# Some Research Activities on Rock Mechanics/Engineering at Nanyang Technological University, Singapore

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**Abstract**

This paper updates some of the recent work on rock mechanics/engineering carried out at Nanyang Technological University (NTU), Singapore. The developments on discontinuous numerical methods conducted under the Underground Technology and Rock Engineering (UTRE) research program are firstly introduced, including the coupling of the FEM and the DDA for rock fracturing analysis, general 2D-DDA educational software development, extended NMM for various types of discontinuity problems, and flat-top partition of unity-based NMM. Secondly, the numerical analysis for Jurong Rock Cavern (JRC) is presented, aiming to create reliable models for the hydrogeological analysis and provided valuable input for the project. lastly, a conceptual master plan of underground space development in the NTU campus is introduced, to illustrate the underground space utilization in Singapore.

**Keywords:** rock engineering,discontinuous numerical methods, seepage analysis, underground master planning.

## 1. Introduction

In land scarce Singapore, space creation is a key strategic area that concerns the survivability and sustainability of the nation. Land use pressures have urged Singapore to take actions to overcome its resource shortage through investing more in the area of space creation. To meet the technological challenges involved with underground space creation, Nanyang Technological University (NTU), Singapore, has conducted many projects related to underground space developmentby a strong team with a wide range of expertise.

One of the most imported projects is Underground Technology and Rock Engineering (UTRE) programmewhich was established in 2003, by the Protective Technology Research Centre (PTRC), NTU and the Defense Science and Technology Agency (DSTA), Singapore. The first phase of the UTRE research programme(UTRE I) was completed in May 2009, and it was successfully extended for another four years (UTRE II). UTRE focuses on research and issues of concern relating to rock engineering and underground construction technology. It aims to: 1) build up capability in rock dynamics research; 2) develop the discontinuous deformation analysis/numerical manifold method (DDA/NMM); 3) develop an integrated digital rock modelling system; 4) conduct research on automatic data acquisition and continuous health monitoring system for underground caverns and tunnels; and 5) conduct advanced fire safety and evacuation research for underground structures. This article summarizes the main research which has been carried out under UTRE at NTU in recent years.

Jurong Rock Cavern (JRC) is another important project for underground space creation in Singapore. It was established in 2007 and finished in 2013. The JRC research project has many topics, one of which is to develop reliable method for hydrogeological analysis.

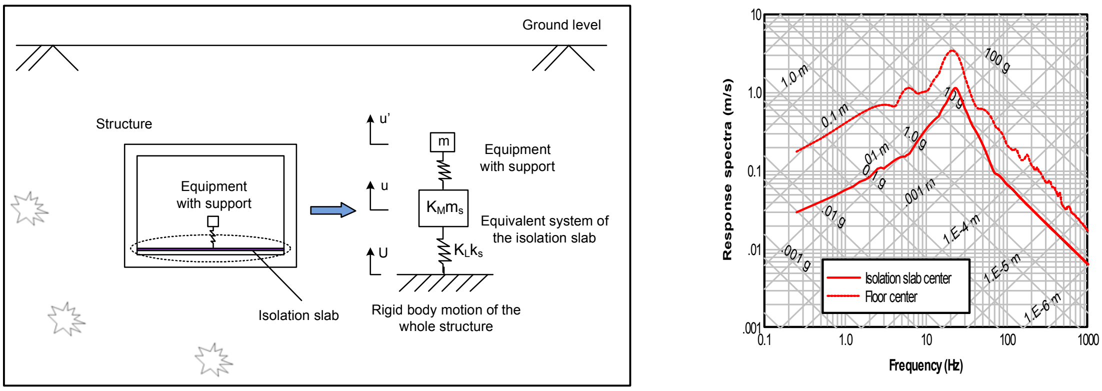
In Dec 2011, to be better served as a driving platform in underground research, Nanyang Center for Underground Space (NCUS) was established to focus on the R&D work in the effective use of underground space in Singapore. The first project in the centrewas NTU Underground Space Exploration funded by Sustainable Earth Office (SEO) in 2012. This project aims to explore the potential use of the underground space underneath the campus of the Nanyang Technological University (NTU).

