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The underground space use: an opportunity to support sustainable infrastructures development

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ABSTRACT
As we navigate through challenging times where the despair for miserable news on climate change and pandemic is balanced out by the hope for the future thanks to new policies and investments, introducing the sustainability parameter while evaluating alternative design options for new infrastructures is essential, particularly in our rapidly growing cities. An intrinsic component of this parameter is the urban resilience, which should be managed properly and take advantage of the underground spaces.
Hurricanes, earthquakes, typhoons, heavy rainfall, heat waves, rising sea levels are some of the examples of new scenarios to be included in the resiliency verification as part of a new infrastructure planning. Not only underground structures offer constructible solutions to all such threats, but they can achieve it considerably limiting the environmental footprint, thanks to available technologies across the entire value chain, from planning and design, to construction, to operation and maintenance.
As a state of the practice, nowadays the tunneling industry supports better project planning, design, and delivery by addressing a broad range of social, economic, and environmental indicators. However, several steps must be followed in the near future if we want to achieve the challenging targets recently confirmed by the COP26:

- technical codes and regulations need to be updated;
- customer demand circularity needs to be implemented;
- construction and materials decarbonization need to be supported by fiscal policies;
- raw materials emissions must be reduced introducing lean manufacturing;
- access to capital for technological innovation is key.

The pathway towards a sustainable resilient future of our infrastructures has been laid out. However, no single player can capture the large opportunities alone, thus the most important mission for all players in the tunneling industry is now to improve communication and collaboration across the value chain, keeping in mind the vision of a greater good for all humankind.

1 TUNNELING INDUSTRY CENTRAL ROLE TO DEVELOP SUSTAINABLE INFRASTRUCTURES

The direct consequences of the Climate Change global actions on the daily business for tunneling industry players are already quite tangible. In fact, in 2015 all United Nations Member States adopted the 2030 Agenda for Sustainable Development, which provides a shared blueprint on how to direct investments to “ensure peace and prosperity for people and the planet, now and into the future”. At its core are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all Countries in a global partnership. Goal 9 to “build resilient infrastructures, promote inclusive and sustainable industrialization and foster innovation” will support both economic development and human well-being, with a focus on affordable and equitable access for all.

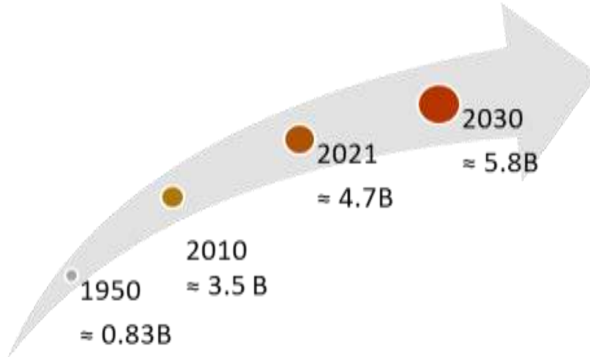

Figure 1. Projected growth of urban populations (in billions)

This strategic goal of the United Nations is even more important for the construction industry if we factor in two critical aspects: on one hand the ongoing trend of increasing urbanization, where it is projected that almost 6 billion humans will be residing in cities by 2030 (Fig. 1) and over 70% of world population will be concentrated in urban areas by 2050, with a corresponding increase in demand for essential services; and on the other hand, the increased resilience of our urban systems to ensure our pandemic preparedness and to deal with the impact of climate change , will require increased volumes for social distancing measures and upgrading of existing facilities.

It seems obvious that rising urbanization will continue to increase the land value, where at the very time when more and larger public spaces are needed as recently confirmed by a Workshop of the Working-Group 20 of International Tunneling Association (ITA-AITES). The answers to the increased demands for urban space and the increased demands made on natural resources, as well as the need to reduce the global waste production, are offered by the use of underground constructions, which creates new opportunities and approaches to sustainability and addresses these realities. The potential economic, environmental, and social impacts of tunnels and underground spaces are immense, with proper planning and development of underground space promising enhanced quality of life in compact, efficient, and sustainable cities. Several studies (Todeschini, 2013) have theorized the need of layering the build landscape, by superposing rather than strictly zoning all elements of urban structure and space, including public, private, and natural realms.

