Challenges in Going Underground in Big Cities

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ABSTRACT: The hearts of many large cities are already congested. City planners are looking for ways to accommodate more people and to supply their needs including means of transportation. High rise buildings, descriptively called "sky scrapers", are common and going higher does not necessarily solve the problem. Increasing the number of people in a congested area severely overtaxes the infrastructure with no space to expand it. Enclosure by sub-urban development inhibits lateral development. The next place to look is underground. Already many buildings have basements, already there are many subways for pedestrians, for metros and for roads and in several cities these are inter-connected. However, if one digs a hole in the road one will encounter lots of utilities and as more metro lines are developed they cross each other and construction to shallow depths in developed urban areas becomes deeper encountering more obstructions and can be very expensive. This paper reviews some of the challenges that face planners and geotechnical engineers when considering how to strategically plan urban development in major cities by going deeper underground.

Keywords: Caverns, Basements, Underground, Planning

1. INTRODUCTION

The last several decades have seen a remarkable increase in the rate of growth of large cities. In particular in South East Asia during the last forty years or thereabouts many cities, such as Hong Kong, Singapore, Taipei, Bangkok, Delhi and others have constructed large capacity, efficient underground rail systems. At the same time, an increasing number of basements have been constructed. Basements have been adopted because of planning limitations on height above ground, and because of needs to locate car parking and utilities below ground. Ground floors have become select and lucrative shopping zones. Because of opportunities to link basements and subways to underground railway stations thereby bringing pedestrians into basements of adjacent buildings, basements are becoming used increasingly for underground shopping malls, for food courts and for other facilities that people can use and enjoy.

Underground construction has demanded the services of geotechnical engineers. Some forty years ago it was common for geotechnical engineers to be engaged only in ground investigation and site characterisation whilst structural engineers designed the structures. However for excavations in excess of 5 metres deep, the effects of locked-in construction strains and the economy of taking into account soil/structure interaction have extended the role of the geotechnical engineer to include design of earth lateral support and to determine the effects of the construction on surroundings ground and structures and thereby assume the role of ground engineering.

In many cities nowadays underground construction from the surface downwards is extensively developed. Some basements have become very deep, such as six or more floors and underground railway stations are forced deeper where successive new lines cross underneath older shallower lines.

It is becoming increasingly common for ground engineers to construct new facilities below existing structures by using mining techniques and ground engineering skills become aligned with tunnelling skills. Designs involve interaction with overlying soil enclosed conditions and analyses of soil deformation that were computed in plane strain, say for the excavation of deep multi-strutted Earth Lateral Support (ELS), now require three dimensional analyses that are much more complicated. Whereas engineers can meet the challenge of going progressively deeper below ground, the numbers of obstacles to construction are generally increasing rapidly, the inherent variations in ground conditions feature more and more prominently and give rise to increased geological risk, for example the uncertainty of mixed ground conditions, and overall the costs for construction are doubling and redoubling. It gets to the point that for some tricky projects the contractors do not even want to bid for the work.

From the planner's perspective, the demand for growth is high in already congested city centres and is a problem. Urban renewal is one solution but even if buildings are replaced by higher buildings the increased population needs servicing with utilities and transportation and transportation corridors are often overflowing and utility reserves below the busy streets are already congested. Moreover much of the development below ground has been opportunistic. Locations of utilities are often on the basis of "first come first served" and are not methodically planned and there is often no room for upgrading.

To a geotechnical engineer the way forward is obviously to go deeper underground. The idea is to locate new works clearly beneath previous developments, to start afresh in unencumbered ground, and whenever possible to locate within horizons of more uniform ground where the geological risks are much reduced and the construction methods can operate faster, more reliably, and at cheaper rates.

2. PLANNING THE USE OF DEEP UNDERGROUND SPACE

Several Government agencies have recognised the value of planning the use of underground space. The foremost examples are Helsinki and Montreal where there are extensive networks of basements, connecting subways and underground transportation systems see Figure 1.