## 2. The UTRE project

### *2.1 In-structure Shock Assessment and Mitigation of Underground Structures*

Underground protective structures are built to protect personnel and equipment from attacks, which are generally monolithic boxes made of reinforced concrete walls and slabs. When an underground structure is subjected to a dynamic load, besides the strength concern of the structure itself, another important aspect is that under a specific loading intensity, the structure itself is slightly damaged or even not damaged, but the sub-structure attached is damaged due to the severe vibration or shock. With the development of technology, equipment and devices are increasingly vulnerable to strong vibration due to their increasing complexity and sensitivity. Therefore, it is necessary to evaluate in-structure shock when designing an underground structure.

To mitigate the in-structure shock, a new design of underground structures is proposed by adding an isolation slab inside the structure, shown in Fig. 1(a). The excitation mechanism for the equipment within the structure is altered and the vertical shock level is effectively reduced, as indicated in Fig. 1(b).




(a) A new design (b) Shock response spectra

Fig.1. Mitigation of in-structure shock of underground structures

### *2.2 Advanced Numerical Modelling for Rock Cavern Design*

Amongst the various numerical methods, the discontinuous deformation analysis (DDA) is one of the most suitable methods to simulate deformations and stabilities of jointed rock mass.However, the old text based file input and output computer program is hard to learn and follow for beginners. By new developed graphical user interface, GUI, as shown in Fig. 2, the software offers friendly graphical toolsto help users graphically define the geometry and jointing in pre-processing. The post-processing tools also provide graph and table output for users' easy understanding the coming out.

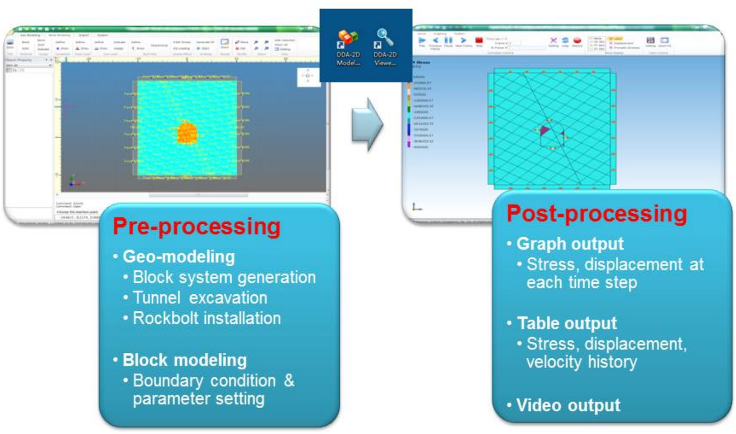



Fig. 2. Two components in educational 2D-DDA software

DDA has the potential for application in studies related to rock engineering. It simulates the response of discontinuous media subjected to either static or dynamic loading. A more complex model with tunnel excavation and rock bolt installation is also available and simulates the tunnel convergence (Nie et al., 2014). A variety of rock and joint properties can be adopted in the model. A screen plotting facility allows the user to instantly view the geometry and physical properties of model. Extensive records during the calculation permit the solution of stresses and displacement are visible, such as shown in Fig. 3.

