Numerical Modeling of Underground Space Design for Livable Urban Areas

Wai Yee Soo[1], **Jay Lee**[2]
1 Associate Director, AECOM, Kuala Lumpur, Malaysia
2 Associate Director, AECOM, Melbourne, Australia

人口の過密な都市部ではインフラ整備に利用できる空間が限られており、都市景観を守るためにも地下空間の有効な活用は不可欠。マレーシアやシンガポールの例に基づき、都市部における地下空間設計の課題を探った。

Abstract

As populations grow in dense cities, so does the demand for space and natural resources. As an option to combat this problem, a growing number of attempts have been made to build underground structures even in the forest of tall buildings, which aids transporting an ever-increasing abundance of resources into the city. The use of underground spaces can help cities meet these increased demands while remaining compact without destroying natural landscapes. Underground spaces have been widely utilized for storage, water conveyance, and power transmission in highly populated urban areas. The development of underground spaces is now becoming essential to the sustainable growth of cities. Recent development of computer simulations for underground structure construction has enabled planning underground spaces under difficult urban environments even in the early stage of various projects.

This paper presents successful cases of underground construction in Kula Lumpur and Singapore with employing computer simulations implemented to achieve safe and robust design and construction of deep excavation and tunneling in a tight time frame, and highlights how the numerical modelling can facilitate saving time and effort for challenging urban construction. The use of underground spaces with aid of numerical simulations can bring more optimal solutions for urban development.

Keywords underground space, sustainable urban development, numerical simulation, finite element analysis

Introduction

Urban areas keep sprawling rapidly over the past decades like seen in mega cities such as Singapore, Hong Kong, Shanghai, Seoul and Tokyo. As populations grow in dense cities, so does the demand for space and natural resources. As an option to combat this problem, a growing number of attempts have been made to build underground structures even in the forest of tall buildings, which aids transporting an ever-increasing abundance of resources into the city. The use of underground spaces can help cities meet these increased demands while remaining compact without destroying natural landscapes. Underground spaces have been widely utilized for storage, water conveyance and treatment, and power transmission in highly populated urban areas. The development of underground spaces is now becoming essential to the sustainable growth of cities. Underground solutions to urban problems tend to be only considered if all other above ground options have been exhausted. However, lessons from past experience reveal more optimal solutions will become possible when underground solutions are considered and evaluated from the planning or initial project stages onwards. Recent development of computer simulations for construction of underground structures has enabled planning underground spaces under difficult urban environments even in the early stage of various projects.

This paper presents successful cases of underground construction in busy urban areas with employing computer simulations implemented to achieve safe and robust design and construction of deep excavation and tunneling in a tight time frame, and highlights how the advanced numerical modelling can facilitate saving time and effort for challenging urban construction. Challenges and difficulties encountered in each case are itemized with numerical solutions adopted presented. The cases presented demonstrate how numerical simulations can aid the design and construction of underground spaces.

Sustainable Development Utilizing Underground Spaces

Rapid urbanization has produced many urban problems such as the need for more housing, roads and railways, water and power distribution systems, sewerage systems, reduction of air and noise pollution and other population growth issues. 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. All these problems should be indispensable for the sake of sustainable development of urban areas.

Past studies have demonstrated the benefit of utilizing underground spaces for smoothing issues associated with dense urban environments due to lacking infrastructure for transit, distribution of resources, goods and services (Boere, 2012, ITA, 2012). The urban problems that may be solved through use of the underground space include:

- Crowding and lack of space (for work and recreation),
- Traffic congestion,
- Aging infrastructures and distribution of resources,
- Environmental conditions such as noise and air pollution,
- Esthetic qualities and image of our urban environmental quality,
- Safety, security, and protection against natural disasters,
- Flooding,
- Sewage conveyance and treatment, and
- Synergy effects of the above.

Probably the most recognized problem is the need for traffic congestion relief in city streets. A number of cities have realized the need for a sustainable approach with regard to their overall traffic planning. Cities like Melbourne and Sydney where the population rapidly grows have shown a strong need for action utilizing underground options (ABC News, 2018). Urban rail systems can significantly save time and cost by providing separated rail systems for commuters in urban areas. Mass transit systems offer other benefits, requiring less surface area than road traffic. By moving from above ground car traffic to underground mass transit systems, enormous amounts of surface land can be freed up for other uses. Continual expansion of underground urban rail systems adds to the success of sustainable urban development.

