Urban Underground Space for Resilient Cities

ITA Working Group 20: Urban Problems, Underground Solutions.

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>> Preface

The International Tunnelling and Underground Space Association (ITA) was created in 1974 with a mission to encourage the use of the subsurface for the benefit of the public and the environment, and to promote sustainable development through advances in the planning, design, construction and maintenance of tunnels and underground space. Working Groups within ITA provide special studies to address the use, sustainable re-use, development, and construction of underground space. Working Group 20 (WG20) has the objective to discover challenges of urban areas, and to arrive at practical and innovative solutions by deploying sustainable and responsible approach(es) to the planning, design, construction, operation and ultimate long-term use of urban underground space. This publication is a follow-up on the report on Underground Solutions for Urban Problems (ITA Report N°11, 2012) and earlier ITA works such as “Why Go Underground” (ITA, Godard, 2002).

The ongoing global urbanisation creates challenges as the growing urban population requires more space to live as well as space for transport and distribution of food, water and energy. Efficient and resilient urban planning, including planning for infrastructure and transportation solutions, is going to become an absolute necessity to keep cities liveable, and will increasingly involve the use of underground space. At the same time, long term developments such as climate change, as well as short-term impacts from natural disasters, can seriously disrupt the stable functioning of an urban system. This report highlights how underground space can help cities be resilient to such external impacts and remain functioning, and takes a look at how these underground spaces themselves are potentially impacted.

We would like to dedicate this report to Harvey Parker (†2020), past president of the ITA, and former member and tutor of WG20. With over 55 years of experience in the tunnelling industry in the US and all over the world Harvey has made significant contributions to signature tunnelling projects through leadership and expertise. He was always present to inspire a wider view on the use of underground space and the benefits it may bring to society; both his work and dedication to making our world a better place are still omnipresent and would inspire our efforts for the years to come. For that, we express our deep gratitude to Harvey, our unique thought leader and mentor. In these consequential times for our planet and our urban dwellings, where climate change and energy shortage already started notably affecting our everyday lives and economies, we hope this report may inspire a wider audience to consider and re-think the use of underground space to make our communities and cities worldwide sustainable, more resilient and liveable.

Wout Broere and Giuseppe Gaspari on behalf of ITA WG20

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>> Executive Summary

Urban resilience is the ability of a city, including its infrastructure and inhabitants, to survive, adapt and grow in the face of challenges both expected and yet unimagined. This report explores the essential role underground space can play in urban resilience, helping to strengthen cities against the acute shocks and chronic stresses of the 21st century.

The world's cities and towns are more densely populated and more interconnected than ever before and surface space is increasingly at a premium. Efficient infrastructure and transportation solutions have become a necessity; and the planned, sustainable, and resilient use of both surface and underground space is of the utmost importance, as shows through examples presented in this report.

Between now and 2100, world population growth is primarily due to take place in the urban areas of coastal cities and, as a result, an ever-larger percentage of the population will suffer from the impact of flooding events. This is aggravated by the increased use of hardened surfaces in urban areas, reducing the absorption capacity of the subsoil and increasing the quantity of run-off water. Flood discharge tunnels and underground water retention basins are a proven and efficient way to alleviate flood risks within existing urban areas. Such underground solutions can also be integrated with underground transportation or parking facilities for a more economical and integral solution. The use of underground space can offer additional possibilities in the mitigation of climate change impacts, as underground spaces are, for example, isolated from surface climatic extremes and thus often have a lower energy demand for heating and cooling.

Globally, infrastructure and mobility solutions are being developed to try and keep pace with increased population and economic growth. The use of underground space, for infrastructure and to create space for multiple urban functions within a small footprint, is an important aspect of compact cities; cities where housing, work, shops, and recreation facilities are located within easy distances. Compact cities are more efficient in terms of energy use, especially the transportation of people and goods. The successful integration of underground space in city developments depends on conscious and continuous cooperation between citizens, city planners, construction experts and policy makers.

Underground structures are proven to be resilient against damage caused by natural disasters, such as earthquakes, as they are mostly separated from the surface by virtue of being underground. However, they can be at higher risk of damage due to sudden flooding. Coastal cities are particularly vulnerable to flooding due to climate change, requiring special attention as the risk of sea level rise and sudden flood events rises.

The use of underground space has proven beneficial to solving urban mobility needs and addressing another challenge – disruption of communities, businesses, traffic, utilities, and services. For the most part, tunnel construction takes place out of sight of the public and minimises surface disruptions within densely built urban environments. Operation-related impacts, including vibration, noise, and dust, are also lower than for similar at-grade transportation solutions. The use of metro networks as well as other underground transportation and utility tunnels leads to a significant reduction of the carbon footprint of urban transportation systems. Using tunnels for transportation promotes the preservation of existing communities, environmentally sensitive areas, and parks, as well as historical structures and cultural heritage. In contrast to at-grade or above-ground alternatives, underground transportation corridors promote economic growth and increase surface property values. Because they are not affected by inclement weather, tunnels also have longer service life due to lower exposure to deicing chemicals and freeze-thaw cycles. Tunnels conform to ground movements in earthquakes and are safer in seismically active areas. As cities and their inhabitants become ever more cognizant of these benefits, they increasingly embrace underground transportation solutions.

Single-bore tunnels can further enhance the benefits of underground infrastructure by significantly reducing the surface disruption caused by cut-and-cover construction within public rights of way that are generally associated with constructing rail or transit stations within dense urban zones. In recent decades, advancements in Tunnel Boring Machine (TBM) technology have enabled many projects that would have previously been infeasible. For example, to date there are more than 50 projects around the world that have adopted very large diameter Tunnel Boring Machines (TBMs greater than 14m in diameter), which enable dual-track, high-speed rail lines or three lane highways within a single-bore tunnel. Recently, TBMs of 17.4m and 17.6m in diameter have been used to construct single-bore highway tunnels in challenging urban environments in Seattle, USA, and Hong Kong. The environmental footprints of such large construction projects can often be mitigated through careful management of the excavated soil and recycling of construction waste material.

Next to new construction of underground facilities, the reuse and repurposing of existing structures is becoming an important concept in achieving sustainability, and to this effect, resiliency. In the context of established and well-developed cities there is a growing potential and intent to reuse and repurpose existing facilities. However, consideration needs to be given to the inherent limitations and restrictions existing facilities might impose due to their original use and purpose, as well as their functional, safety and spatial features. Primary sources of underground facilities that could be ideal candidates for reuse and repurpose include abandoned mines, decommissioned military or transportation and logistics facilities, parking and storage spaces, and unused civilian shelters. Cities that have embarked on reviving and re-purposing such facilities have improved the resiliency of communities and often realise a more compact and efficient city in the process.

Numerous examples presented in this report illustrate that the use of underground space can take many shapes and forms, and increasingly wider and more innovative applications, improving the sustainability and resilience of cities. However, further advocacy remains necessary to persuade authorities and decision-makers to invest in the long-term development of urban underground space use. Allocating necessary funds can be supported by wider campaigns promoting and demonstrating the numerous advantages of underground solutions and the increase in urban resilience they bring about despite the temporary inconvenience associated with their construction and the higher initial capital costs of these facilities over surface counterparts. Resilience of our cities should be viewed as a necessary priority, especially considering the impacts of climate change and population growth.

1 >> Introduction

As the world's population continues to grow, an ever-increasing number of people will live and work in urban areas. The UN's 2017 World Population Report predicts that 2.5 billion inhabitants will be added to the world's cities by 2050 – with almost 90% of this growth taking place in Asia and Africa. By 2060, the global population will break the 10 billion mark, and a further billion will be added by the year 2100. Most people will live in cities, which will grow into mega-cities, where surface space will be at a premium, and underground space can help make a city more resilient and sustainable.

The number and size of mega-cities, with over ten million inhabitants, continues to grow. Such cities are becoming very densely developed and overpopulated. In 1950, 30% of the world's population was urban, by 2050 the projection is 68%. Therefore, there is a real urgency to prepare the world's cities for these predicted increases. Large urban agglomerations have become complex systems with many interfaces, necessary for a city to function and to allow people to live, work, eat and relax there. Many developed cities are reasonably well-functioning as self-organised systems; however, increasingly, they are prone to external impacts, especially natural disasters such as earthquakes and major storms. Issues of liveability, mobility, quality of life and effectiveness of infrastructure are of particular concern. Planning for efficient and resilient urban underground space, including infrastructure and transportation solutions, is an absolute necessity for major cities. Moreover, sustainable use of both surface and underground space is a must.

There have been numerous examples in the past decades of the large and sudden impact that natural disasters can have on the urban environment and the well-being of its inhabitants. The impact of hurricane Sandy on New York, or the Maule earthquake in Chile, are just two of many examples. A common aftereffect is the breakdown of core transportation systems, electricity distribution, and water supply. Even the partial loss of key roads and public transit lines can greatly hinder the recovery of other services at a time when the need of the population is greatest.

Such events have influenced many authors to look at the resilience of urban systems. The Resilient Cities Network[1], for example, defined urban resilience as the ability of an urban system to maintain its functions and recover from shocks and stresses, adapt to changing conditions, while preferably moving towards increased sustainability. At first, this type of research primarily focused on the impacts of sudden short-duration events, such as earthquakes, but more and more the impacts of longer-term events, including climate change and economic downturns, are also being considered.

Earlier reports by the ITA discussed reasons to go underground (Godard, 2002) or the benefits that underground space can bring and the problems that urban underground space can solve (WG20, 2012). This report looks specifically at the relationship and interdependencies between urban underground space and the resilience of urban areas, and presents numerous case studies as examples. Urban areas, including towns, cities, and especially mega-cities, are increasingly using underground space to function in a compact and efficient manner. In general, underground space offers opportunities for the improvement of urban resilience. At the same time, existing underground spaces may contribute to vulnerability, especially if originally planned without regard to increasing weather-related events emerging from climate change.

One of the key findings of these earlier studies is that cities require space to grow and adapt. Timely integration of underground space planning into a city's master plan can lead to denser and more efficient urban environments – 'compact cities'. New and fast-growing cities require space for utilities and transportation systems, while existing well-established cities need space to revitalise and refurbish pre-existing infrastructure as well as add new capacity or functions, usually within the city current footprints. Proper (climate-change-conscientious) planning of underground space and its uses offers opportunities for providing the additional space needed, and to develop cities in a sustainable manner while improving the overall well-being of its inhabitants.

While the use of underground space offers possibilities, it can create other challenges. The direct costs of underground construction are often more expensive than similar sized surface facilities (Linger, 2002). The direct, indirect and environmental benefits of keeping the surface space available for other uses (among other benefits) are, unfortunately, often not considered in such cost estimates. Underground spaces can be difficult to adapt, and more consideration could be given during design to flexible usage over time. On the other hand, a big advantage of underground space is that it is often better protected from the environment and longer lasting than surface constructions. In addition, underground solutions are often more energy and resource efficient and can be more sustainable relative to their surface counterparts. This increased efficiency can help a city to be more resilient in times of disaster, but it should be noted that underground spaces do have vulnerabilities. These are typically related to extreme weather events causing flooding, and issues with ventilation and egress. This report will also present examples of how these vulnerabilities have been managed and overcome.

[1] *resilientcitiesnetwork.org*

2 >> RESILIENCE

Urban resilience is the ability of an urban environment, including its infrastructure and inhabitants, to remain functioning in the face of acute shocks and chronic stresses. This report explores the role underground space plays in urban resilience, considering both short-term events and long-term changes. Underground structures are proven to be resilient against damage caused by natural disasters, such as earthquakes, but they can be at higher risk of damage due to sudden flooding. The risk of flooding requires special attention in the context of climate change, as the risk of sudden flood events rises. At the same time underground space offers opportunities to help reduce climate change impacts. For example, they are insulated from rising temperatures and therefore have a lower energy demand for heating and cooling.

Resilience is a concept that has been applied to a variety of domains of knowledge. Holling (1973) pioneered using resilience as an approach in the context of ecosystems. Since then, resilience has developed from narrow definitions describing it as the capacity to absorb shocks and maintain functions (Holling, 2001), an ability to function in the face of changing circumstances (Hunt and Rogers, 2005), to a wider vision involving the capacity for renewal, re-organisation, and development (Berkes et al, 2003; Folke, 2006), the capacity of a community to withstand significant environmental changes and an ability to return to normal functioning after a catastrophic events (rephrased after Sterling and Nelson, 2013). Folke (2006) described a sequence of resiliency concepts, from a narrow interpretation to the broader socio-ecological context. Where the narrow engineering focus is primarily concerned with recovery after short-term events, the social and ecological focus deals more with adaptive capacity and transformation over longer periods, for instance due to climate change. In that context and considering physical infrastructure development, Rogers et al. (2012) suggested that any solutions being adopted today in the name of sustainability should also be examined as to how resilient they will be in the future.

There are two important aspects of urban underground space resilience – the resilience of the underground structure itself, and the result of using (or not using) the underground on the resilience of a city. The resilience of a city with underground infrastructure fits well into a socio-ecological view, as underground space can be considered a resource as part of an ecosystem (e.g. groundwater), and also involve socio-economic issues such as urban lifestyles, as well as management and operational issues related to infrastructure.

Looking at the infrastructure itself, underground structures are often more resilient to a variety of natural disasters (e.g. hurricanes and earthquakes) (Bobylev, 2013; Sterling et al, 2012; Sterling and Nelson, 2013). The main challenges of underground infrastructure are often posed by a lack of knowledge of their structural condition (e.g. sewerage conduits are often rarely surveyed); the fact that the subsurface often contains many elements of critical infrastructure, the failure of which could result in a huge disturbance to city life (e.g. metro, water, telecoms, and energy supply); and that underground structures and networks are connected physically (through the surrounding soil) and functionally to other networks. Therefore, their vulnerabilities and resilience should be examined as a whole, which is a very complex task. Bobylev (2007) and Bobylev, et al. (2013) detail the interdependencies of different types of underground infrastructure and their resilience under various threats. For instance, underground spaces are less susceptible to external impacts, and their impacts on the surface environment (e.g. noise) is less than above ground facilities. This also often translates into a lower need for heating or cooling, and in some applications underground facilities do not require any temperature adjustment at all. Underground spaces have limited external connections, and flow or movement through these connections are easy to control. Overall, underground spaces are resilient to external impacts and vulnerable to impacts that emerge inside.

UNDERGROUND SPACE IN THE CONTEXT OF COMBATING CLIMATE CHANGE

Underground space use generally contributes positively to climate change mitigation efforts, due mainly to its comparatively high energy efficiency and the long lifespan of these facilities. The major downside rests in the initial excavation and construction of underground space, which is a very energy intensive process. Underground structures in soft ground often require the use of concrete retaining walls and tunnel linings, which use cement and steel, and hence have high embodied energy and contribute to carbon emissions. However, once underground spaces are completed, they require minimum energy to operate due to stable ambient temperatures. The net effect can be a much lower energy and carbon footprint than a comparable aboveground construction over the full life span of the facility.

Underground space use plays a significant role in energy efficiency in buildings. Underground spaces can be connected to above ground buildings via heat convectors, allowing cooling or heating. The subsurface can be used to store energy via small piles and heat convectors, increasing the energy efficiency of the aboveground building (Akhmetzyanov et al 2021). The development of geothermal energy technologies has also evolved in recent years, facilitated by policy drives for energy efficient buildings and renewable energy sources. UNEP (2013) estimates that a 70% reduction in carbon dioxide emissions could be achieved via the housing sector alone. This figure reflects the many opportunities available to increase the energy efficiency of buildings. Global greenhouse gas emissions were estimated at 50.1 gigatonnes of carbon dioxide equivalent (GtCO2e) in 2010, of which 1.4 – 2.9 GtCO2e was assigned to buildings (UNEP, 2013) and growing rapidly. By switching to geothermal energy, many of these emissions could be eliminated.

Excess heat that accumulates within a structure during warm periods can be stored in shallow subsurface underground space and released for heating in winter. In this way, underground space can contribute to 'passive housing', which has a net-zero energy use for heating. Deeper geothermal energy sources, where energy is extracted in the form of hot water or steam, can be used to provide heat for buildings, industrial processes, and even generating electricity. Geothermal energy is a fully or partially renewable resource, depending on the rate of extraction (Sterling et al, 2012). The capacity to generate geothermal energy varies across regions, from easily accessible hot geysers (in e.g. Iceland, Kamchatka) to the need to create deep boreholes. As such, while low temperature shallow subsurface energy sourcing and storage can be implemented in most urban areas, high temperature geothermal energy extraction is only possible in a limited number of locations.

3 >> Compact Cities

The use of underground space, for infrastructure networks and to create space for multiple urban functions within a small footprint, is an important aspect of developing compact cities – cities where housing, work, shops, and recreation facilities are located within easy distances. Compact cities are more efficient in terms of energy use, especially in terms of the transportation of people and goods. The successful integration of underground space in city developments depends on conscious and continuous cooperation between planners, construction experts and policy makers.

While the direct contribution of underground space use to mitigate climate change is important, its greatest contributions are often indirect and relate to sustainable urbanisation. A compact city – a high density urban area – is most efficient in terms of energy use, including indirect indicators like time spent on the transportation of people and goods. According to the OECD, compact cities have dense and proximate development patterns, they are linked by public transport systems, and maintain accessibility to local services and jobs. Dense infrastructure networks minimise the expenditure of energy and integration of underground space is vital to enable a compact city. Use of underground space allows a city to densify and create an urban environment that offers a mix of different functions within the same area. That facilitates concepts such as a walkable city or a 15-minute city, where pedestrian, bike, and public transit transport modes are prioritised over car traffic and are focused on serving a diversity of users around the clock. Such mixed urban environments, especially when creating or freeing up recreational and green spaces on the surface, can lead to a more vibrant city with more inclusive social areas.

Urban compaction is a planning concept that promotes relatively high residential density, with mixed land uses and an intensification of urban functions, usually in a city centre. It is based on an efficient public transport system, like a subway, and has an urban layout that encourages walking and cycling, low energy consumption, reduced pollution and offers opportunities for social interaction as well as a feeling of safety. A compact city is a more sustainable urban settlement than suburbs, created by urban sprawl, as it is less dependent on the car and requires less infrastructure provision. However, achieving a compact city does not just mean increasing urban density, it requires good urban planning, with a compact and efficient city centre.

Moving road and railway infrastructure underground can be very beneficial for a city. However, large investments are needed, and these projects require massive logistical operations involving numerous parties and long construction periods. It is possible to (partially) regain the investment, due to increased property values in the surrounding areas as well as increased safety, reduced travel times, environmental benefits and preservation of open spaces and green areas. If the redevelopment of these areas is properly executed it could benefit a city's ability to grow, as well as increase sustainability and liveability. This would also mean increasing the resilience of a city since resilient cities are cities that promote sustainability, growth and well-being as well as being capable of handling chronic stresses. Moving the road and rail infrastructure underground could do exactly this, and when successful in more cases, could be scaled up, creating more and more liveable space inside the city and improving resilience (van der Horst & Frijlink, 2020).

COMPACT CITY CENTRES AND METROPOLITAN GOVERNANCE

Successful implementation of compact cities requires attention from professional communities of engineers, construction experts, planners, policy makers and decision makers. Most major cities were built hundreds of years ago and have a dense and compact centre, and have continued to grow and redevelop over that period. Information on the location of existing (underground) infrastructure was/is rarely comprehensive and requires compilation of data from several sources, often difficult to obtain. Most municipal stakeholders only have partial access to this information and largely underestimate the potential of underground space. Consequently, urban underground space is often poorly planned, as underground works were constructed on a case-by-case basis and not integrated in the city's development planning. A lack of planning for new infrastructure may cause interference between tunnels, public utilities and building foundations, engender negative environmental impacts on the water table, and restrict further opportunities for development.

Very few cities integrate underground space into their master plans and the vast majority of such plans remain an image without implementation tools. In many cases, it continues to be a 2D mapping exercise, even though GIS tools exist today that can map the 3D location of pipes, utilities and underground facilities, and facilitate future urban development decisions.

In fact, metropolitan governance at multiple government levels can be very compartmentalised, with each municipal governance operating within its own statutes and jurisdictional boundaries. Thus, the steady development of metropolises with cross-jurisdictional infrastructure can be negatively affected if a consensus is not agreed in advance. However, some unification among governing administrations on the development of metropolis-wide growth strategies that allow more resilient future urbanisation including compact cities is evident. In other words, better planning leading to more resilient metropolises can be achieved if the lawful unification of fragmented governments across selected geographical boundaries is secured. Innovative strategic planning is required to develop underground structures in compact city centres, encouraging municipalities to incorporate and extend existing facilities through municipal planning practices.

A good example of governance unification is the Madrid Metropolitan Area, the most populous Spanish urban area, which combined 179 previously separate municipalities into one single government (Comunidad de Madrid) in 1983 upon receipt of its independence from the state government (Tomas, 2017). This unification facilitated the delivery of 193 km of Madrid Metro subway expansion over last 30 years, which is vastly more, for example, than the 43km of mass rapid transit constructed over the same period within the Greater Toronto Area (Toronto Transit Commission, 2021), the most populous Canadian metropolis, that is still governed by 29 separate municipal governments topped by provincial and state governments.

TOWARD A GLOBAL RECOGNITION OF THE VALUE OF COMPACT CITIES

On a more global scale, the value of compact cities using underground space has gained more recognition amongst planners and other professionals, as well as international agencies. The seeds were first sown back in the late 60s, when the oil crisis, sprawling cities, and public deficits shook the world. As a reaction to that explosive situation, the concept of sustainable development gradually appeared in the 70s. That concept of sustainable development was consecrated in 1987 with the report on “Our common future”, commonly known as the Brundtland Report. This report defines sustainable development as «A development which meets the needs of the present without compromising the capacity of the future generations to answer theirs.» Later in 1996, Habitat II proposed a framework for the sustainable development of human settlements and reaffirmed the need for universal improvements in living and working conditions, using mixed use and services at the local level.

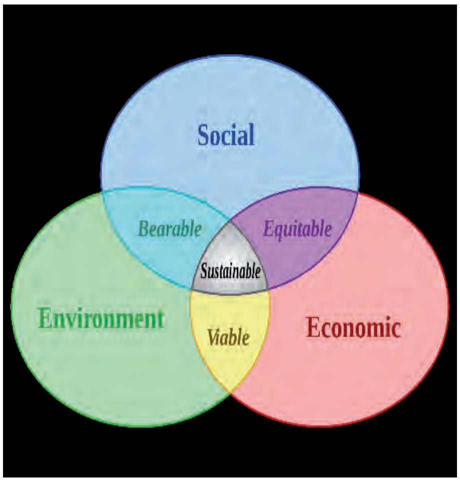

Figure 1: Diagram depicting sustainable development

The notion of ‘Compact Cities’ emerged as a more creative way of reusing existing buildings and forming mixed-use developments. The environmental benefits of compact cities are clear. If you can walk or cycle around your city, supplemented by efficient and clean underground public transport, such as the subway, a compact city can become virtually pollution-free. It is encouraging to see these UN principles now apply to many urban spaces around the world, thanks in part to MoUs signed in the past by UN-Habitat with ACUUS raising awareness of the sustainable use of underground space.

CITIES WITH SUSTAINABLE UNDERGROUND SPACE USE

Despite local particularities, the development of urban underground space is a common and fast evolving trend. Planners have a growing awareness that underground space is not an easily renewable resource, and that we should use it in a sustainable manner. Ageing infrastructure can become a drain on financial resources and deferring operational maintenance can further exacerbate the situation. It is not simply an engineering problem. A crucial step towards the better use of urban underground space is in its integration with the local economy and environment, including the fiscal and budgetary context of the city. For this reason, and many others, urban underground space is not fully realising its value within the sustainable development of many growing cities. The current climate and energy crises brings the promotion of compact cities back into the spotlight.

In a compact city centre, aside from transport infrastructure, stand-alone underground structures, such as basements, recessed buildings and storage facilities, also often exist. These can include commercial basements and underground parking structures under a street or a park. The Teatro Municipal Las Condes, in Santiago de Chile, the controversial iceberg houses of London millionaires with larger basements than above-ground structures (Fig. 2), in the UK, and the famous Temppeliaukio Church in Helsinki, Finland (Fig. 3) are also good examples of stand-alone underground structures.

Another type of structure contributing to the compactness of a city centre is a building connected by an underground corridor to a train or subway station. These usually have a commercial component, such as the Festival Walk in Hong Kong (Fig. 4), the COEX Mall in Seoul (Fig. 5), and the Queen’s Square in Yokohama, Japan.

An even better way to achieve compaction in a city centre, is an indoor pedestrian network or underground city, which is a network of corridors linking multiple mix-use buildings with subway or train stations, such as Hong Kong’s “city without ground” (Fig. 6). These networks may be below grade, above grade (skyways), or a mixture of both, with shops, services and recreational facilities located inside tunnels and caverns that connect to and link with buildings. These indoor pedestrian networks aim to redirect pedestrian flows to reduce conflict with traffic at the surface, protecting pedestrians from rain, hot or cold climates, and encouraging the use of mass transit. They are the extension of the compact city centre above, improving efficiency and the quality of life for citizens. When carefully planned, they can reinforce the “surface life” of a city neighbourhood by allowing convenient pedestrian and transit access that allows a city centre to compete with the car-centric suburban districts.

