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Urban underground space: Solving the problems of today's cities ☆

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ABSTRACT

The world-wide trend of increased urbanisation creates problems for expanding and newly-developing cities alike. Population increase leads to an increased demand for reliable infrastructure, nowadays combined with a need for increased energy efficiency and a higher environmental awareness of the public. The use of underground space can help cities meet these increased demands while remaining compact, or find the space needed to include new functions in an existing city landscape. In many cases, underground solutions to urban problems are only considered if all other (above ground) options have been exhausted. When underground solutions are considered and evaluated from the planning or initial project stages onwards, more optimal solutions will become possible.

Use of the underground is not limited to large scale infrastructure projects. This paper also shows innovative use of the underground for commercial and residential use, storage, water conveyance and treatment, and heritage conservation, and highlights how use of underground can bring more optimal solutions for urban development.

1. Introduction

The world is increasingly an urban environment. Since 2008 more than half of the world population lives in cities and the world population is expected to increase to roughly 10 billion people over the next four decades. As the world's rural population is projected to remain stable in this period, that increase will occur in urban areas. By 2050, 70% of all people will live in cities and the world urban population will have more than doubled compared to the turn of the century (UN, 2007, 2013).

In developing countries, where most of this uncontained population growth will take place, the rapidly expanding cities will need to meet the increased demands for infrastructure. Without efficient transport infrastructure, cities will sprawl away from the urban core, which strains the environment by creating more traffic congestion and travel time, loss of valuable farm land, and inequitable allocation of resources (Longman, 1998; Chen, 2000). In the developed countries the urban expansion is less rapid, but the demographics of the population will change, with an increasingly large group over 60 (Angel et al., 2011). These population changes bring about new demands on the functions a city must provide and on the layout of the city, and call for continuous improvement in sustainable and resource efficient urban development (Camagni et al., 2002; Jenks and Burgess, 2000).

Although high urban density can help cities become more energy and resource efficient, urban density alone is not sufficient to obtain a high standard of living. Comparing the most densely populated cities with the most liveable ones (Wikipedia, 2015; Mercer, 2015) shows there must be other factors involved. This paper proposes that an efficient and integrated use of the underground is one of these factors and gives a brief overview of the possible solutions the underground offers to improve the factors contributing to quality of live: safety, health, convenience, and comfort (UN, 1961).

An urban population that is increasingly aware of the factors that improve quality of living, poses increased demands on their environment with respect to: reliable and safe transport of people and goods; dependable utilities, water distribution and sewerage systems; sustainability of the environment and limited urban sprawl; green spaces and recreational areas; reduced energy use and reduced emissions and noise levels; aesthetics and conservation of heritages; efficient use of real-estate and public space (Broere, 2012). In existing urban areas these demands pose significant challenges, as the space needed for developing new functions or relocating and improving existing ones is often not readily available. Placement of infrastructure and other facilities underground presents an opportunity to find the needed space, but it is often considered only as a last resort. This stems from a paradox, as the underground is considered only when surface space is

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exhausted and no other solutions exist any more for the complex urban problems to be tackled. This complexity and the obstructed access to the underground, created by the lack of space for the problem to be solved, almost inevitably lead to higher cost, giving underground solutions an expensive image, which in turn leads it to be considered less readily (Bosch, 2003; Bobylev, 2009).

In newly developing metropolises that paradox need not exist, as initially the access to the underground is not obstructed and unique opportunities exist, if engineers, city planners and decision makers can come together and recognize that in order to reach an optimal solution, the underground option needs to be considered and used from the start (Sterling et al., 2012). The rapid and unconstrained expansion of these cities is only part of the problem. Structured city planning that includes underground options is still limited to a few examples, see for example Vähäaho (2009) and Li et al. (2013). In general the awareness that the underground offers a possible solution for urban problems remains low, even though the issue has been raised on numerous occasions, e.g. Webster (1914) and Sterling and Carmody (1993). Recently Working Group 20 "Urban Problems – Underground Solutions" of the International Tunnelling and Underground Space Association (ITA) presented an overview of exemplary projects highlighting underground solutions to typical urban problems, in a renewed attempt to raise this awareness (Thewes et al., 2012). WG20 was founded in 2002 as part of ITA in order to identify urban problems that have been solved, or could have been solved, by the use of underground space or facilities, and to increase the awareness inside and outside the ITA. Other groups active in raising such awareness include the Committee on Underground Space (ITACUS), also part of ITA, and the Associated research Centers for Urban Underground Space (ACUUS), an international interdisciplinary association.