The use of underground spaces extends to many applications for the sake of sustainable and environment friendly urban development such as parking, sport facilities, and resource storage. These facilities turned out benefiting not only from saving the occupation of costly surface land but also from saving cost for operation by taking advantage of constant temperature in the ground, which helps keep the running cost for cooling and heating minimized. Fig. 1 and Fig. 2 show the unique use of underground spaces in Finland and Japan.

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 or their combination. Growth of population not only indicates the reliance of more on the infrastructure, but at the same time that the man-made facilities may increase the severity of the disaster. For example, urbanization with increasing paved areas has led 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 illustrated in Fig. 3 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 (ITS International 2012).

It should be also noted that underground structures and metro subway systems have shown excellent earthquake performance of underground structures even against major earthquakes in earthquake prone areas such as Japan (Tashiro and Mutou, 2013).

Fig. 1. Underground swim pool in Helsinki (City of Helsinki, 2014)

Fig. 2. Underground LPG storage (Japan Oil, Gas and Metal National Corp et al., 2014)

Fig. 3. SMART multi-purposed tunnel in Kuala Lumpur (ITS International, 2012)

In addition, analysis of carbon footprints for trenchless and open-cut methods for underground freight transportation has revealed that the total CO_2 production could reduce to one sixths by adopting trenchless method as opposed to open-cut method (Tavakoli et al., 2017).

Even if underground solutions have environmental and disaster preventing benefit for sustainable development in urban areas as mentioned above, there have been debates on cost implications when a decision is sought for aerial (surface) versus underground (tunnel) options. The fact that the initial capital cost of underground projects tends to be markedly higher than for surface solutions mostly leads to the less costly option employing surface solutions such as bridges/viaducts or massive buildings. However, apart from real-estate impacts associated with surface structure solutions, when long term operation costs are considered in addition to direct construction costs, underground solutions would be an option to avoid disappointment in supporting sustainable urban growth.

Challenges and Difficulties Encountered for Underground Space Design in Urban Areas

Despite the benefit of underground solutions in urban development discussed previously, challenges have been encountered when underground structures were built in urban areas including:

- Excessive ground deformation due to uncertainty and irregularity in the ground conditions resulting in delays and harm on workers and/or residents
- Interference with existing structures both under and on the ground surface
- Hindrance due to underground obstacles such as abandoned piles
- Ground water regime changes and their impact on existing structures in an urban area
- Restrictions in time and space to fix up problems occurring underground in an urban area

So far hit and miss methods as well as empirical methods have been routinely used in practical design of underground structures even in an urban area. However, it is becoming more compelling to assess the impact of new structures on existing structures as well as the interactions between closely spaced structures in the ground using advanced analytical techniques ideally combined with feedback from monitoring and instrumentation during construction.

Numerical simulations have enabled assessing the implication of uncertainties borne in the ground and the interactions between the tunnel / underground structures and surrounding ground including the impact on existing structures standing on the ground. Be employing numerical simulations it has become possible to identify locations where construction risks arise and establish mitigation plans in advance, which has enhanced the credibility of underground development schemes in progress and to be planned.

Utilizing Numerical Simulations for Underground Space Design

Numerical simulations have enabled engineers to predict the behavior of underground structures in a realistic way even under complex / extreme loading conditions in complicated ground conditions. Numerical modeling is used as control method in reducing the risk of tunnel construction failures. Since some factors such as settlement and deformation are not completely predictable in rock and soil surrounding the tunnel / underground structure because of the complexity and irregularity of the soil and rock characteristics in nature, using numerical modeling is a very economical and capable method in predicting the behavior of tunnel structures in regard to various complicated conditions of loading. Another benefit of using numerical simulation is in the visual effect with colorful illustrations predicting the tunnel behavior before, during and after construction and operation, which help engineers and operators proactively deal with possible problems occurring to the tunnel / underground structure.

In general, numerical modeling in designing underground structures has the following key benefits:

- Fast and systematic solution over spatial variation
- Possibility of using more realistic non-linear material behavior
- Solution of coupled phenomena
- Fast parametric evaluation.

Particularly three dimensional (3D) numerical modeling is the only effective way to predict the interference in between neighboring structures to be built under the surface in a realistic way. With the recent advances in technology for numerical modeling, 3D numerical modeling has been more often used in various project phases.

Given that 3D modeling aids avoiding potential harm on both existing structures and the underground structure in construction of underground spaces, numerous attempts for 3D modeling have been made in the design of underground transportation infrastructures, lifelines, and other storage facilities in urban areas such as Singapore where the land usage is limited. Three actual cases where 3D numerical modeling was carried out to assist with the design of underground infrastructures are discussed in the following sections.