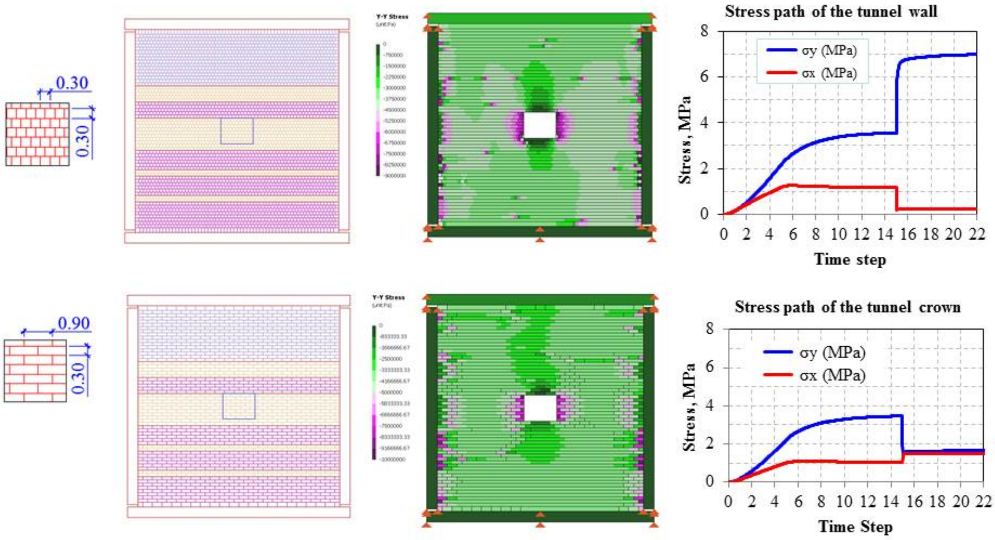
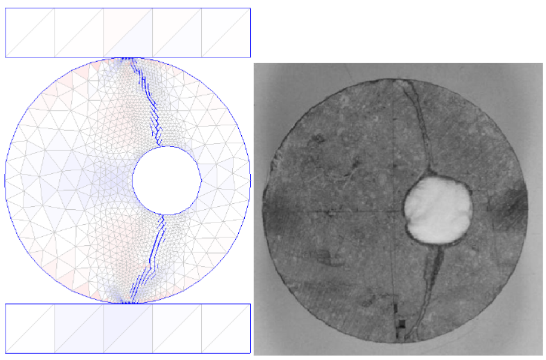


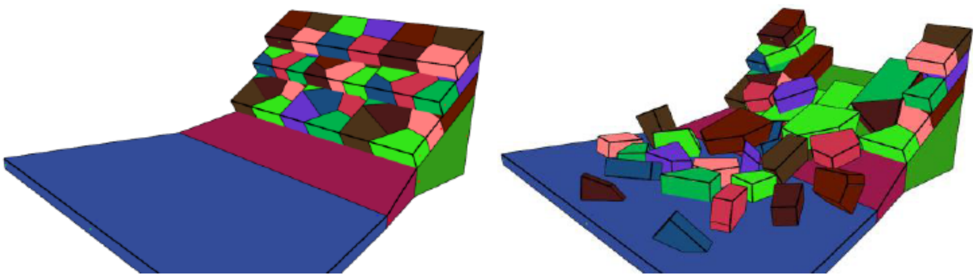

Fig. 3. Examples showing the 2D-DDA software application

In the original DDA method, the deformability of each block is restricted by its first order displacement assumption. To overcome this limitation, it was enhanced by coupling a triangular finite element mesh into each DDA block, with the method termed as nodal-based DDA (NDDA) (Zhao et al., 2011). Later, the NDDA was further improved by incorporating a node splitting algorithm to realize the fragmentation of an intact block. Numerical simulations of several benchmark problems have been carried out to validate the accuacy and efficency of the NDDA. Fig. 4 shows the failure of a Brazilian disc subjected to compressive loading at top and bottom, modeled by NDDA. A crack appears vertically along its diameter, consistent with the theoretical prediction.

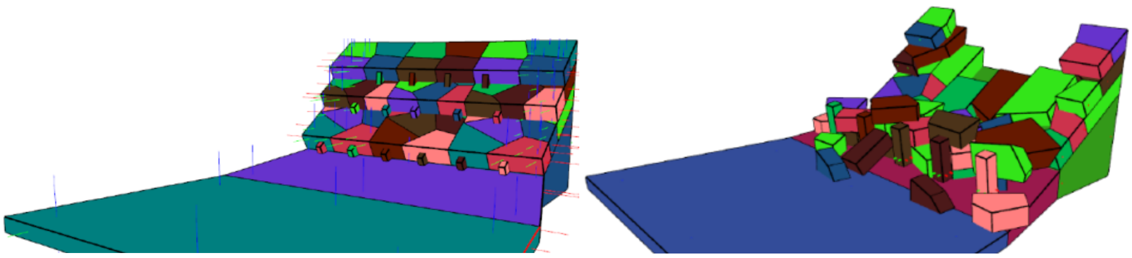


(a) NDDA; (b) Experimental result
Fig.4. Failure of a Brazilian disc with an initial hole