Several studies show the commercial advantages and societal benefits of procurement frameworks such as Transit Oriented Development or Transit Oriented Communities, where new residential accommodations are stacked above new and existing railway infrastructures as an opportunity to requalify (Milan, Italy) or optimize resources (Toronto, Canada). Moreover, nowadays underground construction is considered a spatial asset that extends beyond transport tunnels and utilities to a host of facilities currently occupying surface space.

If underground options are considered at an earlier project stage, more optimal solutions will become possible to realize compact cities and reduce the carbon footprint of our society. A further aspect to ensure success of (underground) construction projects and the efficient use of the large-scale investments will be the opportunity to introduce new technologies leveraging on the digital transformation of the construction industry. Tunneling is at the forefront of these transformations thanks to a growing systems integration in the design processes, including the development of geotechnical and geological data ownership and management systems that will enhance knowledge sharing, will help mitigate risks during construction and overall reduce project costs.

1.1 Tunnel Boring Machines and Segmental Lining

The contribution to CHG emissions from raw materials production is primarily generated by the energy-intensive cement and steel production. Therefore, the recent development of design solutions to introduce widespread use of steel and plastic fibers as primary structural elements for the final lining of underground structures is a critical step towards more sustainability tunnels. Not only can the use of steel fibers considerably cut the incidence of steel to 30-40% in the pre-cast tunnel liner (PCTL) commonly installed by Tunnel Boring

Machines (TBM), but thanks to the industrialization and standardization of the production process, it is nowadays possible to digitally track the efficiency of the casting plants and adjust production in accordance to the job site needs, thus reducing energy consumptions in the hours of peak demand and contribute to overall sustainability of the process.

Mechanized tunneling clearly represents a cutting-edge technology in our industry, with growing research towards the re-use of tunnel spoils as construction materials wherever possible. Underground construction has the major disadvantage of producing large amounts of spoils containing sand, gravel, clay, rock, water, and sometimes contaminated or hazardous materials. The spoils produced by TBM projects, moreover, often have high moisture contents and poor mechanical properties, such that they are commonly regarded as waste, and required dumping in specifically designated lands through dedicated vehicles. However, new technologies for treating spoils on site and re-using them in construction are offering very positive perspectives to the industry. During the 2021 ITA-AITES Awards, the Shenzhen Metro project was awarded in the innovation category for the introduction of a sustainable, efficient, and low-carbon solution for the disposal of shield spoil that has been developed during the construction of Shenzhen Metro Line 14. This project features an overall distance of 50.34 km, employing 49 EPB (Earth Pressure Balance) TBMs for the tunneling works. Through the adoption of an automated, modular, and compact kit used on-site to detect valuable materials to recycle (coarse aggregate, fine aggregate, residual clay and water), a cumulative volume of nearly 11,600,000 m3 shield spoil has been treated across the city, sensibly contributing to the environment by reducing half of the dumping volume of muck, avoiding to mine 4,600,000 m3 of new natural aggregate/sand elsewhere, reducing site operations and trucks trips to cut energy consumption equivalent to 54,520 tons of carbon emissions, saving 1.93 km2 of land, and contributing to preserve 1,160,000 tons of water.

1.2 Conventional Tunneling and Cast in place liners

Similarly, conventional tunneling, encompassing NATM (New Austrian Tunneling Method) and SEM (Sequential Excavation Method), has also seen notable progress in the development of construction means and methods, allowing an update of the tool-box of support systems for both rock and soil grounds. The availability of innovative sprayed waterproofing membranes and the introduction of advanced numerical modelling in the tunnel design, allow in most cases the collaboration between primary support of excavation and final liners, thus reducing cost and time of construction. This innovation translates in immediate benefits to the environment thanks to reduced material use, standardized processes, efficient equipment, and durability of the underground structures.