Case 1 - Singapore cable tunnel and shafts

Transmission corridor cable tunnels were excavated at a depth of 45 m to 80 m below ground level in Singapore to expand the power grid networks. The underground power grid system typically consists of permanent shafts, cable tunnels, and short adits between the shaft and tunnel as shown in Fig. 4.

Temporary shafts and mined tunnels were proposed during the construction in order to expedite the construction progress so that Civil and Structural and Mechanical and Electrical fit-out works for the equipment building above the permanent shaft could be carried out after the tunneling works without substantial time delays. Due to the complex geometry comprising multiple temporary and permanent tunnels and shafts in a limited space, there were concerns relating to stress concentrations on the tunnel and shaft supports as influenced by the construction sequence and proximity of the voids to one another. In addition, there were existing buildings founded on piles in proximity to the deep shafts were located. The impact of the deep excavation and tunneling on the existing piled structures was also of concern.

Ground movement can take place not only due to the loss of ground in excavation but also in association with the variation of groundwater in the surrounding ground during the excavation. An excavation pit needs to be kept dry so that the construction works can proceed without disturbance from water seeping into the pit. Where the water in an excavation pit or tunnel is continued to be pumped out, the groundwater around the excavation draws down eventually to the steady state. This groundwater drawdown can cause changes in the stress regime in the surrounding ground, accordingly resulting in ground movement.

Therefore, where there is deep excavation or underground excavation for tunnel in the vicinity of existing structures like seen in the cable tunnel site as shown in Fig. 5, the design of the earth retaining system and tunnel support should prove to minimize the impact on the neighboring structures.

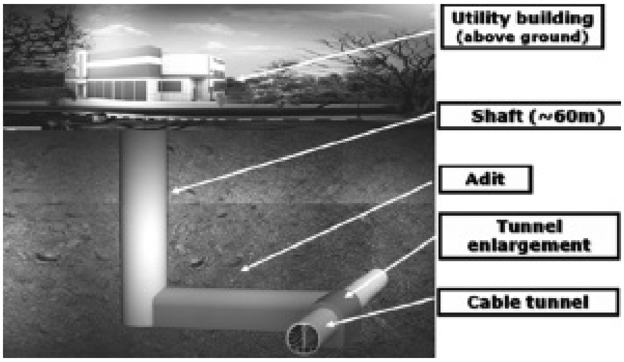


Fig. 4. Underground transmission corridor system

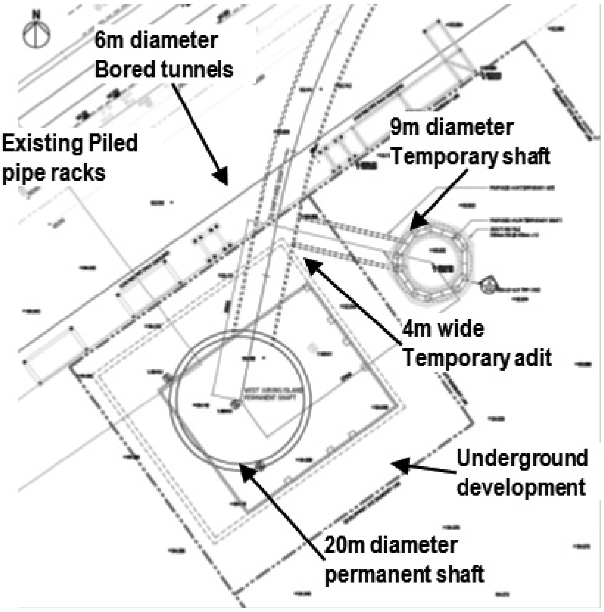


Fig. 5. Layout of cable tunnel and shafts

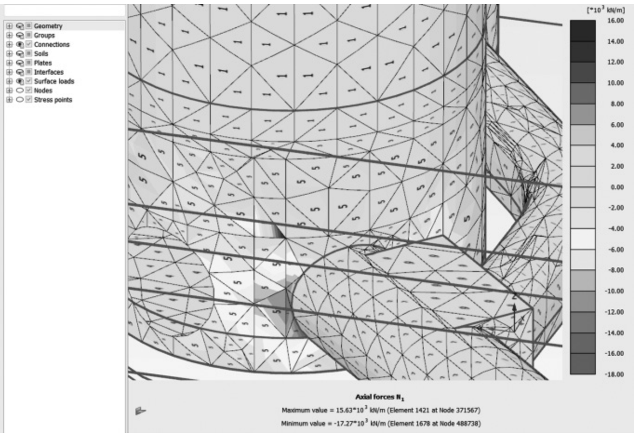
Two key issues were identified including potential harm on neighboring underground structures located close to one another, and potential impact on the existing surface structures founded on piles, which might be affected by ground movement induced from the deep excavation for the shafts and/or the tunnel excavation.

