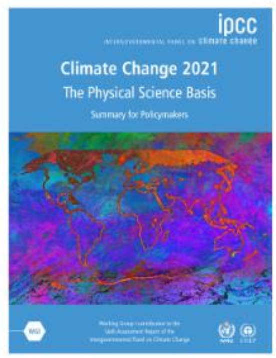

Part 2:
Economy ↔ Energy ↔ Climate







The SCIENCE…!!



OVERALL:

Higher confidence… narrower ranges

FUTURE:

Warming: 1.5°C and 2°C during XXI

Increased frequency & intensity hot extremes

Intensified global water cycle (variability & severity)

Ocean and land carbon sinks: less effective

Changes: irreversible for centuries to millennia

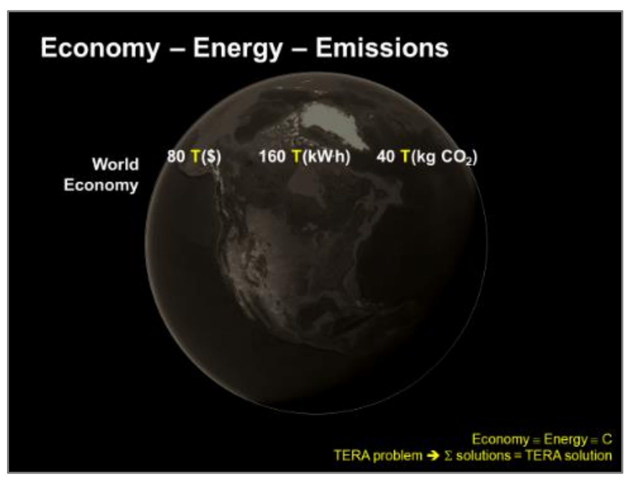
Low-likelihood outcomes cannot be ruled out
(e.g., abrupt ocean circulation changes)

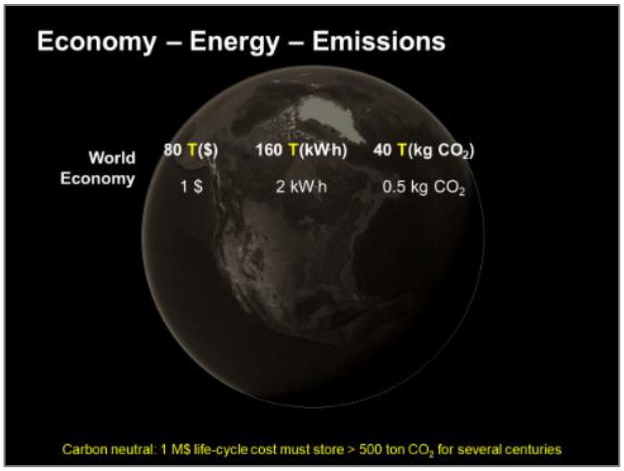
IPCC 2021

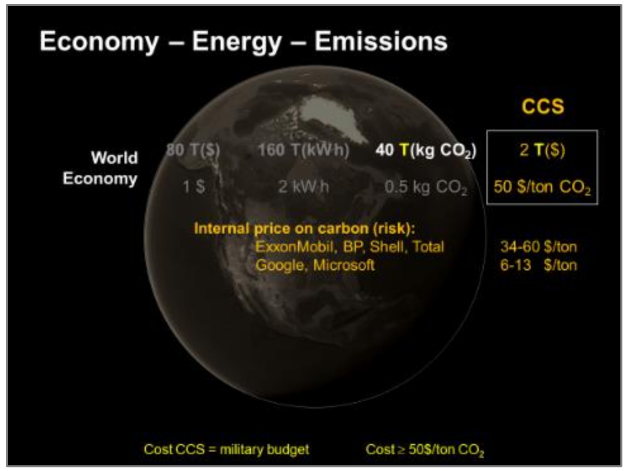
C-to-CO_2

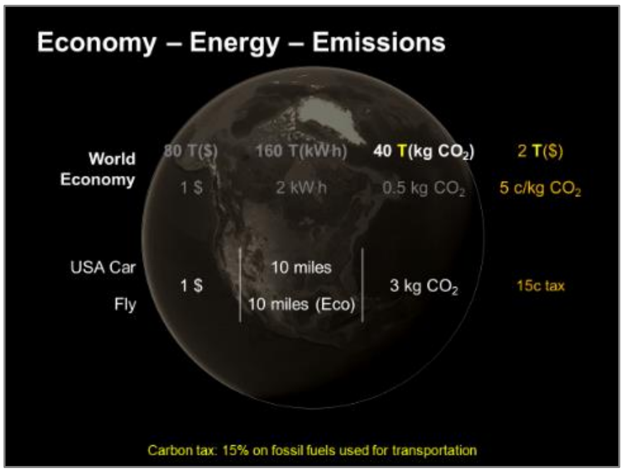
Molar mass	Hydrogen H:	1 gr/mol
	Carbon C:	12 gr/mol
	Oxygen O:	16 gr/mol
	Carbon dioxide CO_2:	44 gr/mol
Hydrocarbon	In H-C-H chains:	C=12/14=86%
	In crude oil ~ gasoline:	C≈85%
Then:	1 gallon gasoline ➔	9 kg CO_2
	1 oil barrel = 42 gallon ➔	400 kg CO_2

$M_{CO2} = 3\ M_{FF}$









True LCA: Energy Cost (lifetime)

Energy Plant Type	Lifetime Cost ¢ / kWh
Wind (offshore)	20
Nuclear	15
PV Solar	9
Coal	9
Geothermal	8
Hydro-electric	8
Gas	7
Wind (onshore)	6

No biasing long term incentives - Charge real-costs

True LCA: Energy REAL Cost (lifetime)

Energy Plant Type	Lifetime Cost ¢ / kWh
Wind (offshore)	20
Nuclear	15
Coal & CCS	12
Gas & CCS	9
PV Solar	9
Coal	9
Geothermal	8
Hydro-electric	8
Gas	7
Wind (onshore)	6

Real-cost pricing ➔ proper techno-economical optimization

Part 3:

The Reimagined Urban

Trees...!

Tree C-balance

C-mass in dry wood	50%
Mean tree offsetting	40 kg_{CO2}/(tree.year)
To compensate 1 ton of CO_2	25 tree.years (~2000$ expense)
To compensate 40 T.kg CO_2	1 T.trees = 10^{12} trees

Executive order (10/16/2020): **1 T.trees**

At 850 trees/Ha ➔

12 M.km² = **1.3 USA**

Old forests are C-neutral ... and even C-negative!!

Wood = construction material & "sustainable" biofuel

Trees in cities: cleaner air, lower temperature (-2°C in Medellin), higher quality of life

Tree inequality: poor neighborhoods = lower tree density

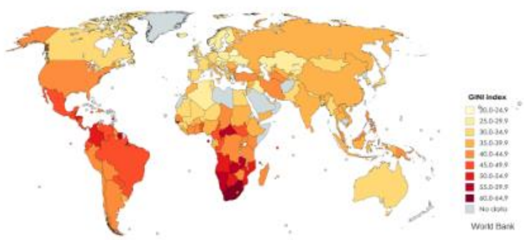
Trees: solar-fueled CO_2 capture *Cities: infrastructure ↓ & trees ↑*

Inequality

➔ migration
➔ city violence

Extreme poverty:	1990 ≤ 1 U$A/day	1.9 billion people (36% of the population)
	2023 ≤ 2.15 U$A/day	720 million people (9% of the population)

"Wealth inequality": has worsen



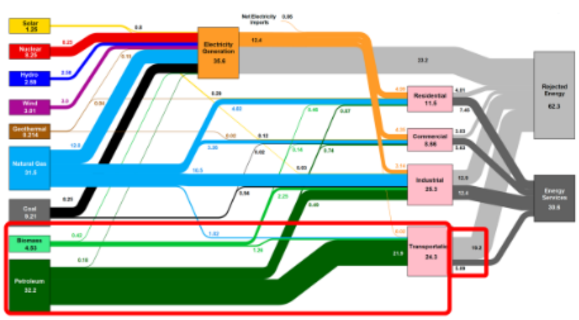
Good news: eradication of extreme poverty - Bad news: inequality not improving...

Urban Development in XXth Century

Atlanta: optimized for cheap oil *High infrastructure-inertia*

Resources - Power USA

2020
TOTAL: 93 Quads
LLNL - DoE



Transportation: Oil-based, and most inefficient!

Energy Density

	[MJ/kg]
Hydroelectric H=100m	0.001
Coal	23
Oil ~ gasoline	45
Hydrogen	140
Uranium (effective)	900,000

Volkswagen (since 2002) 100 km/l

"ultra high efficient vehicles"

Note: 1.0 L gasoline = 10 m² of solar panels for 1 day
100 kWh battery (Tesla X – 500 kg) = 8L gasoline

Fossil fuels: compact engineering *We do have technology for dramatic change*

True LCA in Open System: Boundary?

Shirt?

EV vs. ICE?

Mass transportation

Carbon neutral companies?

Carbon neutral cities?

.....

....

Affluent societies: money saved?

True LCA in Open System: Boundary?

Shirt?

EV vs. ICE? ***keep using the car you have***

Mass transportation

Carbon neutral companies?

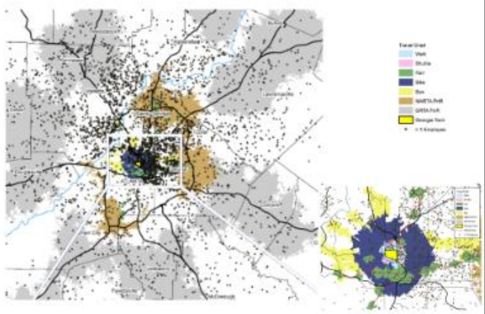
Carbon neutral cities?

.....

....

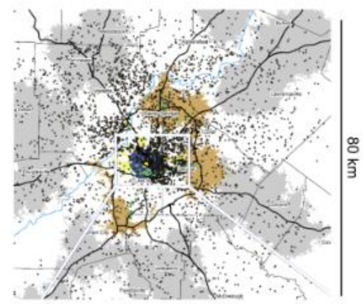
When is the do-nothing the best option?

Atlanta Commuters – Georgia Tech



Atlanta Commuters – Georgia Tech

$$10{,}000\, com \cdot 30 \frac{mile}{day \cdot com} \cdot 250 \frac{day}{yr} \cdot 0.3 \frac{kg\ CO_2}{mile} = 22{,}500{,}000 \frac{kg\ CO_2}{yr}$$



Low-C commuters: 4 options

Atlanta Commuters – Georgia Tech

$$10{,}000\, com \cdot 30 \frac{mile}{day \cdot com} \cdot 250 \frac{day}{yr} \cdot 0.3 \frac{kg\ CO_2}{mile} = 22{,}500{,}000 \frac{kg\ CO_2}{yr} \Rightarrow 560{,}000\ trees$$

658 Ha forest

Low-C commuters: 4 options … the 5th option: 560,000 trees

Cities: C-Neutral…?

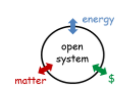
World: >10,000 cities (World Urban Forum, UN))
- 4037 cities: >100,000 people
- 1063 cities: >500,000 people

2022 Urban population
- World: 57% (climbing)
- USA: 83% (climbing)
- China: 64% (climbing)

2050 Urban population
- World: 2/3 (~7 billion people)

Cities → Climate → Cities
- 60-80% global resources → emissions
- Increased absorption: heat island

C-neutral cities by 2050: > 240 pledges
- Transportation (low-emission zones, car-free bicycle streets)
- Build (concrete & steel) & maintain
- Operate (most emissions: post construction): heat/cool & power
- Decarbonize the electric grid
- Waste management



Cities will <u>not</u> be C-neutral by 2050

Coastal Cities: Sea Level Rise & Wind

Coastal population (<100 km from coast & <50 meters elevation)
World & USA: 40% of today's population leaves in coastal areas

Risks: wind, sea level rise, erosion,
flooding, saltwater intrusion ➔ drinking water, septic systems

Sea level rise: 2050: 0.30 m
2100: 1.1-to2 m (without curbing emissions)

Consider 3m sea -level rise (climate + storm) Note: Katrina 10m surge
>99 percent of today's homes in 252 coastal towns would be submerged

Underground in coastal cities?

Coastal Cities: Sea Level Rise & Wind

An October saltwater intrusion could threaten drinking water in New Orleans, so they'll barge in 36 million gallons of fresh water a day

NYC residents urged to FLEE basement apartments as post-Tropical Storm Ophelia sends life-threatening rainwater down on the city

- Ophelia was downgraded to a post-tropical cyclone but was still anticipated to produce deadly surf
- NYC Emergency Management issued a travel advisory through Sunday night
- Commissioner Zach Iscol urged residents to stay vigilant

By MACKENZIE TATANANNI FOR DAILYMAIL.COM

Underground in coastal cities?

Underground: Ants !