2 THE VITRUVIAN MAN: A FRAMEWORK FOR THE SUSTAINABILITY OF TUNNELING PROJECTS

When transferring the general concept of “sustainability” to underground infrastructures, it is important to make sure a practical approach is offered to all players in the industry, with clear benchmarks and achievable targets. For this reason, associating the word sustainability to “saving the environment at any cost” or reducing the actions to “carbon emission” only are over-simplifications. In fact, a sustainable development requires to achieve the optimum balance between environmental impacts, societal needs, and financial net present value. Other models of sustainability exist, but do not differ wildly from the popular Three Pillars Model: criticism has been levelled at this model for depicting the three pillars as separate and therefore mutually exclusive, but the basic concept holds true as inclusive of three different set of needs:

- Social (people)
- Environmental (planet)
- Economic (profit)

If we consider that the economic factor of this model can be easily represented by the Triangle Scheme of Cost-Schedule-Quality which are the elements required to calculate the Return of the Investment of an underground infrastructure, the framework becomes more articulated and moves into a shape which we can borrow from the Vitruvian Man. In its “Codice”, Leonardo Da Vinci is inspired by the work of Roman architect Vitruvius in his book “De architectura” to define the perfect proportions of the human body, inscribed in a circle and in a square so to maintain same distance from all his extremities (Fig. 2). The same equidistance of the pillars defined above can make it for an actually successful underground project.

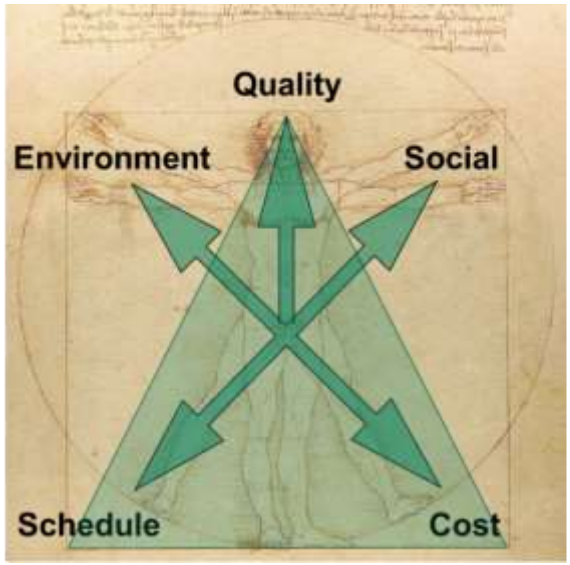

Figure 2. Sustainability framework based on Leonardo da Vinci

As decarbonization is rising to the top of the business agenda in this decade, players in the construction industry can have a significant impact but only if they view environmental, social, and governance (ESG) strategy as a priority and collaborate with other ecosystem stakeholders. In fact, climate change risks and sustainability are now factored into traditional business approaches by investors and asset managers, most contractors and designers are setting ambitious carbon-reduction targets to modify the way they operate, and several organizations are following guidelines to enhance disclosure and mitigation of climate- related financial risks, as suggested by the Task Force on Climate-Related Financial Disclosures (TCFD), created by the G20's Financial Stability Board in 2015.

An optimized design process is critical to reduce embodied and operational carbon, as 25% of it is embedded in the construction value chain and can be mitigated through development of new materials (in the last decade over 80 patents have been registered for low carbon cement) and implementation of digital technologies. A successful example is offered by a cloud based intelligent system for fully automated real-time design of tunnel supporting system developed in 2021 by Tongji University. This is one of the first application of artificial intelligence to a tunnel system consisting of:

- Twin model digitalization via multi-view photogrammetry;
- Automatic identification of the geological structure;
- Rock mass quality classification based on cloud algorithms;
- Automatic tunnel support structure design and verification.

The tunnelling industry is not new to the introduction of automation in both design and construction: not only the whole process of excavating and supporting the ground has been industrialized, but at the design stage, top engineering firms, offer tools that can create a digital twin of the underground system to verify impacts on operations and optimize geometries and solutions not only to meet a more efficient construction schedule but also to minimize maintenance costs and maximize durability. This is related to both transportation tunnels, where simulation of entire fire events in a subway line can help identifying the most vulnerable areas, and water tunnels, thanks to hydraulic modelling which can quickly inform changes of shafts and tunnels via a parametric design tool.