2. Urban underground solutions

Many dense urban environments face problems due to lacking infrastructure for transit, distribution of resources, goods and services. When paired with the demands listed above, these problems can be elaborated to include: traffic congestion; poor environmental conditions due to noise and air pollution; lack of safety, security, and protection against natural disasters and flooding; crowding and lack of space for work and recreation; restrictions when preserving aesthetic qualities and (cultural) heritages of the urban environment; aging infrastructure for distribution of resources, sewage conveyance and treatment; and combination effects of the above.

2.1. Traffic congestion

Probably the most recognized problem is the need for congestion relief in city streets. Time can be saved by using separated rail systems in order to reduce the rush hour traffic pressure. Hundreds of hours per worker per year can be saved in this way, as the cost of congestion in OECD countries is estimated to be equivalent to about 2 percent of the GDP (Godard, 2008).

But mass transit systems offer other benefits, as they tend to require less surface area than road traffic. Studies show that car traffic takes up 30 to 90 times more space than metro systems. Similarly, public road transport takes 3 to 12 times more space (Thewes et al., 2012). By moving from above ground car traffic to underground mass transit systems, enormous amounts of surface land can be freed up for other uses.

Continually improving tunnelling and excavation support technology adds to the success of urban rail systems. Advances in Tunnel Boring Machine (TBM) technology now allow tunnelling in more difficult ground conditions – even below the ground water table – with little disturbance to the surface. The surface influence is nowadays limited enough to realize bored tunnels even in highly sensitive city environments with protected cultural heritages, such as for example the historic city centres of Amsterdam and Rome (Burghignoli et al., 2013).

2.2. Pollution and noise

Highway noise and emissions from vehicles are recognized as pressing problems in urban areas. In order to reduce the noise impact, sound barriers may be erected, but the visual impact of such measures is major. It is often the case that residential property values near freeways are reduced due to high noise levels from cars and exhaust emissions. Also, there are associated health and safety issues for living close to a freeway.

Once again, moving passenger transport from cars to mass transit systems can reduce the noise and pollution impact at the local level, but also at a larger scale as mass transit systems tend to be more energy efficient and substantial energy savings can be obtained by the increased use of metro systems.

Alternatively, over the last few decades, many cities have constructed ring roads and roadway tunnels to improve their traffic conditions and to adapt the road network to the predicted demand. At the same time the travel times have improved and the impact of traffic on the surrounding residents has been reduced. Now, with city developments encroaching on existing ring roads, several cities have started to move surface sections of these ring roads below ground in order to further reduce their impact. Some examples are the double-deck tunnels in the A86 in Paris, the large diameter tunnels for the M30 in Madrid or the cut-and-cover tunnels for the A10 in Amsterdam (Samuel, 2006; Arnáiz and Bueno, 2009; ZuidAs, 2015).

An even greater impact on their surroundings may be caused by the elevated highways, mainly constructed in the 1950s and 60s in a number of, mainly US, cities; for example Boston, Seattle, and San Francisco. These giant elevated structures through down-town areas are now seen as unsightly, noisy, possibly unsafe, and provide only limited access to areas adjacent to the freeway. Many cities are considering or in the process to replace the elevated highways by urban road tunnels. An example is the Alaskan Highway in Seattle, which when completed will be the largest diameter bored tunnel in the world (Gatti et al., 2013).

These transitions from surface or above-surface roads to underground solutions in more or less the same location are often complex and costly. While the original decision to build these roads above ground often focused only on direct construction costs, decision makers should include real-estate impacts, structural life span, and long-term sustainability when making such choices. This would help to avoid such unfavourable situations and reduce the life time cost of urban transport.

2.3. Protection against natural disasters

With concentration of population, urban areas are particularly vulnerable to failures in infrastructure due to ageing of the systems or those caused by other natural forces. Growth of population not only means more people are relying on the infrastructure, but at the same time that the man-made facilities may increase the severity of the disaster. For example, urbanization means more paved area leading to more severe flooding, as well as loss of water resources recharging groundwater.