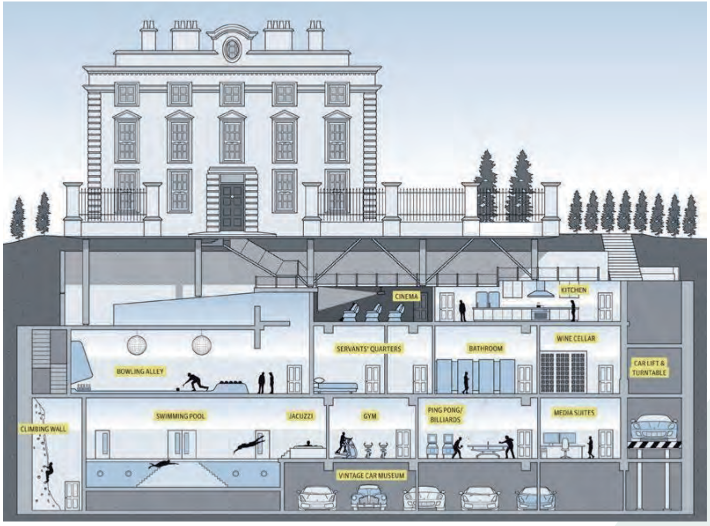

Figure 2: An iceberg house in London.

Figure 3: Temppeliaukio Kirkko Church, Helsinki.

Figure 4: Festival Walk, Hong Kong.

Figure 5: COEX Mall, Seoul.

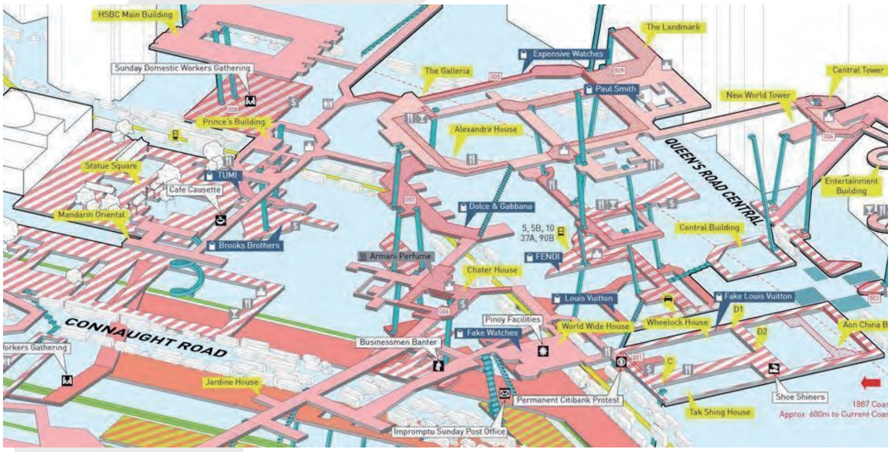

Figure 6: Cities without ground, Hong Kong.

Underground cities around the world are not all similar and the term is used in different ways to promote projects. In general, there are three types of underground city: the radial ones, developed around a subway station; the superimposed ones with underground malls located directly under streets above, as in Japan, China and Korea; and, finally, the so-called organic ones, with corridors connecting buildings perpendicular to streets, and passing through basements. Most examples of these in North American cities (New York, Chicago, Toronto and Montreal) are in compact downtown areas. In each of the three types, to be efficient, an underground city must offer an equilibrium between transportation, commercial and social activities.

It should be noted that many urban underground developments do not result from a lack of space at the surface but rather from a mixture of pre-existing opportunities, such as seasonal climate conditions (e.g., Coober Pedy, Australia City) and/or the availability of abandoned underground mines under a city (e.g., Kansas City), or the occurrence or creation of existing underground infrastructure networks and particularly subways (e.g., Montreal). In general, decisions for such underground developments are most often taken by developers, rather than the result of long-term city urban planning.

Case Example: Asian Underground Cities

In Japan, many underground train and subway stations are connected to underground plazas and passages, mostly operated by private enterprises. Japanese cities rent this retail space below the public domain, directly under streets, providing linear networks of small shops and restaurants that serve to distribute pedestrian traffic from stations as well as providing needed retail and restaurant space. The direct connections to other neighbourhood buildings may be limited. The main reason for this is fire safety, as openings/egress to the surrounding building basements is prohibited unless in compliance with strict fire regulations.

An example of this type of underground city is in Tokyo, a metropolis of more than 14 million inhabitants, located within a greater area of 42 million inhabitants.

Figure 7: Yaesu Shopping Mall, Tokyo.

Figure 8: Queen Square Minatomirai Station, Yokohama.

Most of Tokyo's underground train stations and its 290 subway stations are connected to underground commercial plazas. Unfortunately, the remarkable development of this underground space was so popular, it ultimately caused congestion and led to excessive land values. This led authorities to change the land laws which are now more restrictive near the surface.

There is an exception to this model in Yokohama, where the Queen's Mall subway station is located under a huge commercial mall, on the fifth basement level, but is exposed to surface light and views via a large atrium.

Case Example: American Underground Cities

In the USA, the city of Chicago has the Pedway, a downtown indoor pedestrian network totalling more than 8km, which consists of four separate systems within around 40 city blocks (the largest covering about 10 blocks). The Pedway began in 1951. Today, it connects more than fifty public and private owned buildings and is used by 10,000 people a day. It includes underground pedestrian tunnels, street-level concourses and overhead skyways, which are generally managed and maintained by adjacent property owners.

Case Example: Canadian Underground Cities

In downtown Toronto, Canada, there is an extensive indoor pedestrian network, called the PATH, which connects more than 50 office towers, hotels, department stores, parking garages, subway and train stations over its 29 km length. Like Chicago, it includes underground pedestrian tunnels, street-level concourses and overhead skyways. Instigated in the 1970s, most sections of the PATH were privately built and are owned and maintained by the owners of the properties through which it runs through a cooperative partnership. The city is not involved but encourages property managers to keep its doors to the PATH system open during subway hours.

However, Canada's best example of an underground city is Montreal. Maps of the city's 32 km long underground 'RESO' pedestrian network can be found throughout the city centre and are posted on every street entrance. It criss-crosses under the city like a net with public corridors passing through privately owned building basements, crossing perpendicular to the streets above.

The RESO system is open during subway hours, from 6am to 1am, even if users are walking through corridors owned by private properties. Following 60 years of operation, downtown users can access the RESO from more than 65 buildings, including hotels, shopping malls, universities, conference centres, the public library, and a major hospital. The system spans 80% of the CBD office buildings and 35% of downtown shops. Before the pandemic, half a million people used the system every day and numbers are now gradually returning to normal.

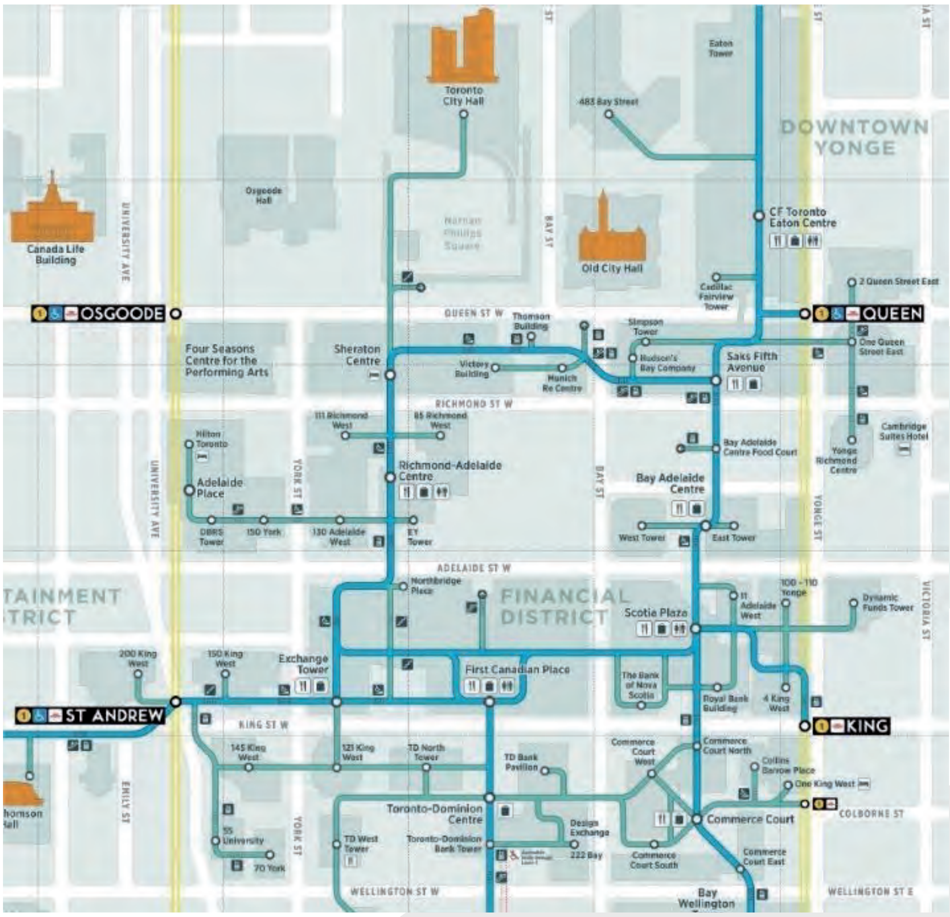

Figure 9: Toronto's PATH Network.

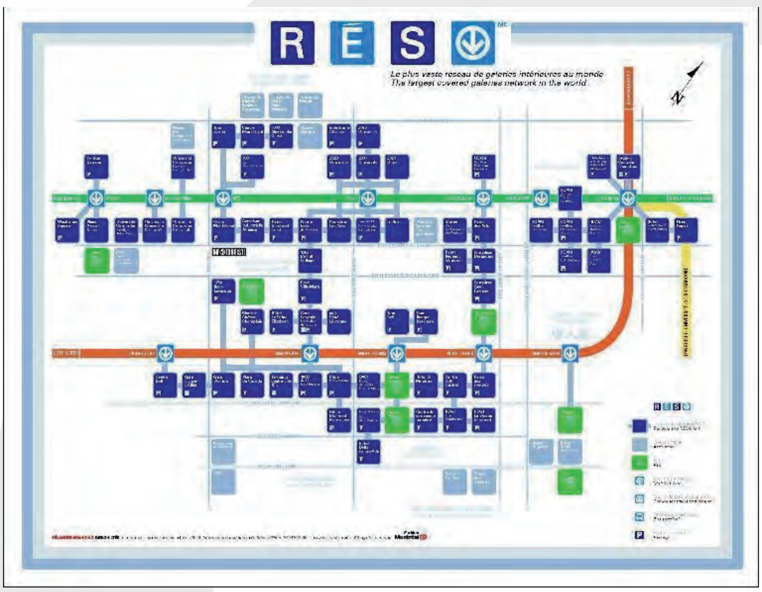

Figure 10: Montréal's RESO underground system.

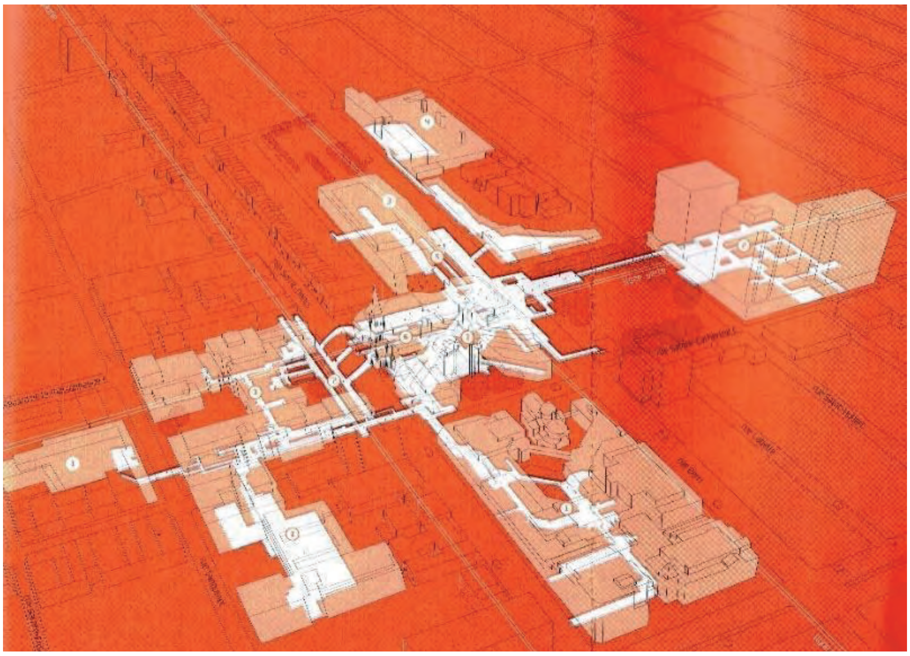

Figure 11: Berri-UQAM network, Montreal (David Mangin).

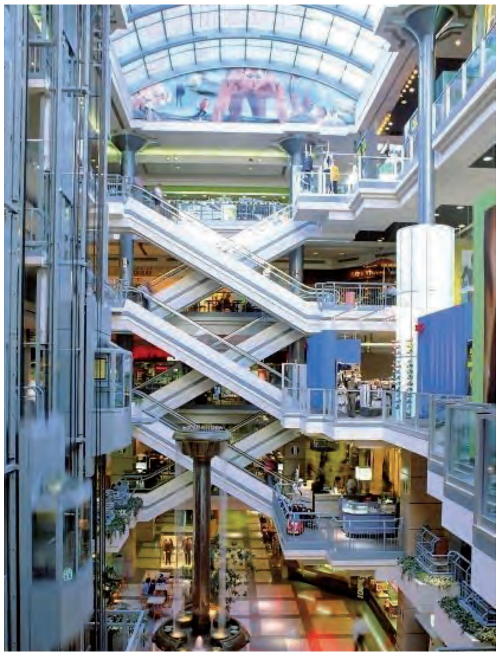

Figure 12: Place Montreal Trust, Montreal.

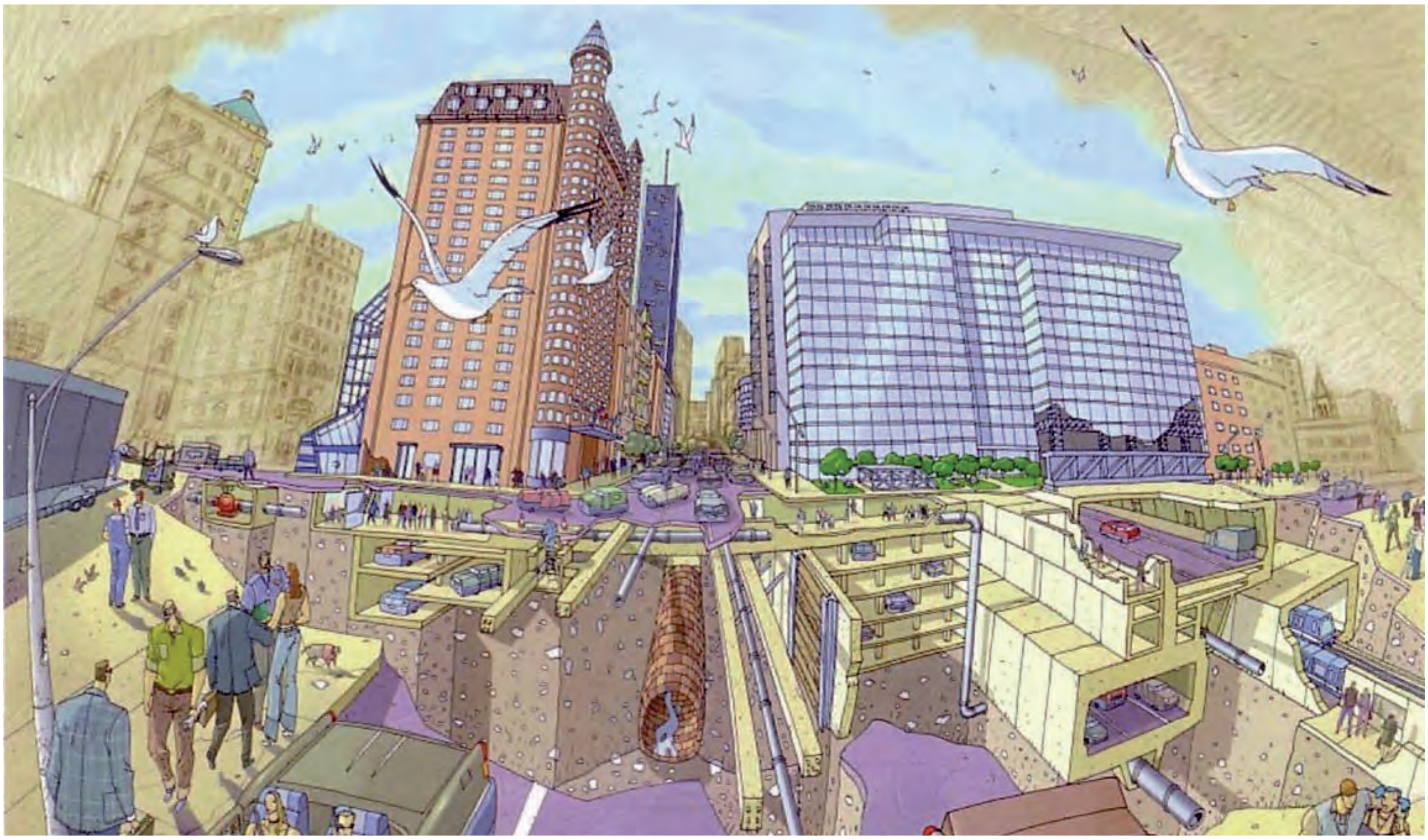

Figure 13: International District Underground Montreal, Artist Pierre Brignaud.

Case Example: European Underground Cities

In Helsinki, Finland, there has been extensive development of underground space, facilitated by good bedrock and favoured due to hard winters. This has given birth to hundreds of stand-alone underground caverns and spaces, many forming significant architectural works, including a swimming pool complex, a church, and a hockey rink. Numerous «parking caverns" and municipal government facilities are also located underground. In addition, the city also has a modest network of underground pedestrian and shopping passages.

In 2010, the city adopted a dedicated master plan for their underground space, aiming to manage the long-term use and preservation of publicly owned areas of bedrock for public utilities. The plan includes space allocated for transport development, water and energy supply, parking, storage, and waste management, as well as civil defence, recreation, public installations, and other uses.

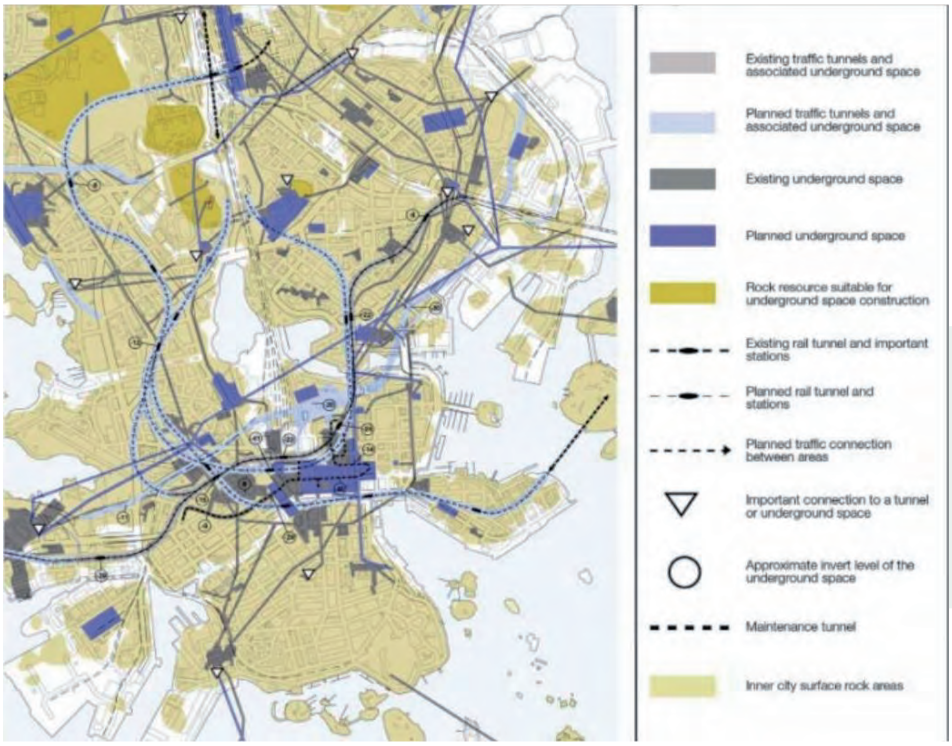

Figure 14: Helsinki's inner city underground master plan.

Case Example: Milan: Learning by Doing to Shape a Better Future

Milan is Italy's largest metropolis, with some 5.3 million inhabitants living in an area of 1,891km². The Municipality of Milan, the Inner City, is Italy's second largest after Rome, with 1.4 million inhabitants. Since becoming the country's economic capital (after Italy's unification), the city has looked to the future, starting with public transport and sustainable mobility initiatives.

Milan was founded more than 2,600 years ago and has a heritage echoing that of Rome, Venice and Florence. But modern-day Milan surpasses the rest of Italy, and most other major cities in Europe, when it comes to urban regeneration. Over the past decade the city has experienced great transformation and extraordinary architectural development, which has totally changed the image of Milan. Now home to many of the continent's most significant urban renewal projects, large areas of the city are rapidly being "re-invented". Twelve key urban renewal areas, totalling more than 5.25 million square metres – including one project that encompasses seven abandoned railway yards and totals more than a million square metres – are being strategically redeveloped based on mass transit oriented infrastructure expansion, mostly underground.

Figure 15: Milan's 2026 Winter Olympic Village is under construction on a former 212,000m² trainyard. The project was conceived as part of a Transit Oriented Development (TOD) plan, integrating the city's railway circle line, metro line M3, possibly future M6, LRT T24 and BRT 90/91 (source: Urbanfile and Milano Today).

This strategy wouldn't be possible without Milan's investment in infrastructure, which resulted in a 4 line metro network that covers 101km, with 113 stations operating, and expected to expand to 160 km and 170 stations shortly beyond 2030. Milan's high urban density forced the Municipality to focus on underground works in order to create infrastructural nodes and mass mobility access infrastructure; which in turn allowed for amazing high-rise developments and refurbishments above ground.

The M1 line, opened in 1964, was constructed mostly from the surface, increasing traffic congestion. The result was that subsequent lines were mostly constructed by manual or automated tunnelling, minimising surface disruptions, but still leaving temporary disruptions at the locations of station excavations. Therefore, the proposed design for the upcoming line M6 includes an enlarged tunnel section that houses the station platforms and tracks and further decreases any surface construction activities, as only limited access shafts are necessary. This additional underground space constructed this way between station boxes offers many possibilities to accommodate other functions, such as shops, storage and utilities, not necessarily limited to metro only.

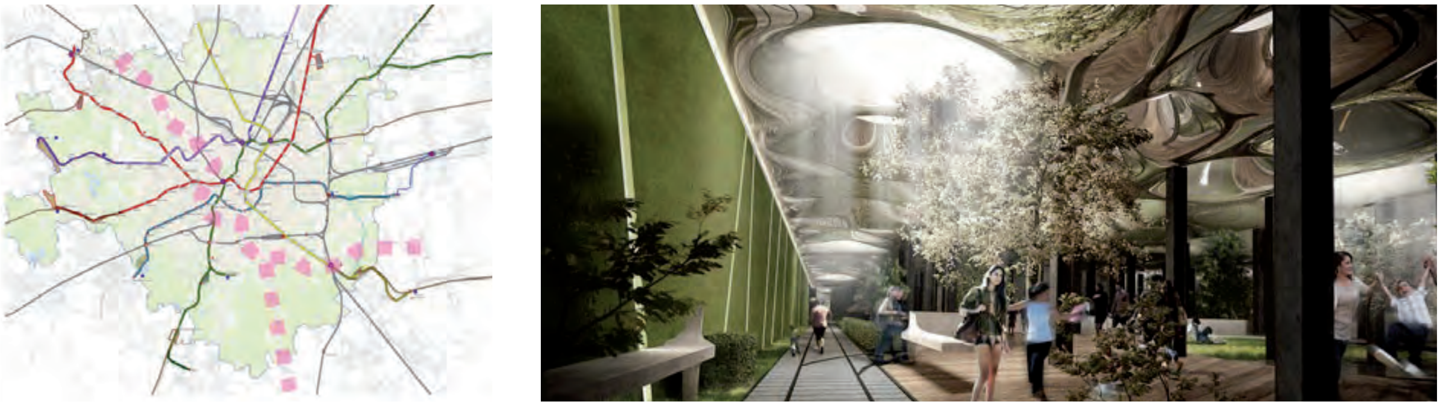

Figure 16: Left, M6 line on Milan's Sustainable Mobility Plan (source: PUMS). Right, future underground spaces vision (source: INHABITAT).

Case Example: Chatelet and Forum des Halles, Paris

Chatelet - Les Halles is one of the largest underground stations in the world. A multimodal transportation hub with 6 underground levels connecting 3 regional train lines, 5 subway lines, a mall, public services and a park. This is a major project for Paris, through which Chatelet became the heart of the city with the arrival of the regional train lines to Paris inner centre in the 70's: at that time, on the site previously occupied by the old central market (Les Halles), a new large station was built that connects the existing metro line stations with the new regional railway station, completed by a large shopping centre and other spaces used for public services (gyms, swimming pools, offices).

As the main gate to Paris, Châtelet - Les Halles is usually the first Parisian impression for travellers and their first contact to urban social activities. The neighbourhood was born as the central market, and that vibrancy is still in that area: the melting pot, the shopping areas… Chatelet - Les Halles is the main meeting point for Parisians. In 2018, a major renovation project aimed to reconnect "la ville dessus et la ville dessous", the uptown and the downtown: the new Chatelet - Les Halles has a modern accessibility plan connecting new vibrant areas of the neighbourhood by smooth walkable paths in an urban park. Spacious walkways are now the link between the transportation levels and the surface, with natural and artificial lightning playing the main role in a new conception of Parisian underground spaces.