(with N. Espinoza)

Underground: efficient construction (ants 10,000 more efficient than TBMs)

Policy ➔ Politicians

Executive

President: law degree
Vice president: law degree

Legislative:
118th US Congress
https://crsreports.congress.gov/product/pdf/R/R47470

House of Representatives (435 members)

- 409 hold college degree
- 352 have served as public servants
- 140 have law degrees
- 8 engineers
- 2 physicists
- 2 chemists

Senate (100 members)

- 99 hold college degree
- 82 have served as public servants
- 51 have law degrees
- 1 geologist
- 1 engineer

Judicial

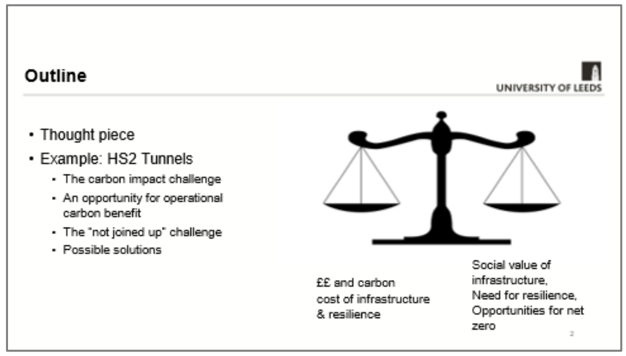
9 members … all law degrees
(4 Harvard, 4 Yale, 1 Notre Dame)

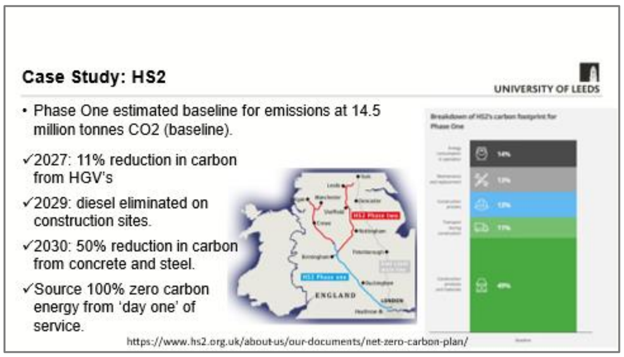
Let's get involved ….!!!

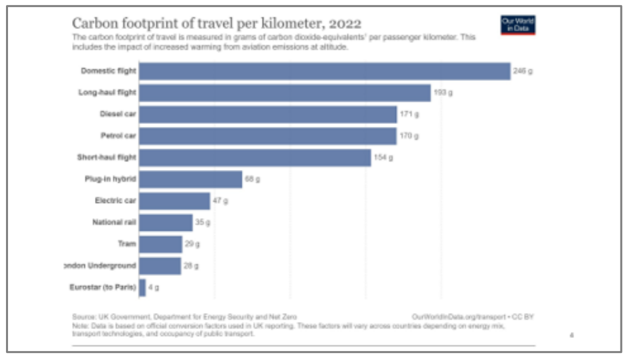
Closing Thoughts

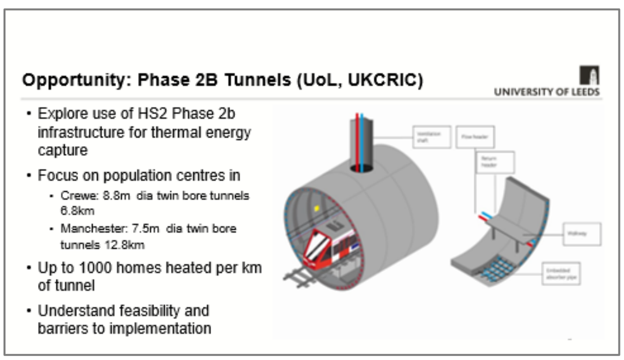
Life and Energy Demand	Quality of life ↔ power consumption.
	Sustainable energy future: QL↑ and reducing consumption↓
	The energy transition will be fueled by fossil fuels
	Increased fossil fuel consumption in the coming decades
	Mining: the bottleneck for the energy transition
Economy Energy Climate	1$ = 2kWh = 0.5 kg CO_2
	True life cycle analyses in an open-system?
	Caution with misnomers … *Fake technologies derail our children's future.*
	Conundrum: what will affluent societies do with savings?
Urban Reimagined	Urban population 60-to-80% … and growing ➔ Cities ↔ climate
	XXth urban developments: low transportation cost
	XXI energy transition: transportation reform
	Coastal cities: 40% of the population – Most vulnerable ➔ underground?
	Trees = solar-fueled C-capture. Bury infrastructure & increased tree density
	Development of the underground: enhanced construction efficiency (ants)


UNIVERSITY OF LEEDS
Underground Infrastructure in the time of a climate crisis. What can we do to help?
Professor Fleur Loveridge
Dr David Barns & Dr Tristano Sainati
Picture curtesy of HS2


Outline
UNIVERSITY OF LEEDS
• Thought piece
• Example: HS2 Tunnels
• The carbon impact challenge
• An opportunity for operational carbon benefit
• The "not joined up" challenge
• Possible solutions
££ and carbon cost of infrastructure & resilience
Social value of infrastructure, Need for resilience, Opportunities for net zero
2

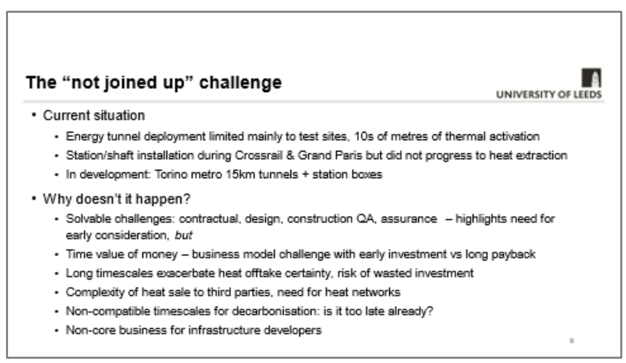

Case Study: HS2
UNIVERSITY OF LEEDS
• Phase One estimated baseline for emissions at 14.5 million tonnes CO2 (baseline).
✓2027: 11% reduction in carbon from HGV's
✓2029: diesel eliminated on construction sites.
✓2030: 50% reduction in carbon from concrete and steel.
✓Source 100% zero carbon energy from 'day one' of service.
https://www.hs2.org.uk/about-us/our-documents/net-zero-carbon-plan/
Breakdown of HS2's carbon footprint for Phase One
14%
13%
13%
11%
49%


Carbon footprint of travel per kilometer, 2022
Domestic flight 246 g
Long-haul flight 193 g
Diesel car 171 g
Petrol car 170 g
Short-haul flight 154 g
Plug-in hybrid 68 g
Electric car 47 g
National rail 35 g
Tram 29 g
London Underground 28 g
Eurostar (to Paris) 4 g
4


Opportunity: Phase 2B Tunnels (UoL, UKCRIC)
UNIVERSITY OF LEEDS
• Explore use of HS2 Phase 2b infrastructure for thermal energy capture
• Focus on population centres in
• Crewe: 8.8m dia twin bore tunnels 6.8km
• Manchester: 7.5m dia twin bore tunnels 12.8km
• Up to 1000 homes heated per km of tunnel
• Understand feasibility and barriers to implementation


6


Opportunity: The Christie Hospital
UNIVERSITY OF LEEDS
• NHS targets for 80% reduction in Scope 1 & 2 emissions by 2032 and Scope 3 by 2039. Net zero by 2045
• Cooling systems required for cancer treatment already at capacity
• High energy demand
• Little space for adaption
• HS2 impacts on their space
CHRISTIE
7


The "not joined up" challenge
UNIVERSITY OF LEEDS
• Current situation
• Energy tunnel deployment limited mainly to test sites, 10s of metres of thermal activation
• Station/shaft installation during Crossrail & Grand Paris but did not progress to heat extraction
• In development: Torino metro 15km tunnels + station boxes
• Why doesn't it happen?
• Solvable challenges: contractual, design, construction QA, assurance – highlights need for early consideration, *but*
• Time value of money – business model challenge with early investment vs long payback
• Long timescales exacerbate heat offtake certainty, risk of wasted investment
• Complexity of heat sale to third parties, need for heat networks
• Non-compatible timescales for decarbonisation: is it too late already?
• Non-core business for infrastructure developers
8

Costs and benefits

UNIVERSITY OF LEEDS

Additional costs

- Additional capital costs
  - Geothermal pipework
  - Installation costs during tunnel construction
  - Higher cost of GSHPs vs ASHPs
- Timing of investment
  - Tunnel design & construction, 2028-2034
  - Time value of money

Benefits (self consumption)

- Higher efficiency GSHPs vs ASHPs (+ CO_2 savings)
- Lower electricity consumption

National Benefit (all scenarios, not costed)

- Availability of heat source
- Reduced demand for green electricity

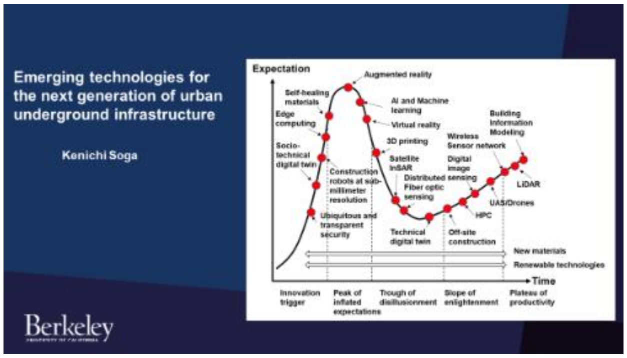
9

Solutions

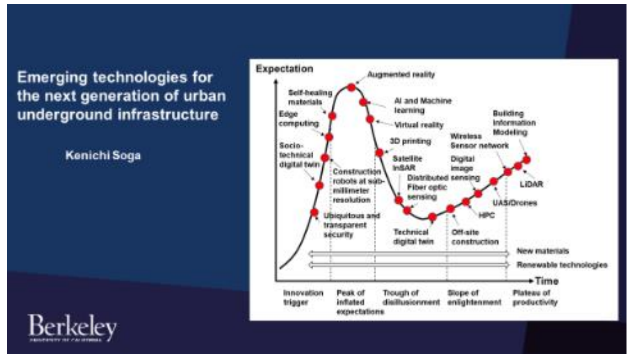
UNIVERSITY OF LEEDS

- Joined up thinking: government departments
  - Policy
  - Costs and benefits
- Appropriate system boundaries
  - Local costs vs national/global benefits
  - Local solutions for greater good
- Appropriate timescales > long term thinking
- Inter-disciplinary approaches

10



Emerging technologies for the next generation of urban underground infrastructure
Kenichi Soga
Expectation
Augmented reality
Self-healing materials
Edge computing
Socio-technical digital twin
AI and Machine learning
Virtual reality
3D printing
Building Information Modeling
Wireless Sensor network
Satellite InSAR
Digital image
Construction robots at sub-millimeter resolution
Distributed sensing
Fiber optic sensing
LiDAR
UAS/Drones
HPC
Ubiquitous and transparent security
Technical digital twin
Off-site construction
New materials
Renewable technologies
Time
Innovation trigger
Peak of inflated expectations
Trough of disillusionment
Slope of enlightenment
Plateau of productivity
Berkeley



Emerging technologies for the next generation of urban underground infrastructure
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3D printing
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Wireless Sensor network
Satellite InSAR
Digital image
Construction robots at sub-millimeter resolution
Distributed sensing
Fiber optic sensing
LiDAR
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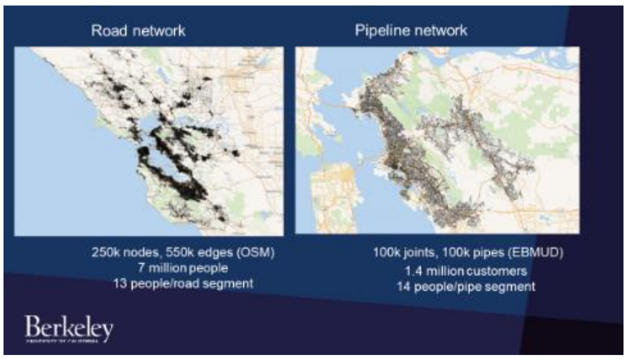
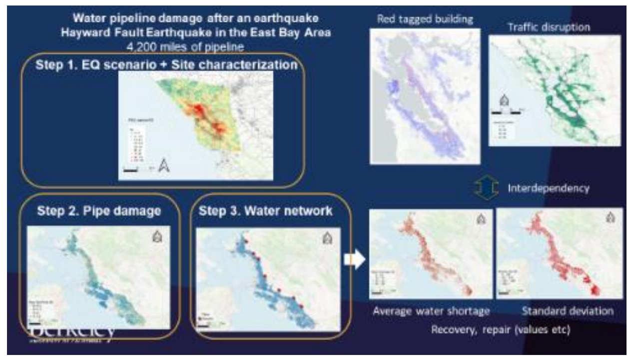
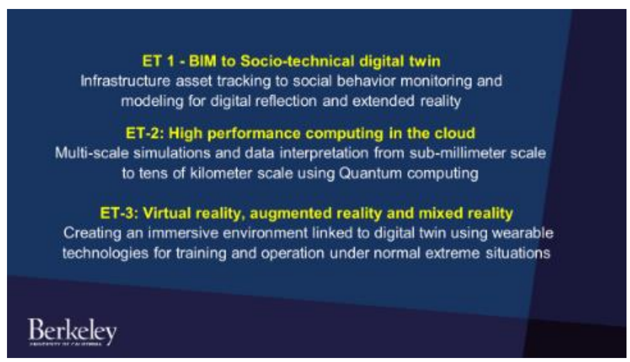