Challenges in design were found in assessing the influence of construction staging for closely neighbored underground structures and controlling potential risks related to the ground subsidence, which might result in damage to the existing pile-founded structures in the ground conditions where soft ground was present with a high groundwater level.

In order to quantitatively evaluate the influence of underground construction activities and their sequence, 3D finite element analyses were performed employing PLAXIS3D to evaluate the impact of excavation of temporary structures in close proximity to the permanent structures, including bored tunnel breakout from the temporary mined tunnel. Attention was paid to the deepest underground shafts, mined tunnels and bored tunnel break-out in country by the time the construction started. Also included was the prediction of ground settlement in accordance with the impact of deep excavation regarding changes on the ground water regime.

As a result of the 3D numerical analyses undertaken, stress concentrations were identified at different locations according to the excavation phases as depicted in Fig. 6. Ground settlement and deflection of the existing piles are also predicted to occur within a tolerable level as shown in Fig. 7 and Fig. 8.

The 3D numerical simulations undertaken facilitated the provision of reliable prediction on likely ground settlement according to deep excavation and tunneling that was used for the optimization of permanent and temporary shafts and management of risks to the existing surface structures without delays.

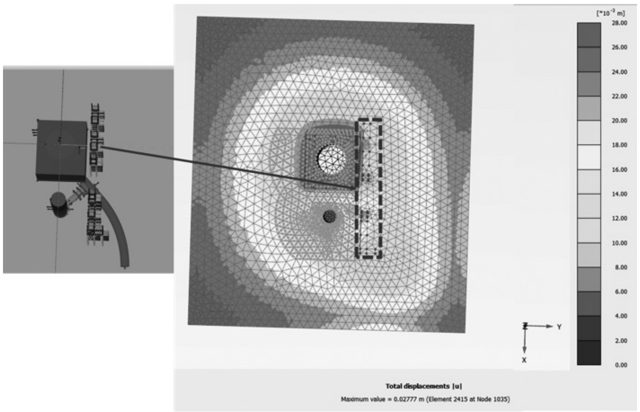


Axial forces N_1

Maximum value = 15.63*10^3 kN/m (Element 1421 at Node 371567)

Minimum value = -17.27*10^3 kN/m (Element 1678 at Node 488738)

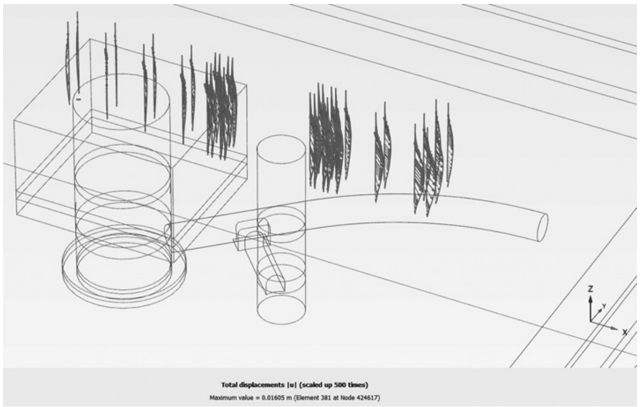
Fig. 6. Stress concentration captured by 3D modeling



Total displacements |u|

Maximum value = 0.02777 m (Element 2415 at Node 1035)

Fig. 7. Ground settlement predicted by 3D modeling



Total displacements |u| (scaled up 500 times)

Maximum value = 0.01605 m (Element 381 at Node 424617)

Fig. 8. Prediction of pile deflection due to tunnel and shaft excavation by 3D modeling

Case 2 - Cut and cover tunnel in the proximity to existing railway tunnels

New cut and cover tunnels were planned parallel to the existing railway tunnels. Due to the constraints in space the geometry of the excavation for the new cut and cover tunnels was designed to take a complex shape. The geotechnical investigation undertaken at the site indicated the presence of soft ground and variation of ground profiles, which was considered unfavorable for the stability of the earth retaining system for the excavation. Fig. 9 shows the layout of the new tunnels together with the existing railway tubes. Fig. 10 illustrates the bird-eye view of the site.