Figure 18: The new Forum des Halles (source: Mairie de Paris).

Case Example: Carrousel du Louvre, Paris

The Louvre Museum's access marked a new landscape in Parisian use of underground spaces: natural lightning, big volumes and high-level smooth materials improve the users' experience entering the Louvre Museum.
Connecting the museum's entrances, rue du Louvre, the Carrousel and the subway, this space has been planned as a multifunctional concept by integrating commercial areas, services, and public utilities, such as auditoriums and exhibition rooms. This project also integrates the archeological area of the Louvre fortress' mediaeval foundations. This project grants that the traveller is immersed in a sensorial experience, only possible by its underground characteristic. The shopping areas with the fortress foundations, the Pyramide marking the "upside down city" and providing the zenithal lightning that became the identity of the Carrousel, city events in the world's largest museum: those are the elements proving that a transformation in urban planning can make underground a federative component of the city and a pleasant and important urban landmark.

This project is a remarkable sign of the most important key points on underground's user experience: pleasantness, fluidity and instinctivity where culture, heritage, social life, and transportation coexist in a major underground space. An urban underground path that became a memorable experience.

Figure 19: The Carrousel du Louvre (source: Carrousel du Louvre).


Figure 20: The Carrousel du Louvre event rooms (source: Carrousel du Louvre).

Case Example: Digital Underground Models for Greater Toronto Area

Digitalisation is an ongoing development in the underground construction industry with new digital technologies assisting us in everything from 3D design to laser navigation, muck management, and GPS positioning, etc. However, the digitalisation of knowledge, collected by humans through historical construction records remains relatively slow and inconsistent, leaving many urban areas without centralised data sources. Historical data on the construction and management of existing underground assets during new underground construction projects can be vital, but there is a pressing need to reduce the replication of the work processes required by each new project team to collect and assemble all necessary data. "Data recycling" should be viewed in the same light as any other recycling, in that it reduces wasted time and resources.

In 2001, the four municipalities that form the Greater Toronto Area (GTA) and nine conservation authorities managing the Oak Ridges Moraine – the main topographical/ geological feature and groundwater source in southern Ontario (Karrow & White, 1998) – combined to create the York-Peel-Durham-Toronto Groundwater Model (YPDT Model). The main purpose of this collaboration was to serve its members with reliable data for the proper management of declining (quantity and quality) groundwater resources

Upon commencement of the project, all available groundwater-related data primarily located with the Water Well Information System database possessed by the Ontario Ministry of Environment (MOE) was digitised first. The YPDT Model was then gradually expanded with a variety of geotechnical borehole and monitoring/water well data collected by partners and private land developers for previous construction and long-term land rehabilitation programs. Focusing on groundwater quantity and quality, the database included all available information on the chemical and physical properties of soils/rocks/water content, described in borehole logs and well records, supported by in-situ and laboratory analyses. As the work continued, the benefits of the database were extended to adjacent GTA municipalities. As it stands today, the Oak Ridges Moraine Groundwater Program (ORMGP - the new brand name) is owned and operated by a coalition of 14 municipalities and government agencies (www.oakridgeswater.ca). Consultants and contractors can now also subscribe to this data. Unfortunately, the database is not well advertised, and consulting and construction companies are underutilising this remarkable resource.

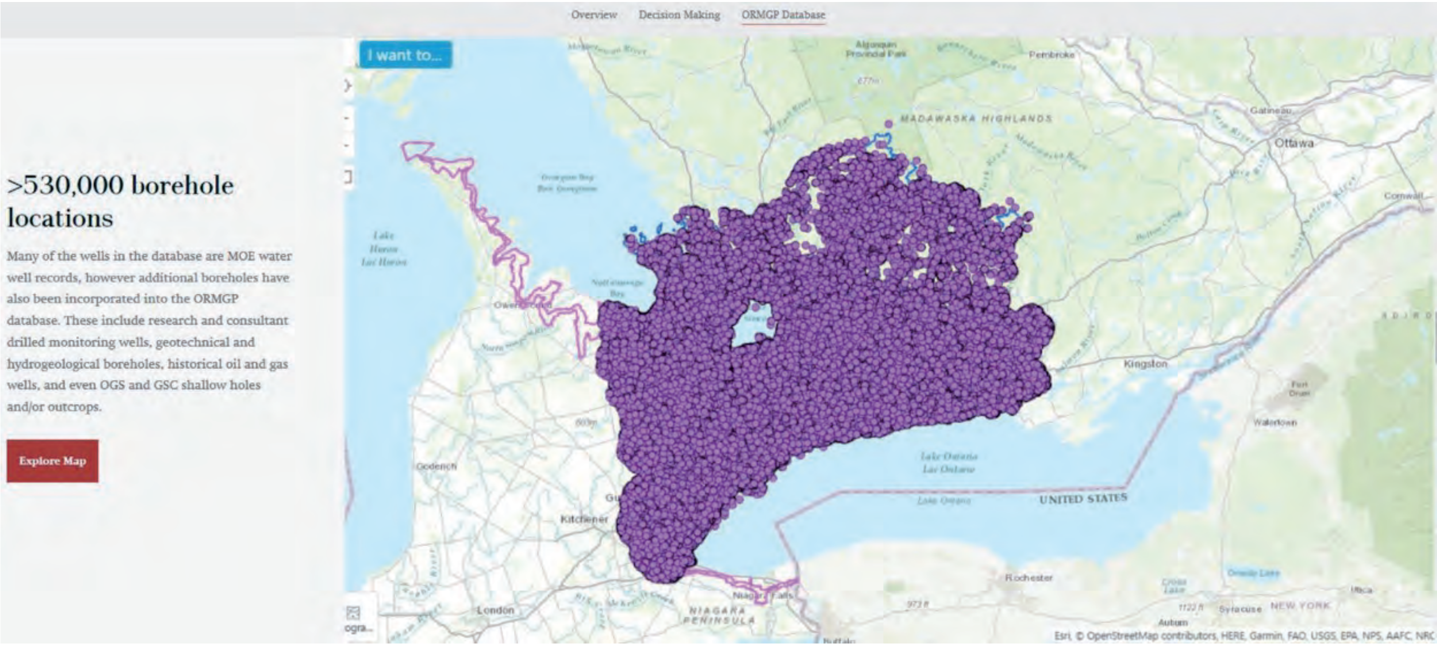

Figure 21: Overview of all boreholes in the Oak Ridges Water database.

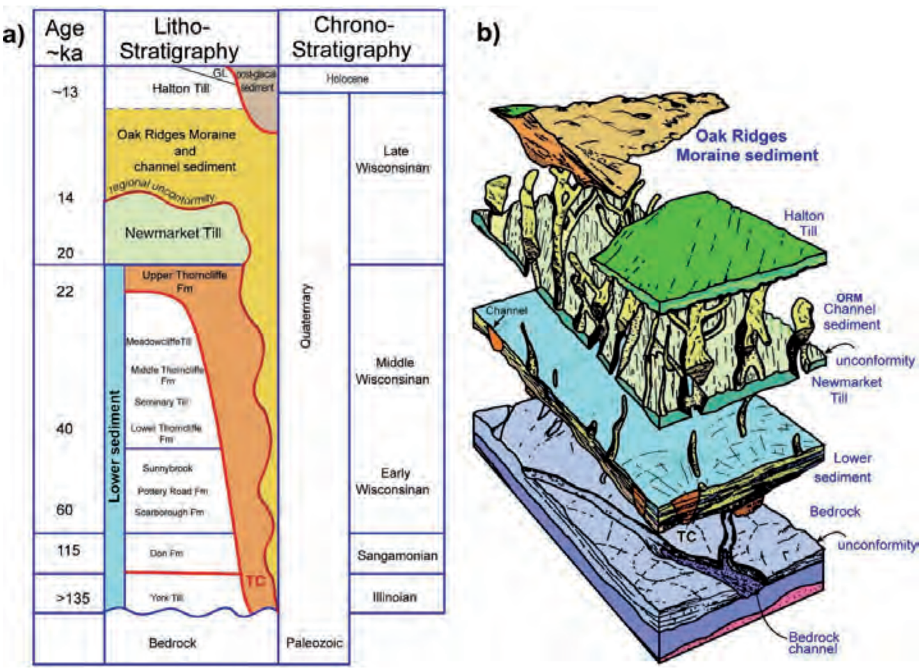

Figure 22: Geological profile with hydrogeological units for the southern Ontario region.

4 >> Natural Disasters

Between now and 2100, world population growth is primarily due to take place in the urban areas of coastal cities and, as a result, an ever-larger percentage of the population will suffer from the impact of flooding events. This is aggravated by the increased use of hardened surfaces in urban areas, reducing the absorption capacity of the subsoil and increasing the quantity of run-off water. Flood discharge tunnels and underground water retention basins are a proven and efficient way to alleviate flood risks within existing urban areas. Such underground solutions can also be integrated with underground transportation or parking facilities for a more economical and integral solution. In contrast, underground structures are often better protected from other natural disasters, such as earthquakes, tornadoes, and other climate change effects such as temperature rises, as they are mostly separated from the surface by virtue of being underground.

Underground structures can clearly help to improve urban resilience, and their use in preventing or mitigating flooding will be further discussed below. But it should not be overlooked that an underground structure also has vulnerabilities of its own (Parker, 2008). When a fire or explosion occurs in an enclosed underground space, the consequences can be fatal, and the risk imposed by underground fire is often more pronounced than that of a surface structure. In case of natural disasters, underground structures can sustain damage, which even if not severe can have secondary impacts. For example, the fracturing of water service pipes during an earthquake and subsequent loss of water pressure, can lead to a situation where fires cannot be easily controlled. In such circumstances it is even more complicated to repair these buried infrastructures if the aboveground situation is damaged, as access may be compromised.

And while underground structures can be designed that help prevent flooding of the surface area, flooding by itself presents a risk to many underground facilities. In the case of flood, large amounts of water may flow into the structure via the underground entrance, ventilation ducts and other openings. This creates a risk of the facility being flooded and could also hinder evacuation attempts from underground facilities like metro stations. The following examples illustrate what damage of underground structures can be caused by natural disasters.

EARTHQUAKE

In 1995, an earthquake hit the southern Hyogo prefecture in Japan with a recorded Magnitude of 7.3 and around 6,500 people died. More than 100,000 houses were completely destroyed, and 7,000 houses were completely or partially burned (JSCE et al, 1998). The damage to mountain tunnels was mostly limited to expansion of existing cracks on lining surfaces, longitudinal cracks in the tunnel shoulder, compression failure at the tunnel crown and so on. About 20 tunnels sustained some damage, which was mostly limited to slight damage, and 10 out of 20 tunnels were damaged to the extent that they needed repairs and reinforcement (Asakura et al, 2000). In the case of TBM bored tunnels, there were cracks and exfoliation in the side walls and shaft entrances, but significant damages, which would lead to loss of functionality, were not observed in any of the underground power transmission tunnels, tunnels for communication, sewer tunnels and sewage pipes. The damage of cut and cover tunnels was mostly limited to cracking at the corners, but the Daikai Station of the Kobe Rapid Transit Railway, which was located in the area of largest seismic intensity, collapsed. At that time, it was generally recognized that underground structures are more resistant to earthquakes than surface structures, but for this single layer 2 span station box, the impact of large shear forces to the reinforced concrete middle column were too large and the entire structure collapsed. Restoration took almost 7 months (Umehara, 1996, Hiroto et al, 1996).

Before the 1995 Kobe earthquake, there were limited standards for the seismic design of civil structures, and seismic design was considered according to the importance of each structure. Following the Kobe earthquake, seismic design for most civil structures became mandatory and seismic design was considered for new underground structures. Also, reinforcements to deal with seismic loads for existing structures were conducted at the same time. As a result of these measures, a complete collapse and loss of function has not been observed for underground structures after 1995.

From this experience of a damaged underground structure during a severe earthquake, we can learn that it is extremely important to design underground structures not only from the viewpoint of easy construction and maintenance, but also with sufficient strength to ensure the protection of life. Fortunately, underground structures are more resilient to earthquakes than above-ground ones (figure 1, and above-ground levels and exits of an underground structure experience most damage during earthquakes. However, evacuation routes from the underground can be blocked, so having emergency supplies in the facility could be an important preventive response measure.

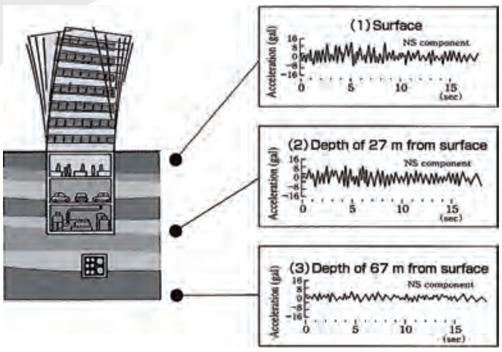

Figure 23: Impact during an earthquake at different depths (source: National Land Agency of Japan, 2001) published in Bobylev, N. (2007). Sustainability And Vulnerability Analysis Of Critical Underground Infrastructure. In: Linkov, I., Wenning, R.J., Kiker, G.A. (eds) Managing Critical Infrastructure Risks. NATO Science for Peace and Security Series C: Environmental Security. Springer, Dordrecht.

TSUNAMI

In 2011, the Tohoku Earthquake occurred in the Pacific close to the coast of Japan. The resulting tsunami generated by this earthquake was extensive and more than 23,000 people were confirmed dead or missing (Yamazaki, 2012). Direct damage by the tsunami to underground structures was not confirmed, but in areas hit by the tsunami, significant damage due to debris and driftwood to electricity, gas, and water supply systems were observed as well as damage to other infrastructure. However, in the case of underground facilities such as conduits and manholes, the survey results confirmed that the extent of damage was overwhelmingly lower than that of above-ground facilities such as utility poles. The study confirmed that installing infrastructure underground is highly effective against tsunamis and secondary damage caused by tsunamis.

FLOOD

In recent years, because of climate change, the number and size of typhoons has increased, with an accompanying increased occurrence of heavy rain events with over 100 mm of rainfall per hour. This has increased the risk of flooding in urban areas (MLIT, sd). A large amount of water flowing into an enclosed space like underground structures, can cause complete flooding of below ground levels, which is likely to result in a major disaster. One example occurred in 1999, when record-breaking rainfall in the northern Kyushu region resulted in one fatality in the basement of a building in Fukuoka City which completely flooded. No accidents resulting in loss of life have occurred since then, as countermeasures to flooding of subways and underground malls have been implemented in urban areas like Tokyo, Nagoya, and Kyoto. In an enclosed underground space, the limited amount and size of entrances are effective in blocking anything from the outside, but past disaster experience revealed that entrances can become a main route for the inflow of water and at the same time an obstacle for rapid evacuation.

IMPACT OF CLIMATE EVENTS

The increased concentration of human populations in urbanised areas is a compelling reason to act urgently on climate change. This call for action is immediate since interdependencies and interconnections of people, infrastructure and assets within affected areas create risks that require solutions at a global scale. Urban populations have grown by around 400 million people between 2015-2020 globally and more than 90 percent of this growth occurred in less developed regions. At the same time, the most rapid growth in urban vulnerability has been in unplanned areas and in smaller to medium urban areas in nations where income, resources and adaptive capacity is limited or lacking.

Coastal cities have been disproportionately affected by climate change due to their concentrated assets and economic activities. Narrow coastal zones house a large number of people. Accelerating sea-level rise has already impacted subsiding coasts, leading to flooding at high tides and coastal flood damage. Risks to coastal cities are projected to increase by at least one order of magnitude by 2100 if significant mitigation actions or adaptive modifications to coastal assets are lacking. Cities are obligated to undertake climate resilient development and adapt through urgent actions (including governments actions) toward mitigating greenhouse gas emissions. Presently there are many urban adaptation gaps that exist globally, for all types of climate change hazards, and their associated risks remain unresolved. At the same time, this presents an opportunity to integrate adaptation strategies to address the issues and incorporate them into developments of the new cities and modifications of the older cities through retrofitting, upgrading and redesigning existing infrastructure including underground spaces. Such strategies must utilise existing knowledge to achieve the required level of adaptation (Figure) through everyday urban planning and development. Likely a mixture of possible strategies and measures would be most effective. Truly this is a limited opportunity considering the global urbanisation trend. An additional 2.5 billion people, projected to be living in urban areas by 2050, could benefit from Climate Resilient Development. Planning, design and maintenance strategies implemented for urban areas and their key infrastructure would determine level and patterns of exposure to effects of the climate change, social and physical vulnerabilities as well as capacities for resilience.

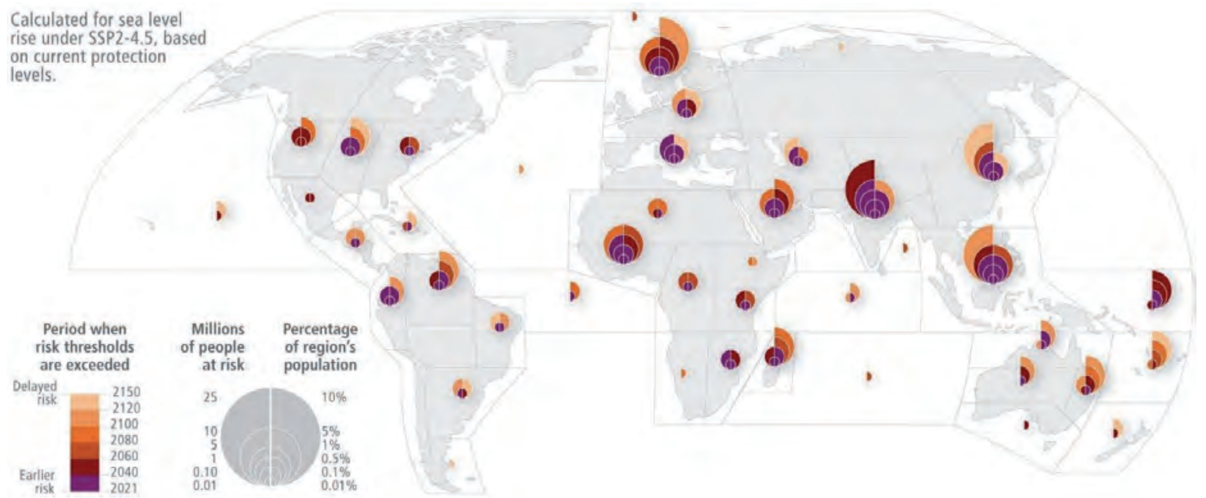

Figure 24: Projected number of people at risk of a 100-year coastal flood. [The size of the circle represents the number of people at risk per IPCC (Intergovernmental Panel on Climate Change) regions and the colours show the timing of risk based on projected sea-level rise. Darker colours indicate earlier in setting risks. The left side of the circles shows absolute population at risk and the right side the share of the population in percentage.].

With the increased urbanisation of large areas, where rivers, streams and creeks are placed in artificial restrained channels, and increasingly large surfaces are covered with asphalt and concrete, reducing the capacity of the subsoil to absorb rainwater, flood events have become more frequent than ever. Intense flooding events due to large and sudden rainfalls, events that used to occur only once every hundred years, seem to have their occurrence increased, as several researchers noticed in many locations (cite sources). Most studies correlate the increased frequency with the influence of climate change. Additionally, for coastal cities there is another major increase of flood risk, due to sea level rise. Even though the full extent of sea level rise is not clear yet, some cities are already being affected by the combination of sea level rise and subsidence.

Creating flood reservoirs and rivers underground, such as flood tunnels, reservoirs and shafts, has been a mitigation measure to minimise or even stop the damages brought by those events. On the other hand, tunnels also have their limitations, as they are under threat of flooding when sea level rises, or when a cloudburst event occurs. Therefore, society needs to look further into mitigation measures, as well as adapting development schemes, considering the possibility these natural climate events become even more frequent due to climate change. Some examples are mentioned here to show how underground construction can improve urban drainage and decrease damages to urban areas. Also, further considerations are made specifically related to the impact of sea level rise on the underground.

In Buenos Aires, the Maldonado tunnel project, finalised in 2013, has doubled the capacity of water drainage flow in the city. According to Vardé & Guidobono (2011), more than 35 flooding events have occurred in this area since 1985, leading to the death of 25 citizens and millions in damages. They mention as an example an event in 2001, where 140 mm of rainwater poured in 3 hours. The Maldonado project started construction in 2008 and consists of two 6.9 diameter tunnels, with 4.5 and 10 km extension, constructed together with 3 intake and 1 outlet shafts, plus a 100 m channel. All the water coming from the Maldonado Creek can now be easily directed through this system, going straight to the Rio de la Plata.

Another case study, highlighted below, is the SMART tunnel in Kuala Lumpur. This is designed in such a way that it can change its operational mode from a road traffic tunnel to a flood relief tunnel when needed. This allowed for the economic construction of a flood reduction measure and a way to alleviate traffic pressures at the same time. This shows there are many ways of improving resilience in underground space, and many existing and innovative engineering solutions can be found.

Further, we should also consider the need to adapt to sea level rise, as already many cities are suffering its earlier effects, such as Jakarta, Indonesia or Venice, Italy. Apart from an increase of mean sea levels by an estimated two to three feet at the end of the century, this will also lead to increased heights of storm surge levels. Storm surges pose a more acute and prominent risk to many cities. And when the flood risk of underground facilities is not managed with defences separate from the city's or country's main flood defences, even a partial flooding of an urban area may lead to a complete flooding of the underground. According to Jacob (ref. Kensinger, 2021), the metro system in Manhattan, New York, would take only 40 minutes to be completely flooded. Considering that 136 coastal cities with more than 1 million inhabitants exist, and it is estimated that here at least 10% of the population (around 40 million people) are living in the coastal floodplains, there is also an increasing amount of infrastructure constructed that is exposed to high probability of flooding. In particular, there are many existing underground spaces in coastal cities that are over a century old that are highly vulnerable to sea level rise and need immediate protection, as they often have not been designed with any protection from flooding taken into account. In general, there is an increased need for solutions, where underground spaces are intrinsically integrated into the environment, but at the same time they need to be protected from flood events and storm surges.

In the case of rail or metro systems there is an inherent resilience in dealing with earthquakes, but with floods or tsunamis the station entrances and tunnel portals make these systems extremely vulnerable. Therefore, for example, the NoordZuidlijn in the Netherlands is built with penstocks on each end of the submerged tunnel sections. This could be a great solution for other metro systems in low-lying areas where the vulnerability is very apparent. As another example, in Bangkok the risk with regards to flooding is tackled by bringing the metro station entrances to a level two to three metres above the surrounding surface, to prevent easy inflow into the metro tunnels due to flooding.

Figure 25. Bangkok metro entrance (wikimedia, picture by Waerth (CC BY-SA 3.0)).

IMPACTS OF ONGOING URBANISATION

One of the main threats to (underground) urban infrastructure stems from water ingress and leakages (Bobylev, 2007). As a result, basically any gradual or sudden change to the long-term flow patterns of water, both surface water and groundwater, can be a threat to urban infrastructure. The vulnerability stemming from ongoing urbanisation, where that causes gradual changes in water flow patterns, needs to be acknowledged and understood.

Ongoing urbanisation is almost always accompanied by deforestation and hardening of ground surfaces, and with redirections and relocations of surface streams. Therefore, established long-term surface water patterns and their velocities keep changing, whilst low lying spaces within the urban area essentially become catchment areas, highly susceptible to flooding even due to the rain events of regular intensity. As such, the threats for any given urban area due to its ongoing urbanisation must be recognized and could be mitigated via rigorous stormwater management systems. For example, after almost 400 homes flooded in the City of Mississauga (part of the Greater Toronto metropolitan area) after heavy rainfall in 2009, the city's stormwater mitigation program[2] was revisited. The number of revisions has resulted in many improvements including some innovative solutions including underground stormwater storage facilities uniquely located within the open spaces (public parks) owned by the city. The 2 ha Eastgate park facility[3] with 13.5 ML (megaliters) storage capacity arranged via a system of 1.5 m diameter pipes about 2 m deep was installed in 2018. Similarly, the 1.5 ha Sandalwood park's facility of 15 ML capacity (photo below) was constructed in 2021 with the Mississauga Valley and McKenzie parks currently underway.

Slow ongoing urbanisation can lead to issues as well. In many rural and semi-rural areas, water and wastewater services are either managed individually by each household or by small-scale communal providers. With easy access to groundwater, it is often arranged via groundwater supply wells and septic beds for wastewater (sewage) disposal. Over the years of water extraction and wastewater infiltration, local groundwater (or surface water) quality and quantity decline, forcing rural communities to seek more expensive water and wastewater alternatives. In many cases, these alternatives are ensured via more centralised water withdrawal facilities, always associated with some changes to the established groundwater/surface water conditions, triggering groundwater recovery in some locations and potential declines in others. Groundwater recovery and redistribution are extremely slow processes and as such, it is hard to account for as part of strategic resilience mitigations. An example derives from the Municipality of York Region[4] growth. Mainly rural and semi-rural before 1971 and fully relying on groundwater as a water supply, it has grown to about 1.8 million residents.

With the development boom in Canada around the 1990s, this metropolis tripled its population to 0.5 million in 1991 requiring more centralised water and wastewater management. The switch to Lake Ontario as a water supply has allowed all southern supply wells (communal and individual) to be abandoned. This change has caused groundwater recovery that, unfortunately, was not accounted as part of the initial water switch decision. Thus, unforeseen water imbalance issues were mitigated case-by-case as they occurred.