Figure 1 Part of the undergound network at Montreal

This model has been copied in many cities, in particular where connections form basements can be made to new underground railway systems. In Singapore, basement connections linking the surrounding developments to underground train stations are planned upfront. Developers are required to build these links and provide public right of way, through planning conditions. Moreover combined utility tunnels have been implemented in Singapore's new downtown area at Marina Bay, to minimise road opening for the laying of utilities, see Figure 2.

Figure 2 Combined utility cable tunnel

Many cities in South East Asia have multiple underground connections between basements, subways, and transportation corridors. However these measures are related to underground developments that are near to the surface. By contrast, planning for the use of deep underground space is less popular.

Deep underground development in soil and mixed soil and rock is difficult and expensive whereas development of caverns and tunnels in rock are comparatively less expensive. For several decades caverns in rock have been used notably for storage of oil and other utilitarian uses. Caverns for occupational uses such as sports facilities have featured in Scandinavia for many decades. Some of the early caverns were created by quarry operators who marketed the crushed rock for civil engineering projects thereby producing caverns at very low cost, or even at a premium. Iconic developments in rock caverns are the magnificent Gjovik Sports and Concert hall in Norway in a cavern that is 91m long and 61m wide, see Figure 3.

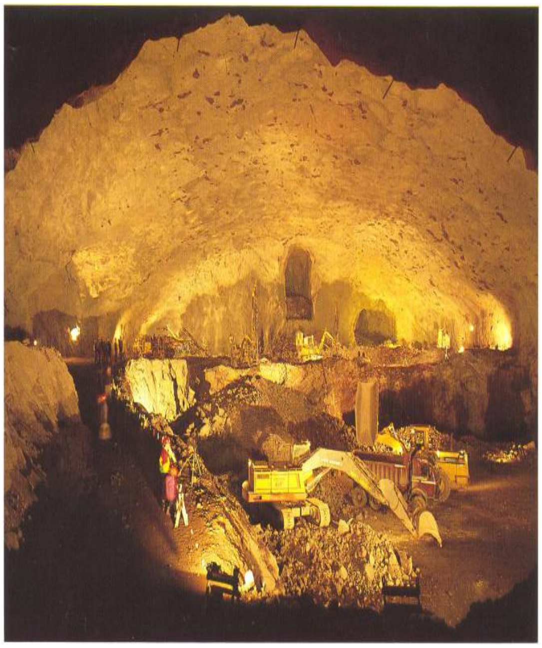

Figure 3 Excavation for Gjovik Stadium, Norway (Photo NGI)

Systematic planning for development of caverns for various uses is not yet common. Hong Kong Government commissioned studies commencing in 1990 (ARUP (1989), (1991) & (2001)). The latest of these studies identified locations that would be suitable for development of caverns and uses that could be planned for caverns. There focus has been on institutional use and completed projects include a sewage treatment works at Stanley for 35,000 people, see Figure 4, two explosives stores, a refuse transfer station and a salt water reservoir.

Figure 4 Sewage treatment works at Stanley, Hong Kong

Design is underway for a sewage treatment facility in caverns serving a population of 800,000 people at Sha Tin in Hong Kong and further studies are underway for more uses of underground space.

In Singapore, steps are being taken to safeguard deep underground spaces for suitable uses, based on the geology and compatibility with surrounding uses. This will be done as part of Singapore's long-term strategic planning process. Upfront planning will also ensure that access points and any supporting facilities at the surface can be provided for at the master planning stage e. Current projects include large caverns, already constructed by Jurong Town Corporation for lease for storage of oil, and a planned warehouse and data centre (Chan et al 2014), a planned Science City (Figure 5), and some other uses.