If design is important to offer sustainable underground spaces, the application of principles of Lean Construction to the tunneling industry is uttermost important. Pioneered by Toyota in the manufacturing industry, it is a philosophy that incrementally improves performance to achieve zero waste for:

- Materials
- Labor

- Time
- Money
- Storage

Studies of the University of Toronto and of the University of British Columbia supported by the Author are currently identifying areas were cost of underground projects can be optimized through data analytics and appropriate models for demand forecast. Tunneling, more so than other types of construction, benefits from repeatable tasks and therefore lends itself to benefit from LEAN philosophies:

- Materials are delivered when and where they are needed;
- The length of the critical path can be minimized;
- Zero defects can be achieved through pre-casting;
- Flexibility in the processes and in the design is allowed;
- Components and methods are standardized (toolboxes);
- Procurement from nearby sources is a state of the practice;
- Selection of the right methods minimizes the re-work;
- Reducing equipment is required due to reduced spaces;
- The ability to control emissions underground is critical;
- Top-down methods allow to reduce surface land needs;
- Shoring systems can approach close to existing structures;

Nowadays, most metros and subways across the globe are TBM excavated with other underground excavation methods limited to construction of stations. With TBM technology significantly improved, larger diameter TBMs can also include station platforms and the first ones of non-circular shapes (elliptic, rectangular already in use) are currently in use for construction of shorter tunnels. According to United States Environmental Protection Agency (USEPA) with application of more TBMs, the engines' emissions including carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxide (NOX), particulars matter (PM) and sulphur oxide (SOX) are declining. This reduction proves the fact that the underground systems' ecological footprint declines and the hope for the future is that from the Contractual, Legislative & Regulatory standpoint Carbon Credits and reduced taxation can be accordingly be introduced for the underground space preferred utilization.

It is already proven that most public procurement agencies in all continents already mandate the use of Envision Framework for their new Projects, most of the time requiring a minimum Gold (40% of total applicable points) or Platinum (50%) level to be achieved by bidders as established by the Institute for Sustainable Infrastructure. Envision has been successfully applied to more than 125 infrastructure projects, collectively worth more than US$106 billion in infrastructure development and, for example, is integral part of the evaluation for the upcoming Ontario Line in Toronto.

In summary, the application of the "Vitruvian Man" framework allows to identify few key action areas to evaluate or to improve the sustainability of underground projects:

- Design for flexibility of the underground spaces;
- Foster materials innovation and re-utilization;
- Standardization and industrialization of processes;
- Equipment optimization and re-cycling;
- Improve resilience towards climate change and future pandemics, thus reducing cost / carbon for reconstruction.

3 THE RESILIENCE OF UNDERGROUND SPACES: MAJOR CASE HISTORIES

The immense variety of the underground systems gives rise to an equally vast array of systemic risks, identifying which is made more difficult by the different characteristics of the projects in question, either being for transportation of human beings, water, goods, etc. When characterizing the resilience of a system, it is necessary first to identify the threats which can involve a process of contagion that spreads individual failures to the system and evaluate their level of interconnectedness. The combination of high impact hazards, with low probability and certainty of propagation, is hard to predict and makes arduous the task of the policymaker trying to address systemic risk. Consequently, evaluating the resilience of an underground project shall be based on the risk management approaches but must extend to address cascading effects of system failure. Resilience approaches emphasize the characteristics and capabilities that allow a system to recover from and adapt to disruption, and a commonly-accepted definition describes resilience as the ability of a system to perform four functions with respect to adverse events: planning and preparation; absorption; recovery; and adaptation.

Underground structures have intrinsic resilience thanks to the isolation provided by the soil or rock overburden, protecting from the disastrous events that occur above ground. Take hurricanes, earthquakes, tornados and ballistic threats for example, underground structures typically provide a great resistance to these, but they are not completely protected, even when the entrances are fully sealed. In fact, underground structures do have vulnerabilities for example, it has fatal consequences when an internal fire or explosion occurs, more so than aboveground structures. A fracture of water service pipes during an earthquake (like in Kobe) can also lead to fires that cannot be easily controlled. It is even more complicated to repair buried infrastructures if aboveground everything is compromised.