The creation of an artificial Spring Creek that draws its water from a semi-capped former communal well in Unionville was a solution to ease local basements' flooding. Intersections with railways, where regional roads were deepened to create underpasses were equipped with dewatering systems for constant groundwater removal to keep the roads dry (e.g. the intersection of the Major Mackenzie road with the rail bridge near Newkirk road is constantly pumped with about 8 l/s extracted for close to 30 years). Several stormwater ponds (e.g. Henderson St. stormwater pond) initially designed as "dry" became "wet" requiring stormwater system redesigns to avoid downstream floods even during normal rain events. As per above, the impacts to urban resilience due to any change on the long-term groundwater and surface water balances are time-delayed and difficult to track. However, they must be recognized and properly accounted for in maintaining the urban area's resilience.

Figure 26: Stormwater chambers are installed under the City of Mississauga's Sandalwood Park.[5]

[2] *https://www.mississauga.ca/services-and-programs/home-and-yard/stormwater/stormwater-system/*
[3] *https://www.accessenvironment.ene.gov.on.ca/instruments/9678-AHFK6H-14.pdf*
[4] *https://www.york.ca/york-region/york-region-turns-50*
[5] *https://canada.constructconnect.com/dcn/news/infrastructure/2021/04/mississauga-storm-management-facility-rooted-underground-in-sandalwood-park ????*

Case Example: Flood Storage and Parking – Museumpark, Rotterdam

This underground flood basin is in Rotterdam, the Netherlands. It is in a country that is highly prone to flooding if not for the extensive system of dikes and canals to keep the country safe – as a third of the country is situated well below the sea level. Since the city of Rotterdam is densely populated, especially the city centre, there is a land scarcity to construct extra canals to deal with heavy rainfalls. In many locations it is not even possible to construct separated sewers for rainwater and wastewater. The underground flood storage (OWB) is one of the measures Rotterdam has taken to limit flooding in the centre of Rotterdam.

The facility consists of an underground parking garage, containing 1,150 parking spaces over three underground layers. For the pedestrians there is a clear route with light wells on both sides of the underground space to allow for natural daylight. The space below the entrance ramps to the parking serves as flood storage. When it rains heavily, this area can fill up completely within 30 minutes, after which half of the sewers in the city centre will empty into the OWB. This causes the sewer system to have enough capacity to process the rainwater. Once the sewer system is empty again, the water in the OWB gets pumped back into the sewer with two pumps and thus flows through the sewer to the wastewater treatment. The water storage can contain up to 10 million litres of water and is 60 metres long, 30 metres wide and 7.5 to 8 metres high.

The area on top of the facility, also known as the water square because of its shape, is an open grass field bordered by trees, and contains a sports field and a playfield on a small artificial hill. The sports field is lowered one metre into the ground and is surrounded by steps that function as a grandstand for spectators. During prolonged rainfalls the water square is closed and will gradually fill up until the sports fields are flooded and the square becomes an additional water storage basin. Without the OWB, an average of ten overflow events per year would occur, meaning that rainwater mixed with wastewater flows into the canals. This has been reduced to once every two years with the OWB and causes the water quality in the canals to improve significantly.

Combining the function of a parking garage with a water storage facility, however remaining separate at all times, leads to an optimal use of the scarce space in the heart of the city.

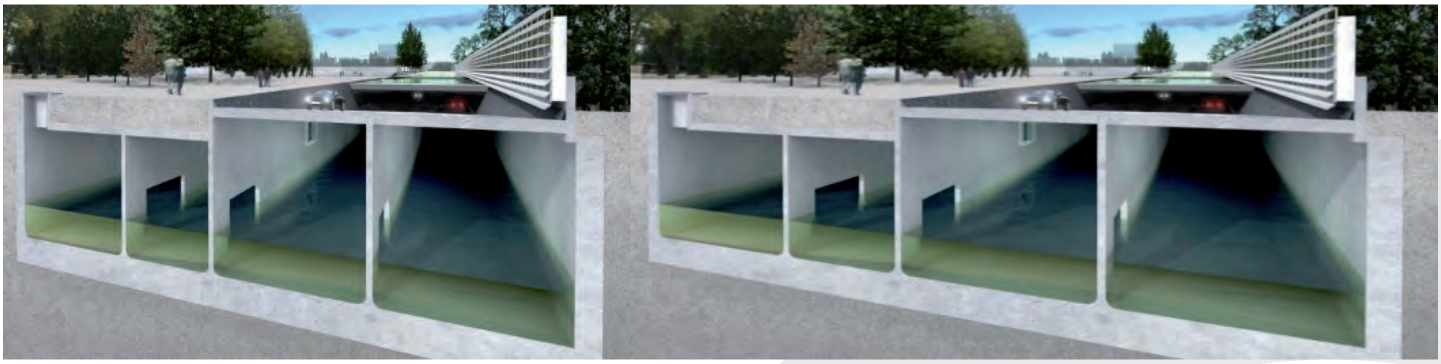

Figure 27: Museumpark underground water storage and parking.

Case Example: Deep Tunnel Sewerage System, Singapore

Because the aboveground space in Singapore is becoming increasingly scarce, more facilities have to go underground. Also, there is a need for clean drinking water for the island, with little to no waste. The Deep Tunnel Sewerage System is a profitable and sustainable solution to allow for the collection, treatment, recovery and removal of wastewater from homes, businesses and industrial areas to ensure a sufficient supply of safe and clean drinking water. As part of the project also the sewage treatment plant has been located underground.

The project consists of two phases, phase one was completed in 2008 whereas phase two is expected to be finished by 2022. The project has a lifetime of 100 years wherein no maintenance is needed and has therefore obtained many awards and recognitions such as the title "Water project of the year 2009". The main principle is using gravity fed deep tunnel sewers, hence the name, to transfer used water to water recovery plants across the shore areas. The water is then decontaminated and cleaned into NEWater or is being transferred back into the sea through drains. NEWater is a developed concept of clean high quality reclaimed drinking water.

A system of sewers leads to two 50m underground tunnels, once phase two is completed, with a diameter of 6.5m and a length of 80km that cross Singapore with three key water retrieval plants in the northern and western ends of Singapore. Once phase two is completed, the current water recovery plants and pumping stations can be removed to clear the space for future projects.

Basically, this project improves the water quality of residents in a sustainable way.

DTSS ensures that every drop of water is reused, because the wastewater is collected in its entirety, treated and purified into NEWater. By doing so, the total water recycling rate is increased from 30 to 55 percent of the total water demand. By increasing the dependability of the water system, environmental protection is obtained by minimising the cross-contamination between the water system and water abstraction.

Figure 28: Deep Tunnel Sewerage System [https://www.pub.gov.sg/dtss/about].

Case Example: POP-UP, Sponge Parking in Copenhagen

This project was initiated by Third Nature, COWI and Rambøll in 2016. The main drive is to restrict the visible parking spaces on the streets, while thinking about securing cities against heavy rainfall and at the same time providing more urban spaces. This planned project should be a solution to all these issues and should provide climate adaptation accordingly.

Instead of providing three separate solutions to the motivations mentioned above, the scope of this concept is to create a multifunctional parking facility that acts as the figure below shows. The water reservoir starts out empty and the parking structure functions as a normal underground facility. In case of heavy rain, the rainwater will slowly fill the water reservoir, making the parking facility move up. Access to both the parking facility and the urban space is possible through an opening in the structure wall, where a spiral ramp will lead the pedestrians up to the urban space and the cars up and down in the structure. Once the heavy rain turns into a cloudburst, the parking facility will shoot up in the landscape, the access to the urban space as well as the parking facility remains the same regardless of the water level in the reservoir. This is where this concept exceeds structures like the multi-functional parking garage in Rotterdam that was the first case study discussed in this paper. The urban space and the parking facility remain completely accessible without any restrictions. In case of a 500-year event, the reservoir is filled to maximum capacity and the parking facility is raised to the highest level, whereas the two lowest parking levels remain under terrain to maintain resistance and stability plans and ensure that the structure remains in place and does not drift away.

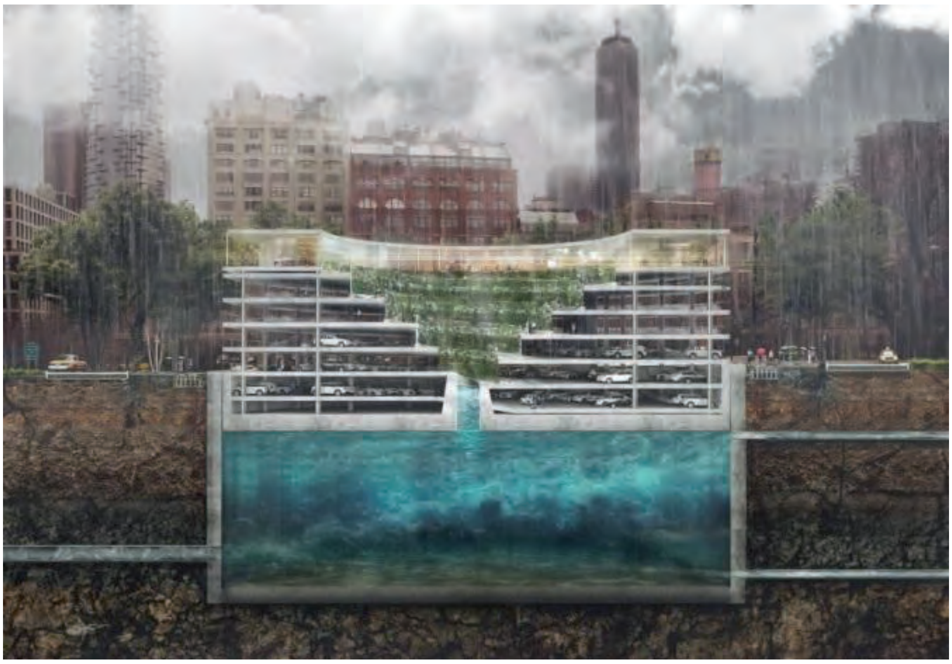

Figure 29: Impression of POP-UP concept [https://www.tredjenatur.dk/en/portfolio/pop-up/].

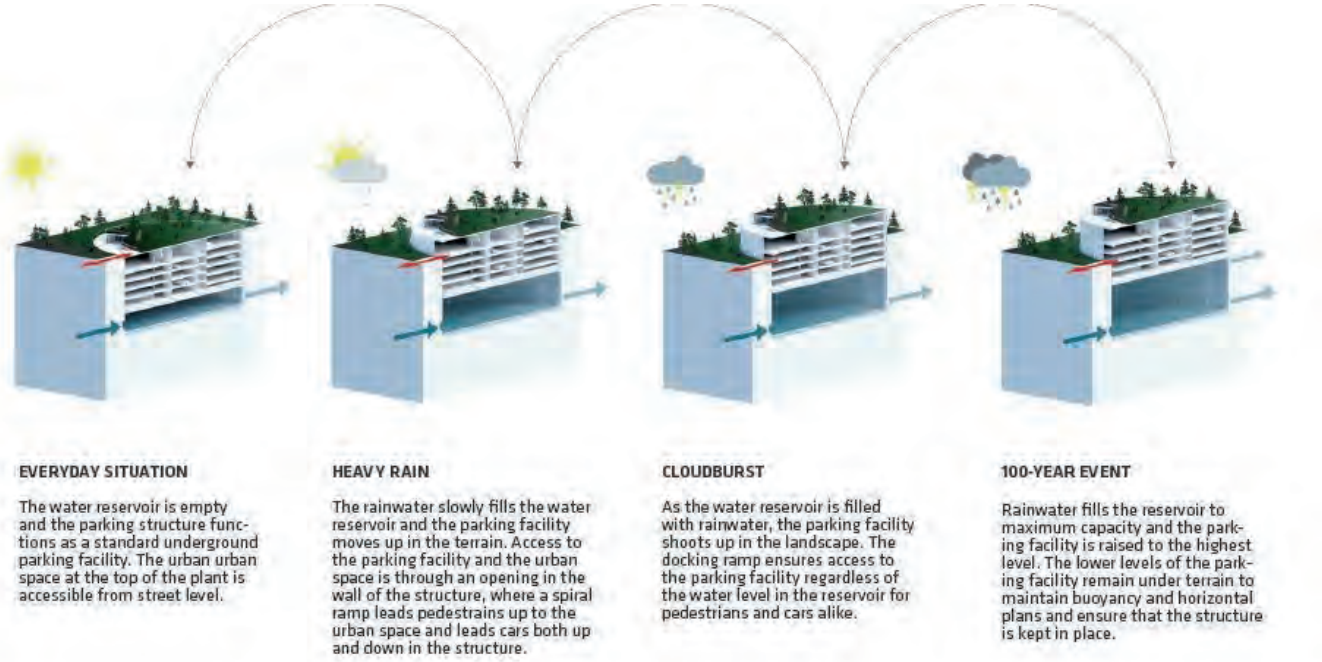

Figure 30: POP-UP concept explained [https://www.tredjenatur.dk/en/portfolio/pop-up/].

Case Example: SMART Tunnel, Kuala Lumpur

Kuala Lumpur is the capital of Malaysia. It is a large densely populated urban city that has a high risk of extreme flooding. The city's authorities have been developing numerous plans and projects to make the city more resilient to flooding. This project had two main drives, one was to solve the recurrent flash floods in the city centre of Kuala Lumpur and the second was to reduce the traffic bottleneck located at the Kuala Lumpur Southern Gateway.

The Storm water Management and Road Tunnel (SMART) qualifies as the largest tunnel in Malaysia in length and second largest in Asia. It consists of a storm water bypass tunnel that is 9.7 km long and a double-deck road tunnel of 4 km within the former. The SMART project uses a twin box culvert and a storage reservoir to take care of flood water. SMART works in different modes. During normal conditions, when there is only little rain and no storm, the first mode applies where the road tunnel can be fully utilised by vehicles. The second mode is activated when there is a modest storm going on, leading the floodwater into the bypass tunnel in the lower conduit of the road tunnel, leaving only the upper conduit open for vehicles. In case of a heavy storm, the SMART system activates the third mode, leading to a full closure of the motorway tunnel for motorists. The vehicles will have time to leave the premises after which the automated gates open up allowing floodwater to enter. The fourth mode is applied when the heavy storm continues up to two hours, starting from the moment the third mode is activated. The tunnel will then be completely evacuated of traffic and will remain closed for four days. The tunnel is then only utilised for flood passage.

The entire tunnel has escape shafts, which contribute to the ventilation and air quality for motor vehicles, after each kilometre. In case of flooding, these shafts are being protected by fresh air injectors and exhausts. The fans are found outside the tunnel and create a flow between the different shafts. This is especially helpful in case of fire, to get rid of smoke sufficiently.

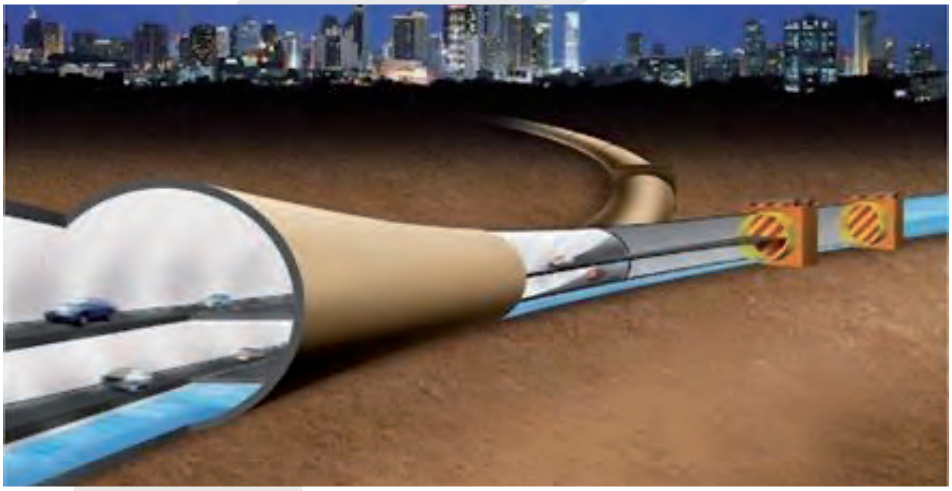

Figure 31: SMART Tunnel impression [https://www.roadtraffic-technology.com/projects/smart/].

Case Example: Metropolitan Area Underground Discharge Channel, Tokyo

Tokyo has seen a rapid urbanisation that mainly consists of concrete surfaces and lacks soil and vegetation.it makes a terrible flood sponge, and with global warming, increased urbanisation and increasing extremes in weather conditions, flood management is a necessity. Tokyo's crowded suburbs are surrounded by rivers and canals, which have been quite a threat to this large city due to their regular month-long monsoon flooding and typhoons. The basins of the Nakagawa and Ayase Rivers are surrounded by large rivers such as the Tone, Edogawa, and Arakawa. The land in this area is shaped like a bowl or dish, resulting in the accumulation of water. Also, the slopes of the rivers aren't steep, which means they don't easily flow into the sea, thus with every heavy rainfall the water level barely drops.

Since Tokyo is known for its huge density, there was no other way than to find a solution underground. In cities as densely populated and urbanised as Tokyo, flood tunnels are often used to improve the flood water management system. And so, the G-Cans project or officially Metropolitan Area Outer Underground Discharge Channel was brought to life.

The MAUDC is a tunnel or underground river that leads flood water from the Nakagawa River, the Kuramatsu River and others to the Edogawa River. The overall length of the tunnel is about 6.3 km long, with a diameter of 10 m running 50 m underground below Route 16. This is even deeper underground than the subway, because of its potential inference with future area usage and also the fear of the land being divided. Going this far underground also insured the project to be completed quicker and easier.

The concept was to connect existing rivers and waterways to overflow pipes and drains, which allows the above ground drainage system in central Tokyo to continue in operation with an expanded underground capacity. Essentially the MAUDC was built to reduce the effect of flood water to the surrounding areas by a complex operational system containing different facilities.

The graph below illustrates the purpose of the G-Cans. In only 17 years' time, it has already been operated more than 120 times.

After completion of the MAUDC, a flood analysis focused on the period after completion of MAUDC was performed and this simulation shows that the effective reduction of flood damage is very huge. The reduction of flood damage amounts to almost 2.7 billion USD (Exchange rate 1 USD=100 Yen) within 30 years and this well exceeds the construction cost. In addition, the impact of the MAUDC includes not only an improvement in the safety and resilience of the area, and leads to a reduction of flood damage, but also serves to improve land value at the surface. In Kasukabe city, where the MAUDC is located, it improved the resilience of the city against flooding, which improved the attractiveness for enterprises and 25 new companies invested in this area. Also, the MAUDC is open to the public and has become one of the famous infrastructure tourism spots, thus it plays an important role for regional activation (RICE, 2020).

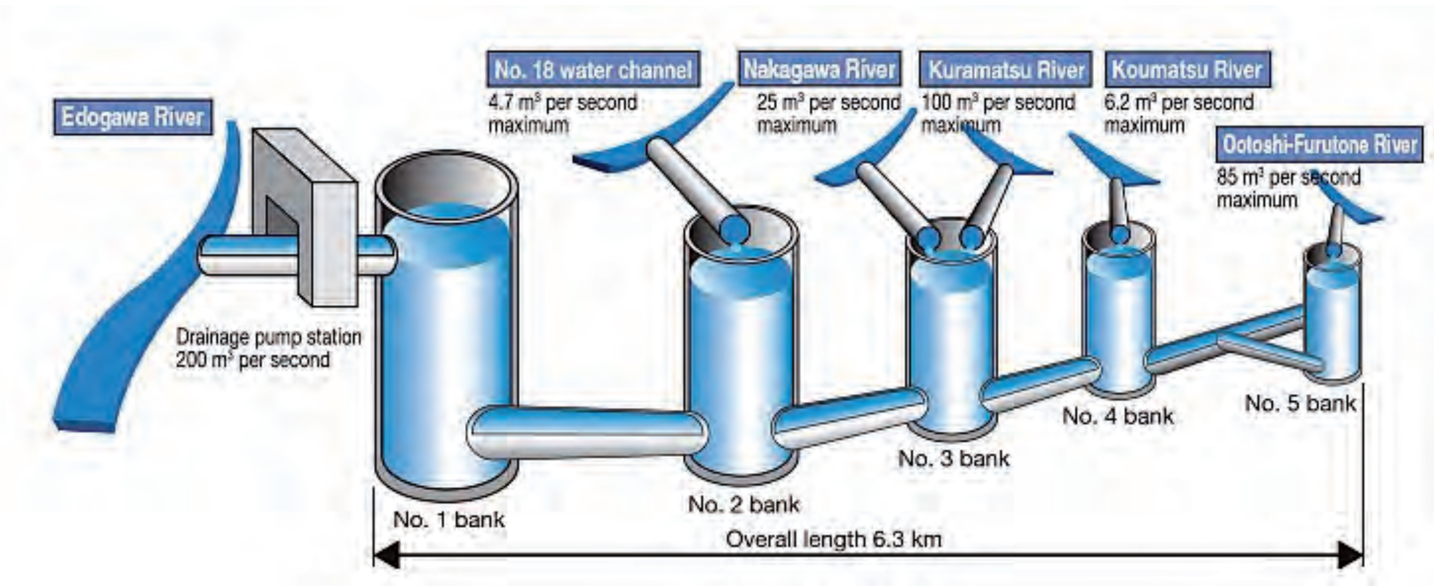

Figure 32: Conceptual diagram MAUDC.

Case Example: Storm Water Collector Along Vistula River in Warsaw, Poland

A 9.5 km long and 3.2m diameter Vistula collector is being built in Warsaw. The collector will be located at a depth of 6 to 15 m along the streets of Wybrzeże Kościuszkowskie, Wybrzeże Gdańskie and Wybrzeże Gdyńskie. The collector is to limit the negative effects of climate change by reducing the risk of flooding during heavy rainfall, increasing the safety of sewage treatment plants by ensuring their even distribution, sealing the sewage collection system and increasing the retention capacity of the sewage system. It is an element of the project to extend the retention capacity of the capital's combined sewage system. The collector's task is to transport and retain sewage and rainwater taken over from the existing storm collectors on the left bank of Warsaw. Thanks to this and other investments carried out as part of the construction of the Central Sewerage Network Management System, the risk of storm sewage discharge to the Vistula River, as well as local flooding in Warsaw, will be reduced. Thanks to the obtained capacity of the collector, corresponding to more than 13 Olympic swimming pools (approx. 50000 cubic metres), a more uniform transport of sewage to the treatment plant will be ensured, which will also significantly increase the safety and efficiency of its operation.

The Vistula collector is constructed using the microtunnelling method. Behind the cutterhead, successive sections of the new pipeline are pushed into the ground. It will be the longest microtunnel of this diameter (up to 3.2 m) made using this method in Poland. The tunnelling itself should be completed by the end of 2022. The tunnel boring, as well as other works related to the construction of the longest section of the collector, are carried out 24 hours a day, 7 days a week. The technology used for laying the pipeline is the safest trenchless method both for the environment and for the workers themselves. It also allows to minimise the number of works carried out on the surface, and thus reduce communication difficulties for the citizens of Warsaw. The laying of the pipeline is remotely controlled, which, while maintaining full precision, allows to limit the number of people working underground.

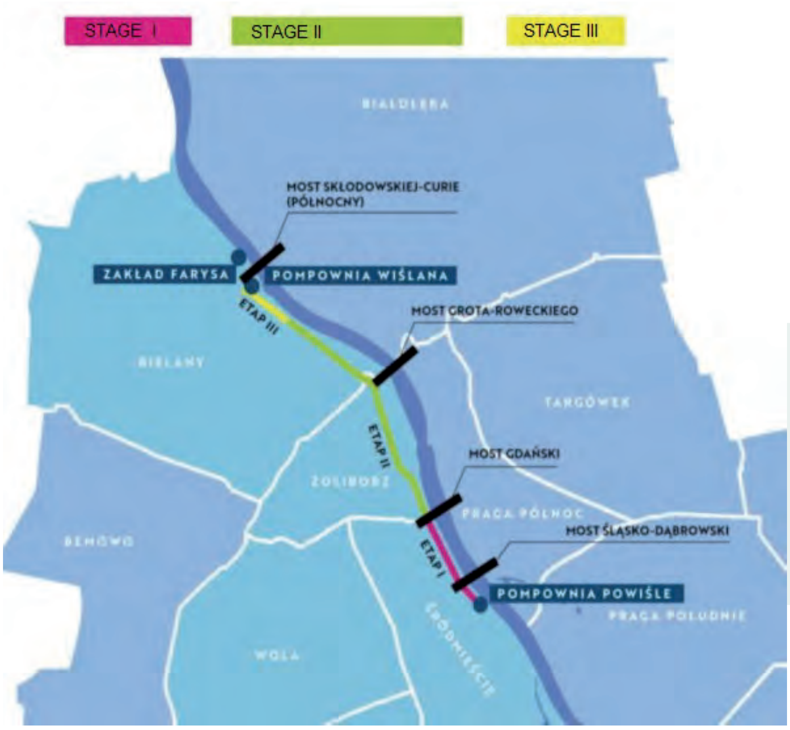

Figure 33: Map of Warsaw showing the Vistula collector.

Figure 34: Construction site of Vistula collector.

Figure 35: Construction site of Vistula collector

Case Example: Massive storm water reservoirs, Madrid

The main function of underground storm water storage reservoirs is to temporarily store the water collected by the sewerage network in order to regulate its passage to the treatment plants, where it is cleaned and then discharged into the rivers in the best condition. Two of the largest underground water reservoirs in the world, Arroyofresno and Butarque, are located in Madrid.