Figure 5 Proposed Science City, Singapore
(Photograph courtesy of Jurong Town Corporation)

Singapore and Hong Kong have special planning restraints. They have limited territory and a high density of population. The limited areas of land are already intensively developed. There has been extensive reclamation to create more land but more fill is in short supply. Therefore it is a logical and practical to include extensive underground space in their strategic planning. However planning for extensive use of underground space should be considered for the centres of other major cities in South East Asia which are already congested and are surrounded by extensive suburbs or metropolitan areas.

3. GEOTECHNICAL INPUT TO PLANNING UNDERGROUND SPACE

3.1 Urban Planning

Urban planners need input from other disciplines including geological and geotechnical input. Amongst several factors to be considered when drafting a strategic plan, a base plan of the underlying geology is usually included but for planning underground space it is essential.

Strategic planning of the surface is usually based on allocation of permitted uses of land and is defined on two dimensional plans. In strategic plans major features are included such as expansion of urban areas and identification of new urban areas, allocations for rural uses such as farming, mining, and nature reserves as the case may be.

Strategic planning is not detailed. Details are developed in master plans drafted in compliance with basic principles of the strategic plans such as overall zoning of land use and occupation. Master plans are predicated on current needs and on financing. They develop the block layouts within the overall current strategic plan. Master planning takes strategic plans forwards for implementation. Master planning considers means of access for otherwise enclosed land, and reserves for various uses such as transportation corridors and utilities and defined and these often lead to blocks of parcels of land, at the surface, for which there will be a planned use.

Master planning for underground development has two major differences compared to planning at the surface. Firstly the planning can be carried out in three dimensions with development including access at multiple levels. In this respect, it would be preferred to locate uses with large populations to be nearer to the surface to facilitate means of access and escape. Whereas activities with minimal population, such as warehousing or storage and areas with restricted access and requiring less access, could be located at greater depths. Likewise Emergency Vehicle Access (EVA) can be facilitated. EVA is a reserve at ground level and emergency evacuation and fire suppression is therefore limited in height by the reach of ladders from ground level. Below ground EVA could be provided at a range of depths, for example by a spiral ramp with connections to the occupied space at several levels. Secondly planning considers rights of way that are necessary on the surface. Similar rights of way will apply for deep development, not only through, but potentially above and below other property. Notably, right of access to air is almost taken for granted at the surface whereas below ground access to air and exhaust of stale air has to be provided and therefore air supply and exhaust become a utility for which provision should be made including reserves of space with connection ultimately to and from the surface.

3.2 Role of the Geotechnical Specialist in Planning

The role of the geotechnical specialist for master plans is primarily in site characterisation for purposes of planning the disposition of facilities such as route selection for road and rail, and optimisation of location of important facilities. For Master Planning involving underground space such as caverns and tunnels and associated structures the site evaluation is important so that these may be determined in a balanced manner taking into account all of the relevant opportunities and restraints. For this purpose it is common to use a Geographical Information System (GIS) whereby all geological data, along with other site data and spatially determined planning parameters, are filed and accessible and can be weighted for quantitative comparison of alternative scheme.

Fundamental to development within rock is the identification of the top of the rock and the disposition of the types of rock and their structure. Often there are a preferred structural directions such as are defined by adverse features to be avoided such as faulting and zones of deep weathering. There are other factors such as in situ horizontal stresses and by tightness of joints that affect the need or not for structural support and which control conductivity to ground water. Such features govern the cost and time for construction and possible maintenance costs in the future.

When a master plan is adopted, specific projects are identified and then they are progressed through stages of planning, preliminary and detailed design, and construction.

At the planning stage of a specific project, the geotechnical engineer's role is similar to that at the stage of master planning but the activities, for example of site characterisation are carried out in more detail. Site specific ground investigation (GI) is carried out. Methods of GI are well documented. However of particular value to describe in this paper is rock coring at the location of the caverns especially using directional coring for access from an off-site location or to core in a specific orientation within the location of the caverns. Ground water is often an issue and packer tests are often used and it is important to note that a test of outflow by applying a positive pressure will often result in a larger flow than is measured by pumping out and measuring inflow in the same rock between the same locations of packers and that, tests in boreholes at different orientations can identify anisotropy in the hydraulic conductivity of the rock, see Figure 6.