Therefore, tunnels resilience should not be taken for granted and it is necessary to understand risks, benefits, and capital / operational impact of the required mitigation measures. Rail and metro systems have excellent resilience in dealing with earthquakes, but with floods or tsunamis the station entrances and tunnel portals make them extremely vulnerable. In the Netherlands, the Noord Zuidlijn is built with pen stocks on each of end of the submerged tunnel sections. This is a great solution for the New York metro system, where the vulnerability is very tangible, particularly after Hurricane Sandy. In Bangkok the issue with regards to flooding is tackled by bringing the entrance up two to three meters above ground to prevent the metro tunnel from flooding during the Monsoon Season. The SMART tunnel in Kuala Lumpur is designed in such a way that it can interchange between a traffic tunnel and a flood relief tunnel several times a year. As long as the issues are acknowledged, underground projects' flexibility allows to tackle the risks and not improve the resilience of the system itself but of the overall city.

As confirmed by global case histories, the underground structures are intrinsically correlated to urban climate resilience and vice versa. It may be more difficult to confirm whether they are resilient to the second largest emergency of our era, the pandemic risk. Back in the 1960s, Montreal in Canada embarked on a visionary project designed to cover exposed railway tracks connected to Central Station, located in the heart of downtown. From a small initial development, the RÉSO, commonly known as "The Underground City," has since developed into a network spanning 33 km in length, connecting hotels, museums, universities, offices, banks, homes, a bus terminal, metro stations, train stations, an amphitheater amongst other buildings allowing 500,000 people to traverse the city safe from the inclement weather daily. As of these years, the system is proving to be extremely resilient with its massive volumes to all requirements of the new pandemic, including social distancing.

While Montreal is uniquely advanced in its vision, stakeholders around the world today are examining ways to repurpose existing underground assets previously constructed to address other needs. In Toronto, TTC's Bloor-Yonge Station Capacity Improvement Project was approved to meet increasing demand and it represents an opportunity to fight Covid-19. Preliminary design considered a series of cost-effective solutions in expanding the cut-and-cover station box over the existing Toronto Subway Line 2 and connecting it through ventilation openings in the existing cast-iron tunnel liner. The Bloor-Yonge station is one of the oldest and most crowded subway stations in the heart of the city of Toronto. It serves more than 200,000 passengers daily and likely will continue to face significant ridership growth in the foreseeable future. Among the challenges for this project is that the station is located within the extremely complex urban settings including heritage and high-rise buildings. The adoption of innovative design methods, with full adoption of BIM technologies and the integration of cutting-edge construction methods will ensure the serviceability and structural integrity of the existing subway tunnels as the expansion of the underground spaces will take place. In the UK, limestone mines in Corsham, Bath, were converted into ammunition depots and cold war bunkers to address wartime needs. A new project underway to make innovative use of these empty underground facilities is expected to include a state-of-the-art communications center, storage facilities, and much more. In north-central Paris, an abandoned underground parking garage located below a 300-unit affordable housing complex has been repurposed to host, among other services, an “underground permaculture”, a 3,500-square-metre subterranean farm called La Caverne, producing 54 tons of vegetables a year.

Bunker Arquitectura gained international recognition in 2010 for the Earthscraper, an inverted underground skyscraper, proposing a mixed-use underground development for installation in Mexico City’s main plaza. Descending 1,000 feet below the surface, the inverted pyramid also featured a central void for natural light.
Based on the literature, underground structures resilience can be confirmed by identifying an appropriate list of characteristics which shall make the systems flexible enough to ensure a redundant responsiveness to the threats identified. For example, in Rotterdam the multipurpose parking facility Museumpark in case of heavy rainfall has a water storage basin that helps relieve the city from flooding thanks to its spatial and functional diversity, thus increasing the flexibility of the whole city. The MAUDC (Metropolitan Area Underground Discharge Channel) in Tokyo was designed for a similar scope but the resulting damages from a critical event would still risk flooding surrounding areas; thus, the City is looking at improving its resilience against major earthquakes.