In episodes of heavy rainfall, the peak flow collected exceeds the treatment capacity of the treatment plants or the transport capacity of the sewage network. This is when the storm water reservoirs come into operation. These excess flows are diverted to the reservoirs, where they are temporarily stored until the storm passes and can be conveyed and treated. These storm reservoirs are huge underground infrastructures built to store the first rainwater, which is also the most polluting water - even more polluting than sewage - because it carries all the dirt accumulated in the streets and on the asphalt. In this way, the reservoirs prevent the treatment plants from exceeding their maximum flow and having to discharge the excess, untreated, into the receiving watercourses.
On days with heavy rainfall, the water seeps through the sewers, but due to its enormous volume, it cannot be treated immediately. For this reason, this water waits in the storm reservoir until it stops raining. It is then gradually conveyed to the sewage treatment plants. This not only prevents pollution of the rivers, but also prevents possible flooding and environmental damage. The water is directed to the water reservoirs through huge collectors that can be up to seven metres in diameter, almost like underground tunnels. In addition, before reaching the reservoirs, the water passes through a series of filters to retain solid pollutants such as plastic bottles and other objects. Many of the solid objects that arrive with the rainwater accumulate at the bottom of the tank. They are subsequently removed by means of different cleaning systems. In this way, they fulfil a double function: they prevent flooding and preserve the quality of the rivers, retaining the first rainwater, which, by dragging metals from the atmosphere, solid waste from urban roads, oils from vehicle engines, etc., can be even more polluting than wastewater in dry weather.

The Community of Madrid has a network of 65 storm reservoirs, the largest in the world, which, like the entire sewerage network, is managed by the public company Canal de Isabel II. 36 of these ponds are located in the city of Madrid and can store more than 1.4 cubic hectometres of water, equivalent to almost 400 Olympic swimming pools, thus making Madrid a city with one of the largest networks of storm reservoirs in the world. Among them, the Butarque and Arroyofresno storm reservoirs are among the largest in the world, with a storage capacity of approximately 400,000 m3 each.

The Arroyofresno storm pond is located within the grounds of the Club de Campo Villa de Madrid under the golf driving range in the vicinity of the Manzanares River. It is 290 metres long, 140 metres wide, and has a usable surface area of 35,000 m2 equivalent to the surface area of five football pitches, reaching a depth of 25 metres greater than a six-storey building. It could hold 4 stadiums like the Santiago Bernabéu filled with water. Thanks to storm reservoirs such as these, the first rainwater is retained in the subsoil until the treatment plants have the capacity to treat it. Once treated, the water can be discharged back into the rivers in the best possible conditions without posing an ecological threat to their natural functioning.

Figure 36: 400.000m^3 Storm water reservoir in Madrid, Spain.

Case Example: New York City Area and Tunnel Resiliency

The New York area has experienced two catastrophic weather events in the last 20 years, Superstorm Sandy (Sandy) in 2012 and a few extreme rain events including Ida in 2021. Each of these events exposed vulnerabilities to the city's underground network of tunnels. Sandy exposed vulnerabilities related to storm surge while the storm Ida exposed vulnerabilities related to extreme street flooding. Since these events, the various transportation agencies in the New York City (NYC) area have undertaken extensive modifications to their systems to prevent similar occurrences.

During Sandy, many of the tunnels that cross beneath the rivers bounding Manhattan Island were flooded because their portals were below the storm surge level. Agencies have installed flood gates, rigid and flexible, to prevent not only current storm surge levels, but also storm surge levels including future sea level rise. Ida presented another challenge for underground spaces; the existing openings at street level, normally used for passive ventilation or station access, were inundated by street flooding.

This prompted NYC to re-evaluate their street drainage modelling to take into consideration more extreme rainfall events that would likely become more severe as the climate changes become more pronounced and start manifesting themselves more frequently. The mitigation measures included upsizing and supplementing of the existing drainage lines to handle anticipated increased street flow. Also, damages to electrical equipment and electronic systems are very impactful. Water, especially sea water, causes electrical systems to short and the residual precipitant, such as salt, is extremely difficult, if not impossible, to remove.

Specific examples of these various protective measures that have been taken in the New York area include the Port Authority Trans Hudson (PATH) subway system providing subway services between the States of New Jersey and New York. The PATH tunnels are part of a legacy system dating back to the late 1800's.

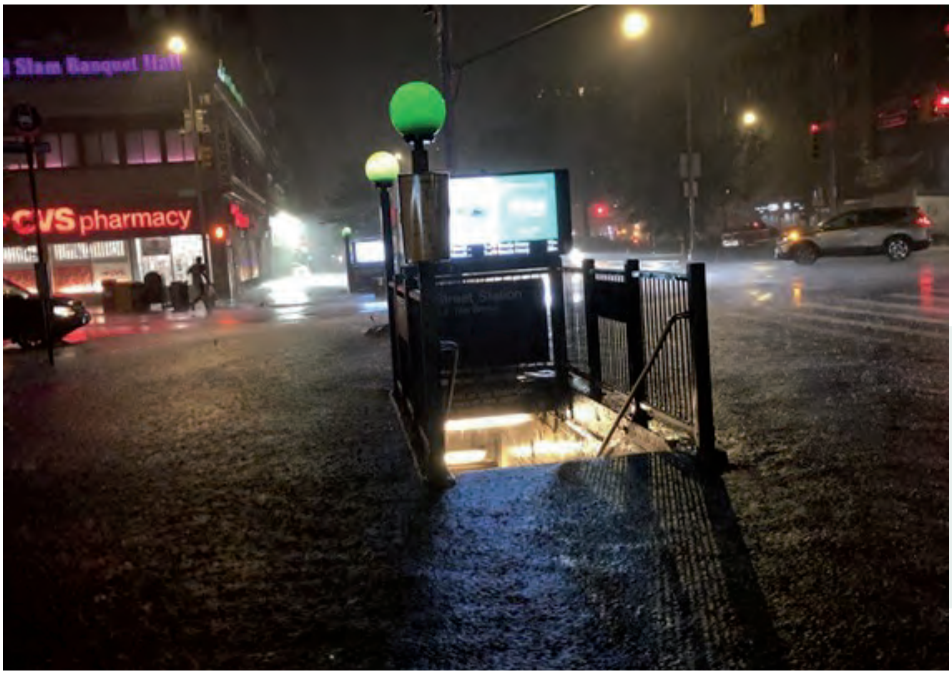

Figure 37: Flooded streets and metro entrances during Ida.

Figure 38: Metro entrance with flood protection measures.

The system has entrances immediately adjacent to the Hudson River and thus vulnerable to both storm surge and sea level rise. The vulnerable entrances have fixed elevations and cannot be practically raised above flood levels. As a result, the entrances are being modified to sustain the flood loads with a combination of flood rated glass walls and rapidly deployable, flexible membrane barriers at entrances. This combination of systems preserves the aesthetics of the entrances and allows the subway system to operate until it is necessary to deploy the flexible barriers.

Similar to PATH, the NYTA is employing flexible membrane barriers to seal station entrances, and is using simple, easily deployable covers for the multitude of ventilation grills they have at street level.

During Sandy, four of Amtrak's six under river tunnels were inundated. The inundation occurred at their portals on the Hudson and East Rivers. These vulnerable areas have since been protected with flood walls. Other vulnerable structures, such as ventilation and access structures were retrofitted with flood proof doors and easily deployable stop logs systems.

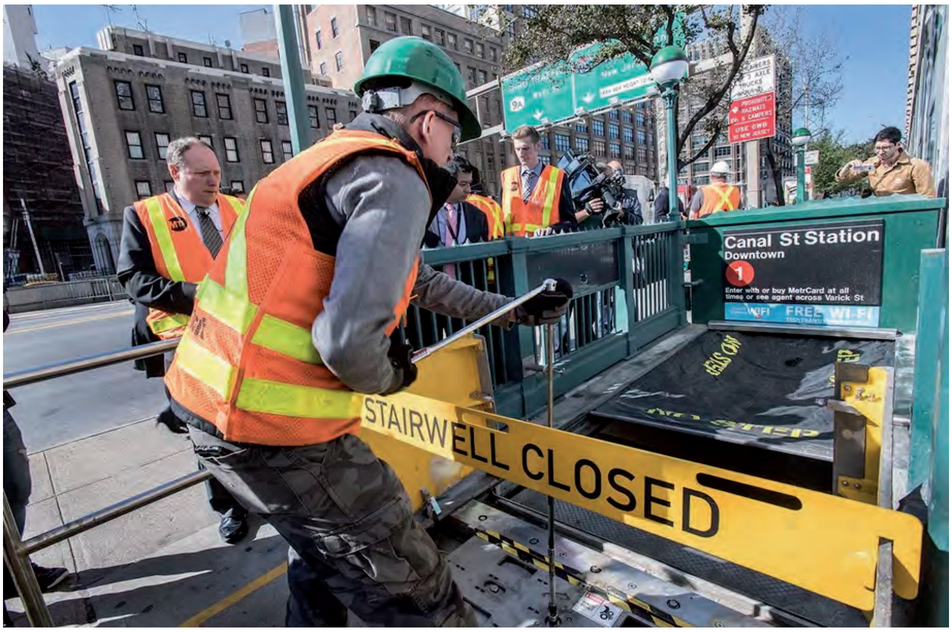

Figure 39: Aftermath of flooding event.

5 >> Sustainable Urban Infrastructure

Using tunnels for urban infrastructure frees up surface space for other uses and reduces the environmental impacts of noise and vibrations. It also allows to improve urban mobility whilst protecting existing (heritage) surface constructions. Modern large-diameter tunnels can fit multi-lane motorways in a single tunnel tube with a limited required right-of-way, which also reduces the impact and nuisance during construction. Also, the environmental footprint of such large construction projects can be reduced by careful management of the excavated soil and recycling of construction waste material.

As cities are becoming very dense, the use of urban surface space is reaching a premium. Efficient infrastructure and transportation solutions are becoming an absolute necessity, and sustainable, resilient, and planned use of both surface and underground spaces is of utmost importance. Cities are developing infrastructure and mobility solutions to keep up with increased population and economic growth as the issues of liveability, quality of life, and effectiveness of infrastructure greatly affect urban economies.

The use of underground space has proven beneficial to solving urban mobility needs. Addressing another challenge while constructing subsurface transportation facilities — disruption of communities, businesses, traffic, utilities, and services – has become an increased focus of modern cities that have lived through consequences of urban construction impacts.

Using tunnels for transportation, with minimum disturbance to urban life, promotes protecting the existing communities and its cultural heritage including environmentally sensitive areas, parks, and structures of historical significance. For the most part, tunnel construction takes place out of sight of the public and minimises surface disruptions within densely built urban environments. Construction-related impacts, including vibration, noise, dust, as well as visual (aesthetic) impacts are lower when constructing bored tunnels than those for similar at-grade transportation solutions. In addition, tunnels usually raise property values along a corridor. Due to their inherent resiliency to inclement weather, tunnels have longer service life due to lower exposure to de-icing chemicals and freeze-thaw cycles; their resilience to floods caused by climate changes could be addressed by timely planning and design. Also, tunnels conform to imposed ground deformation limits and are safer in seismically active areas. As cities and their conscientious citizens become ever more cognizant of all these benefits, they increasingly embrace underground transportation solutions.

Developing an overall and infrastructure-specific master plan is key to achieve more sustainable urban development. Such a plan could include initiatives to combine multiple services as part of new infrastructure networks. For example, various cables, water pipes and air conduits can be combined within the transit and transport tunnels. The immediate benefit of such multi-purpose infrastructure tunnels can be the decrease of construction costs and thus the costs of the end-products (services and goods) to the public. As identified by (Kondrachova, 2021), the lowest cost (about $1000 CAD) for each excavated cubic metre of soil among 73 infrastructure projects in the Toronto area (1990-2020) is achieved on transit tunnels of about 6 m internal diameter constructed by the earth pressurised mechanised tunnelling method (earth-pressure balance boring machines, EPB). The high cost-efficiency of this construction method for construction of large diameter tunnels and the possibility to use these tunnels as combined services/goods tunnels opens up new possibilities to develop and optimise urban infrastructure networks.

Another step toward more sustainable urban development can be achieved via more effective construction waste recycling programs. As recommended by (Working Group 14 and 15 ITA, 2019), tunnel spoil can be recycled and used for temporary construction purposes, for dams, embankments, landfills, erosion protections, etc. However, among the challenges for successful recycling are existing legal norms defining tunnel spoils as waste, which eliminates their re-use in principle. These findings extend to all types of excavated materials and wastes produced by any construction process, not only by tunnelling, and still require industry attention for promotion of more coordinated recycling that can be achieved. This can be imperative to reduce each project's environmental footprint and construction cost. The environmental norms limiting the re-use of excavated soils/spoils should be revisited to encourage some incentive measures and achieve effective recycling of all types of construction wastes. This will assure an overall reduction in the use of the remaining natural resources and energy, and achieve better sustainability and resilience.

Large-bore tunnels further enhance the benefits of underground infrastructure by significantly reducing surface disruption during construction of cut-and-cover work in public right of way, generally associated with constructing rail or transit stations within dense urban zones. Figure 40 demonstrates the growth of large-tunnel boring machine diameter over time. To date, there are at least 45 projects around the world constructed using TBMs larger than 14 metres (46 feet) in diameter.

Advancements in large-diameter TBM technology have enabled new types of projects that would have previously been considered infeasible. For example, the Grauholz Tunnel, constructed in the late 1980s in Switzerland, was the first tunnel with a diameter larger than 9 metres (30 feet) that enabled a dual-track high-speed rail line within a single-bore tunnel. In the mid-1990s, the Trans Tokyo Bay Tunnels (14.1 metres diameter) were the first to accommodate a two-lane highway within each bore. In the late 2000s, in Madrid (Spain), the tunnel of 15.2 meters diameter was constructed to accommodate three lanes of the M-30 highway housed within each of the two bores.

Figure 40: Growth of TBM diameter over time.

In mid-2010, the City of Seattle started benefiting from a large TBM called 'Bertha' that left behind a four-lane underground highway. The record 17.5m (57.5-ft) diameter SR 99 tunnel was built to replace the ageing and seismically vulnerable double-deck Alaskan Way Viaduct (Figure 41) without disrupting the heavy traffic flow or the adjacent congested business district during construction. After its completion, and the demolition of the existing above-grade state highway, the tunnel reconnected the downtown community to the Seattle waterfront.

The traditional configuration for urban subway projects traditionally relies on two, single-track tunnels for bidirectional transit. This arrangement frequently requires cut-and-cover construction for the stations and crossovers, which could be highly disruptive to the community and may bring the benefits of underground mass transit into question. The availability of large-diameter TBM tunnelling technologies now allows station platforms and crossovers to be housed within a single bore, thereby eliminating cut-and-cover excavations and reducing surface impacts. In addition to civil, architectural and structural requirements, single-bore tunnels also accommodate fire and life safety requirements, such as emergency ventilation and egress, as well as wayside track equipment, including practically all rail and facility systems required by modern transit facilities.

The single-bore arrangement for mass transit has been successfully implemented in Spain for the Barcelona Metro Line 9 and is currently being planned by other transit agencies. In the U.S.A., the Santa Clara Valley Transportation Authority (VTA) is considering a single-bore tunnel with in-tunnel station platforms as part of the Bay Area Rapid Transit Silicon Valley Phase II project (VTA's BSV Phase II) in San Jose, California. As shown in Figure 42, station platforms are stacked inside the 14.6 metres diameter tunnel. Station entrance shafts would be located off the public right-of-way to reduce surface disruption. Adits would be constructed using a sequential excavation method to provide passenger connections between the station entry and the train platforms. Additional adits would be used to create pathways for ventilation, emergency egress, and other systems.

Figure 41: City of Seattle's Alaskan Way Viaduct was replaced by large diameter bored tunnel (photo right: wikipedia.com).

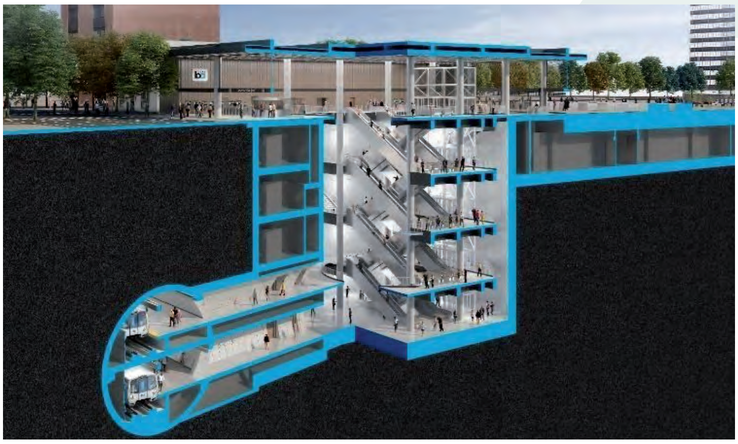

Figure 42: A single-bore subway station design being planned for the VTA's BSV Phase II project.

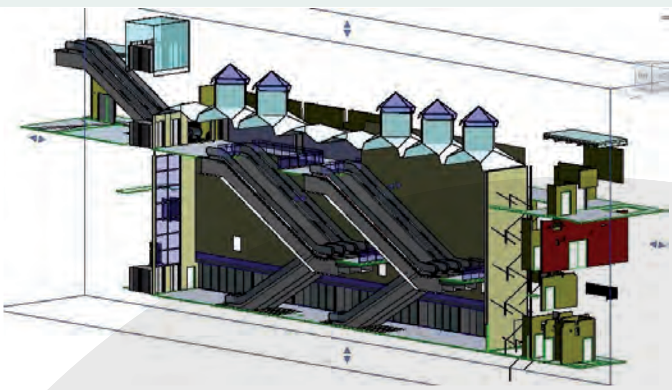

Figure 43: BIM for a underground transport system (Politecnico Milano, 2023).

Urban transit professionals in the tunnelling and civil engineering industries have risen to the challenge of solving urban mobility by developing and delivering large-bore transportation tunnels that minimise disruption to communities, businesses, and services both during construction and in service. While cities and communities have increasingly embraced large-bore solutions and benefited from the large-diameter TBM technologies, the trajectory of tunnel diameter growth has not plateaued yet. The technological boundary and innovation will continue to expand, equipping the engineering communities and transportation agencies with continually bigger and better tools to serve mobility needs, while preserving livability, quality of life, and effectiveness of infrastructure. In addition, it is likely that solving urban mobility by dissecting communities through implementation of surface solutions would be left in the past.

Apart from tunnelling itself, there are technological developments in other fields that help change the way we can identify, analyse, and provide solutions to urban problems, and how to make the best use of underground space. Especially new digital design tools represent a great opportunity and open up enormous possibilities for a new way of working. The use of Building Information Modelling (BIM) methodologies can enable better integration of information by incorporating collaborative and shared designs, construction, and data management. In this way, all relevant elements involved in the project can be combined in a digital model in which underground spaces are represented visually, holistically, including information (attributes and metadata) of their features so that they can be managed efficiently.

The usefulness of these new digital ways of managing existing and new urban infrastructures is especially interesting from the point of view of generating resilient underground infrastructures capable of facing the challenges to come, associated for example with population growth and concentrations in large cities, the responsible use of underground water as a scarce resource, or natural disasters associated with climate change or armed conflicts. Being able to know, update new uses or changing information, and maintain valuable digital information over time, means that this information can and should be known and shared by the different agents involved in decision making throughout the use and behaviour of the underground infrastructure, from the first planning phases, during construction, operation and maintenance, and until its life cycle is completed and its possible rehabilitation for reuse and adaptation to new uses is considered.

Likewise, the development of Big Data allows us to analyse and link huge amounts of information on which to develop increasingly complex models that simulate the evolution of various trends, such as climate, seismic events, flooding, geological, hydrogeological, geotechnical, topographical, and social facts, demography changes, or new urban developments, and study their impact by uses, consumption, and emissions, for instance. This also makes it possible to check their resistance to changes and their robustness and can therefore help to anticipate the prediction of critical situations.

Instrumentation and monitoring devices will be able to collect more and more information, in real time, on the behaviour of tunnels and their impacts (changes on the hydrogeological environment, or the carbon footprint and other emissions), and check or predict these impacts, as well as feed the measurements back into digital models. Virtual reality and augmented reality will enable the sharing of case studies whose experience can optimise resources and benefit decision-making to generate ever more resilient and sustainable underground spaces. All these potential capabilities will be extraordinarily useful for knowledge and decision-making by governments, management bodies and users for increasingly efficient construction and maintenance of resilient infrastructures, and indeed its growing application is already a reality today.

Case Example: Seattle Alaskan Highway Viaduct replacement

The cross section of the Washington State Department of Transportation's SR 99 bored tunnel in Seattle, as illustrated in Figure 44, was designed to improve driver's sight distance, tunnel safety, and traffic operations while optimising the tunnel diameter and space allocation within the bore. With a 16.1 meters internal diameter, the tunnel accommodates two 3.3 metres wide travel lanes and 2.5 metres (west) and 0.5 metres (east) shoulders in each direction, while allowing for 4.7 metres vertical clearance.

Figure 44: SR 99 bored tunnel cross section.

TBM Bertha bored beneath streets, utilities and more than 150 buildings of downtown Seattle. To minimise impacts, several measures were implemented to control the ground movements so that the existing overlying structures and facilities saw no damage due to tunnelling. The tunnel permanent structure (liner) provides for a resilient solution; it forms a permanent watertight ring structure, composed of reinforced concrete segments, that supports the roadways. It required a special seismic design to sustain minimal damage during moderate earthquakes and maintain the structural integrity should a rare earthquake occur.

The watertightness of the lining joints between the segments during seismic events was achieved with special gaskets; for the first time, cyclic testing of the tunnel lining gasket was developed to ensure the gasket material is resilient under repetitive cyclic loading and its watertightness never compromised. The tunnel seismic performance is additionally enhanced by allowing relative movements between the liner and interior structures. Resting on continuous corbels, interior frame systems of walls and slabs expand and contract longitudinally; being independent of the tunnel rings, they accommodate relative deformations between these structures and the rings themselves.

In addition, to overcome damaging effects of the operating environment, the concrete mix was designed to deliver dense and relatively impervious concrete. Rebar covers were determined through comprehensive concrete durability studies and models calibrated for 100-year design life to improve the tunnel resiliency. All these measures, enabled by outstanding advancements in tunnelling technology, had set a new bar for creative yet robust and durable solutions under densely populated cities. The tunnel incorporates an innovative fire life safety solution: during fire emergency, ventilation dampers at the incident location would open to extract smoke into the exhaust air plenum on the outer side of the roadway wall, which is connected to emergency fan plants at the north and south portals. Vehicles ahead of a fire incident would continue to travel and exit the tunnel. Motorists behind the incident would safely evacuate into the fire-rated and pressurised egress corridor located on the opposite side of the roadway wall. The space above each roadway is used for lighting, signs, fire suppression sprinklers, and other tunnel systems. The space below the lower roadway is used for utilities and sump pumps. The tunnel overall solution provided for one of the world's largest, most resilient and safe transportation solutions beneath Seattle's busy streets while eliminating the noisy surface structure and opening the Seattle waterfront to public and business to enjoy.

Case Example: Istanbul Strait Road Tube Crossing

The Istanbul Strait Road Tube Crossing, also called the Eurasia Tunnel (Figure 45) provides for a transportation connection between Asia and Europe and represents another innovative use of a large single-tube bored tunnel. The tunnel is designed to ease traffic congestion across the Bosphorus Strait for use by light vehicles (cars and minibuses). It improves connections to a wide network of highways, increases capacity across the Bosphorus by approximately 100,000 vehicles a day, and saves motorists up to 45 minutes of commuting time – all without disturbing the historically significant area within which it was built.

The 3.4 km long subsea bored tunnel, constructed using a slurry TBM of 13.7 m diameter (Figure 46), accommodates stacked roadways and houses two lanes on each level with a vertical clearance of 3 metres. The region's variable geology, hydrology and propensity for seismic activity, combined with high water pressure and the large diameter double-deck configuration, made the Eurasia Tunnel one of today's most challenging projects connecting the two continents. Both tunnel construction and permanent structure the TBM (Figure 46) left behind met stringent requirements in terms of watertightness, structures material durability and responsiveness to seismic events, as well as systems safety, and provided for a resilient and robust transportation solutions that responded to the needs of one of the most dense mega-cities.

Figure 45: The Eurasia Tunnel..

Figure 46: The Eurasia Tunnel TBM, designed for 13-bar hydrostatic pressure.

Case Example: Mumbai Metro Line 3 project

Mumbai, formerly known as Bombay, is the capital of Maharashtra state in India and the financial capital of the country. It is a major commercial centre and a principal port on the Arabian Sea. As per 2011 Mumbai was the most populous city in India with an estimated city population of 12.5 million and a population of over 23 million within the Mumbai Metropolitan Region.

Due to the high population density, narrow streets and high rainfall during monsoons, moving around in Mumbai is a very difficult task. According to the TomTom Traffic Index report 2019 Mumbai is the most congested city in the world. India-based think tank IDFC Institute revealed similar findings in that what should be an average 30-minute drive in Mumbai more than doubles to 66 minutes. Commuters in Mumbai waste 55 per cent of their time stuck in traffic, equating to roughly 11 days in traffic for the average person, assuming a 30-minute commute. It gets worse during the monsoon season when a 30-minute journey becomes 70 minutes.

Traffic congestion in central Mumbai is much above the average. The existing infrastructure of the local railways is very old and often floods when it rains. Hence, there was an immediate requirement to construct a faster, reliable and sustainable transport system. Mumbai Metro Line 3 was planned to ease the traffic movement in Mumbai. It is a 33.5-km long line which will connect Cuffe Parade business district in the extreme south of the city to SEEPZ in the north-central with 26 underground and one at-grade station (Figure 47). The cost of this corridor is estimated at ₹30,000 crore (US$3.9 billion). Line 3 is expected to reduce road congestion, besides reducing the load on the Western railway line between Bandra and Churchgate.

Figure 47: Mumbai Metro Line-3 system map (Terratec, 2018).