Another promising method for jointed rock mass analysis is the numerical manifold method (NMM), which is suitable for discontinuity problems because of its dual cover system. The 2-D NMM has been extended and successfully applied to various applications (An et al., 2010a, 2010b). The group has extended the 2-D NMM to 3-D domain (He and Ma, 2012), and a general 3-D contact algorithm was subsequently developed (He 2010). The proposed 3-D NMM has proved to be accurate, efficient and stable through simulating several typical examples. The 3-D NMM was also applied to conduct stability analysis of rock slopes and tunnels. Fig. 5 shows the initial state of a rock slope and the final state under gravity with the friction angle set to be 12°. Two types of stabilization techniques, i.e. concrete buttresses and fence barriers were investigated with their effectiveness in protecting a nearby road were clearly shown in Fig. 6.



(a) $t = 0$ s; (b) $t = 3.606$ s
Fig. 5: Failure process of a rock slope



(a) concrete buttress; (b) Fence barriers
Fig.6. Effectiveness of stabilization techniques

***2.3 3D Geological information system in Singapore***

This group concentrates its effort to develop a Digital Rock Engineering system, which comprise a 3-D Geological Information System (3DGIS), a 3-D Engineering Construction System (3DECS), a 3-D Environmental Analyzing System (3DEAS) and a 3-D Modelling Sytem (3DMS). The four parts of the system are interconnected as illustrated in Fig. 7.

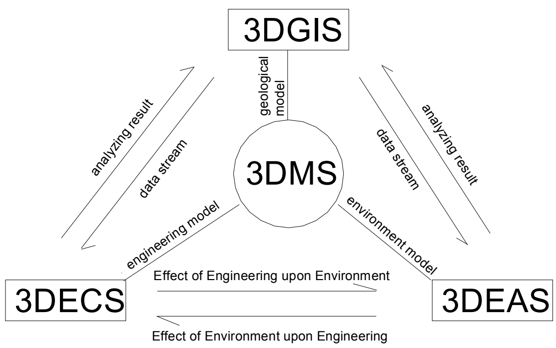



Fig. 7. Digital rock engineering system

A 3DGIS software called 3DRock+ has been developed, incorporating 3-D data models and relational database for borehole information (as shown in Fig. 8). A digital elevation model (DEM) in 3-D of the whole of Singapore's main island and the surrounding seabed has been created. Built on top of the DEM is the 3-D surface geological model of Singapore which established the framework to model subsurface geological structure. Subsurface modeling and analysisand multi-layered surfaces have been successfully implemented into the 3DRock+(Fig. 9).