Key issues identified include the impact of the excavation on the existing railway tubes as well as the stability of the earth retaining wall under the constraints in space and difficult ground conditions. Since the edge of the excavation was only a couple of meters away from the wall of the existing railway tube, the deflection of

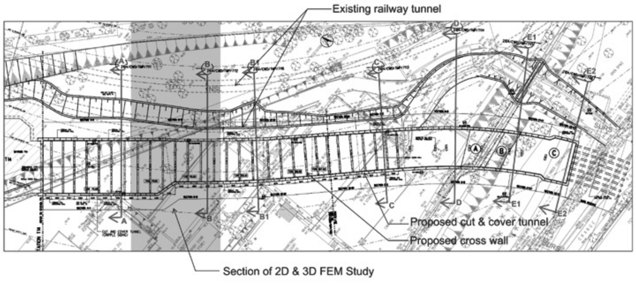


Fig. 9. Layout of cut and cover tunnel excavation in the vicinity of existing railway tunnels

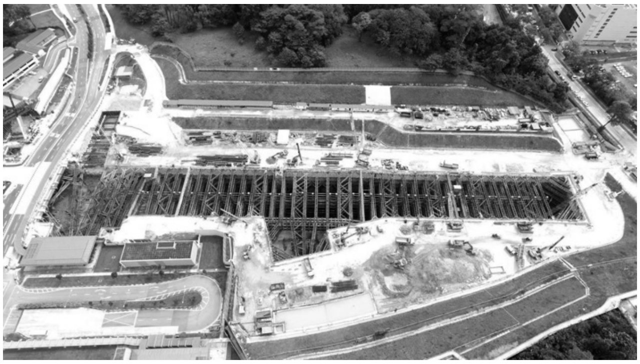


Fig. 10. Bird-eye view of cut and cover tunnel excavation

the earth retaining wall for the excavation should be carefully managed within a strict tolerance to minimize any potential impact on the existing railway tubes.

Challenges in design were found in optimizing the wall support system. While the stability of the earth retaining system can be improved with an increased number of wall supports, a dense layout of wall supports might result in restrictions in the work space, which would hinder the progress of site works and provoke concerns about the safety management in the restricted spaces.

Thus the wall support layout needed to be optimized with ensuring the stability of the wall and no harm on the neighboring tunnel tubes. Numerical analyses were carried out to enable optimization of the design of the earth retaining wall considering construction staging and three dimensional effects.

Two dimensional (2D) finite element analyses were first undertaken at the cross section where the excavation becomes closest to the existing railway tube as shown in Fig. 11. The retaining wall stiffness and the vertical spacing of wall supports were determined based on the results of the two dimensional analysis. However, the two dimensional model had limitations in accounting for the effect of construction sequence/stating along the tunnel alignment. Since the excavation and support staging in the direction of the tunnel alignment (out of plane direction in Fig. 11) was expected to affect the behavior of the earth retaining system and ground retained, three dimensional effects associated with the spacing of wall supports and construction staging should be taken into account to design the layout of the wall support system. A three dimensional (3D) numerical model was subsequently created using PLAXIS3D as illustrated in Fig. 12 to undertake additional analyses in a more realistic manner for the sake of the design optimization.

Considering the importance of the impact on the existing railway tubes from ground movement induced by the variation of the groundwater conditions according to the progress of excavation, both a tanked (undrained) case and steady state (drained) case were included in the 3D numerical models as seen in Fig. 13. The results calculated from the steady state case analyses appeared to govern the design of the earth retaining system.

Both the 2D/3D numerical analyses confirmed the earth retaining wall designed safely to retain the

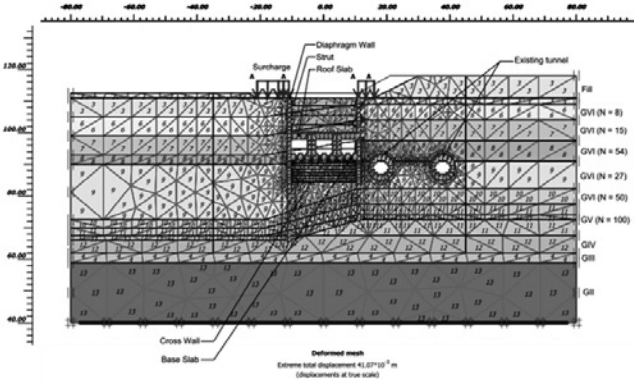


Fig. 11. 2D PLAXIS model for cut and cover tunnels in close proximity to existing railway tunnels