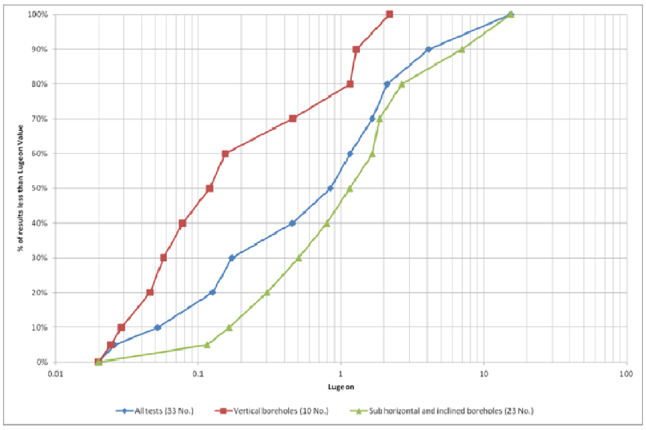

Figure 6 Lugeon tests carried out at different inclinations in Granite in Hong Kong

Another important activity is the determination of initial and permanent support of the tunnels and caverns. As a guide, the cost of a permanent structural lining to a tunnel can approximate to the cost of excavating the rock from a tunnel. Conservatively including unnecessary structural lining can double the cost of the civil engineering works of constructing the caverns and tunnels.

The final stage of planning in this context is the preparation of detailed design for construction which includes the detailed planning of the temporary stages of construction. At this stage, the ground characterisation should be well developed and specific ground conditions should be determined for purposes of design. Tasks that are specific at this stage are to predict or estimate the interaction between the construction and the surrounding ground and property. There are two related issues, ground water and ground movement. These are very important at relatively shallow depth and in developed areas. Fundamental to any civil engineering is to design to prevent collapse. Likewise design is required to prevent excessive inflow of ground water. It is also very important to limit the ground movement and dewatering. For construction in very deep competent rock, little or nothing may be noticed at the surface. However for shallower works and certain types of rock the effects can be unacceptable at large distances. For example, subsidence of the ground by 1 metre was recorded contemporaneously with pumping out water from a tunnel that was excavated more than 90 metres below the level of the site and was designed to be at least 30 metres below the top of the bedrock, see Figure 7.

Figure 7 Subsidence of more than one metre

Furthermore draw down of ground water and consolidation of overlying soils was recorded over 2 kms from the tunnel but not uniformly. (Endicott 2014)

Geotechnical and tunnelling engineers will be familiar with an empirically derived method for estimating the subsidence of the ground above a tunnel as it is mined. The method assumes that vertically above a tunnel the ground settles as a trough and the shape of the settlement trough overlying the tunnel is assumed to be a Gaussian curve. (Ref: Mair 1993) See Figure 8. Parameters of bulk stiffness modulus and Poisson's ratio are used to characterise the ground whether it is a type of soil or a type of rock. In many cases the results provide a reasonable estimation and sensitive structures are identified and monitored or supported to with stand the deformations as appropriate. However over dependence on this method is not advisable because, for example, in fractured rock the deformation behaviour can be anisotropic. Simple numerical modelling shows that the subsidence trough can be offset to one side of the tunnel and the potential collapse mechanism can be offset to the other side (Ref: Mirlatifi et al 2014). For excavations in rock a proper understanding of rock mechanics is necessary.