	DESCRIPTION	YEAR 2031	YEAR 2041
	Reduction in Vehicle Trips / Day	5,54,556	6,65,468
	Reduction in Fuel Consumptions -petrol & Diesel (in l.)/day	2,95,495	3,54,593
	Avg. Daily Money Savings due to Reduction in no. of Vehicle Trips (Rs. lakhs)	191.99	230.39
	Reduction In Pollution Emission Due To Reduction in no. of Vehicle Trips (Tonnes/Year)	8,256	9,907

Table 1: Mumbai Metro Line-3 estimated benefits (Mumbai Metro Rail Corporation Limited, MMRCL).

The project did an initial assessment of trees to be affected by construction and it was estimated that the project will affect 5,012 trees, of which 1,331 will be cut and the remaining 3,681 will be re-planted in other parts of the city. Per the terms of the contracts awarded to various consortia, they are in-charge of transplanting affected trees and planting new trees to make up for those cut down. The contract requires consortia to plant three times the number of trees cut down for the project and maintain them for a period of at least 3 years to ensure minimum effect on the environment.

Further, the reduction in vehicle usage as a result of people switching to metro instead of other modes of transport would reduce carbon emissions by an estimated 9.9 million kilograms and 6.6 Lakh reduction in vehicular trips per year. Further, as per data on the official website of Mumbai Metro Line 3 the new line is expected to have following impacts-

Mumbai accounts for 18.5% of total accidents in India. Operation of Mumbai Metro Rail will provide improved safety and lower the number of accidents. There will be net savings of 182km road infrastructure which otherwise would be required to cater the additional load over the present 1,889km road network. Requirement of about 10% of road infrastructure will be reduced. The project is proposed to create many employment opportunities, about 5,000 persons are likely to work during construction for five years and about 1510 persons for operation and maintenance of the proposed system.

In mid 2022 around three-quarters of the project is complete, and the line is expected to be operational by 2024.

USE OF SFRC TBM SEGMENTS IN MUMBAI METRO LINE 3 PROJECT

The project is being constructed as seven construction contracts (UGC 01 to UGC 07). The scope of contract UGC 02 is to design and construct four underground stations (CST, Kalbadevi, Girgaon and Grant Road), 5 km long twin TBM bored tunnels and NATM platform tunnels in all stations except the CST station.

The TBMs are driven through the stations followed by widening of these tunnels by NATM construction methodology to construct platform tunnels for this project. During construction of NATM platform tunnels, the originally constructed segmental lining is dismantled. These sacrificial segments are designed with Steel Fibre Reinforced Concrete (SFRC) to reduce the overall quantity of steel required in the project.

Using SFRC is a step closer to sustainable construction practices. The use of SFRC reduces carbon footprint by-

1. Reduction in steel requirements in tunnel lining and hence low carbon emission related to steel.
2. Less transportation requirements and reduction in carbon emissions.
3. Since elimination of reinforcement bars leads to the elimination of requirements for concrete cover, tunnel lining can be thinner. Hence reducing the amount of steel, cement and aggregate requirements.

For this project, SFRC TBM lining was proposed for a 4.2km tunnel. The requirement of steel reduces from 85kg/m3 of concrete to 40 kg/m^3 of concrete when compared to conventionally reinforced TBM segments. This led to saving 2,100t of steel in the project, which is equivalent to emissions of 3,780t CO_2 equivalent. Apart from steel requirements, indirect benefits such as savings from transportation of materials and savings from elimination of requirement to fabricate rebar cages also made the construction sustainable.

Case Example: Dhaka subway project

Bangladesh is one of the most socially, demographically, economically, geographically, environmentally, and climatically vulnerable regions of the world. With a population of approximately 164 million people in an area of 147,570km², Bangladesh is one of the most densely populated countries in the world, as well as being the 8th most populous country. More than eight million working hours have been lost on Dhaka roads each day in 2022 (Fig. 47), which is significantly higher than the five million working hours lost each day in 2017.

The increasing amount of time spent in traffic is reducing the amount of time spent with family members and on other tasks, posing a hazard to mental health, according to a recent study by the Accident Research Institute (ARI) of Bangladesh University of Engineering and Technology (BUET).

Figure 48: Dhaka road congestion.

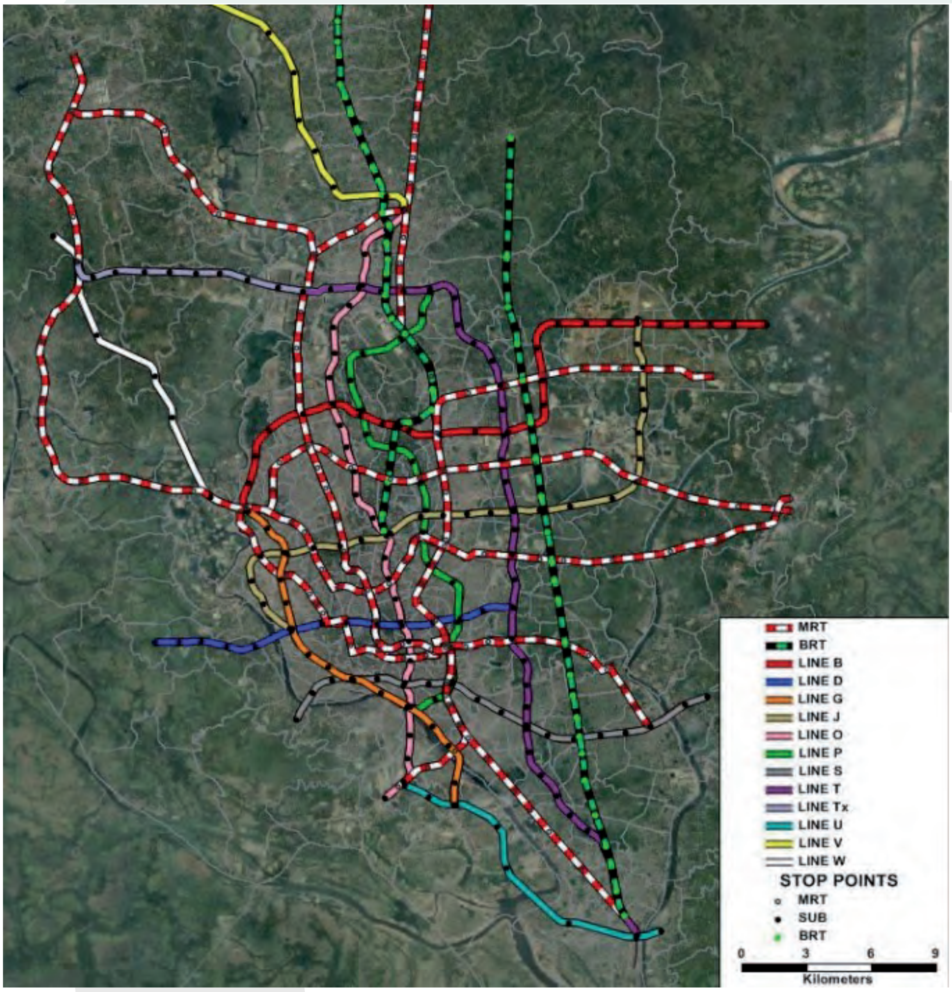

Figure 49: Mass Rapid Transit (mainly subway) network planning in Dhaka (BBA, 2022).

This rapid urban and population growth, which has not been matched by the provision of transportation infrastructure, is causing increasing traffic congestion, along with the attendant loss of productivity and health and environmental problems. In order to mitigate traffic congestion in the city and to enhance the mobility of the city's residents and visitors, on a sustainable basis in the long term, the Government of Bangladesh has begun implementing a mass transit system comprising 5 mass rapid transit (MRT) rail lines and two bus rapid transit (BRT) lines. The first metro rail line (MRT Line 6) is under construction, while the next two lines, Lines 1 and 5, are under planning and design (Fig. 49). Works for BRT lines are also in progress.

Dhaka has a flat topography given that its surface elevation ranges between 1-14 metres above the mean sea level. Dhaka annually experiences floods during the monsoon season due to the overflow of rivers and heavy rainfall. Therefore, flooding is a major risk in Dhaka and any infrastructure must be resilient to it.

One of the most constraining aspects of the Dhaka Subway project will be water issues, both surface and groundwater. As is the case with most of Bangladesh, most of the Dhaka Metropolitan Region is composed of relatively flat and low-lying alluvial plains and, as such, is subject to flooding due to heavy monsoon rains, tidal flooding, or river flooding due to snow melt in the Himalayas. The level of the deep-water table varies both in plan and over time. In the Central Dhaka area, successive pumping over the years to use the water reserves has gradually and considerably lowered the water level at depth, so that it is now generally below 70m deep. In the peripheral areas, where the presence of Holocene deposits predominates and there is less pumping, the deep-water level is typically at the surface and up to 20-30m deep.

The deep position of the water levels is conditioned by this forced pumping, so that, if it were to be interrupted, the situation of the groundwater would foreseeably recover the natural equilibrium, very close to the surface in the flood plains areas around the +0 or +2 level. Throughout the useful life of the infrastructure (100 years), the design has considered that the water level could be as high as +9.0 in some areas of the city and its surroundings.

Such extreme situations condition the design and construction in such a way that, during the temporary excavation phase on most of the site, deep water could be maintained in these positions, favouring the construction of the tunnels, stations and connecting spaces.

Subway infrastructure development projects are carried out to benefit the general population by creating rapid services such as shortening distances or speeding up transportation services, favouring the sustainable development of this megacity.

For the dimensioning of the system, storage periods of 1 and 2 days, along with tunnel lengths of 800 and 1500 metres have been assumed. In the next phases of the project, the dimension of the tanks shall be adjusted according to the obtained drain distances for each case. Water storage tanks and treatment plants systems for the collected flows will be integrated to be able to discharge the flows back into the natural or surface drainage system. From an environmental point of view, it is worth highlighting the integration of the challenges of climate change in the planning with the objective of significantly reducing carbon dioxide emissions, considering a robust and resilient design in anticipation of a possible increase in the frequency and intensity of rainfall and flooding and of the water level in the area.

Bangladesh is one of the world's most vital economies with the strongest growth potential, therefore a mass, rapid and efficient transport is required. Currently there are some metros on going but still there are several logistical constraints to the development of a massive integrated underground subway network capable of mass and efficient transport. However nowadays significant improvements reached in tunnel technology might overcome greater challenges to make this huge and difficult project feasible and considering the social profitability, the project seemed to be viable.

Mainly there is a firm will on the part of the authorities to have an efficient mass transport network that will help to promote the modernization of the city and the country considering the challenges in terms of population growth and taking into account the challenges in terms of climate changes. In addition, during the construction of tunnels, large and deep stations and related structural elements (shafts, ramps, galleries, tanks, etc.), enormous quantities of debris are produced. The smart use of underground space can be targeted at improving transport, reducing gas emissions to the atmosphere, and, at the same time, obtaining land for reuse by creating raised embankments for new urban development areas in existing flood plains, which cannot currently be used by citizens. This can both meet a necessity and provide an opportunity for future development.

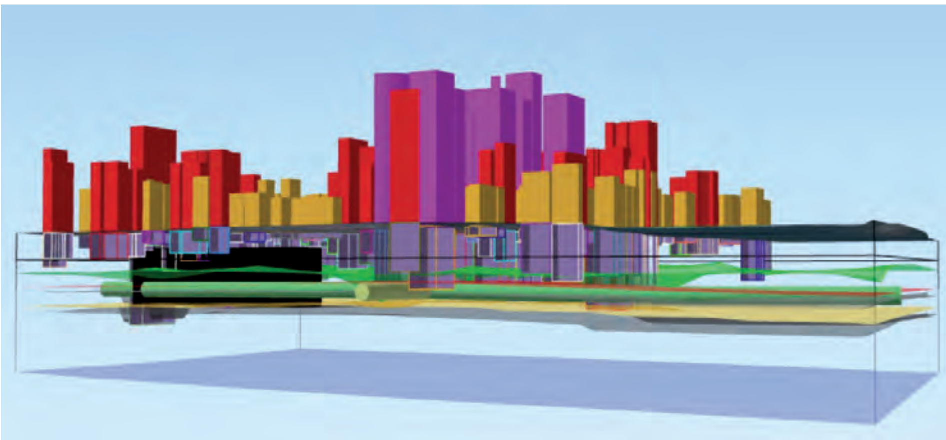

Figure 50: 3D GIS model showing different upgraded and underground for Dhaka subway project (TYPSA, 2021).

Case Example: Grand Paris Express

The new rapid transit lines project in Ile-de-France will be the new Parisian belt, a sustainable and efficient infrastructure composed by 200km of tunnel and 68 stations, that was the input for rethinking the entire region. This project aims at completely reinforcing Parisian mobility, with 4 new rapid lines, 2 existent lines extension and creating new mobility hubs (Fig. 51).

A new neighbourhood's sustainable development: the metro changes social habits, and therefore the approach to the city will change, with fastest links to Paris and, above all, between other urban centres mainly located in the Ile-de-France region. The transport project, reinforcing urban activities, is transforming the main French economic and social core, introducing an integrated, social-mixed, and sustainable Parisian urban dimension; the most relevant result is that the inter-peripheric contacts are favorized and reinforced; these new lines will helping to change the barycentric functioning of the Parisian metropolis, thanks to the new possibilities to cross the city without necessarily passing through the centre.

In this project, the underground was the leading input for urban planning. With 30 to 50 metres deep stations, the Grand Paris Express teams worked from the very beginning on a symbiosis between engineering, architecture, design, and urban planning. The stations are the new urban life's epicentres and actively participate in creating a new network system, combining and linking territories and cities where the user is the main actor.

The station is the core, the platforms are the starting point. The underground spaces were planned as part of the city life, fully integrated in the neighbourhood in terms of services, utilities being the new meeting point for neighbours, travellers, and inhabitants. The key was to assure a fully connected relationship between underground and surface, between the station and the city, the upside-down city by exploring in between. A sustainable and connected compact city.

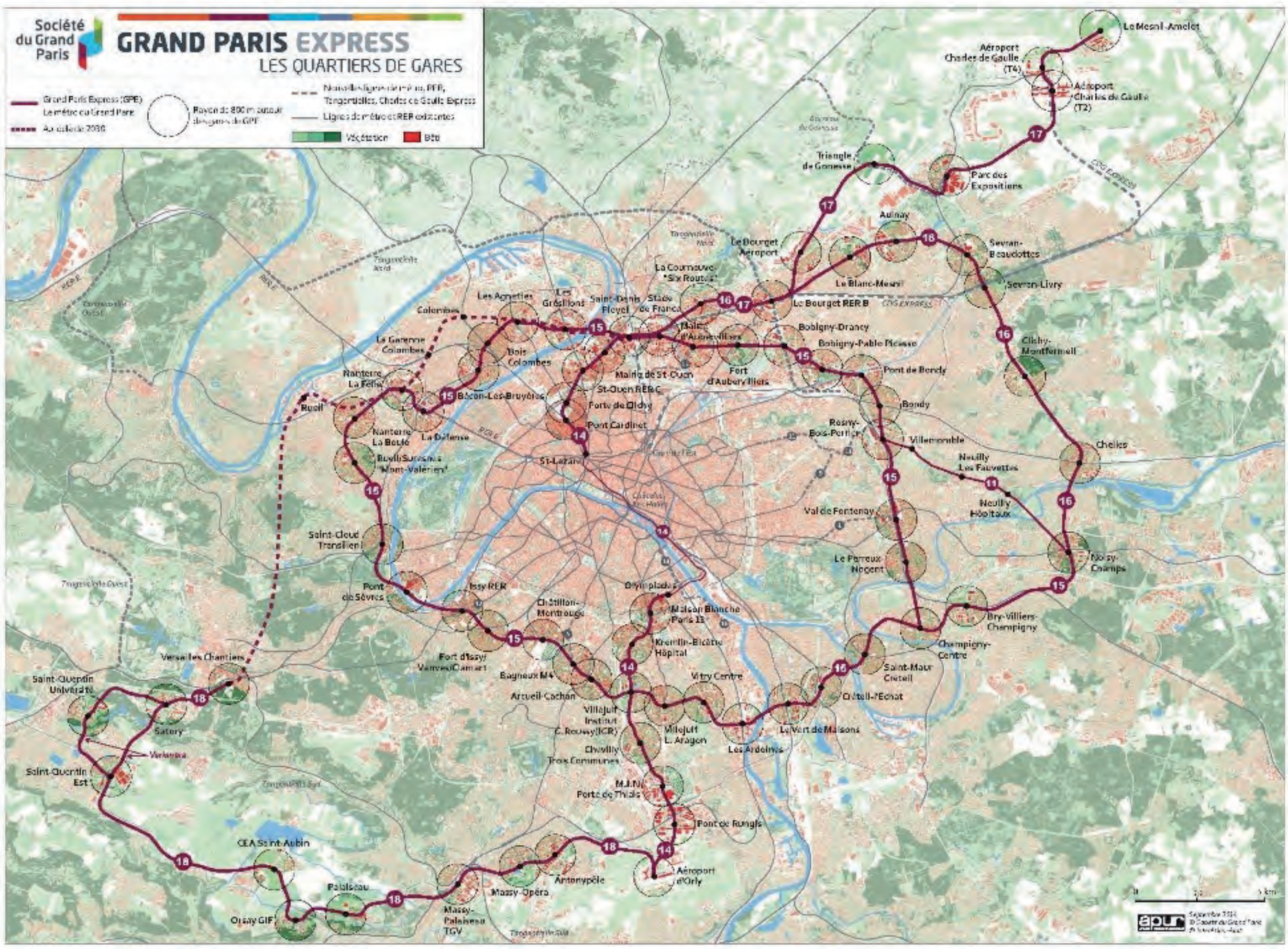

Figure 51: Ile-de-France "Les quartiers de gares": urban operations related to Grand Paris Express project (source: APUR)).

Reuse & Repurpose

Reuse and repurpose is an important concept toward achieving sustainability and to this effect, resiliency. In context of the existing cities there is a growing potential and intent to reuse and repurpose existing facilities; however, considerations need to be given to inherent limitations of this concept primarily due to restrictions the existing facilities might impose by their original use and purpose as well as their functional, safety and spatial features. Primary sources of underground spaces that might present considerable candidates for reuse and repurpose are abandoned mines; old military, transportation, and logistics facilities; previous parking and storage spaces, and unused civilian shelters. Cities that embarked on reviving these facilities, providing them with a new needed purpose, improved on resiliency of their communities.

Resilience starts with the ability to deal with change, but is also closely linked to sustainability, as preferably a resilient system aims to become more sustainable as well. Various studies on sustainability and circularity have introduced a so-called 9-R model, where the R's refer to different stages of circularity, from Recycling to Redesign. Two main concepts in this model are Reuse and Repurpose. As such usage of existing structures greatly reduces or even avoids the need for new construction materials, the resulting footprint of new facilities is lower, leading to improved sustainability.

In the underground of ageing cities there is often a growing potential to reuse and repurpose existing facilities, as there have already been so many successful underground projects in the past. Existing structures do impose limitations on the potential reuse, given the way they have been originally constructed. The new function will have to accommodate the restrictions set by the pre-existing infrastructure, safety considerations and spatial compatibility (Niessen et al, 2020).

The former function of abandoned underground spaces can vary massively. Examples of primary functions of underground space are, extraction of raw materials, military operations, transport and logistics, sheltering, parking and storage. The potential opportunities of reuse depend largely on the conditions that were set by its original purpose. Therefore, it is crucial to look at these different origins separately to determine the optimal opportunities. We will focus on transport systems, bunkers and mines.

METRO AND RAILWAY SYSTEMS

One category of abandoned spaces are metro stations and tunnels. In some cases, these had to close because of rerouting or lack of ridership. In many larger cities, such as Paris, London and New York, abandoned tunnels and stations could be found. Although several have been demolished over time, many more remain untouched or are partially used. There have been many ideas and proposals for the rehabilitation of those platforms and tunnels but almost none have been realised. It is likely that high investment costs or other reasons including environmental or permitting obstacles have prevented timely repurposing of these facilities to meet cities' contemporary needs. Where these hurdles have been overcome, the benefits of reusing the underground space led to some creative solutions.

Potential reuse of these facilities is for research and educational purposes. Safety in transport tunnels is a very important study area. Providing that safe application could be achieved, Carvel (2005) suggested using the abandoned tunnels to gain information about fire events in tunnels including testing safety equipment, systems and emergency procedures. Besides fire experiments the abandoned tunnels are perfect for emergency personnel training exercises. These tunnels and platforms can mimic a real operational underground metro fire.

In addition, Disimile (1990) described the potential of the Cincinnati Rapid Transit Railway conversion into a wind tunnel for research purposes; however, this application never gained required approvals.

With no trains on the rails, abandoned tunnels offer new possibilities for other transportation modes. The City of London investigated the possibility of creating an underground pedestrian and bicycle network to minimise pedestrian fatalities; they intended to transform the abandoned tunnels into pedestrian and bike paths and the platforms into cultural and retail spaces. They even planned to harness the kinetic energy of the users with a Pavegen system; however, the constraints of the original structure made it impractical for the proposed reuse (O'Sullivan, 2015).

The climate of underground tunnels could be harnessed for agricultural purposes. The tunnel's cool, damp and dark environment might support growing mushroom farms. One example project is the Mittagong mushroom tunnel in Australia where a kilometre long abandoned railway has been repurposed (Zhang, 2014). Twilley (2020), however, states that the temperatures in many railway tunnels vary and that using appropriate mushroom types (those that could withstand specific underground climate) is essential.

In Madrid, a section of an old tunnel remained unused for almost half of a century, when it was integrated into an exhibition of contemporary art, with the aim of giving it a new life as a modern and sustainable space of culture. It became an Exhibition Hall that has achieved an outstanding reputation in the field of international architecture, (so-called 'ephemeral architecture').

Case Example: The tunnel of Mittagong

This railway was completed in 1869 from Sydney to Goulburn in Australia with a length of approximately 224 km. It served its purpose until a new double line opened in 1919 and this line was abandoned. During the Second World War, the tunnel was assigned as a bomb shelter, but this was withdrawn when it was taken by the Royal Australian Air Force. They used the railway tunnel to store explosives until 1953 when it was closed again after the war (LSE, 2020).

The railway tunnel has been used for growing exotic mushrooms since 1987. The used part of the tunnel is 650m long, 30m deep and buried under solid rocks (LSE, 2020). The natural conditions in the underground railway tunnel, high moisture level and low temperature, are ideal for growing many exotic mushrooms. The specific atmosphere in the tunnel is very similar to the environmental conditions in the mountains of Japan, China and Korea (LSE, 2020). Those species of mushrooms naturally grown there are now produced in the tunnel of Mittagong. Some examples are Chestnut, Nameko, Enoki or King Brown (LSE, 2020).

Figure 52: Mushroom farm in tunnel of Mittagong (LSE, 2020).

Case Example: Underground Bike Paths

In 2015, the Gensler research institute proposed to transform the abandoned railway tunnel under London into cycling routes and the platforms into cultural and retail spaces. The project would use double tunnels for parallel pathways and a kinetic paving to generate electricity. This paving would generate power by footfall and friction from the bicycle tires. Although the tunnels won’t be connected to the surface, rental bikes would be available at every entrance (O’Sullivan 2015). The project won the Best Conceptual project price at the 2015 London Planning awards. Even with the prize the project fell in oblivion (Gensler, 2020).

Figure 53: Underground cycling tunnel(Gensler, 2020).

Case Example: Old tunnel refurbished as an art exhibition hall, Madrid

A cultural space of 2,400 square metres, located in Nuevos Ministerios, in one of the buildings of the Ministry of Transport, Mobility and Urban Agenda, in Madrid, was inaugurated in October 1983 under the name of «La Arquería». The most relevant contemporary architecture has been exhibited here, with the aim of disseminating architectural culture in Spain.

Next to the train tunnels that ran under the square in the interior of the ministerial complex, just under the arcade, there was another smaller tunnel with a service track. For some reason the track was closed, and a section of it was left under there, enclosed and unused. It is not easy to find information about the history of this somewhat mysterious construction, and one has to rely on the memories of older people. It seems that at one time, between the Republic and the new regime, it was used as a bunker. In 1982 a part of La Arquería, the northernmost part, was glazed and converted into an exhibition hall dedicated to architecture and urban planning. Underneath, the section of the old tunnel remained unused until 2003, when it was integrated into the Exhibition Hall, preserving its spectacular concrete vault. In 2020, renovation work began so that from the end of 2022 it will be the venue for an exhibition of contemporary art, with the aim of recovering its essence and giving it a new life as a modern and sustainable cultural and exhibition space.

The Exhibition Hall has achieved an outstanding reputation in the field of international architectural culture, and specifically in the speciality of exhibition design and installation, the so-called ephemeral architecture, which has been recognised with numerous awards. After its refurbishment as an art centre, the hall will become an exhibition venue to recover the heritage of this old tunnel and continue to host initiatives that encourage the dissemination, promotion, and research of architectural heritage, both above and below ground.