Road network
Pipeline network
250k nodes, 550k edges (OSM)
7 million people
13 people/road segment
100k joints, 100k pipes (EBMUD)
1.4 million customers
14 people/pipe segment
Berkeley

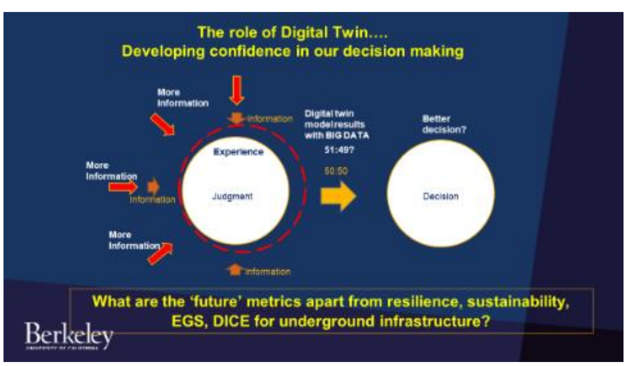


Water pipeline damage after an earthquake
Hayward Fault Earthquake in the East Bay Area
4,200 miles of pipeline
Step 1. EQ scenario + Site characterization
Red tagged building
Traffic disruption
Interdependency
Step 2. Pipe damage
Step 3. Water network
Average water shortage
Standard deviation
Recovery, repair (values etc)

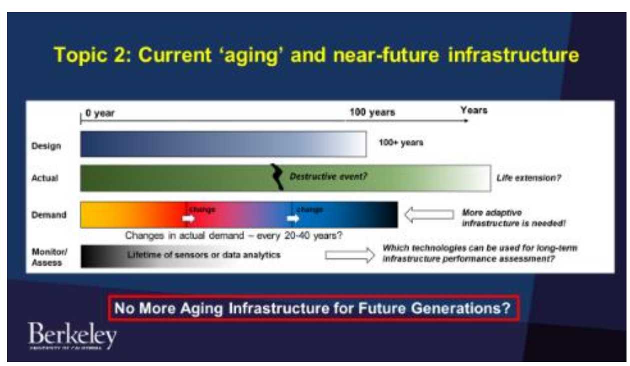
Wildfire evacuation simulations
Serious games
0 hour 0 minute



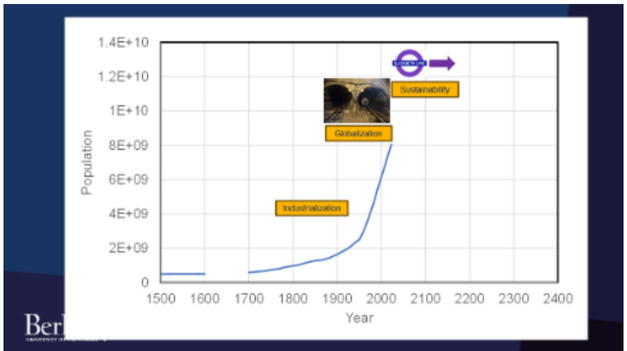
ET 1 - BIM to Socio-technical digital twin
Infrastructure asset tracking to social behavior monitoring and modeling for digital reflection and extended reality
ET-2: High performance computing in the cloud
Multi-scale simulations and data interpretation from sub-millimeter scale to tens of kilometer scale using Quantum computing
ET-3: Virtual reality, augmented reality and mixed reality
Creating an immersive environment linked to digital twin using wearable technologies for training and operation under normal extreme situations
Berkeley

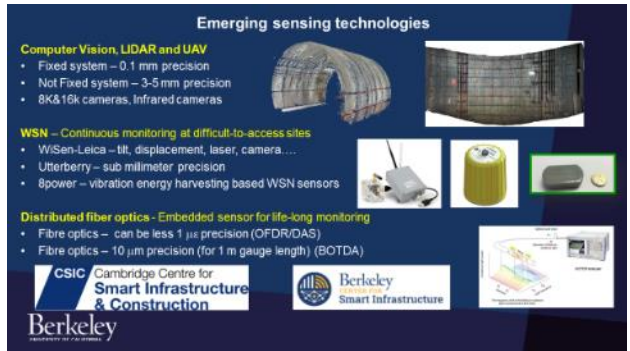


The role of Digital Twin….
Developing confidence in our decision making
More Information
Information
Digital twin model results with BIG DATA
51:49?
50:50
Better decision?
Experience
Judgment
Decision
What are the 'future' metrics apart from resilience, sustainability, EGS, DICE for underground infrastructure?
Berkeley

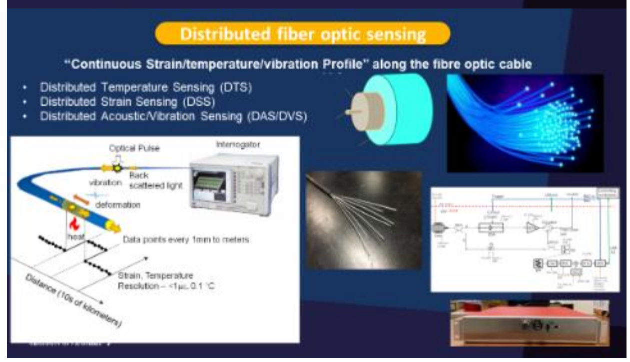


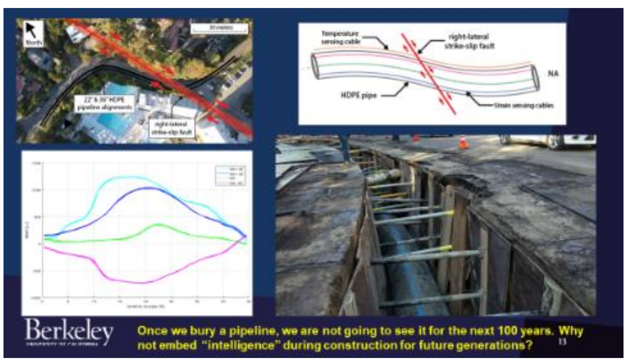
Topic 2: Current 'aging' and near-future infrastructure
0 year
100 years
Years
Design
100+ years
Actual
Destructive event?
Life extension?
Demand
change
More adaptive infrastructure is needed!
Changes in actual demand – every 20-40 years?
Monitor/ Assess
Lifetime of sensors or data analytics
Which technologies can be used for long-term infrastructure performance assessment?
No More Aging Infrastructure for Future Generations?
Berkeley

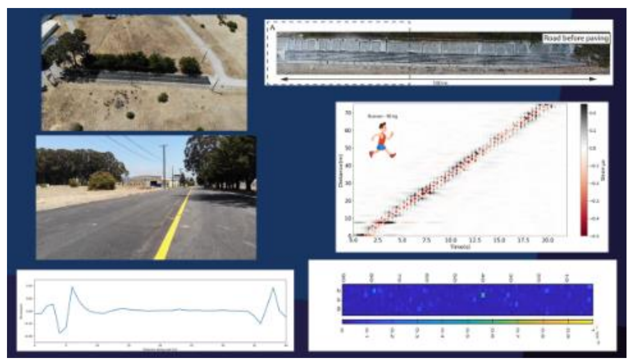

1.4E+10
1.2E+10
1E+10
8E+09
6E+09
4E+09
2E+09
0
Population
1500 1600 1700 1800 1900 2000 2100 2200 2300 2400
Year
Industrialization
Globalization
Sustainability

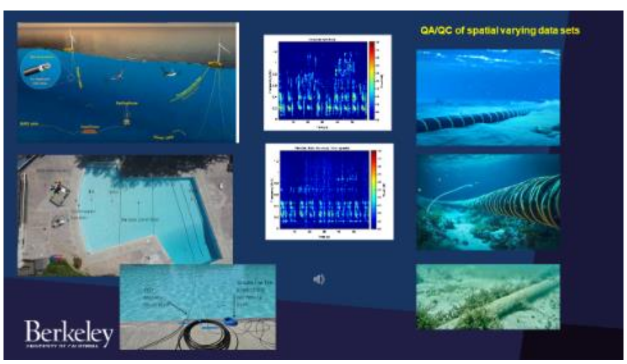

Emerging sensing technologies
Computer Vision, LIDAR and UAV
• Fixed system – 0.1 mm precision
• Not Fixed system – 3-5 mm precision
• 8K&16k cameras, Infrared cameras
WSN – Continuous monitoring at difficult-to-access sites
• WiSen-Leica – tilt, displacement, laser, camera….
• Utterberry – sub millimeter precision
• 8power – vibration energy harvesting based WSN sensors
Distributed fiber optics - Embedded sensor for life-long monitoring
• Fibre optics – can be less 1 με precision (OFDR/DAS)
• Fibre optics – 10 μm precision (for 1 m gauge length) (BOTDA)
CSIC Cambridge Centre for Smart Infrastructure & Construction
Berkeley Center for Smart Infrastructure
Berkeley

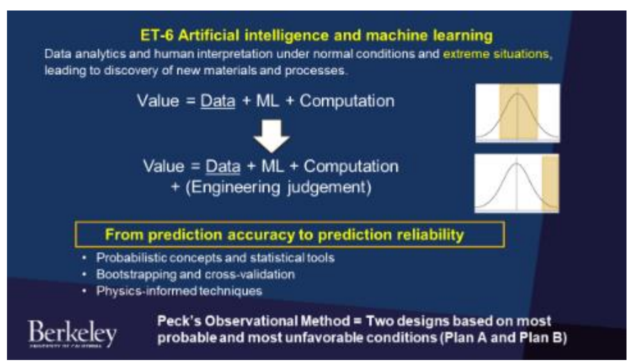

ET-4: Distributed sensors and network
(Satellite, fiber optics, wireless sensor network, etc)
Sensors everywhere with 5G/IoT, creating hyperconnected networks
ET-5: In-field Autonomy
(inspection, construction and maintenance)
Autonomy using drones, humanoids and super large robots.
Berkeley

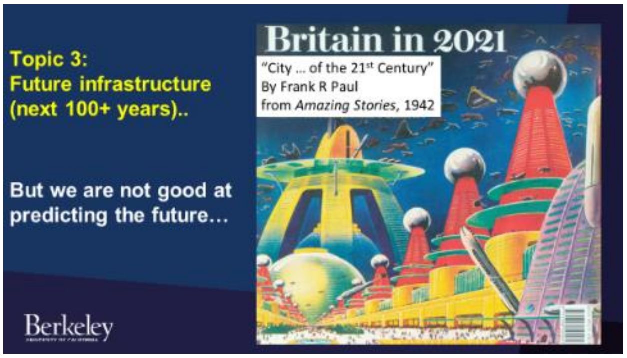

Distributed fiber optic sensing
"Continuous Strain/temperature/vibration Profile" along the fibre optic cable
• Distributed Temperature Sensing (DTS)
• Distributed Strain Sensing (DSS)
• Distributed Acoustic/Vibration Sensing (DAS/DVS)
Optical Pulse
Interrogator
vibration
Back scattered light
deformation
heat
Data points every 1mm to meters
Strain, Temperature Resolution – <1με, 0.1 °C
Distance (10s of kilometers)

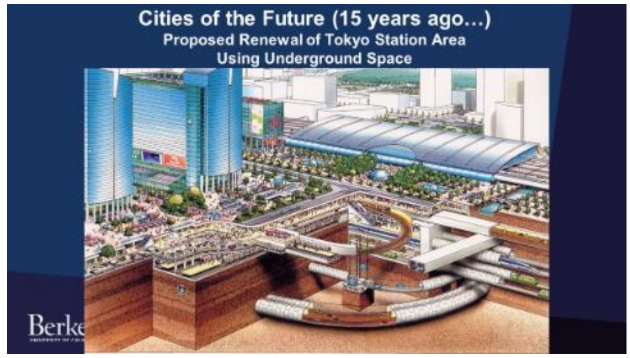

Temperature sensing cable
right-lateral strike-slip fault
HDPE pipe
Strain sensing cables
NA
Berkeley
Once we bury a pipeline, we are not going to see it for the next 100 years. Why not embed "intelligence" during construction for future generations?