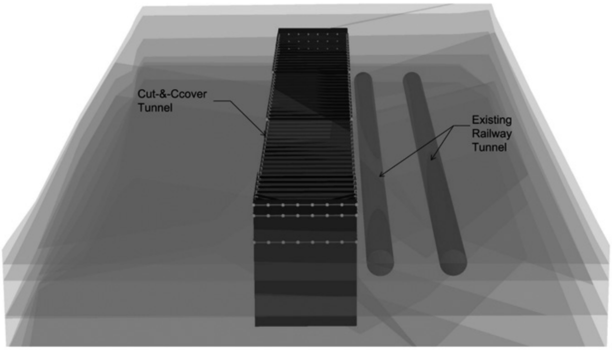
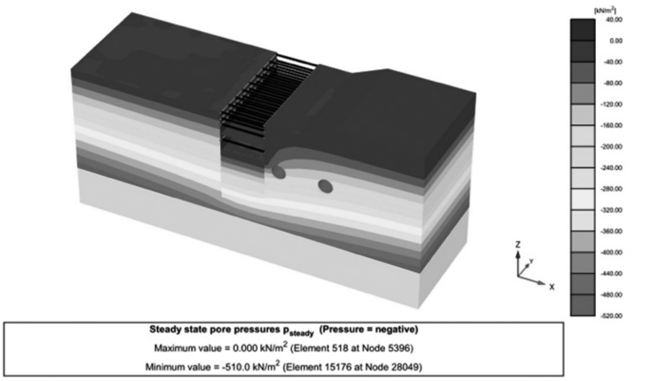
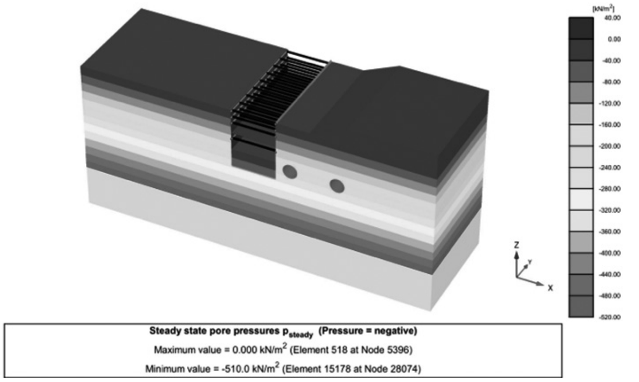


Fig. 12. 3D PLAXIS model for cut and cover tunnels in close proximity to existing railway tunnels



(a) Water pressures for tanked case (Undrained)



(b) Water pressures for steady state (drained)

Fig. 13. Water pressures reproduced by 3D modeling

excavation with no significant harm on the existing railway tunnels as shown in Fig. 14.

As a result of the 3D analysis undertaken in addition to the 2D analysis, the benefit of 3D numerical modeling was understood including:

- The 3D model assessed approximately 40% lesser movement of the existing railway tunnel due to the excavation than the 2D model at the same section.
- The 3D model assessed approximately 35% lesser deflection of the Earth Retaining wall than the 2D model.
- The force in wall support (strut) appeared to reduce to 50 to 80% in the 3D model compared with the 2D model.
- The member forces in the retaining wall appeared to be relatively comparable in both the 2D and 3D models in terms of the magnitude and location, while the 3D model overall generated lower forces than 2D model.

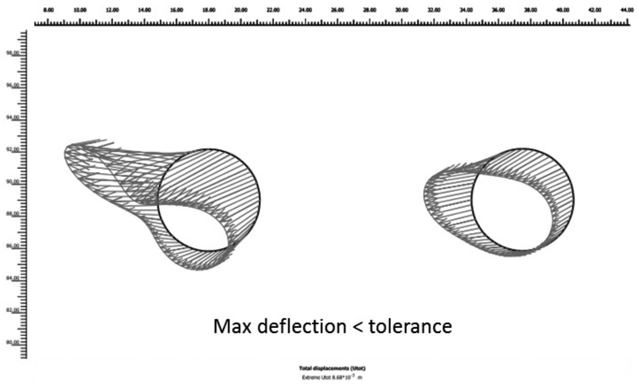


Fig. 14. Deformation of existing railway tunnels

It is obvious that the 3D model enabled assessing the deflection / forces of the wall and the neighboring railway tunnels in a lesser magnitude than that from the 2D model, even considering the more realistic construction sequence. The benefit of 3D modeling can aid optimizing the design for deep excavation with mitigating the potential harm on neighboring structures.