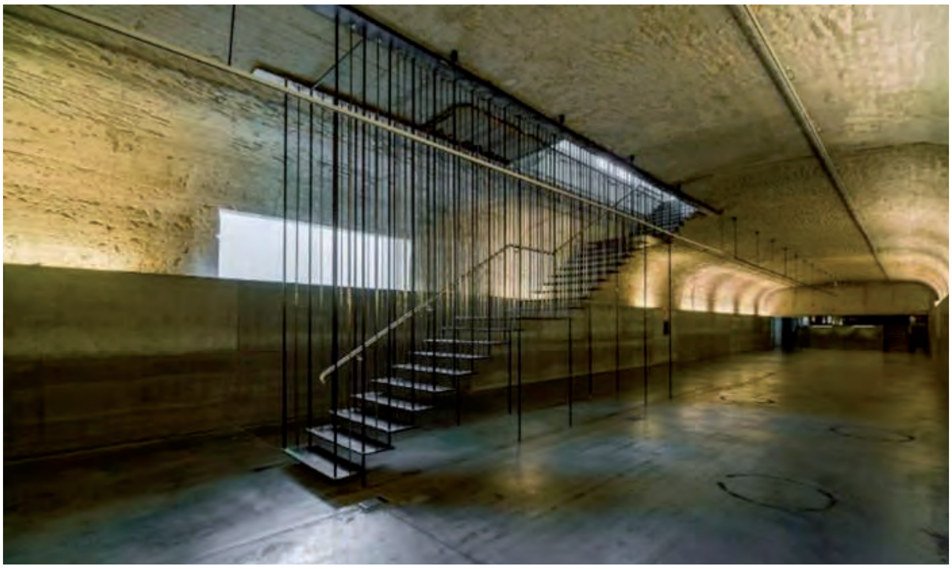

Figure 54: Refurbishment Underground space for cultural exhibitions. https://www.esmadrid.com/informacion-turistica/sala-de-exposiciones-arqueria-nuevos-ministerios

BUNKERS

In the last century, many bunkers were built, and they can be divided into two main categories. There are battlefield bunkers which were predominantly built during the Second World War. These are constructions that are meant to protect soldiers from incoming fire, and typical for these structures is that they are often only partly below ground and relatively shallow buried. On the other hand, there are shelters that are built to withstand attacks of different types. These shelters were built during the Second World War to protect citizens from air raids or after the war to safeguard people from nuclear outfall (Garrett & Klinke, 2019). These are mostly located deeper below ground and may have only limited access potential. These shelters had to be “self-sustaining closed-system environments where the necessary ingredients for human survival – oxygen, water and food – are secured over an extended time frame” (Garrett & Klinke, 2019).

Air raid shelters from the Second World War were often in basements of houses or multi-purpose structures such as tube or train stations and tunnels. The nuclear bunkers were often much larger and formed large systems such as the Burlington bunker in the United Kingdom. This is a bunker complex built by the British government to protect 4,000 central government employees in the case of a nuclear attack. It was a totally self-sufficient complex of over 30 acres and 60 miles of road, equipped with underground hospitals, cafeteria’s and one of the largest telephone connection stations in the United Kingdom (BBC, 2020).

For reuse purposes, the most difficult characteristic of bunkers is the enormous strength of the construction itself. The walls of these structures are often metres thick and heavily reinforced. This results in structures that are very hard to remove or change. Another interesting characteristic of military bunkers is that they often have become national heritage. Due to the historic significance of these structures, they are labelled as important heritage sites. This results in restrictions on the further options on how to deal with these systems. In the Netherlands some military bunkers from the Atlantic Wall are considered cultural heritage and thus they are not allowed to be removed. This makes it even more important to develop new usage options for these structures.

Similarly, after the Cold War the use for the nuclear shelters was lost and especially Europe was stuck with vast amounts of bunker structures. Recently, interest in these bunkers surged, as according to Beck, people are intrigued by the ambivalence of the structures. They can fluctuate "between the visible and invisible, architecture and engineering, ruins and rubble, violence and inertia, the spectacularly symbolic and the blankly dumb" (Ziauddin, 2017). Moments like this create opportunities to redevelop existing underground spaces, often already within the city centres, at a lower investment cost than a completely new underground facility would amount to. But what new functions are possible within these shelters?

Because bunkers are often designed to house people in crisis situations, it would be logical to consider making this the permanent mode of use. A large constraint on this is the fact that the bunkers are underground and therefore no natural light reaches these spaces. People have a physical and psychological need for daylight and thus they are reluctant to live underground. In Germany a lot of so-called "Hoch bunkers" were built and as these types of bunkers are completely above ground, they are much more suited for a conversion to housing. This is because after renovations daylight can be made available inside the rooms. There are several projects in Germany where these high-lying bunkers are converted to apartment buildings such as in Siegen (Plan3, 2020) and in Bremen (Bunkerwohnen, 2020). Also, military and nuclear bunkers completely underground have been transformed to houses. In Vuren, the Netherlands, a military bunker has been transformed to a vacation residence (Frearson, 2014). In China, approximately 10,000 nuclear underground shelters were constructed and some of these shelters have since been used as residential units (Ming, 2020).

The next potential form of reuse of bunkers is underground farming. According to Nelson et al. (2010) food security in 2050 could be at risk due to the rising world population and climate change. They state that "higher temperatures, shifting seasons, more frequent and extreme weather events, flooding and drought" could have a devastating impact on worldwide food production. This is the reason alternative types of farming are being investigated. Underground farming offers a solution to many of the above-mentioned problems. In an underground bunker a controlled environment can be created which protects the crops from dangers such as drought, extreme weather conditions or higher temperatures. Because the farm is under a big layer of soil, there is a large isolation capacity which delivers a constant temperature. Also, the fact that the crops are grown and harvested within the city itself provides large benefits such as reduced carbon footprint and longer shelf life (Nelson et al, 2010). The first project of this kind has been realised in a bunker in Londonwhere all kinds of crops are grown but also in France where they cultivate oyster mushrooms (Florin, 2018).

One category where, given the specific qualities of bunkers, the reuse potential is substantial is data storage. As more and more people are using digital devices and the capabilities of these devices are growing, so is the need for data storage facilities. It is estimated that in the period from 2015 to 2021 alone, the required data storage capacity has increased by a factor of 2.5 (Statista, 2020). Due to this and growing concerns on data security, there is a movement towards the underground storage of data. With this growing capacity there are large sustainability problems around these data centres. Data centres produce enormous amounts of waste energy in the form of heat and must be cooled. Due to this, CO_2 emissions for data storage already in 2008 were as high as that of the global travel industry (Fettweis, 2008). This is where underground facilities pose an enormous advantage. As cooling occurs naturally in underground spaces, energy costs can be significantly reduced (Harper, 2017).

There are several other main advantages of underground data storage. The first is the fact that these bunkers often only have a single entrance. Due to this, these facilities can be easily secured from intruders. Also, an advantage is the fact that underground nuclear bunkers are blast proof and well protected from magnetic pulses that could disrupt data security (Sverdlik, 2016). A further main advantage is that underground bunkers are almost instantly ready for use. Data storage doesn't need extensive remodelling and thus the speed to market is faster (Harper, 2017). A lot of these facilities are already realised. In the Hague an old WW2 bunker has been repurposed as a data storage facility (Omroep West, 2020) and for the Burlington bunker mentioned above data storage is also the suggested use (Colson, 2020). Also, in the USA (Houston Bunker, 2020), Switzerland (Miller, 2020) and Sweden (Bahnhof.net, 2020) large scale data centres have been built.

The last category for the reuse of the underground bunkers is the cultural and leisure sector. Because many functions in the cultural sector only need a large enough room, bunker spaces could easily be modified to a cultural function. Also, the mysterious character of these old war time structures makes it an attractive location for alternative companies. There are many examples in which nuclear and military bunkers are transformed to serve a cultural purpose. In the Netherlands for example, on top of two military bunkers, an extra structure was built that integrated the bunkers. The new combined construction now serves as a luxury retreat (UNstudio, 2020). In Germany, bunkers have been transformed to theatres, co-working spaces and even band repetition rooms. But also bars and restaurants can be formed in these old bunkers. In China an old nuclear shelter was transformed to one of Shanghai's most popular bars (Cityweekend, 2020). And in Russia, an old nuclear complex was remodelled to an event location, restaurant, bar and museum

Case Example: Living in Nuclear Shelters in China

During the '60s and '70s of the 20th century Chinese local authorities constructed vast bunker systems underneath their cities. In this period, approximately 10,000 nuclear shelters were built in the nation's capital Beijing alone. In the first part of the 1980s, the country opened its doors to the world around them and at that time the defence department of Beijing decided to lease these bunkers to private landlords (Ming, 2020)..

Nowadays, the number of people living in these shelters is large and unknown. The estimates range from 150,000 people living in these bunkers up to even one million residents (Feng, 2016). In recent times, Beijing has become one of the most expensive cities in the world to live in. In 2017, the home prices in Beijing rose almost 30 percent on a year to year basis (Sheng, 2017). Data from the Chinese government shows that wages of immigrant workers increased only 14 percent when the cost of living rose roughly 22% in 2014 (Feng, 2016). This causes migrant workers to make their way to the underground where housing costs are only one third of housing above ground (Feng, 2016).

When these bunkers were built, amenities such as plumbing, electricity and sewage systems were included. Due to this these shelters are habitable but in the absence of the right ventilation the conditions in the bunkers are sub optimal at best. The local requirements for the minimal surface area per person are four square metres but this is often not followed (Ming, 2020).

Figure 55: Shelter-home [Picture sources: http://www.qdaily.com/cooperation/articles/toutiao/24308.html. https://www.163.com/dy/article/G6DTH9UV0538CLGA.html]

Figure 56: Shelter-home.

Figure 57: Shelter-home.

Case Example: Farming: Vegetable Farm Underneath Streets of London

The first underground farm that has been planted is situated in an old World War Two air raid bunker. The bunker is in the southwest part of London and lies 33 metres under the streets. The name of this modern farm is Growing Underground.

The farm consists of two rows of LED lid gantries in which micro greens and salads are grown (Belton, 2020). They produce sixteen different crops among which are broccoli, coriander, green basil and purple radish. These crops are produced hydroponically which means they grow in water instead of ground (Belton, 2020). Because they are underground and farm hydroponically, they don't have to use pesticides at all and consume 70% less water than traditional farming methods (GrowingUnderground.com, 2020). The use of the bunkers is ideal because they are not hindered by rain or wind.

The ground above the bunker works as insulation and thus fluctuating temperatures is also not a problem. Due to LED lights the energy consumption of the farm is higher than usual but according to the owners the yield also substantially increases. Compared to greenhouses the yield increases over twofold and compared to outside farms the increase is around 15 times (Belton, 2020).

Also, the location of the farm offers sustainability benefits. Whereas traditional farming is outside the city, underground farming can be done in the heart of the urban area which results in less transport kilometres and thus less costs and less carbon emissions. Also, the shelf life of the products is elongated as a result of the shorter transport time and absence of the need of interim storage.

Figure 58: Artist impression underground farming (growing-underground.com).

Case Example: Data Storage: Hyper Secure Data Storage Facility in the Centre of Stockholm

In the 20th century, the Swedish government built a 1,100 square metre facility in the centre of the country's capital Stockholm. In 2008 Sweden's biggest internet service provider Bahnhof turned this former nuclear bunker into one of the most secure data centres in the world. It became famous in 2010 when WikiLeaks hosted their servers in the data centre.

The facility is situated 30 metres underneath Stockholm in a Cold War nuclear bunker (Harper, 2020). The entrance of the data storage is fortified with a 40-centimetre-thick steel door and can only be reached by a tunnel (Bahnhof.net, 2020). Due to this, the facility has the capacity to withstand a hydrogen bomb. The data centre has two old German submarine engines which function as back-up generators (Pionen, 2020). Other components of the facility are "underground waterfalls, greenhouses, simulated daylight and a 2,600-litre saltwater fish tank" (Harper, 2020).

Figure 59: Inside the Stockholm data centre (wikipedia.org).

Case Example: Culture: Social Hot Spot in a Russian Bunker

The Tagansky Protected Command Point was built in the 1950s in the centre of the capital Moscow. Now known as bunker GO-42 or just bunker-42, this elaborate bunker system is situated 65 metres below the street of Moscow and has an area of 7,000 square metres. It is located near and connected with the underground metro station Taganskaya. In the 60s of the 20th century, the bunker was re-equipped to continue operation in the event of a nuclear attack. To operate underground for a protracted time, a stockpile of food and fuel was compiled. Also, two artesian wells were constructed to provide a long-lasting supply of fresh water (Tagansky, 2020). The facility could feed 3,000 people for a time of 90 days when a nuclear attack would happen (Garfield, 2020). Under normal circumstances, the bunker could house around 600 people for work and living (Tagansky, 2020).

Figure 60: Bunker-42 (bunker42.com).

In 2006, the Russian Federal Agency for State Property Management sold the complex to a private company for 65 million rubles. At that time, that was equal to approximately 2 million euros. The company changed the bunker system to a large cultural complex. There is a large Cold War museum and a tour can be booked to walk through the bunker system. Several rooms in the complex can also be booked for conference spaces and as a wedding venue. Besides this, it also houses a restaurant and a karaoke bar (Garfield, 2020).

MINES

Underground structures that are very susceptible to being abandoned are mines and quarries. Many of these are privately operated and will be abandoned for economic reasons. And although that might make it attractive for the owner to seek a new purpose for the existing space, the original focus on the most economic excavation of the mineral creates the situation that many mines are not easily repurposed as they have been constructed only for short term operation and stability. Still, there are numerous examples of reused mining sites, with a wide variety of uses ranging from agriculture to tourism, storage or even heat generation using geothermal energy.

Agriculture is the most basic way to reuse mining sites, but this may be limited due to pollution of soil groundwater that often occurs during a mining operation. Therefore, for the future exploitation of these areas as agricultural space there is an economic incentive to keep the space clean during the initial mining operation. Alternatively, like in greenhouse farming the actual farming can take place in completely isolated planting beds and there is less dependency on the original ground conditions of the site. This widens the potential for using this underground space.

The second form of reuse as categorised by Cui (2020) is resource development, where the existing underground space can be used to generate resources for use above ground. This way the mine keeps its value as a resource supply, but often with a changed resource as output. All solutions identified within this category produce some form of energy. Proposed options include coal gasification and methane extraction. These have the potential to reduce the pollution caused by the mine while using up the remaining finite resources.

A more sustainable option in this category is that of using deep mines as a source for geothermal energy. Because of the large depths the temperature might rise enough to warm up water to be used for heating-systems. However, as the water at these depths will not be close to boiling point, turning it directly into electricity won't be possible. There are numerous examples around the world of using abandoned mines as a source of geothermal energy. However, Guo et al. (2018) note that most projects are small scale and there are still questions about the sustainability of these projects when used on a large scale.

The third type of reuse is tourism, education and entertainment. This is the most imaginative solution to cope with abandonment of any underground structure. However, the realisation of these projects is mostly limited to museums, since many of the older underground mines lack the right conditions. The main problem here is that these exhibitions take place in relatively safe and easy to re-purpose mines which wouldn't be likely to be in the high-risk category. Furthermore, these museums only use up a small amount of space generated by the mine. Therefore, it is questionable whether this type of solution solves the main problems regarding safety, subsidence and efficient underground space use.

The most eye-catching project within this category is the Shanghai Wonderland Hotel. This tourist building was placed against the edge of a former open pit mine (Tan, 2019). Another interesting project is the Ice World Water Park in Changsha, which also features a touristic activity within an open pit mine. Important to note is that these touristic activities don't face the problems regarding lack of daylight because of the open pit setting. Therefore, these projects, as mentioned earlier, don't really face one of the biggest challenges regarding using underground space as set within the scope of this paper.

The next category identified by Cui (2020), called social services, faces the same problems. Cui (2020) regards landfill and parking as social services. However, the potential for these activities lies more in the fact that it is some type of storage rather than it being a social service. Therefore, it is more interesting to consider these within an overall category of underground storage. There are various proposed types of goods which could be stored within mines ranging from regular warehouse goods to hazardous chemicals. Firstly, looking at a warehouse like functionality, the main concern is the available infrastructure within the mine. The temperature and humidity might need to be regulated and for non-bulk storage there needs to be an easy way to order and distribute goods.

For the other types of storage, a low permeability of the ground is the biggest boundary condition. Especially in the case of landfills or storing of dangerous chemicals. Otherwise, the risks surrounding abandoned mines regarding pollution might only be worsened. Furthermore, it does not solve the issue of efficiency of underground space use and it's questionable if this is a sustainable solution. The storage of long-term hazardous materials could create a liability for next generations.

The most realistic form is bulk storage. Oil and gas storage are the main proposed solution for mines with low permeability. However, there may also be potential to use these sites for storing energy in the form of heat as is done in cold-warm heating systems.

In general, mines tend to have low level uses after re-purposing. This is probably due to three main factors. Firstly, the necessity for using these spaces is not high enough when it comes to housing or active job-creation. In general, the mines are outside densely populated areas and the above ground alternatives are therefore not yet depleted. Secondly the usage of mines creates difficulties in operation such as daylight and safety. Lastly, only a part of the mine was excavated using techniques that favour reuse afterwards. The reuse potential is heavily dependent on the state of the mine after abandonment. And this in turn is heavily dependent on the mining-methods used.

Case Example: Technology Centre, Kansas City

Located 10 km from the centre of Kansas City is an underground business-centre built into a former limestone mine. While mining activity still continues there is already an availability of around 1.3 square kilometres to be used for storage and other business opportunities (SubTropolis, 2020). Although there are 55 different companies housed within the mine (Hunt, 2020), the most interesting use that will be evaluated here is as a data-centre. Other uses include painting cars and storage of books, food and highly valuable items. One of the big beneficial factors for usage of abandoned mine space as a data-centre is the cooling capacity needed for these places.

For these structures isolation is one of the most important design-requirements. Because of the location of Kansas City far away from any stabilising water body the temperatures can become quite hot during summer. Since the underground maintains a constant temperature, which is just below 20 degrees Celsius when close enough to the surface, these shallow mines are perfect for running servers or other environment-sensitive processes. Conversely, going too deep isn't possible because the temperatures will rise. Therefore, this use is best implemented in relatively shallow mines.

Secondly, this limestone mine has been excavated using the "room and pillar" method [62]. Within this method the mining pattern is horizontally based, creating large rooms with natural pillars which have been left in place as a bearing structure. Due to this horizontal orientation, there is a high surface to volume ratio which makes the space use more efficient when being repurposed. Furthermore, careful mining of limestone in the relatively shallow underground doesn't create significant environmental hazards.

Lastly, the use of closed mines or any type of underground space creates a relatively secure environment for storage of strategically valuable data and processes. Data-storage and communication are vita to the existence of our current-day society. Therefore, locations that supply these functions may become a strategic target.

To conclude, the main boundary conditions supplied by the mine that favoured this project are its shallow location, the usage of the "room and pillar" method for excavation and the safe environment with the key attributes being the constant low temperature and the high level of security.

Figure 61: View inside the Kansas City data center with the pillars from the room and pillar excavation method still remaining. (stckc.com).

Case Example: Turda Salt Mine, Romania

The Turda salt mine in Romania is special because it has been repurposed more than once. The first mining activities at the location are believed to have been executed by the Romans (Turda, 2020). This is due to the fact that unknown mining activities were uncovered in 1976. However, because of a mine collapse this site was destroyed. The first written evidence of the existence of mining activity in the area dates back to 1271.

After closing of the mine it was turned into an aircraft shelter during the second world war. Underground space was very useful to the occupants at the time because of the air strikes of the allied forces. Therefore, the Turda salt mine is not the only example of a mine turned into a military facility. More famous is the bunker called "La Coupole", a former mine which was converted into a V-2 launching base in order to hit London. Important to note, is the large difference in infrastructure and dimensions between a regular mine and a large military complex with specific purposes. In the case of "La Coupole" there was a major amount of slave labour needed to finish the project.

After the war, part of the Turda salt mine was used to store cheese. And its most recent purpose is a theme park, attracting a high number of tourists. The site has found a way to exploit its potential even though its primary purpose was abandoned. One of the contributing factors to the success of this project is the type of resource present – for example, a coal mine could present additional issues regarding gas formation within the mine. Furthermore, the previous use of the mine as military infrastructure, which is not essentially economically motivated, could be beneficial to the number of facilities and adjustments already present. Lastly, the mine is relatively shallow which makes it possible to use the whole site.

Figure 62: Ferris wheel inside the Turda salt mine (metro.co.uk).

Case Example: Lefdal Mine Data Center, Norway

Ten years ago, a group of people had an abandoned mine available and an idea of transferring it to a modern facility to accommodate computers and data centres. The idea came up when the person responsible for mine operation had to discontinue its operations. It started almost as a joke, but investors thought it was a great idea simply because of natural conditions; a cold fjord outside, a lot of renewable energy, a lot of space in the mine, and the underground provided high security & safety.

In 2017, Lefdal Mine Data Center (LMD) was commissioned and is on its way to becoming the world's largest, safest and most environmentally friendly data centre. Lefdal Mine was one of the world's largest olivine mines, located next to Nordfjord in western Norway. The mine has large caverns in six levels, in total 75 pcs. and expandable area of 120,000m2 and has a total length of 500m and width of 350 m and reaching a depth of 160m. Mineral extraction created 5 levels of caverns and adits that comprise the mine layout. All levels are connected with a 2000 m long spiral tunnel and are accessible today. The caverns are 18 m high and 15 m wide. The mine has one entry tunnel and the IT space is located 600 metres into the rock mass, it is kept dry by discharging water by pumping. The cavern temperature is constant at 8 degrees Celsius.

Level 3 is now being utilised for data storage, level 1 holds the power and infrastructure network. Phase 2 for data storage will be level 4, then level 2 will follow for Phase 3, and finally the deepest level, level 5 is for future development. This facility constitutes the world's largest raw building for data centre and storage use. Located by the fjord provides opportunity for cost-effective cooling using in-house developed cooling technology based on sea water. Server parks emit a lot of heat, and therefore have great cooling needs. Building a data centre in the old mine means that data is safe. A natural disaster will not affect the centre. In addition, it is cheaper to build and operate the data centre inside the mine than placed on the ground.

LMD has the possibility of housing up to 200 MW capacity. With its modular design, time to market is 6-8 weeks. Customers can reserve space and capacity for future growth. It can facilitate all known concepts for whitespace solutions and the facility structure enables a streamlined solution for IT containers in different shapes and sizes in a cost-effective way. The data centre can customise power density, temperature, humidity, operational equipment, tier levels and all related services. It takes water from a 500-metre-deep fjord – stable cold water – available on 24/7/365-basis to heat exchangers, then to each designated data storage level. The data storage depends on a 350 MW local renewable power production, from local hydropower.

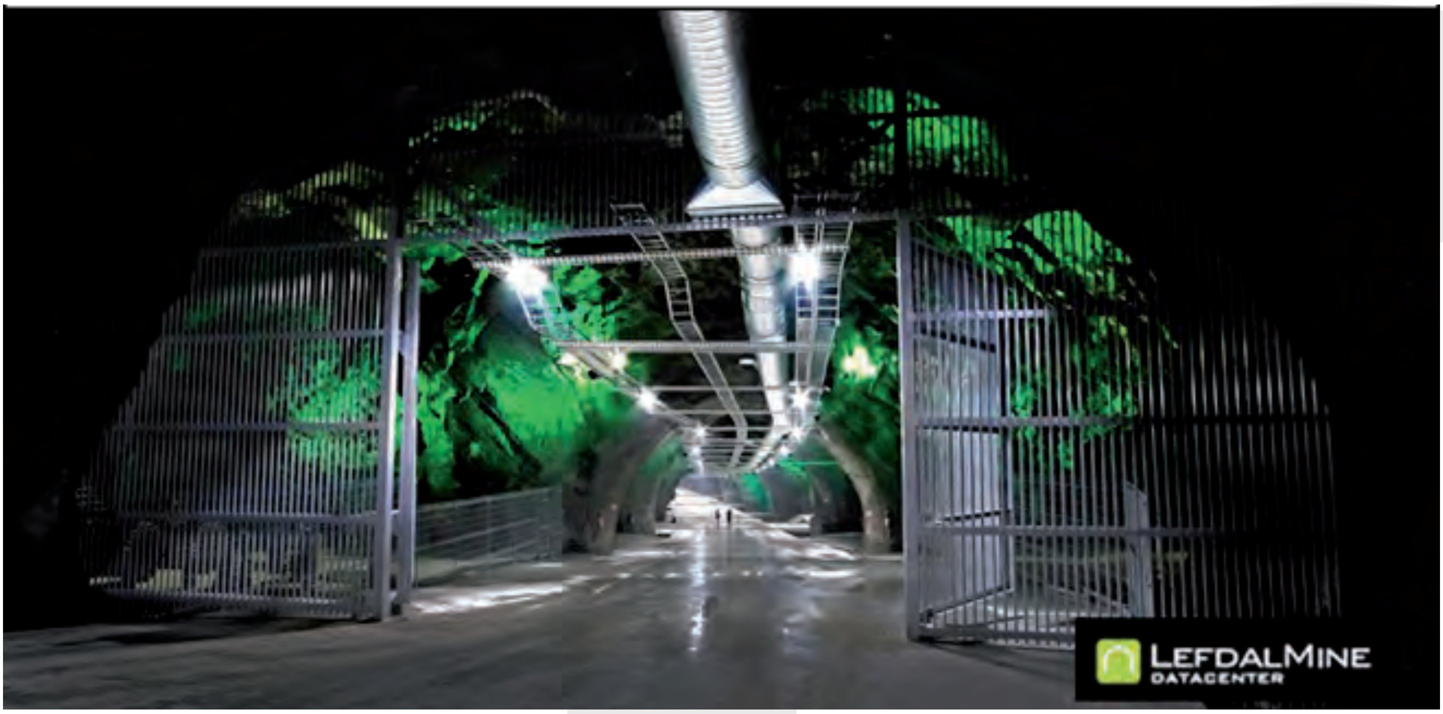

Figure 63: Entrance to Lefdal Mine Datacenter [https://www.lefdalmine.com/lefdal-mine-datacenter-nominated-dcd-award/].