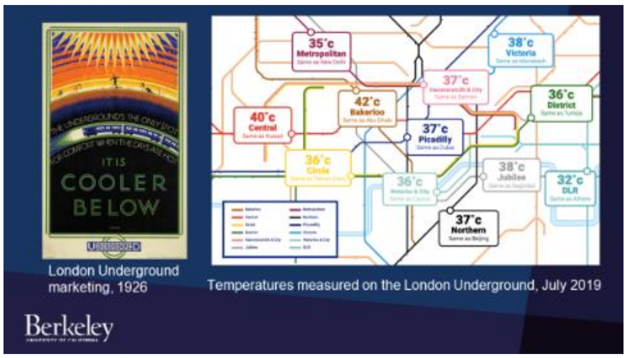

Road before paving

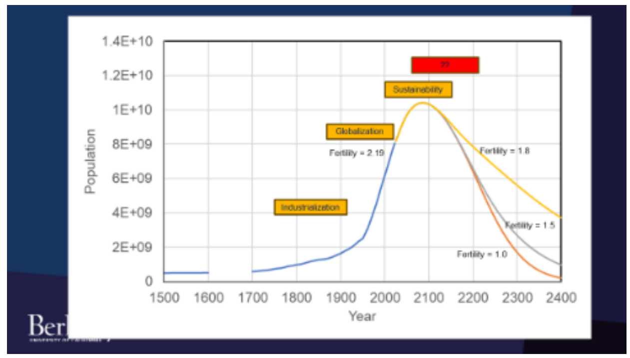

QA/QC of spatial varying data sets
Berkeley

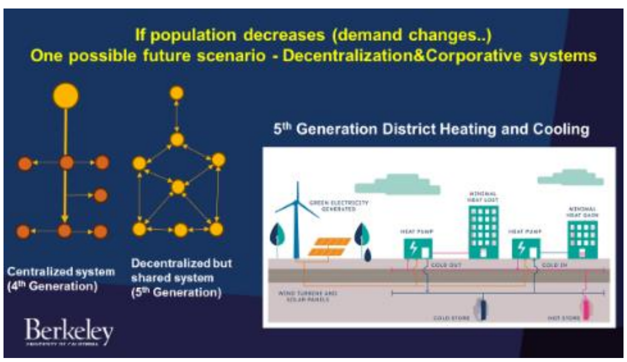

ET-6 Artificial intelligence and machine learning
Data analytics and human interpretation under normal conditions and extreme situations, leading to discovery of new materials and processes.
Value = Data + ML + Computation
Value = Data + ML + Computation
+ (Engineering judgement)
From prediction accuracy to prediction reliability
• Probabilistic concepts and statistical tools
• Bootstrapping and cross-validation
• Physics-informed techniques
Berkeley
Peck's Observational Method = Two designs based on most probable and most unfavorable conditions (Plan A and Plan B)

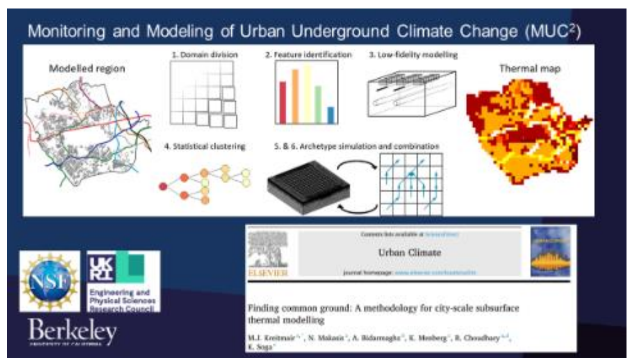


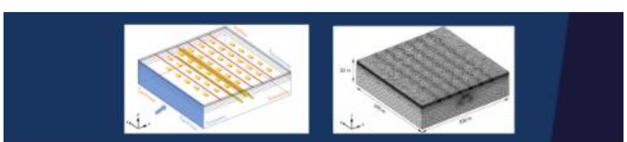






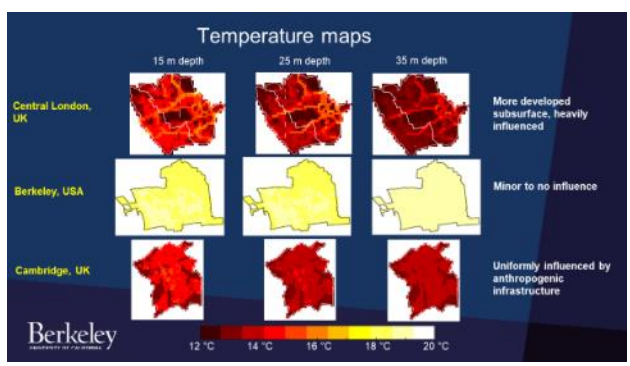


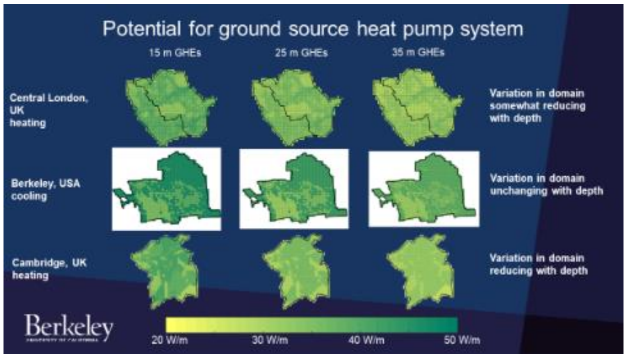




Training features for decision tree.

	Feature	Description	Unit
Natural	$\lambda_{ground,av}$	Ground thermal conductivity averaged over depth	[W/(m K)]
	$\rho_{ground,av}$	Ground density averaged over depth	[Mg/m^3]
	$C_{p,ground,av}$	Ground thermal capacity averaged over depth	[kJ/(kg K)]
	$k_{h,ground,av}$	Ground hydraulic conductivity averaged over depth	[m/s]
	$\epsilon_{ground,av}$	Ground porosity averaged over depth	[-]
	GW_{avg}	Groundwater level - below surface	[m]
	dHH	Hydraulic head difference at dominant direction	[m]
	k_s	Shade factor	[-]
	$T_{upstream}$	Upstream groundwater temperature	[°C]
Built	$A_{basements}$	Percentage of basements over surface area	[%]
	$A_{buildings}$	Percentage of buildings over surface area (used to determine number of sewers)	[%]
	Tunnel count	Number of tunnel lines within domain	[-]
	$d_{tunnel1}$	Depth of centreline of first tunnel line	[m]
	$d_{tunnel2}$	Depth of centreline of second tunnel line	[m]
	Tunnel In Aq	Number indicating how many tunnels are within an aquifer (in increments of 0.5)	[-]

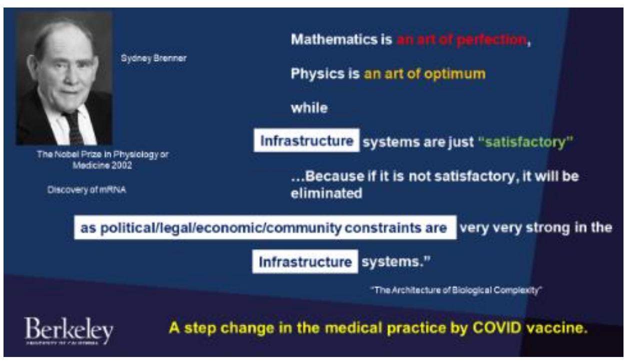


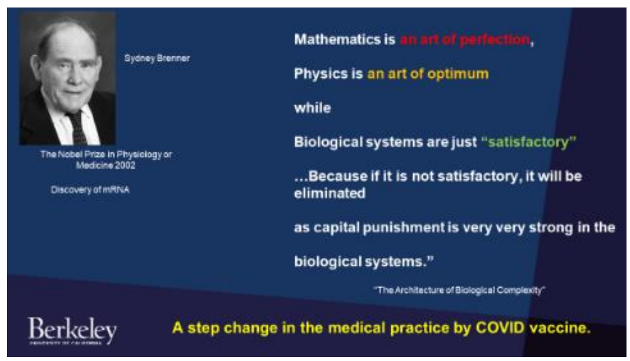

Potential for ground source heat pump system
15 m GHEs
25 m GHEs
35 m GHEs
Central London, UK heating
Berkeley, USA cooling
Cambridge, UK heating
Variation in domain somewhat reducing with depth
Variation in domain unchanging with depth
Variation in domain reducing with depth
20 W/m
30 W/m
40 W/m
50 W/m
Berkeley


Decentralized but shared community
(Smart and connected community)
• Buildings/Living
– Water reuse – repurposing existing underground infrastructure
– Energy generation and storage
ET8: Renewable technologies
Energy generation and storages at micro-scale (personal, building, street block, district?)
Berkeley
26


Decentralized but shared community
(Smart and connected community)
• Buildings/Living
• Transportation
– Remote working and less centralized service
– Autonomous car with less congestion (more packed but well controlled driving)
ET-9 Edge computing
Local decision making rather than centralized decision making
ET-10 Ubiquitous and transparent security
Automating trust by block chain, digital ethics and service integration
Berkeley
27


Decentralized but shared community
(Smart and connected community)
• Buildings/Living
• Transportation
• Manufacturing
– Locally produced food
– Locally produced goods
Underground goods production
ET11: New materials
Zero or negative carbon, self-healing, sensing and adaptive
ET-12: Off-site Autonomy at sub-millimeter resolution
3D printing to self-assembly and operation at sub-millimeter resolution.
Berkeley
28


Sydney Brenner
The Nobel Prize in Physiology or Medicine 2002
Discovery of mRNA
Mathematics is an art of perfection,
Physics is an art of optimum
while
Infrastructure systems are just "satisfactory"
...Because if it is not satisfactory, it will be eliminated
as political/legal/economic/community constraints are very very strong in the
Infrastructure systems."
"The Architecture of Biological Complexity"
Berkeley
A step change in the medical practice by COVID vaccine.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Mathematics is an art of perfection,
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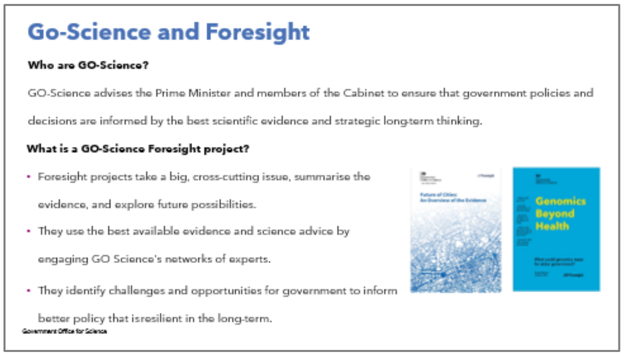
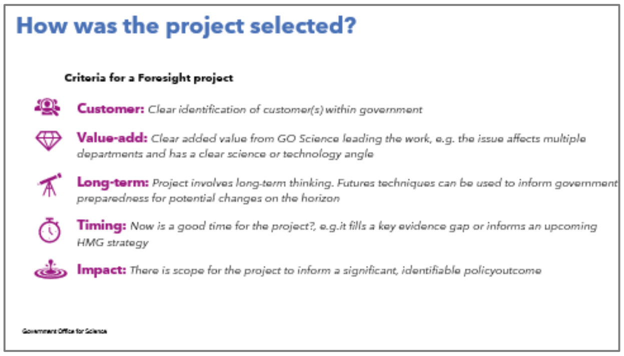
...Because if it is not satisfactory, it will be eliminated
as capital punishment is very very strong in the
biological systems."
"The Architecture of Biological Complexity"
Berkeley
A step change in the medical practice by COVID vaccine.

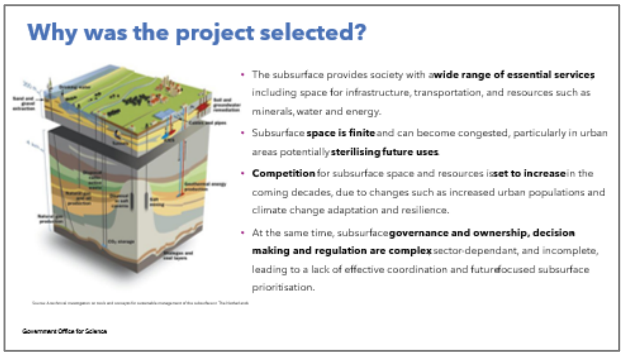

Thank you
soga@berkeley.edu
Berkeley

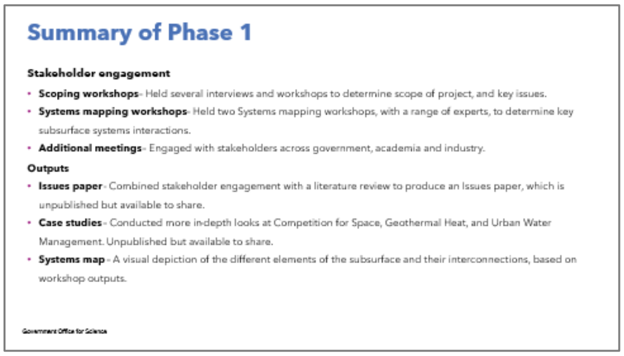

Government
Office for Science
Foresight
Future of the Subsurface
Progress Update
Matthew Ball, Holger Kessler, Cara Nicol, Jack Snape, Emily White