Changes can still be made to our underground systems, but it is important to avoid that improving resilience to certain stresses at one point in time may render the system more brittle in the face of shocks at another time. In fact, resilience of a system is less a singular moment when a disruption incurs losses: instead, it is more a process of how a system operates before, during, and after the threat arriving, and this is why introducing a Resilience Matrix is powerful as much as it is a Risk Matrix (Fig. 3).

		physical	information	cognitive	social
Sources of collapse during the 4 phases	prepare	sensors	data creation	understanding	interaction
	absorb	facilities	data collection	mental models	collaboration
	recover	equipment	data manipulation	preconceptions	self-synchronization between individuals and entities
	adapt	capabilities	data storage	biases / values	

Figure 3. The Resilience Matrix for Underground Structures

Resilience is assessed by providing a value in each cell that summarizes the capacity of the system to perform within that domain and period of time. This helps to identify those parts of the system that need to be made more resilient. It also helps to identify where a solution to one problem may create other problems elsewhere. However, resilience matrices do not capture the temporal characteristics within decision making that could cause shifts in preferences or needs over time, requiring policy makers to continually update their matrix outlook at regular intervals and to combining qualitative and quantitative approaches.

6. CONCLUSIONS

As we navigate through very challenging times where the despair for daily miserable news on climate change and pandemic is balanced out by the hope for the future thanks to new policies and investments, introducing the sustainability parameter while evaluating alternative design options for new infrastructures is essential, particularly in our rapidly growing cities. An intrinsic component of this parameter is the urban resilience, which should be managed properly and take advantage of the underground spaces.
Hurricanes, earthquakes, typhoons, heavy rainfall, heat waves, rising sea levels are only some of the examples of new scenarios to be included in the resiliency verification as part of a new infrastructure planning. Not only underground structures offer constructible solutions to all such threats, but they can achieve it considerably limiting the environmental footprint, thanks to available technologies across the entire value chain, from planning and design, to construction, to operation and maintenance.

As a state of the practice, nowadays the tunnelling industry supports better project planning, design, and delivery by addressing a broad range of social, economic, and environmental indicators. However, several steps must be followed in the near future if we want to achieve the challenging targets recently confirmed by the COP26:

- technical codes and regulations need to be updated to specify and adopt technological innovations and to create legal frameworks for competitive procurement methods;
- customer demand circularity needs to be implemented by lowering demand for primary resources through design and process optimization, including re-use of materials;
- construction and materials decarbonization need to be supported by fiscal policies and incentives to shift to alternatives that are more energy efficient;
- raw materials emissions must be reduced introducing lean manufacturing, electrification of processes, and increasing closed-loop circularity for materials and components;
- access to capital for technological innovation is key to achieve the ultimate goal of net-zero emissions at an ecosystem level, but abatement costs are not currently standardized globally on a net-present-value (NPV) basis.

The pathway towards a sustainable resilient future of our infrastructures has been laid out. However, no single player can capture the large opportunities alone, thus the most important mission for all players in the tunnelling industry is now to improve communication and collaboration across the value chain, keeping in mind the vision of a greater good for all humankind

4 REFERENCES

Admiraal H., Cornaro A. (2020). “Future cities, resilient cities – The role of underground space in achieving urban resilience.” Underground Space, Volume 5, Issue 3, Pages 223-228.

AECOM, “The future of infrastructure. Sustainable Legacies: COP26 Report”, 2021

Blanco Jose Luis, McKinsey & Company, “Call for action: Seizing the decarbonization opportunity in construction”, 2021

Broere W., Gaspari G., Marotta M. (2021) “Into the future.” ITAcet, ITA-AITES Lunchtime lecture series #6

Goldman Sachs, “The Net Zero Guide”, 2020

HRH The Prince of Wales, “Terra Carta - For Nature, People & Planet”, January 2021,

Institute of Civil Engineers, “CESMM4: Civil Engineering Standard Method of Measurement”, 4th edition, 2012

Institute of Sustainable Infrastructures, “Envision: The Blueprint for Sustainable Infrastructure”, 2012

Kharraz, S.K. (2020). “Metropolitan Area Outer Underground Discharge Channel”.

Keizrul, A. (2004). “Stormwater Management and Road Tunnel (SMART) a Lateral Approach to Flood Mitigation Works”.

Kannapiran, M.R.K. (2005). “A Study and Evaluation on SMART Project, Malaysia.”

McKinsey & Company, “The next normal in construction”, 2020

McKinsey & Company, “Delivering sustainable infrastructure: Insights from industry leaders”, 2021

Sterling, A. B. (2012). “Sustainability issues for underground space in urban areas”. Urban Design and Planning, 241–254.

The Green Construction Board, “Three Years On Report”, 2015