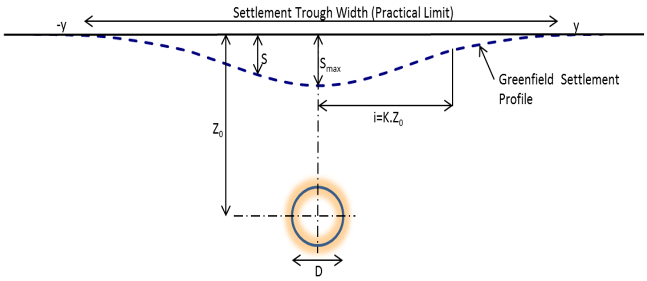

Figure 8 Prediction using Gaussian Method (from Mirlatifi et al)

For deep caverns the in situ stresses can be fundamental to the stability of the cavern, especially if the horizontal in situ stresses are big. However, proper assessment is necessary. A popular method of measuring in situ stresses in rock is by over-coring. Of necessity, the rock that is unloaded is the piece of core and is only a few cms in diameter. For rock that is uniform horizontally this method should be reliable in vertical boreholes. In practice many rocks are not very uniform horizontally. An example is tropically weathered igneous rocks, such as Kowloon Granite in Hong Kong where dominant sub-vertical joints have weathered to Grade V saprolite soil with a density reduction from 2.6 T/m2 to, say 1.8 T/m2 which, on account of leaching, one would expect a release of stress or strain in the rock yet excessive horizontal stresses have been reported. Surely when evaluating in situ tectonic effects it would be better to evaluate strain in a geological body since the heterogeneous stiffness would result in different stresses measured in the same fields of strain. Measurements interpreted as strain are more uniform. (Ref Gray 2014)

3.3 Mistakes can happen

Geotechnical engineering is based on simple concepts. Although several sophisticated tools are in use they are simple to operate, and easy to get an answer that is wrong. Simple concepts can be easily copied and easily misapplied and mistakes of insupportable magnitude can happen. For example in 2004 the Nichol Highway in Singapore collapsed as a consequence of the collapse of temporary works for a tunnel that would have been over 30m deep. (Ref COI 2004) There was inadequate design of a very simple detail of the connection between a steel strut and the waling beam. The detail was used for several layers of strutting. Such connections have been a standard detail for decades with gusset plates which are inexpensive and effective. There was a misunderstanding of the real time on-line monitoring such that men were working more than

25 m below ground whilst the steel strutting system was failing progressively around them and four workers were killed. At the start of the design of temporary works there was a misunderstanding of how to use a computer programme. Although there is some excellent work around I have seen these same mistakes repeated.

4. CONCLUSIONS

Planning

Many large cities in South East Asia have congested central areas with ongoing demand for occupiable space, utilities and transportation.

Where the near surface underground space is also congested then a logical alternative is to develop deeper underground space.

Around the world there are many uses for underground space. Strategic planning such as on a rolling 30 year programme should plan now for developments in the future and underground space should be included.

Professionals

Geologists, geotechnical engineers and tunnelling engineers have an important role to play at all stages of the process. They should give basic advice on the geology of the planned area for strategic planning. They should give more detailed advice for Master Planning. This should include a geological study of the rock head, the rock types and the rock structure to play a role in the determination of the layout, orientation and sizes of the caverns and tunnels.

For planning of specific projects specialist skills are needed in more detail than in the master planning stage for the development of a basic plan into viable schemes.

For the design of a specific project there is planning of the methods of construction. This planning requires a good understanding of the expected ground conditions and should provide mitigation of geological risks. Mining in rock requires a good understanding of rock properties and behaviour. The process requires reasonable estimates of the effects of the construction on the surrounding areas including lowering of ground water and settlement of the ground and buildings. The design should include the necessary monitoring and remediation measures where necessary.

Mistakes can happen

Much of geotechnical engineering relies on simple concepts. These can be readily copied and run the risk of applying them incorrectly. For these large projects the consequences of misunderstanding or incorrect work can be very costly and at times fatal.

It is essential that the industry observes good practice and makes sure that mistakes do not happen.

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