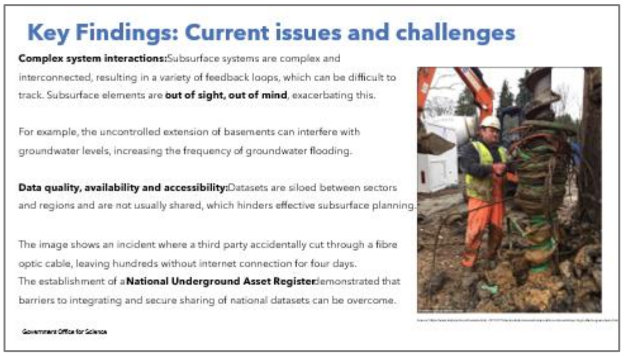

Government
Office for Science
Foresight
Well and consciously governed underground resources may significantly increase the resilience of economy and society.
Hámor-Vidó et al, 2021. Underground space, the legal governance of a critical resource in circular economy. Resources


Go-Science and Foresight
Who are GO-Science?
GO-Science advises the Prime Minister and members of the Cabinet to ensure that government policies and decisions are informed by the best scientific evidence and strategic long-term thinking.
What is a GO-Science Foresight project?
Foresight projects take a big, cross-cutting issue, summarise the evidence, and explore future possibilities.
They use the best available evidence and science advice by engaging GO Science's networks of experts.
They identify challenges and opportunities for government to inform better policy that is resilient in the long-term.
Genomics Beyond Health
Government Office for Science


How was the project selected?
Criteria for a Foresight project
Customer: Clear identification of customer(s) within government
Value-add: Clear added value from GO Science leading the work, e.g. the issue affects multiple departments and has a clear science or technology angle
Long-term: Project involves long-term thinking. Futures techniques can be used to inform government preparedness for potential changes on the horizon
Timing: Now is a good time for the project?, e.g.it fills a key evidence gap or informs an upcoming HMG strategy
Impact: There is scope for the project to inform a significant, identifiable policy outcome
Government Office for Science


Why was the project selected?
The subsurface provides society with a wide range of essential services including space for infrastructure, transportation, and resources such as minerals, water and energy.
Subsurface space is finite and can become congested, particularly in urban areas potentially sterilising future uses.
Competition for subsurface space and resources is set to increase in the coming decades, due to changes such as increased urban populations and climate change adaptation and resilience.
At the same time, subsurface governance and ownership, decision making and regulation are complex, sector-dependant, and incomplete, leading to a lack of effective coordination and future-focused subsurface prioritisation.
Government Office for Science


Summary of Phase 1
Stakeholder engagement
Scoping workshops - Held several interviews and workshops to determine scope of project, and key issues.
Systems mapping workshops - Held two Systems mapping workshops, with a range of experts, to determine key subsurface systems interactions.
Additional meetings - Engaged with stakeholders across government, academia and industry.
Outputs
Issues paper - Combined stakeholder engagement with a literature review to produce an Issues paper, which is unpublished but available to share.
Case studies - Conducted more in-depth looks at Competition for Space, Geothermal Heat, and Urban Water Management. Unpublished but available to share.
Systems map - A visual depiction of the different elements of the subsurface and their interconnections, based on workshop outputs.
Government Office for Science


Key Findings: Current issues and challenges
Complex system interactions: Subsurface systems are complex and interconnected, resulting in a variety of feedback loops, which can be difficult to track. Subsurface elements are out of sight, out of mind, exacerbating this.
For example, the uncontrolled extension of basements can interfere with groundwater levels, increasing the frequency of groundwater flooding.
Data quality, availability and accessibility: Datasets are siloed between sectors and regions and are not usually shared, which hinders effective subsurface planning.
The image shows an incident where a third party accidentally cut through a fibre optic cable, leaving hundreds without internet connection for four days.
The establishment of a National Underground Asset Register demonstrated that barriers to integrating and secure sharing of national datasets can be overcome.
Government Office for Science


Key Findings: Current issues and challenges
Subsurface planning lacks coordination, direction and prioritisation: Stakeholders emphasised failures in coordination and planning of subsurface projects is a recurring issue, and the growing need for a stronger system of prioritising competing demands in an increasingly congested subsurface.
Subsurface governance, regulation and ownership is complex, inconsistent, and incomplete: It is spread across national, regional and local bodies that can by sector and locality.
Although local government is largely responsible for subsurface planning, there are currently no overarching subsurface policies to govern or support initiatives such as climate adaptation at the local level.
Space can be used on first come first served principle, and the subsurface has been described as the 'final frontier'.
Government Office for Science

Key Findings: Demand drivers and future challenges

Population increases and densification: Increased demand for infrastructure above and below ground, including utilities, transport tunnels and building foundations.

Climate change: Direct impacts include more frequent extreme heat and rainfall events. **Adaptation and resilience** measures involving the subsurface include incorporating sustainable drainage infrastructure, novel use of below-ground spaces for infrastructure, living and food production, tree planting for cooling and updating infrastructureto cope with heat.

Net Zero Transition: Many net zero solutions require new subsurface infrastructure, including EV charge points, district heating networks and ground sourced heat/cool. Future technologies that may help reach net zero include CCUS, hydrogen and compressed air storage.

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Key Findings: Demand drivers and future challenges

Water: Impacts of climate change and population pressure are likely to continue to increase demand for groundwater and need to manage excess rainfall and alleviate flooding

Subsurface technological innovation: Advances in tunnelling and excavation technology and improved scanning and mapping technology can reduce the cost of underground construction. The reuse of existing infrastructure is increasingly being considered to reduce costs and carbon usage.

Tree planting projects: Trees can reduce heat effects and increase air quality, but a barrier to planting is uncertainty over ground conditions and buried services. Trees and utilities compete for urban space.

Other key challenges: Include ageing subsurface infrastructure, new digital rolbuts and protecting/reserving of ground for future Geological Disposal Facilities (GDF). The subsurface also contains critical resources and infrastructure relevant to national and international security and resilience.

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Systems map

- Systems maps are a systems thinking approach which visually depicts the system, including relationships between different aspects and feedback loops.
- The systems map was developed through two workshops with 1012 experts across a wide range of subsurface uses, and later refined within the team at GO-Science.
- The map splits the subsurface into five subsystems: the deep, shallow and surface physical systems, external drivers, and the institutional system.

Example interaction

- Ground source heat installations (shallow physical) increase, causing the following interactions:
- Shallow physical: Capacity of the ground to provide heat/cool decreases; Demand for electricity distribution infrastructure increases
- Surface physical: Surface transport build and repair increase
- Institutional: There is no clear owner/decision maker for this

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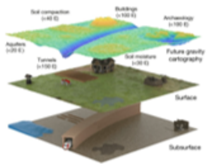
Use of Emerging Technologies

- **Quantum Sensing:** Ultra-precise sensors allow us to map under the surface and detect a variety of hidden infrastructure including mineshafts, sinkholes, pipes and tunnels. (Expand- Uni of Birmingham).
- **Fibre Optics to monitor ground behaviour:** Cambridge Centre for Smart Infrastructure has led to development and installation of optical fibre and conventional monitoring instrumentation on four major Crossrail sites.
- **Moun detection** an emerging technology to track and measure muons produced by cosmic rays, enabling the imaging and mapping of subsurface structures
- **Remote sensing:** increasingly detailed and realtime information from space such as InSAR (Interferometric Synthetic Aperture Radar) can be used to measure ground deformation with high precision.



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Use of Emerging Technologies continued:

- **Digital Twins:** an emerging technology that creates virtual representations of a physical system or object with real time interactions between them. Geological Surveys and other organisations are building "twins/models" of the natural environment
- **Artificial Intelligence:** Tech start-up Exodigo promising to deliver AI-based scanners. Current project in UK with Colas Rail using their technology as part of the light railway expansions for the Eastside Metro Expansion project in Birmingham.
- **Robotics:** vehicles and drones are getting increasingly smaller, autonomous and better connected. http://pipebots.ac.uk/ 'aims to revolutionise buried pipe infrastructure management with the development of micro robots'

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Stakeholder engagement

We have engaged widely with a range of stakeholders across government, academia and industry, including:

- **Government:** DESNZ, DSIT, DfT, Defra, DLUHC, Cabinet Office
- **ALBs/Local Gov/DAs:** National Protective Security Agency, British Geological Survey, Ordnance Survey North Sea Transitioning Authority, National Infrastructure Commission, Planning Inspectorate, Environment Agency, Nuclear Waste Services, Natural Resources Wales, Greater Manchester Combined Authority, Greater London Authority, Glasgow City Council, Transport for London
- **Academics:** Newcastle University, Manchester University, Aberdeen University, Imperial College London, Birmingham University, UCL, Oxford University, Oxford Brooks University, Lancaster University, Portsmouth University, University of Edinburgh, University of Cambridge, ETH Zuerich
- **External:** Arup, Atkins Global, Urban Design Group, Trees and Design Action Group, StreetworksUK, Highways Authorities Utility Committee

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Key supporting quotes

Key stakeholder support:

DSTL Subterranean Team - "the subsurface presents enormous challenges but also significant opportunities, especially for science and technology to contribute to the benefit of UK interests"

DESNZ Clean Heat Team - "subsurface risks in many Heat Network (HN) schemes are putting off contractors - providing accurate and detailed information on what is underground will reduce the risks and costs of constructing HNs

Greater London Authority Infrastructure Team "there is a vital need for a more coordinated approach to management of the subsurface in order to decide how we can reuse abandoned assets, where new trees are planted, and Sustainable Urban Drainage Systems (SuDS) are installed.

Department for Transport- Highways Policy Team - "understanding how the space beneath our highways and railways is managed and used to facilitate decarbonisation and adaptation to Climate Change is essential"

National Infrastructure Commission- Economic Analysis Team - "very interested in the outcomes of Phase1 in particular how knowledge of the subsurface supports our aim getting infrastructure delivered in a timely fashion"

Government Office for Science

Government Office for Science

Foresight

Thanks for Listening

Stay in touch

Email: foresight@go-science.gov.uk

Appendix F. Notes from breakout and plenary sessions

Session 1: NBIF tour

The UK delegates toured UKCRIC's National Buried Infrastructure Facility. Based at the University of Birmingham, it is a unique facility for research, education and training in:

- buried infrastructure-ground interaction,
- soil stabilization and improvement,
- geophysical sensing,
- pipeline detection and condition assessment,
- tunnelling,
- trenching & trenchless technologies, and
- structural performance of transport-ground-pipeline systems and green-grey infrastructure interdependencies.

Session 2: Keynote presentations, breakout session, witness snapshots

Keynote presentations

Keynote presentations were delivered by Patricia Nelson, Chris Rogers, Carlos Santamarina and Fleur Loveridge. The presentation slides can be found in Appendix E.

Session 2 keynote speakers provided thought pieces in advance of the workshop, which delegates were asked to read before attending. The purpose of the pieces was to provide the delegates with each keynote speaker's perspective on the big questions, major gaps and opportunities for underground infrastructure. The pieces were designed to inform, inspire and provoke and they provided a starting point for the workshop.

The thought pieces are reproduced in Appendix B alongside a specially-commissioned piece on systems of systems, which was also circulated ahead of the workshop. Following the workshop, the pieces were edited for publication and appear on the UKCRIC website as a short series on underground infrastructure.

Breakout session

Three transatlantic breakout groups met to answer the following questions:

1. What points were you glad the keynotes raised?
2. What wasn't covered in the keynotes that needs to be discussed at this workshop?

Group 1

Chairs: Patricia Culligan (US) and Graeme West (UK)

What points were you glad the keynotes raised?

- The value of the underworld and appreciation of facilities and infrastructure housed by the ground.
- Linking infrastructure systems to stakeholders, which then feeds into questions of the value of the underground to various stakeholders, who owns and realizes this value, and who is responsible when something goes wrong. What is the return on investment, over what timescale, who pays, and when? Linkages between stakeholders and value also feed into questions of investment capital versus return on investment as well as the value of maintenance.
- Need to consider underground infrastructure as a system of systems, which means that we also need to consider performance in an integrated way.
- Project management should consider underground as the system of the systems and consider clients in a sustainable way. For example, who are the clients today and who are the clients in the future.
- Considering the ground as an infrastructure.
- Idea of new materials for underground construction – can think of this in the context of reducing asset degradation, including as a result of underground climate change.

- ESG, but modelling cannot currently alleviate the uncertainties in predictions in the relationship between ESG and the ground.
- The National Underground Asset Register (NUAR).

What wasn't covered in the keynotes that needs to be discussed at this workshop?

- Why underground? There is a reason that urban areas develop above ground and before underground development happens. So, when should underground be considered, and where? A lot of underground infrastructure development might not even go on in the US and UK.
- How far down should infrastructure go?
- There was no discussion of shrinking cities and the need to decommission (or repurpose?) underground infrastructure.
- Use of underground for extreme events, including human survival during extreme heat events, for example.
- Sharing resources and data.
- Who owns or has responsibility for the underground (e.g., the effects of a pipeline leak), even if temporarily? National and international policies and regulations are in play.
- Use of underground for information flows – for example using sewer flows to detect disease outbreaks.
- Role of underground for the re-optimization of our cites for new conditions.
- Role of data, digital tools and AI for design, building and maintenance efficiencies. Data fragmentation, openness, access, accuracy, and sparsity. Who is responsible if things go wrong?
- Education – of future engineers, the public, policy and decision makers, etc.
- Regulation of the underground.
- Legacy assets and legacy data.
- Underground architecture.
- Cost of maintenance and decommissioning (and how we decommission).