Underground rivers can be constructed to increase run-off or divert storm water. Large diameter tunnels have been bored below cities such as Buenos Aires and Tokyo for this purpose (Dal Negro et al., 2012; Miyao et al., 2000). The SMART tunnel in Kuala Lumpur takes this concept a step further, as this tunnel functions as a road tunnel during dry periods and is closed off for traffic and used as a storm-water tunnel during flooding periods (Abraham, 2008).

Also, it should be realised that the underground may provide a setting that is difficult to build in, but that underground structures offers better natural protection against environmental elements, including destructive weather and seismic events. Underground facilities and metro systems are less prone to earthquake damage have suffered little or no damage in major earthquakes (Wallis, 2010; Tashiro and Mutou, 2013).

2.4. Lack of space and preservation of heritage and environment

Most of the underground examples above are not intended for a long-term human presence. This stems from the human preference to live, work and recreate above ground. Historically, underground structures were primarily intended for shelter or served as entry and connection points for mass transit systems. Over time, a wider range of functional facilities has taken up underground residence, but often still with a short intended stay for individuals below ground. Mostly the aim was to free surface space for other human needs and to improve the living conditions of cities. Examples such as underground car parks, shopping malls or underground storage facilities have been documented by Thewes et al. (2012).

Recently, the aim is more and more to not only keep surface space free and to create new space and functions, but to do so in a manner that preserves existing buildings and cultural heritages. This is especially true for public functions housed in historic monuments. A few examples of museums with newer underground extensions are the Louvre in Paris, the Rijksmuseum in Amsterdam and the Mauritshuis in The Hague. In all these cases additions to existing monuments have been realized without lowering the visual quality of the original buildings, and at the same time creating new floor space, with limited access points and a small footprint in order to preserve the security of the buildings and their collections.

And such underground extensions to monumental buildings are not limited to public buildings, but nowadays also include private residences, with the iceberg houses of London as the grander examples of the possibilities the underground offers (Reynolds, 2015).

2.5. Utilities and infrastructure

Focusing on the larger underground facilities it is easy to overlook the many utilities that are traditionally placed below ground. As discussed in Bosch and Broere (2011) the increasing amount of different utilities that is placed in the shallow subsurface strains the available space in the utility layer. Especially the addition of separated sewage systems for household waste water streams and storm water and of distributed heat-and-cold storage systems or shallow geothermal systems requires a large underground footprint if all placed directly in the ground. If not properly regulated and zoned, the increasing number of utilities creates underground space shortages in the shallow subsurface utility layer, and often causes increased surface disruptions given the increased number of parties that needs to inspect, repair or replace their underground utilities.

Utility tunnels, small tunnels placed at shallow depth that in turn contain cables and ducts for different utilities, are a solution here. Not only do they reduce the effective footprint for utilities, as they can be placed closer together inside the utility tunnel, but these utilities can also be inspected and repaired without the need to dig in the subsurface. Hunt et al. (2014) shows that already for a limited number of utilities such a multi-utility tunnels can be cost effective.

Not only utility pipelines, but also the associated treatment plants and facilities can be placed underground. Underground waste water treatment plants such as in Stockholm, Rotterdam or Guangzhou City show how such facilities not only free up space at surface, but also reduce the olfactory impact to neighbouring residences normally associated with these plants and help reduce the overall environmental impact of waste water (Watertechnology, 2015; Waterworld, 2010).

3. Conclusions

Underground development is an important tool in developing and reshaping urban areas to meet the challenges of the future. Placement of infrastructure and other facilities underground presents an opportunity for realizing new functions in urban areas without destroying heritages or negatively impacting the surface environment, and at the same time brings opportunities for long-term improvements in the environmental impact of cities and more efficient use of space and resources. These benefits are there for existing, redeveloping cities, but can be implemented for newly developing cities more easily and more cost effectively, for even greater benefits.

The number of examples given in this paper is limited, but already in this small set it can be observed that many of these underground solutions can solve or help improve multiple of the problems that urban developments face: traffic congestion; environmental problems; lack of (green) space; need for protection against disasters; lack of infrastructure for food, energy, water and sanitation.

When planning and developing cities, the underground should not be overlooked by planners, engineers and decision makers. Raising the awareness of the benefits underground space can bring is a first step towards a systematic use of underground space in urban environments.

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