Case 3 - Access to existing sewer and maintenance shaft in Singapore

An extended operation of the existing deep tunnel sewage system in Singapore necessitated long-term maintenance, which required new access to the tunnel from the ground surface. A new maintenance shaft was planned to be built connecting to the existing deep underground swage tunnel as shown in Fig. 15. Due to the complex geometry of the maintenance shaft and its connection to the neighboring structures in a busy area, the design should take into account interactions with the neighboring structures.

Key issues identified include the assessment of the impact of excavation for the new shaft on the neighboring structures as well as the sewage tunnel considering complex construction staging in a confined space.

Challenges in design were found in determining the best suitable construction sequence of the excavation and installation / removal of supports and slabs with estimating the impact of the construction sequence on

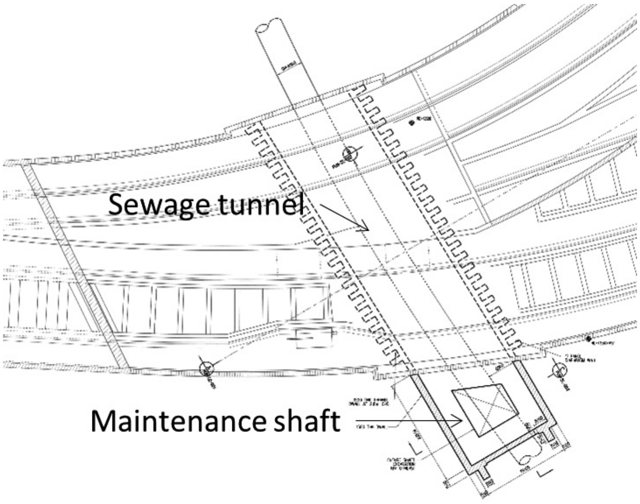


Fig. 15. Layout of maintenance shaft to sewage tunnel

the existing swage tunnel. Because the geometry of the structural components was interrelated in 3D directions, 3D modeling in Fig. 16 was conducted to estimate the deflection of the structures and surround ground so as to predict the deformation of the sewage tunnel underneath the shaft and adjacent structures.

The 3D numerical modeling indicated the deformation of the sewage tunnel was estimated to be controlled within the tolerance as shown in Fig. 17.

Numerical simulations enabled establishing mitigation or remedial plans in advance so that the interference of newly built underground structures with existing structures can be minimized.

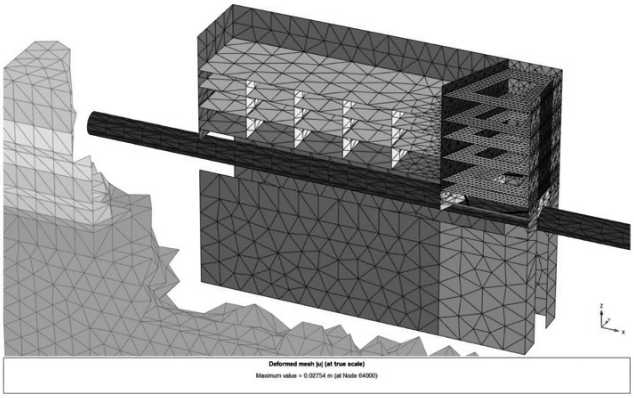


Fig. 16. 3D PLAXIS model for maintenance shaft connecting to sewage tunnel

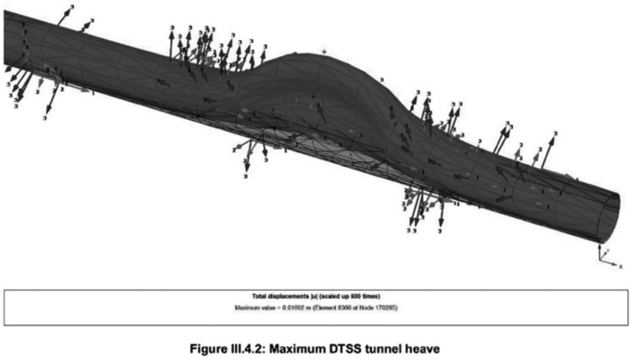


Fig. 17. Deformed sewage tunnel after exaction of maintenance shaft in 3D numerical modeling

Concluding Remarks and Recommendations

The use of underground spaces has been rapidly increased in busy urban areas to minimize the disturbance of surrounding landscapes. Underground development is an important solution 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.