Group 2

Chairs: Jelena Ninic (UK) and Cliff Davidson (US)

What points were you glad the keynotes raised?

- Systems thinking.
- Value.
- Sustainability and resilience. Each keynote had a different perspective and they are concepts that vary by discipline. Both cannot be simultaneously maximized. They need to be balanced.
- Risk and resilience and the needed balance between climate mitigation and adaptation.
- Modelling methods and techniques. These need an objective function.

What wasn't covered in the keynotes that needs to be discussed at this workshop?

- Do we know the potential of our underground, and can we realise it?

- Metrics and quantifications are needed illustrate the value of the underground. The value proposition needs to be clear, as does the cost of not doing something. What is the cost of business as usual?
- How do we define and measure quality of life and the impact underground infrastructure has upon it? Now and in the future.
- Do we have the necessary tools and data? What can we learn from other countries?
- Can engineers enhance what nature already provides? Allowing nature to do what it does best? We must learn from observing the natural world.
- More social scientists need to be involved, for example in understanding how infrastructure responds to societal choices (and vice versa). The approach needs to be interdisciplinary.
- Predict and provide will not work as we are already outside of our planetary boundaries.
- Ecosystems of tools are needed for urban planners to influence how the future of the underground will look. These need to be co-developed with industry.
- Inventory of the undergrounds is needed. This is especially needed in the US. This would allow reporting of underground assets (location and condition). We are living on legacy information and this is not sustainable.
- Proactive maintenance is required. We need to stop working to breakage.
- Do we have models of change to underground infrastructure from climate change and sea level rise?
- We do not zone the underground in the way we do on the surface. It is often not clear who owns or is responsible for the underground. Stakeholders are fragmented and there is a lack of data about vulnerability (geospatial and asset-related data).
- How can academia amplify, learn from and add value to industry-led innovation, which has been considerable over the last 50 years? How do we continue this level of innovation? Innovation comes from industry. Academia creates multiplied benefits.
- We need better mechanisms for communicating with decisionmakers and policymakers. Where are the examples of strong infrastructure governance? Singapore?
- Can we appropriate ‘moonshoot missions’ for the underground?
- What is the first step in a staged process?
- We speak about infrastructure as an ‘asset’, as if the world is a construction site with assets either under construction or being maintained. We should consider infrastructure as a ‘process’ – unfinished and ongoing infrastructure activity.

Group 3

Chairs: Melissa Bedinger (UK) and Lucio Soibelman (US)

What points were you glad the keynotes raised?

- Engagement of civil engineers with the public and decision makers
- Systems of systems. We need to look at second- and third- order effects, not just first-order effects.
- Adaptive and iterative design and action learning.

- ESG. What does this mean for the underground? How do civil engineers engage with ESG? How to towns and cities use ESG?
- Using the Earth's heat as a resource.

What wasn't covered in the keynotes that needs to be discussed at this workshop?

- Governance of the underground: ownership and maintenance.
- Embedding engineers into government.
- How climate change will affect existing assets.
- How the proportions of different types of infrastructure will change in the future and what this means for the underground.
- The impacts of shock events such as war and pandemics. How much energy is used during a war? How can we recover sustainably from these shocks? These need to be accounted for in future scenarios.
- Energy transitions: Quality of life has been perfectly related to the amount of energy consumed. How do we translate this into underground activities?
- What else can be brought from above ground to below ground?
- Incorporating incremental change
- Really big thinking about the sub-surface (e.g., earthscrapers).
- Future metrics and infrastructure analytics. Need to measure economic as well as social effects. Do not just measure in numbers
- Digital twins for the underground.
- Interrelationships between infrastructures, where we draw the system boundaries.
- Protecting the sub-surface natural environment.
- Adaptive and performance-based design.
- The impacts of shrinking cities.
- Linked carbon accounting
- Underground infrastructure as a means to equity, to a just transition
- Moving from seeing the subsurface as a hazard to seeing it as an opportunity

<u>Witness snapshots</u>

Four delegates who had been asked to act as 'witnesses' to the first day provided their feedback. The witnesses were selected for their professional backgrounds and the unique perspectives they could bring to the workshop.

Debra Phillips (Senior Lecturer in Environmental Engineering, Queen's University Belfast)

- Drivers that must not be ignored:
  - Climate change
  - Decreasing urban populations
  - Population growth
- Real time, high quality monitoring of assets. What are the consequences of past poor monitoring of underground asset conditions?
- Underground assets are not widely discussed in other spheres, for example, in environmental health.

David Garner (Head of Engineering (2 Bar and Below), Cadent Gas)

- The UK's utilities are at the crossroads of climate, technology and cost.
- Traditional and deeply-rooted research and development in industry does not link as closely as it should with academic research. Industry and academia must work together to influence policymakers. Industry is always talking to policymakers and can help academia do this in a mutually-beneficial way.
- There is an opportunity within the gas sector to repurpose the network for clean fuels such as hydrogen.
- UKCRIC's facilities can help industry.

Luis Betencourt (Professor of Ecology and Evolution Research, University of Chicago)

- Politicians, governments, they do not want to go underground, but large cities have incredible underground infrastructure. When cities become very dense, they go underground. For these cities, the cost-benefit trade-off has shifted. Large, dense, wealthy cities are going underground.
- How has climate change and technology shifted (is shifting) the cost-benefit analysis?
- Where, when and for what purpose should we go underground? Not all assets have to be underground all of the time (e.g., trains). Weather-proofed infrastructure may be best underground.
- The benefits of going underground are diffuse (e.g., reducing traffic congestion) and cannot be split into public and private. As such, the metrics should also be diffuse (e.g., public health, congestion, land values).
- Low and middle-income countries do not have the budget to go underground.

Ruchi Choudhary (Professor of Architectural Engineering, University of Cambridge)

- There are outward and inward facing roles for academia. Outward, we are encouraged to work with markets, economists and social scientists. What is the past value of this? What are the outcomes that can be harnessed? Where are the success stories? These need to be surfaced, celebrated and built upon.

Session 3: Breakout session, plenary session

Breakout session

Six breakout groups, three in the US and three in the UK, met independently to answer the following questions:

1. What services will underground infrastructure need to deliver in the future?
2. What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?
3. What can and should be done better right now below ground and what savings can be made now when doing things underground?

Group 1 US

Chairs: Dulcy Abraham and Amanda Elioff

- What services will underground infrastructure need to deliver in the future?
- Where do people live, how they live, where they work – will define how infrastructure services will be delivered.
- Younger students / decision makers of the future → likely to change where infrastructure / what infrastructure is placed where? how?
- Better ways to deliver power
- Multiple uses of infrastructure systems (streets carrying multiple services)
- Heavy energy-intensive systems vs. circularity (close the loop) → heat within the system; treat/process some of the water – do this on scale/decentralized – maybe below street
- Land use and land value
- Develop business incubators which can solve infrastructure related problems
- Underground systems – not self contained – both over-ground and underground
- What services will underground infrastructure need to deliver in the future?
    - Sanitation
    - Stormwater
    - Power
    - Telecom
    - Transportation
    - etc.
- Agility of systems – need to account for change in population and use of services - >> use of distributed systems
- Influence of risk (climate change) on how systems are designed and used → New York – elevating the ground to build infrastructure → need tools/standards for design (Example provided by Kenichi)
- What can and should be done better now below ground and what savings can be made now when doing things underground?
- Investigate how changes (local demand, climate change) influence current best practices in design
- Standardized methodology for developing an underground asset management system - pathways – facilities similar to UKCRIC facilities

- What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?
- Evaluate impact of circularity/decentralization on:
    - Resilience
    - Sustainability
    - Centralization of information; standardization of services/maintenance – for equitable access to services
- Start treating cities as research platforms/testbeds/innovation beds to explore infrastructure challenges (green infrastructure, energy, climate islands)
- New tools for design / new design standards
- New Materials for construction / new construction processes – subsurface and over surface
- Synergies of collocation of services
- Robotics with ML in 'controlled' environments (possible in utilidors/utility corridors?) – Systems have to be re-engineered.
- How to build faster, retrofitting capabilities (to address leaking in transportation tunnels)?
- If cost of energy doubles, how would the planning and installation of infrastructure systems change?

Group 2 US

Chairs: Jason DeJong and Youssef Hashash

- Q1 What services will underground infrastructure need to deliver in the future?
    - Services (Sadler et al. 2018, from C. Rogers) (now, future*)*
        - Anything that can be justified by CAPEX
        - Provisioning services: minerals, water, heating/cooling, parking, energy storage, food, shipping, goods, computer systems, IT / telecom, agriculture, energy, transportation, sewage, waste, shopping /commerce,
            - Pedadors, bikeadors, utilidors,
        - Regulating services: temperature, water flow, sewage,
        - Supporting services: strength, stiffness,
        - Ecological services: natural groundwater flow, biota, ecological base
        - Societal services: land value, community mending
        - More innovative design (conservative design currently dominates)
        - Temporal dimension (not currently considered)
- Q2 What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure? 10-30 yr horizon
    - Construction of developed underground plan (e.g., utilidor) with value detailed and justified
    - Automated low-cost preventative maintenance → enables proactive management
    - No goods distributed above ground (e.g., no trucks above ground)
    - 50% of geothermal temperature regulation
    - Monitored & instrumented smart infrastructure
    - Point of consumption energy generation & storage integrated system
    - Reduce cost of underground development → characterization, new materials, excavation, installation

  - Policy that underground permitting requires data sharing of underground characteristics and build condition
  - Integrated and validated interdependent modelling of underground systems that can be used by practice, policy, etc.
  - Overcome barriers for technology adoption in industry (e.g., ASTM standard blockade, liability?)
  - Where should we put infrastructure where we are not currently putting it?
  - What about decentralised systems that, that for example, don’t require pipelines? Or should systems be more centralized?
  - What is beyond the state-of-the-practice in terms of what people are thinking or doing in the future with regard to new uses?
  - Is there a role for underground infrastructure to help with climate change and hazard events?
  - What are the barriers and enablers?
    - E.g., climate change, financing, coordination across sectors, valuing the underground space / market creation, uncertainty, doing things the way they've always been done (why?), safety, regulation, capabilities of Local Authorities (outsourcing), ownership (In America if you own the surface you own the subsurface), equity, decision-making.
- Q3 What can and should be done better right now below ground and what savings can be made now when doing things underground? 0-5 yr horizon
  - Redirect 40% of current budget spent on reactive repair to proactive maintenance and future planning
  - Eliminate direct burial
  - Move all housing above-ground (no basement living)
  - Communicate that current replacement rate is 200-300 years → 100% over design service life
  - Template for how to quantify value (ESG) proposition of underground installation
  - Reassess ADA service provision underground
  - Integrated planning and zoning of the underground
  - Detail mapping of underground – geotech & environmental
  - Ownership definition/transition of subsurface (private ownership below ground?)
  - Interconnect silos of underground infrastructure (mapping, construction, and maintenance)
  - Comprehension of hazard identification and characterization (above & below ground)
  - Accelerate technology transfer and implementation to industry (both rehabilitation & new construction)
  - Quantitative evaluation of underground activity/changes on surface infrastructure
  - How to we evaluate underground vulnerability to extreme events (e.g., flooding, sea-level rise)
  - Data sharing with policy makers
  - Increase geothermal capacity
  - Uncertainty quantification
  - Doing things underground is expensive. How can this barrier be overcome? Should, or can it ever, be inexpensive?

- What is / do we know the current state of practice?
- What is / do we know the current state of research?
- What is / do we know the desired future performance?
- What does underground infrastructure look like when ‘done well’?
- What are the essential elements of underground infrastructure?
- What are the embodied values of underground infrastructure?
- What are the economic, societal and environmental outcomes underground infrastructure aspires / should aspire to achieve?