Case Example: Katowice "Culture zone" including Silesian Museum of Art, Poland

The old "Katowice" coal mine had operated since 1823 and was closed in 1999. Currently, the mine area with the renovated historic buildings is the Katowice «Culture Zone», where the new seat of the Silesian Museum of Art, the seat of the Polish National Radio Symphony Orchestra and the International Congress Centre were built. The old "Katowice" coal mine facilities (Figure 64) were included in the design and transferred to a very innovative building of the new Silesian Museum of Art.

The new building of Silesian Museum of Art includes 3 underground exhibition levels and 3 underground levels of car park (Figures 66, 67, 68 & 69).

Figure 64: The facilities of "Katowice" coal mine (http://www.muzeumslaskie.pl).

Figure 65: The facilities of "Katowice" coal mine (https://pl.wikipedia.org/).

Figure 66: The mockup of the Museum project (http://www.muzeumslaskie.pl).

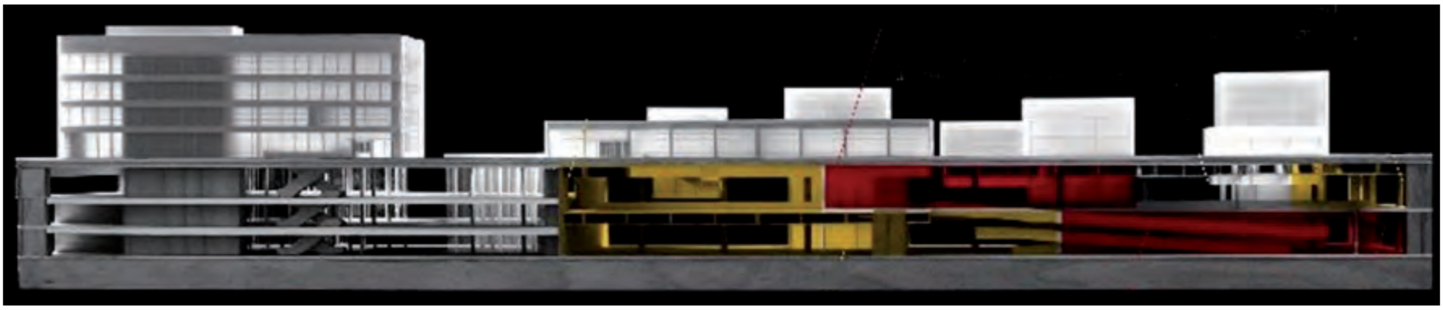

Figure 67: The cross section of the Museum(http://www.muzeumslaskie.pl).

Figure 68: New buildings of the Silesian Museum of Art adopting old facilities of the coal mine (http://www.muzeumslaskie.pl).

Figure 69: New buildings of the Silesian Museum of Art adopting old facilities of the coal mine (http://www.muzeumslaskie.pl).

Case Example: Wieliczka Salt Mine, Poland

The origins of the mine date back to the 13th century when the first lumps of rock salt were accidentally found. It made it possible to obtain salt by mining methods – the first shaft leading underground was struck as early as the second half of the 13th century.

Over the centuries (more than 700 years) the mine grew to nine levels, 26 shafts, with a maximum depth of 327 metres.

In 1996 a decision was made to end industrial salt production in Wieliczka. Since 1976, the underground Wieliczka has been listed in the register of monuments, and in 1994, it was declared a national Historic Monument by the President of the Republic of Poland. Throughout history, the way of thinking about the "Wieliczka" Salt Mine has changed from an industrial plant to a world-famous tourist attraction, a place of unusual events and a health resort. Nowadays, miners protect and renovate the historic areas of the Mine and take care that it survives in the best possible condition for future generations.

Today, "The "Wieliczka" Salt Mine is also a Health Resort (https://www.wieliczka-saltmine.com/health-resort) that specialises in prevention and treatment of respiratory system diseases, using the unique characteristics of the underground microclimate.

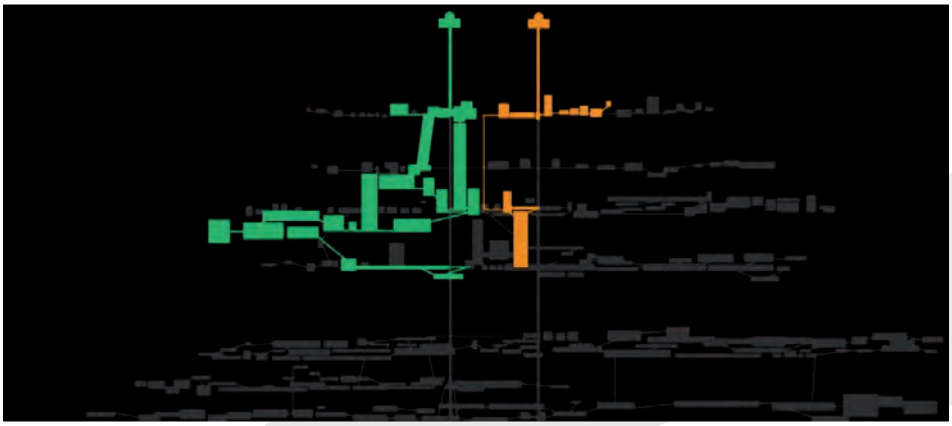

Figure 70: Wieliczka salt mine scheme (https://www.wieliczka-saltmine.com/).

Figure 71: The Weimar chamber (https://www.wieliczka-saltmine.com/).

The bioclimate of the treatment chambers is characterised by an exceptional bacteriological purity of the air, the absence of allergens and pollutants, a constant low temperature (13–14.5°C), high relative humidity (60–80%) and a high level of ionisation, in particular with chlorine and sodium ions, but also with magnesium and calcium ions.
Additionally, the Health Resort is the only facility in Poland where treatment and rehabilitation of respiratory system is complemented with treatments based on natural brine from the local salt deposit, located at a depth of 255 m. A stay 135 metres underground, in the Wieliczka" Salt Mine Health Resort, has a soothing effect on respiratory diseases and allergic ailments. The healing air has a positive effect on both the mood and the condition of the entire body.

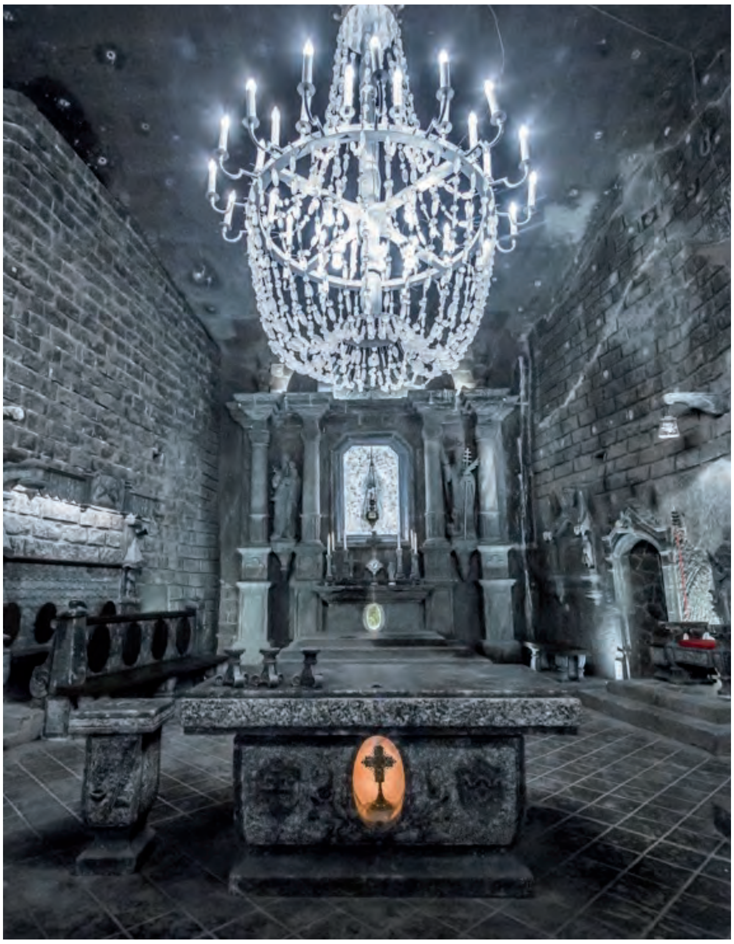

Figure 72: St Kinga's Chapel is a unique work of sculptor miners and one of the most magnificent underground temples, located at a depth of 101 metres below ground. (https://www.wieliczka-saltmine.com/).

Figure 73 : Wessel Lake Chamber - in this chamber there is a lake filled with natural Wieliczka brine. Around the lake there are separate places for group and individual exercises and relaxation. (https://www.wieliczka-saltmine.com/health-resort).

Figure 74 : Boczkowski Chamber - relaxation area. (https://www.wieliczka-saltmine.com/health-resort).

Case Example: Rome: Lessons And Responsibilities from the Past, Italy

POSSIS NIHIL VRBE ROMA VISERE MAIVS, you'll never see anything greater than Rome, quotes an ancient roman motto, and it's truly been like this for centuries, when Rome was considered CAPVT MVNDI, the world's capital. That's why the Italian Capital is still nowadays the world's first city for artistic heritage, capital of a Country again world's first in such a field and has the world's largest historic centre. And OMNES VIÆ ROMAM DVCVNT, all roads lead to Rome, they used to say in that period, Rome being the centre of a remarkable network of roads, aqueducts and sewers partially still existing nowadays. And sometimes not only existing but used as well by modern means of transport. For example, the famous Furlo Tunnel (Galleria del Furlo in Italian) is a tunnel built in AD 76-77 at will of Roman emperor Vespasian to create a shortcut passage along Via Flaminia, connecting Rome to northern Italy. The tunnel is named after the Latin word forulum, which means «small hole». In spite of such name, as engineering work the Furlo Tunnel was not small at the time, and wouldn't classify as a small civil work today as well, being 38.30 m long, 5.47 m wide and 5.95 m tall and excavated throughout calcareous rock across a gorge in a mountain area. Moreover, this tunnel lasted for centuries as the only road from Rome northwards and for many more as the quickest and more direct. Remarkably, the tunnel still was the main road from Rome to northeastern Italy in the '80s, when a new parallel highway with tunnel section was built alongside, leaving the old Flaminia route to local traffic only. However, traffic was not interrupted and the tunnel is still accessible today, almost two thousand years after its construction.

Sebastiano Serlio, celebrated XV-XVI century Italian architect and Classicism scientist, made in 1544 the famous statement QVANTA ROMA FVIT IPSA RVINA DOCET (how great Rome was, ruins themselves teach us); we notice that not only ruins but also still functional infrastructures tell us how great Rome was.

However, ruins and monuments clearly dominate Rome's landscape and territory, in its world's largest historic centre, throughout the rest of the city and metro area and, last but not least, underground. Rome's subsoil is in fact, as is easy to guess, the world's archaeologically richest. An immense heritage and asset, but also a harsh problem and heavy responsibility: how to excavate modern infrastructures in Rome facing the risk of destroying such a legacy?

This is one of the problems at the roots of Rome's metro lacking extensions and one of the main causes of its very high cost. Rome is a large city,

but its relatively low inhabitant/km² density for the central municipality, less than ⅓ of Milan or Naples, makes it harder for public transport to

Fig 75. Galleria del Furlo (Furlo Tunnel), Italy, on the historic Flaminia road between Rome and northeastern Italy. Epigraph on the left says "IMP(erator) CAESAR AVG(ustus) / VESPASIANVS PONT(ifex) MAX(imus) / TRIB(unicia) POT(estate) VII IMP(erator) XVII P(ater) P(atriae) CO(n)S(ul) VIII / CENSOR FACIVND(um) CVRAVIT" which means "Emperor Caesar Augustus Vespasianus, in the year of its 7th authority, claimed Emperor for the 17th time, Fatherland's Father, Censor, had this built". Road is still used today (Source: Picasa 2.7).

properly serve the city. The network has 3 lines (A, B and C), 60 km and 75 stations plus 1,5 km and 2 more stations under construction on line C. Consequently, Rome is also Europe's most motorised city with a bewildering 72 cars per every 100 inhabitants, more cars than driving licences. Peculiar historic reasons have slowed down Rome's mass transit development but also the local lack of a clear disincentive about the systematic use of cars in urban context had severe consequences.

Preventive archaeological surveys for station and shafts areas are used, as well as TBM excavated tunnels at a depth between – 27 and – 55 m, therefore by far below archaeological strata, which never goes deeper than 10-12 m. The archaeological excavations in stations and shafts areas require the complete excavation of the soil volume of archaeological interest. Also studies of interactions with monuments and buildings, often UNESCO heritage sites and therefore protected, are needed. Finally, all the monuments impacted by the Line C works are continuously monitored by means of large-scale vibrational, structural, geomatic and geotechnical monitoring. Such a procedure is costly and means that the construction costs are among Europe's highest for a metro line. But considering Rome's need for more mass transit and artistic heritage's safeguard, MELIVS ABVNDARE QVAM DEFICERE.

Figure 76: Ancient Rome's finds and remains along under construction segment of Line C (source: Metro C spa). The amount and quality of archaeological sites disclosed along line C route is bewildering and metro civil works are a great opportunity to bring them to light making them accessible to mankind (source: Metro C spa).

Case Example: Naples: Re-Use And Social Bases Living the Present, Italy

Naples is an extraordinarily rich site from geographic, geological, historic and social points of view. These unique conditions have led to the development of a peculiar attitude regarding the underground. Firstly, Naples has always been a very populated area, since its foundation in VIII century BC till Italy's Unification in 1861, when it was the most populated Italian City: this always implied a need for space that was not easy to satisfy due to steep hilly orography and the important volcanic presence of Vesuvio. On the other hand, the volcanic geology itself offered a solution: most of Naples subsoil is composed of tuff, a magmatic, porous rock very easy to shape and excavate, relatively light but resistant, fireproof, with good thermic and an acoustic insulator. In a nutshell: excellent for constructions, especially underground.

In the Naples underground lies in fact a maze of tunnels, cavities and tanks excavated during history with several purposes: communication routes, shelters, aqueducts, warehouses, even living places. According to Napoli Sotterranea (Underground Naples), an Association founded in 1988 to set off and spread the knowledge of this extraordinary heritage asset, this maze forms a hidden city which represents the "negative" of surface one. Naples underground city is spread below the entire old town. The creation of such an unique environment is not the result of a single master plan, but instead the stratification of actions dictated by different needs over the history of the city, with different timings and different purposes; the only common element is the versatility of tuff rock and the resilience of its citizens. First was the creation of cisterns by the Greeks around 470 BC to get construction materials. Then in the Roman period the predominant need was to extend aqueducts, distributing water through a widespread network of particular channels ("cuniculi"). Since the Kingdom period, XIII century, extraction of tuff to get more construction material to sustain the City's expansion became the focus. Tuff extraction was arranged "bottom up", requiring particular techniques to keep stability of the underground and to avoid collapses. More recently, underground Naples gradually morphed to something more clandestine, being used as shelter, secret shortcuts and passages, undetectable routes, aiming to escape dangers, oppression or, sometimes, the Law.

A remarkable example among Underground Naples is the Bourbon Tunnel (a.k.a. in Italian as Galleria Borbonica): an underground passage which was built to connect military barracks with the Royal Palace. Such a link was conceived under the monarchy of King Ferdinand II of Bourbon for military purposes, to make troop access from barracks to palace and court evacuation on the opposite way much quicker and safer (and unseen). It is significant to notice that this infrastructure met the King's need of safety not only in the case of foreign invaders, but also in the case of internal revolts: an adaptable and resilient infrastructure. Bored underneath the hill of Pizzofalcone, Bourbon Tunnel also connects to several other Underground Naples tunnels and structures. Later on, the tunnel was used as a shelter during the Second World War, giving shelter to citizens during air bombings. Several wrecks, vintage cars and a discarded fascist monument recovered there belong to this period. Nowadays the Tunnel is open for tours, together with the rest of Underground Naples, but all of this underground network could be extremely useful in case of war or other disasters being ample, extended, safe, insulated and freshwater provided.
One of Naples' assets making the city most resilient.

Naples has further underground spaces. The railway network is partially underground and Naples has Italy's oldest underground railway link. Since 1993 the City has got a metro with 2 lines, over 20 km extension and 26 stations, which makes it Italy's 3rd after Milan and Rome. Naples metro is characterised by the remarkable architecture and design of its underground stations, making them among the world's most iconic and captivating. This is the result of a plan that, in addition to improving the city's mobility, aimed to create an enjoyable and attractive environment, consolidating the Neapolitans tradition to go underground. Famous architects but also local artists have been involved in creating this architectural interface, often using symbolism and local oriented storytelling elements. Naples Metro iconic stations are also known as Art Stations meaning the special attention paid in making their environment beautiful, comfortable and functional.

Figure 77: Bourbon Tunnel, Underground Naples (source: Associazione Culturale Borbonica Sotterranea).

The Art Station project, also known as the Hundred Stations Plan, was set to entrust station architecture and design to contemporary artists and architects. Art Stations host over 180 art operas created by 90 international authors and young local architects, combining different architectural styles together contemporary and with a strong bond to local reality and culture.

Toledo station, a Line 1 station located in S.Giuseppe neighbourhood, next to the famous Spanish Neighbourhoods area, heart of the old city, is the best example. Designed by Spanish architect Óscar Tusquets, it's been many times awarded for its beauty.The station is equipped with three exits, Montecalvario is one connected by a 170 m gallery. External spaces implied a vast pedestrianisation and a remarkable system of skylights provide efficient and suggestive illumination. Statues, sculptures, mosaics and even photos accompany the passengers' path from surface to train platforms. Works of art portray elements of local landscape, culture, folklore and even people, whose faces have been photographed and become part of local art. Toledo station can be therefore described as a social hub strictly rooted in Naples tradition, making art of everyday life and ensuring to passengers a welcoming, familiar environment underground.

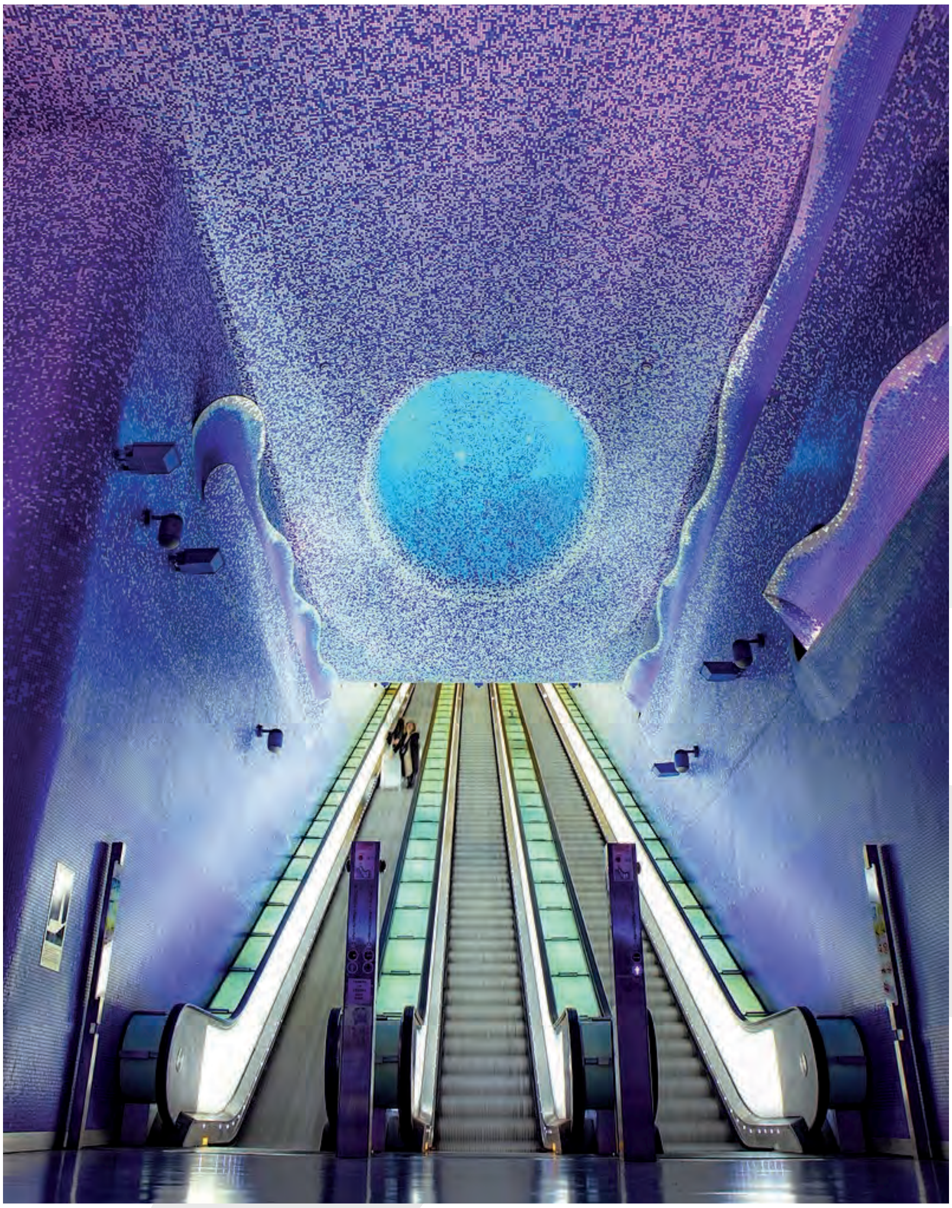

Figure 78: Toledo station, stairway to exit and mosaics (source: ParsonsPhotographyNL).

7 >> In Closing

The need to improve the resilience and sustainability of urban areas is urgent, in view of the impacts that climate change and ongoing world population growth pose. Compact cities are an effective solution to provide more resilient and sustainable urban regions. These are dense urban regions with emphasis on availability of facilities with minimum transportation needs; with an emphasis on cycling and walking as primary modes of transportation, more efficient energy use, lowered pollution levels and enhanced social interactions. Furthermore, they offer indirect benefits of shorter time spent on transportation, lower accidents and lower expenses.

Compact cities can be planned and realised only with engagement of various stakeholders such as municipalities, decision makers, city planners, engineers and architects. Therefore there is a need for compact city planning with a long-term goal of achieving integrated and efficient use of available space for economic activities, transportation and social interactions, and at the same time maintaining existing infrastructure without compromising the possibility of future sustainable developments.

Underground space utilisation plays a major role in the compact city development. This has been recognized by UN-Habitat and they have already proposed to promote the use of underground space to efficiently redevelop existing cities and plan newly developing ones. The benefits of compact cities can be noticed in various examples from around the globe. Underground shopping centres and underground transport hubs in Canada, Japan, Korea and China connect above ground buildings with underground commercial spaces, pedestrian walkways and rail/metro transportation networks and create extended indoor areas which offer many facilities for their citizens. Chicago's Pedway, with its 8kms of pedestrian underground network or Toronto's Path, connecting more than 50 office towers, hotels, department stores, and parking to the subway and train stations over its 29 km, as well as Montreal's RESO, with 32 kms of underground pedestrian network connecting 80% of office spaces and 35% downtown shops, are just some examples. Other examples of underground public facilities are found in Helsinki which offers an underground swimming complex, church and hockey rink among many other facilities. Compact cities like Helsinki and Milan have plans for further upgrades to their urban space and include the underground development in their master plans. These developments are promising and will be landmarks to a sustainable urban future.

Use of the underground can help make a city more resilient as underground structures are often more resilient to a variety of natural disasters, such as hurricanes and earthquakes, and to external environmental impacts such as noise and temperature change. In addition, underground placement of many utilities and other vital infrastructure improves their resilience and as a result that of the city.

On the other hand, underground structures are often more vulnerable to the impacts generated inside, such as fires, and internal flooding due to groundwater infiltration or surface floods. Careful planning and design allows underground constructions to counter these vulnerabilities and even create solutions for disaster resilient urban infrastructure, combating events such as extreme flooding. This report highlights pioneering cases from across the world, such as the SMART Tunnel in Kuala Lumpur; the Metropolitan Area Underground Discharge Channel in Tokyo; or the massive storm water reservoirs in Madrid. In addition, underground space has a number of inherent benefits, like temperature stability and the inherent strength of the surrounding soil that prove to be quite helpful to combat natural disasters even when it has not been specifically designed to do so. Eminent examples are earthquake resilience, seen in the aftermath of the 1995 Hyogo prefecture earthquake in Japan, and in heat wave relief experienced in Europe and particularly Paris in 2006.

Historically, ageing underground infrastructure may require adaptation to extreme weather events and natural disasters. While climate change and its urban impacts are growing challenges, many historical underground structures have not been designed to address those and may require upgrading and refurbishment to do so. Next to refurbishing, reusing and repurposing of existing underground facilities is becoming an increasingly important aspect in keeping existing cities vibrant and improving their resilience and compactness. Abandoned mines, old military complexes and shelters or disused transport tunnels all offer possibilities for reuse and can be given a new lease on life. Cities that embarked on reviving these facilities, providing them with a new needed purpose, improved on the resiliency of their communities and realised a more compact and efficient city in the process.

Finally, developments in construction technology offer many new possibilities. Advancements in tunnel boring allow for increasingly large diameter tunnels that would previously have been considered infeasible. These tunnels provide means to combine different transportation modes in a single tunnel, have two-way traffic on separate decks within a single tunnel, or combine road tunnels and storm overflow channels in the same construction. All these solutions provide more functionality at a limited footprint. And even though the construction activities for such new constructions have an environmental impact, careful management of excavated material and construction waste has lowered the impact in recent years, and the long term benefits offered by the reduced energy need of improved traffic systems and public transport facilities far outweigh the short term impact and investments. All in all, use of underground space can take many forms and shapes, from reusing old to creating new structures, and with integration in the existing city network can greatly improve the resilience and sustainability of both existing and new cities.

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