Numerical simulations using 2D and 3D advanced computational tools have significantly assisted with achieving underground development enhancing the efficiency of design and risk management in construction. The three case studies are presented in this paper to highlight the benefit of advanced numerical simulations

The 2D and 3D numerical models discussed in this paper were developed using the finite element method (FEM) to simulate the construction process for underground structures in a realistic fashion. The models were used to predict the behavior of tunnel and underground structure deformation under different loads in complicated conditions illustratively. The advantaged of the numerical modeling discussed in this paper include its capability of coupled analysis of multiple phenomena such as changes in a groundwater regime by seepage analysis as well as those in a stress regime due to excavation independently or dependently depending on needs. This advantage will be maximized with further development of computational technologies and advanced soil / rock models which can represent the true behavior of ground where excavation takes place. Predicting the effect of all natural factors on tunnels is always challenging. One of the most significant advantages of the numerical modeling cases presented in this paper is in predicting the critical area surrounding the underground structure as well as in the structure against complex loads prior to commencing the tunnel construction, which enhance managing potential risks.

The use of underground spaces with aid of numerical simulations can bring more optimal solutions for urban development. With knowing the growing opportunities for underground development, the following future development is recommended to further expand the use of advanced numerical modeling to improve the design of the underground structures:

- Development of more sophisticated models for soils and rocks as well as structural components which can better represent the actual behavior of ground and components incorporated into the ground model for underground construction,
- Upgrade of structural models and assessment/design tools,
- Combining with other visualizing techniques such as Building Information Management system,
- Budget allocation for massive numerical models
- Feedback from monitoring and formalizing the processing with back analysis, and
- Design approaches to embrace 3D modeling and visualizing techniques.

The authors look forward to increasing opportunities to make contribution on sustainable development of urban areas utilizing underground structures which can be safely designed and built by the employment of advanced numerical modeling.

References

1) ABC News. (2018) Melbourne's population explosion threatens to create a 'Bangkok situation', Australian Broadcasting Corporation, https://www.abc.net.au/news/2018-10-15/melbourne-will-be-australias-biggest-city-which-party-has-policy/10358988

2) Broere, W. (2015) Urban underground space: Solving the problems of today's cities, Tunnelling and Underground Space Technology, Elsevier, http://dx.doi.org/10.1016/j.tust.2015.11.012

3) City of Helsinki. (2014) Urban Underground Space Sustainable Property Development in Helsinki, City of Helsinki Real Estate Department

4) Dal Negro, E., Boscaro, A., Laham, D. (2012) Successful TBM operations in urban environment: the ''Arroyo Maldonado" project in Buenos Aires. In: Proceedings of the ITA-AITES World Tunnel Congress 2012 – Tunnelling and Underground Space for a Global Society.

5) ITA Working Group. (2014) Urban Problems – Underground Solutions, ITA Report No 11, International Tunneling and Underground Space Association

6) ITS International. (2012) Success of Kuala Lumpur's dual purpose tunnel, https://www.itsinternational.com/categories/detection-monitoring-machine-vision/features/success-of-kuala-lumpurs-dual-purpose-tunnel/

7) Japan Oil, Gas and Metal National Corp. et al. (2014) Japanese first hydraulic containment type LPG underground storage cavern at EL.-150m - Namikata and Kurashiki national stockpile bases-, Outstanding Civil Engineering Achievement Award, JSCE, 9.

8) Lee, J., Zheng, A., Soo, W., Shibano, T. (2017) 3D modeling for design of vertical shafts, mined tunnels, bored tunnels and associated works in urban Areas , Southeast Asian Conference and Exhibition in Tunnelling and Underground Space 2017 (SEACETUS2017) Subang Jaya, Malaysia 2017.

9) Miyao, H., Kamoshita, Y., Kanai, M., Fukumoto, K. (2000) Underground river tunnel for flood control by shield tunneling. In: The Tenth International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers.

10) Soo, W. (2016) 2D & 3D FEM for deep excavation and tunnelling in urban areas, PLAXIS User Meeting 2017.

11) Tashiro, Y., Mutou, Y. (2013) Disaster-prevention measures for Tokyo metro tunnels. In: Anagnostou, G., Ehrbar, H. (Eds.), World Tunnel Congress 2013 Geneva – Underground – the way to the future!, pp. 275–282.

12) Tavakoli, R., Najafi, M., Tabesh, A., and Ashoori, T. (2017) Comparison of Carbon Footprint of Trenchless and Open-Cut Methods for Underground Freight Transportation. Proceedings of Pipeline 2017, ASCE, 45-55