Group 3 US

Chairs: Janille Smith Colins and Sunil Sinha

- Q1: What services will underground infrastructure need to deliver in the future?
    - Infrastructure related to the energy transition
    - Energy storages
    - More water storage from micro water treatment plants
    - Sensors and detection from urban underground infrastructure
    - Thermal heating
    - More than water and power; protection from heat and extreme cold; goods movement; heat for above ground; carbon capture
    - Water via storm surge; flood control etc.
    - Power transmission; off-shore to onshore; cross country
    - Mobility and transportation
    - Novel moves of transportation
    - Natural infrastructure
    - Power and Energy transition theme extracted from Q1:
        - Energy: The topic of energy, storage, heat, transition for new kinds of energy productions
            - Power transmission, off-shore, on-shore, transfer, and storage of underground energy sources
            - Wireless power transformation (move electricity)
            - Wireless technology
        - Climate change and adaptation: The underground as an opportunity or a threat to climate change, adaptation
    - Infrastructure Assessment theme extracted from Q1:
        - Age/Cost/Maintenance: Smart proactive maintenance program | cost of infrastructure, is the infrastructure appropriate; age of the infrastructure.
            - Demand for infrastructure
        - Materials: phasing out carbon heavy materials; instrumentation and condition assessment of subsurface infrastructure; baseline assessment
        - Data needs: Interactions between physical and digital infrastructure and needs
- Q2: What transformative changes and improvements need making to achieve the desired future performance of the underground?
    - Inclusion of women and minorities in the construction industry

    - Sea change in thinking in priorities; decentralization towards resilience; expectations for our infrastructure
    - Identify existing infrastructure.
    - Improving the prediction of subsurface conditions
    - Self-healing materials and systems
    - Designing for adaptability
    - Smart maintenance planning and implementation
    - Research into human well-being in confined spaces
    - Centralization and decentralization services
    - Challenges of ESG for infrastructure
    - Materials and concrete alternatives
- Q3: What can and should be done better right now and below ground and what savings can be made now when doing things underground?
    - Addresses life safety issues faced by frontline workers
    - Identify underground fires and leaks
    - Decommission obsolete storages tanks
    - Address major system leaks
    - Risk evaluation in the current landscape; trade-offs are shifting and our infrastructure is stagnant
    - Adjusted design criteria; is 100 years realistic? Appropriate?
    - Surface/subsurface interactions
    - Partnerships with with public and private utilities
    - New materials; rethinking our infrastructure with new technologies and capabilities in mind
    - How do we challenge the belief that the underground is expensive?
    - Improved mapping of critical infrastructure and methods for monitoring new infrastructure
    - Better data collection and sharing
    - Better data analytics
    - Knowledge, uncertainty and impact to communities theme extracted from Q3:
        - Knowledge and uncertainty, risk evaluation, identification of sub-surface conditions deficient infrastructure condition assessment
        - What are the leaks and the impacts to communities?
        - Workforce, safety

Group 4 UK

Chair: Jamie Standing

1. What services will underground infrastructure need to deliver in the future?
    - The ground is the infrastructure. How can it be quantified?
    - Balance between resilience and optimization of materials. BIM currently leads to unnecessary overengineering.
2. What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?

- Underground infrastructure needs cohesive short-, medium- and long-term plans to form a programme of research and other activities. It needs a framework within which research programmes fit.
- Underground infrastructure collectively contribute to quality of life and so they should be considered collectively.
- Multi-utility tunnels (MUT), although they may be less resilient and so need constant monitoring.
- Ownership and responsibility:
    - Who owns a MUT? Who carries the responsibility and the risk if it fails?
    - Bridge owners are responsible for the bridges on which utilities that are attached to the bridge rely.
    - It is unclear in the UK whether road owners own the land under the road.
    - Who owns the subsurface? Who has responsibility for the state of the services in the sub-surface? Planning and regulations could clarify and police these elements.
- BIM for the underground, powered by accurate data. BIM underground is quite advanced in industry, but they do not share their data. How can BIM for the underground be designed to enable sharing of data and collaboration as well as protecting competitive advantages?
- BGS and NUAR are the starting points for data.
- Do we really understand what we have done to the subsurface and what this means for the future? The implications of groundworks are hard to determine. Engineers could be required to leave the underground in a usable state. The London Underground will not allow some subsurface works because the impact and stresses on the tunnels are unknown.
- Funding should come from multiple Government departments: DfT, Energy, Housing. There needs to be a compelling ROI and links to Government priorities.
- Financing from the private sector is driven by shareholder priorities, which may not align with priorities for underground infrastructure.
- The savings for doing things better underground are long-term and thus tricky to action.

3. What can and should be done better right now below ground and what savings can be made now when doing things underground?
    - Experienced engineers need to oversee underground assessments and BIM
    - Reducing, recycling and repurposing.
    - Underground services tend to be independent, but geographically co-located, making them interdependent (the ground is the interdependent stratum).
    - Archaeological finds can disrupt plans for doing things underground.
    - Replacing and repairing services causes damage to the ground and to the surface. Who is responsible for making sure damage is minimized?
    - How can we make utility providers share information?
    - Should we start with the roads? Does everything link to roads? Is this the best route for gaining traction with decision-makers?
    - How to do stuff underground without being disruptive.

- New infrastructure can incorporate sensor technology. This is harder for legacy infrastructure.
- 3d mapping of underground utilities.
- Using AI to data mine legacy and current documents and datasets, but this will not eliminate the need for an engineer.

Group 5 UK

Chair: Irem Dikman

1. What services will underground infrastructure need to deliver in the future?
    - Visible and transparent infrastructure system enabled by geospatial data highlighting vulnerabilities and interactions.
    - Accessible, shared and harmonized shared data.
    - Data fit for smart infrastructure to enable automation, AI and machine learning.
    - Visualization to enable interpretation.
    - Many actors are already coming together on underground infrastructure, but not with regard to data.
    - For what is the data to be used?
        - Vulnerability assessment and cascading failure risks.
        - Opportunity assessment and enabling planning for future use of the underground space.
        - Sustainability. Infrastructure enables sustainability and can be used to achieve net zero emissions.
        - System of systems modelling to understanding the multiple layers: society, environment…
        - Predictability
        - Efficiency
        - Resilience
        - Clime change impact
        - Social equity and value
        - Social acceptability is important
2. What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?
    - Enablers
        - Technology
        - Expertise
        - Value of data
        - The underground is not a homogenous space and it exists in 3d – how deep do we go? Shallow for things like EV charging. Deeper for transport.
    - Barriers
        - Security and cybersecurity concerns
        - Conflicts between stakeholders
        - Cost, contractual and other commercial barriers (very important)
        - Lock out – using the subsurface for one use prevents it being used for another use.

3. What can and should be done better right now below ground and what savings can be made now when doing things underground?
   - Potential case studies
     - Digital twin of a university campus to demonstrate efficiency
     - Large scale modelling to convince stakeholders
   - Construction methods
     - Underground construction is different from surface construction
     - Best practice from surface construction brought to the underground
     - In the UK there is a 20% uplift for working underground to cover the uncertainties.
   - All construction projects to deposit data with BGS to be made publicly available.
   - Moving non-passenger transport underground (e.g., goods, food), on automated systems
   - Underground infrastructure is not visible and so there is little public awareness

Group 6 UK

Chair: Sergio Cavalaro

1. What services will underground infrastructure need to deliver in the future?
   - The same services that we have now will be needed in the future, but these will be added to and their relative importance with change: water, energy, EV charging, underground farms, underground data centres (to protect critical services), habitation in a changing climate.
   - New modes of transport, such as the Hyperloop.
2. What transformative changes and improvements need making to achieve the desired future performance of underground infrastructure?
   - Sensor monitoring and self monitoring of assets (e.g., for degradation).
   - New materials. Reduce reliance on concrete. Self-healing materials. Waste as materials.
   - Nature-based solutions and biomimicry.
   - What else uses the underground that we can support? What natural services may we be disrupting?
   - Mapping to know where assets are located.
   - Increasing efficiency (e.g., robotics).
   - Governance models to enable rapid deployment of maintenance and new infrastructure.
   - Equity model.
   - Challenges:
     - Those who are disrupted may not see the benefits of the disruption.
     - Do centralized systems increase resilience?
3. What can and should be done better right now below ground and what savings can be made now when doing things underground?
   - Better data management.
   - Better ontologies are needed (e.g., naming conventions).
   - Monetization of services (e.g., Google Maps).

- Better models to assess hard to identify benefits.
- Multipurpose underground infrastructure to dilute the cost and increase the value.

Plenary session

One plenary session in the US and one in the UK addressed the following questions:

1. What research is needed to do underground infrastructure (much) better in the future?
2. What are the big research questions?
3. What is needed to answer those questions (e.g., policy/regulatory shift, equipment, training)?

Plenary US. Chairs: Thomas O'Rourke and Mark Reiner.

- Research needs / questions
  - Climate change event at the surface and how it impacts the underground across geographies.
    - What are the maintenance needs across geography and hazards?
    - Root causes and deterioration models of current and future materials and scalable to size, - projects and systems
    - Designing for adaptability – physical, social, economic, climate changing conditions
  - The underground as a source for heating and energy storage, and transmission
  - Self-healing materials and systems - and its applications to the underground alternative materials underground
  - How do you assess it, deploy it, and repair it (e.g., self-healing grout)
  - Designing for longevity and how some parts of infrastructure have survived past their lifecycle and others have not
- Moonshots for Underground Infrastructure Transformation. Overarching themes:
  - Underground master plan
    - Ownership
    - Costs/valuation
    - Knowledge of existing infrastructure (condition, abandoned, location, accuracy, other metadata)
    - Potentials for energy, water, waste segregation decentralization
    - Proactive maintenance
    - Incorporate ESG into planning process
    - Community mending
  - Storage (energy, water, minerals) and generation
    - Role in energy transition
    - Role in water availability (human-made or natural, e.g., aquifer, cistern) and mitigation of flooding
    - Role in waste as a resource
    - Role in energy generation
  - Adaptation (adjusting for demand, positive or negative)
    - Proactive maintenance
  - Movement/transportation (what can be moved to the underground)
    - Packages, pedestrians, EVs, bikes (non=emission transit, low-noise)

        - EV charging underground
        - Colocation, e.g., utilidors for all infrastructure sectors (wet vs. dry)
- Cross-cutting themes across all moonshots
    - Data (tools to make data into relevant information for practitioners developing infrastructure)
        - Spatial, temporal, analytical
        - SCADA – operational and maintenance
        - Models, digital twins, BIM…etc.
        - Sharing of data across agencies
    - Employing emerging and latest underground tools and best practices
        - Pragmatic and useful integrated models and validation
        - Increase efficiency of underground construction, monitoring and operation
    - Cost and Implementation
        - Public/Private Partnerships, life-cycle costing, design/build/operate
        - Zero carbon costs
        - Partnerships with utilities, universities and AEC (architect, engineering, construction)
    - Subsurface as Infrastructure (Chris Rogers) and Nature (Jason DeJong)
        - Engineered, but consider natural benefits
        - Nature's infrastructure
    - Materials for underground infrastructure transformation
        - Regenerative
        - Zero carbon (green concrete)
        - Adopt standards for new materials to be accepted by design/construction
    - Social Impact
        - Who, when, where, why for underground infrastructure transformation
    - Diversity, Equity, and Inclusion
        - Research
        - Design
        - Construction (workforce)
        - Universal access
    - Climate Change – acute (storms), chronic (sea level rise), geohazards and future impact to infrastructure
        - Zero carbon and carbon capture to mitigate climate change
        - Sustainability and resilience
        - How social impacts from climate change will affect infrastructure design
- Roadmap toward moonshot implementation
    - What are the synergies across the moonshot themes?
    - Communication development with agencies, professional agencies
    - Standard for new materials, equipment, and processes need to be in front of implementation
    - Model validation before implementation

    - Develop financial connection to innovations; upfront capital, life-cycle costing to prove Return on Investment
    - Post project implementation – urban observatory

Plenary UK. Chairs: Liz Varga and Esdras Ngezahayo.

1. What research is needed to do underground infrastructure (much) better in the future?
    - Understanding the consequences up to now of all subsurface construction and engineering. Do not treat the ground as an aside.
    - Understanding the ownership of and right of ways within the subsurface. The Foresight Future of the Subsurface project will provide some of these answers. See also Foresight of Cities: Development Underground.
    - Consideration of underground space in 3D.
    - Creation of better deterioration models (coupled built and natural environment) to understand the impacts of climate change and other hazards.
    - Understanding of the trade offs between asset replacement and asset repair. Asset management strategies.
    - Mapping asset location and performance (which is sometimes linked to condition).
    - Devising appropriate governance, regulation, ownership, business models and ways of working to make sure they are fit for future underground infrastructure to attract public and private investment.
    - Horizon scanning to determine what services are needed in the future and how what this means for infrastructure and subsurface infrastructure.
    - Understanding the current system dependencies and modelling how future infrastructure will impact these (e.g., does the charging infrastructure create new risks for gas mains?).
    - Creating a BIM for the underworld.
    - Leveraging and improving trenchless technologies.
    - Understanding the links between underground infrastructure and health (e.g., pollution reduction, freeing up space on the surface).
    - Combining US and UK ontologies, map forms, model language, and so driving a step change in sharing information..
    - Identifying the new technologies needed to characterize assets (e.g., sensors, new data sources, quantum technologies)?
    - Understanding the impacts of overground processes on the underground.
    - Understanding the consequences of changing soil condition.
    - Understanding designed versus as-built and as-used.
    - How do we develop new tools, techniques, systems models to deal with not only changing contexts (e.g., climate event, new technology) but also changing criteria (e.g., performance, resilience, sustainability, etc.)
    - System performance models (sensing – location + condition > deterioration models > system performance models)
2. What are the big research questions? In the break that followed, delegates voted on the questions. They are presented here in their order of popularity, from most to least.
    - Adaptive questions:

    - What changes in regulation, standards, codes and governance are needed to unlock and implement changing practices for improving knowledge and data about the subsurface?
    - How can the buried infrastructure stakeholders collaborate better?
    - What are the risks posed by climate change and how can these be controlled for buried assets?
    - How can we create scalable, repeatable, robust buried infrastructure solutions (e.g., BIM step wise approach)?
    - How do we fully value underground infrastructure and the subsurface and its contents?
    - How to deal with legacy buried infrastructure? Urban mining, reuse, risks of not reusing or removing (e.g., unused gas pipes may collapse).
    - How to transfer knowledge across the globe to maximize best practice that is context sensitive?
    - What role can buried infrastructure play in achieving net zero targets (e.g., offshore wind has a buried component)? How can we design a net zero adaptation for the subsurface?
  - Transformative questions:
    - How can the subsurface be made smart (e.g., with sensors)? How do we know with accuracy what is beneath the surface (geological survey's only capture the natural environment)? Creation of an underground observatory. This is a challenge because sensor signals are blocked when underground and getting power to underground sensors is difficult.
    - How to transform subsurface engineering practices to protect and enhance the ground's properties for future exploitation?
    - How can we create self-aware, self-maintaining materials, products and assets that do not need human interaction and intervention (e.g., maintenance). How can we minimize the number of interactions we have with the ground, because every time we intervene we damage the ground?
    - Where, what, and at what scale can we use untapped subsurface heat sources? How do we exploit them?
    - Which technologies need to be developed to transform buried infrastructure engineering (e.g., quantum, robotics, AI)?
    - How do we create a trenchless world?
3. What is needed to answer those questions (e.g., policy/regulatory shift, equipment, training)?
  - Understanding the consequences of subsurface engineering.
  - Who owns the ground? What right of ways need to be known? Who is responsible? Who governs? In different contexts?
  - What deterioration of coupled built and natural environments and consequences for performance?
  - Asset location and condition (and other proximate assets above and below ground). What is the quality of the data and how can it be improved? What technologies and data sources are needed?

- What future delivery of services are needed for designs of buried infrastructure? How aware of future requirements do we need to be to make best use of buried infrastructure?
- Are standards fit for purpose? Are regulations? Are ways of working, as built, as designed, as used in conflict?
- Need a BIM for the underworld and integration of ontologies with other sectors to drive information sharing – digital twin or digital model.
- Need valuation of the underground in the context of other services and assets.
- Through-life asset management, asset extension, circular economy, tipping point for new versus repair.
- Leveraging trenchless techniques.
- Consequences of soil and soil condition on buried infrastructure.
- Collaborations. Building the networks of practice, government and academics (across disciplines) to address these questions.
- Coordinated education – building skills and competencies across engineering, the social sciences and other disciplines (e.g., Turing Data Centre Programme skilling up engineering in AI).
- An understanding of the economic and policy scene.
- Increased awareness of the importance of underground infrastructure, and increased engagement.
- Capacity to create test beds and thus support implementation pathways to avoid the TRL "valley of death".
- Development of a sector framework. Connected Autonomous Vehicles have done this.
- Materials and engineering science for buried infrastructure to build confidence and promote knowledge transfer.
- Capacity and enablers to create an ecosystem (rather than reinventing the wheel).
- Compelling narratives and counterfactuals linking to society's wider net zero mission (and other drivers of change).
- Coordinated data, access to data, knowledge of data we cannot easily access.
- Systems approaches that include governance and business models.
- Develop clear ideas on urban metabolism, energy storage, rainwater harvesting, compressed air, movement of people and goods, with clear picture on movement of things rather than movement of resources.

Session 4: Keynote presentations, breakout session

Keynote presentations

Keynote presentations were delivered by Kenichi Soga and Holger Kessler. The presentation slides can be found in Appendix E.

Breakout session

Three transatlantic breakout groups met to answer the following questions:

1. Where are the synergies, tensions, gaps and opportunities between the 'big research questions' identified by the USA and UK in their independent sessions?
2. What else is needed to support the two research communities, separately and collectively, in answering those questions?

Group 1

Chairs: Patricia Culligan and Chris Rogers

Three opportunities were identified for big-research questions/ programs:

1. Underground master plan (USA) and Transforming Subsurface Practice (UK)
    - How do we define or begin to view ground as an Infrastructure? For example, when we excavate ground, we might loosen the soil, which then does not allow the soil to support a pavement. So, some activities add value to the ground – a new pipe transporting water, but also devalue the ground – soil has less bearing capacity.
    - But, well beyond this soil strength and stiffness, soil has a temperature, nutrient value, infiltration capacity, etc. So, to truly value ground as infrastructure that provides eco-system services, we need to measurements that help quantify the services ground provides.
    - Led to the idea of setting up 'Subsurface Urban Observatories' sharing resources across US and UK:
        - How to quantify/ measure properties?
            - Issues with sensors include challenges related to signal strength,, energy requirements, durability, even the capacity of existing sensors to measure the properties we might need
        - What spatial and temporal measurement densities are needed?
        - Structure for data lakes?
        - Can we map impact on subsurface of above ground stressors? Climate, population shifts, etc.
        - Can we understand ground's ability to deliver ecosystem services?
        - How does above and below ground infrastructure changes impact ground's ecosystem services?
        - Can above surface observations, or satellite observations help?
    - Might wish to pilot on a campus – urban university campus – or a private piece of land. Scale of maybe 1km by 1km. Need several test beds.

2. Self-Aware and Self-Maintaining Subsurface Assets – the idea of the ‘The Smart Subsurface’
    - Smart or better technologies for underground construction, which are cheaper and less intrusive
    - New materials for underground construction that are self healing, self maintaining, report on their state, etc. This would require new regulations
    - Sensing technologies and IoT for subsurface asset management
    - Some challenges are to do with
        - Asset ownership – which probably also speaks to data ownership
        - Governance of assets
        - How to do integrated management of assets, if each asset is owned, or governed individually?
3. Use of ‘Underground for Storage and Mobility’
    - Energy storage – e.g., compressed air storage in underground spaces, and use of underground to support energy balancing between buildings and storage statements
    - Stormwater and water storage and balancing demand across different spatial scales
    - Use of underground for material, people and package (etc.) storage and mobility

Group 2

Chairs: Jelena Ninic and Cliff Davidson

- Synergies
    - UK ahead of US in NUAR – how can US help advance this technology?
        - Identify future use cases and applications
        - Creating accessible, usable, copyright cleared, secured key datasets for research and innovation
            - Requires teaming/partnership of research, city/gov’t, and industry
        - Efforts to increase data curation and sharing
        - Integration of data from different systems
        - Underground observatory – pilot for infrastructure innovation
        - Minnesota DOT (& FHWA) have moved towards that
    - Vulnerability analysis in cities – interdependency/interdependence of infrastructure systems
    - Define resilience of infrastructure – evaluation matrix that is defined internationally
        - Metric(s) to assign value to underground infrastructure
    - Define value and zoning of underground space – could drive how underground infrastructure is placed
    - Define ownership of underground space – could place responsibility to trigger preventative action
    - Design methodologies – shift to incorporate time scale, where design target is to maintain a condition level over time, with variable loading and performance

demands in time. This now requires continuous monitoring and system upgrading integrated within maintenance.
    - Development of planning systems, developed through partnerships with university, city, and industry
- Tensions
    - Design codes
    - Data security
    - Regulations
    - Legal liability
    - Hazards driving design priorities
    - Fuel uses and resources (natural gas network vs. electricity)
    - Ability continuously track and update inventory information
    - Managing risk (draw from risk registers)
- Gaps
    - US has no NUAR (Minnesota DOT maybe the closest implementation)
    - Technology – provides ability to monitor
    - Implementation – decision/investment to monitor infrastructure
    - Metrics – resiliency, monetary value, social value,
    - Integration of infrastructure and human activity (tracked via social media & web abstraction)
    - DIKW (data, information, knowledge, wisdom) pyramid – Extraction from data to information to knowledge
        - We are flooded in data, but information and knowledge extracted is minimal
    - Connecting performance with construction events – limited by poor data quality
    - Effects of climate change on cities – prepared groups to capture perishable data (both damage but also processes/cost/timeline/strategy for recovery) from extreme events, which requires immediate and longer-term tracking → create lifelines emergency response team… would enable case history of resilience (could reach out to NIST center of excellence for an example)
- Opportunities
    - Develop international metrics (matrices) to evaluate resiliency, value, etc.
    - Develop national resiliency strategies (evaluate current status, integrate, and develop plan)
    - ASCE to publish book on how to evaluate infrastructure framework – Infrastructure Resilience – How to Evaluate, Manage, etc. - https://sp360.asce.org/PersonifyEbusiness/Merchandise/Product-Details/productId/303911505?_ga=2.19899576.1006051242.1695998472-118679888.1692822211
    - Develop emergency response team to focus on infrastructure damage AND recovery
    - Re-imagine design methodologies so that maintenance and adaptive design are integrated
    - Strategies to reduce risk of future constructions

Group 3

Chairs: Melissa Bedinger and Lucio Soibelman

- Q1 Where are the synergies, tensions, gaps and opportunities between the ‘big research questions’ identified by the USA and UK in their independent sessions?
    - Tensions:
        - Access to data vs securing data.
        - Public vs private business case or mission (e.g., competing goals, the best for the most amount of people vs. profit)
        - Local vs national (e.g., regulation and ownership)
        - Short term vs long term goals and investment
        - Cost vs quality
        - Safety vs convivence
        - Individual vs Collective interests
        - Development vs preservation (e.g., preserving historic and cultural resources)
        - Academia vs Government and supporting developing of IP
    - Synergies:
        - Minimize disruptions
        - Maximize efficiency
        - Adoption of SMART infrastructure (e.g., Sensoring, automation, etc.)
        - Resilience for climate change and manage demand (e.g., decommission, commission, redesignation, etc.)
        - Integrated planning
        - Collaboration
        - New technologies
        - Data sharing
    - Gaps:
        - Developing future infrastructure for gas industry distribution and conversion to more efficiency fuels (e.g., 20% hydrogen, using polycarbonate liners, designed for no leak for 50 years)
        - Incomplete data and knowledge.
        - Fragmentation of ownership and responsibility.
        - Lack of standards and best practices, or resilience design criteria.
        - Limited understanding of emerging risks.
        - Inclusion of arts in STEM (i.e., STEAM)
        - Broader impacts of US/UK advancements related to resilient and sustainable underground infrastructure, on less developed areas that will need to improve infrastructure.
    - Opportunities:
        - Working with utilities allows for testing and exploring of ideas for problem solving related to both operations and incident management.
        - UK national labs function allow for open coordination, research coordination, cross-collaboration between labs and industry:
            - Innovate UK is organization that allows both academia and industry to work together on project-based solutions, there is government funding to support use cases and data collection.

                - Technology Readiness Level approach applied: method for assessing the maturity of a technology. It is a nine-level scale, with TRL 1 being the lowest level and TRL 9 being the highest level.:
                    - TRL is used by governments, businesses, and other organizations to make decisions about funding, research, and development.
                - Government level lead collaborations with UK and Netherlands
        - Government level lead collaborations with UK and Netherlands
                - What else is needed to support the two research communities?
        - Development of communication protocol language to improve data sharing and decrease inefficiency.
        - Creation of vehicle for data exchange on global, analogous to a modern-day FDR New Deal for data infrastructure.
        - Developing a federated model to allow data to be shared and accessed without being centrally stored.
        - Identification of organization that is had larger umbrella that includes network of transdisciplinary professionals to support collaboration.
        - Hazard research needs to be practically useful – requires collaboration with agency responsible for providing service (e.g., utility agency).
        - Bridge the gap between fundamental research and application.
    - Other
        - Case demonstrated that data integration on subsurface (e.g., geology; soil interaction; water pipe depth, diameter, etc.) but information shown was for super user, where access is limited to certain users:
            - There is access provided to other users that are more limited, such as for student research projects.
        - In US, access to underground data is restricted and controlled, requiring certain security access and clearances.
        - Issue with understanding how data can actually be used, for both optimization and quality life improvements as well as used by bad actors, e.g., data related to critical infrastructure.
        - Tension related to homeland security related resilience of community and protection of assets, which require special relationships with utilities and government agencies to improve coordination.
        - Working with utilities allows for testing and exploring of ideas for problem solving related to both operations and incident management.
- Q2 What else is needed to support the two research communities, separately and collectively, in answering those questions?
    - Development of communication protocol language to improve data sharing and decrease inefficiency.
    - Creation of vehicle for data exchange on global, analogous to a modern-day FDR New Deal for data infrastructure:
        - Invest in a national data backbone.
        - Create a public data commons.

        - Support data literacy and education.
        - Protect data privacy and security.
        - Promote data sharing and collaboration.
    - Developing a federated model is a distributed architecture that allows data to be shared and accessed without being centrally stored. This can be achieved by using a variety of technologies, such as secure multi-party computation (SMC), blockchain, and distributed ledger technology (DLT).
    - Identification of organization that is had larger umbrella that includes network of transdisciplinary professionals to support collaboration.
    - Hazard research has, over the years, expanded beyond engineers to social sciences, emergency management, economists, etc.; work needs to be practically useful – requires collaboration with agency responsible for providing service (e.g., utility agency)
    - Bridge the gap between fundamental research and application, NSF has new directorate to address gap, other Partnership for Innovation (PFI)