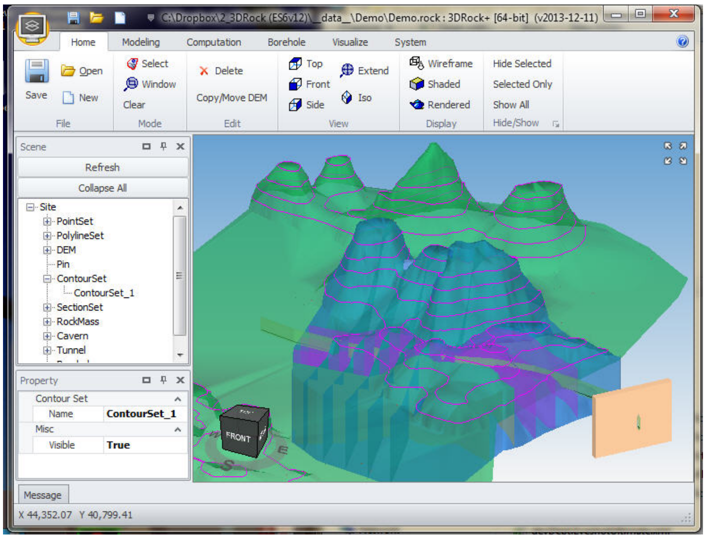



Fig. 8. Subsurface modeling and analysis

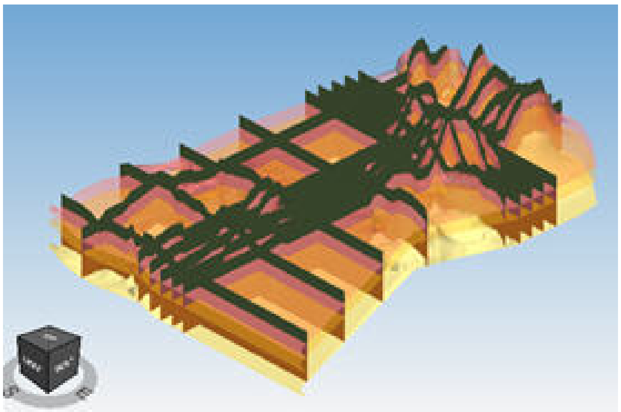


Fig. 9. Modeling of multi-layered surfaces

### *2.4 Multi-media modeling for evacuation*

Studies by this group are on the development of a numerical tool to simulate the emergency evacuation from underground space. A comprehensive numerical model for evacuation modeling was proposed based on cellular automaton (CA). This CA model provides a framework for modelers to incorporate various features such as tenability condition, visibility range and multi-velocity etc. into the simulation of evacuation. Basically, the model uses two factors, viz. spatial distance and occupant density to calculate the danger grade of CA cells. In order to make the simulation more reasonable, four types of human behavior were taken into account in the model. They are: 1) Familiarity effect. Group members will help one another in emergency because people are likely to behave in a benevolent way when they know each other, especially when they are from the same family or they travel together in the same group. 2) Unadventurous effect. Most people will try to exit through the same route they entered a building because occupants generally do not want to use a new exit they have no experience with. 3) Inertial effect. People are inertial creatures because they do not like to stop what they are doing. Once they move towards a certain exit, they usually continue heading the same direction. 4) Flow with the stream. The movement of an individual occupant will conform to the dominant direction of majority of surrounding occupants.Besides human behavior, tenability conditions are also incorporated into the proposed CA model to consider the effect of smoke. The movement speed of evacuees is an important factor in evacuation modelling since it has direct effect on evacuation time. Therefore, a series of experimental tests were conducted to investigate the speed of human's movement. Figs. 10 and 11 show the evacuation from a multi-story building and a tunnel, respectively.

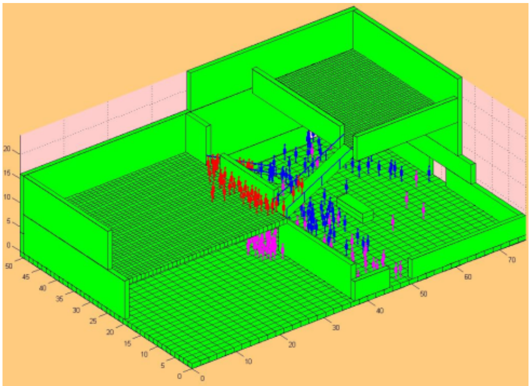


Fig. 10. Evacuation from a multi-storey building

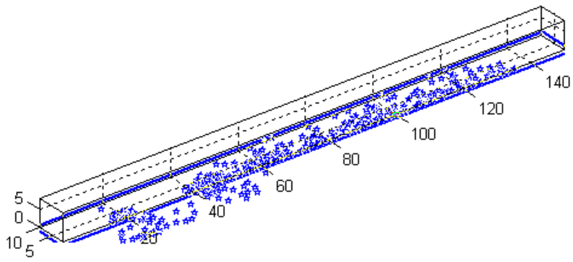


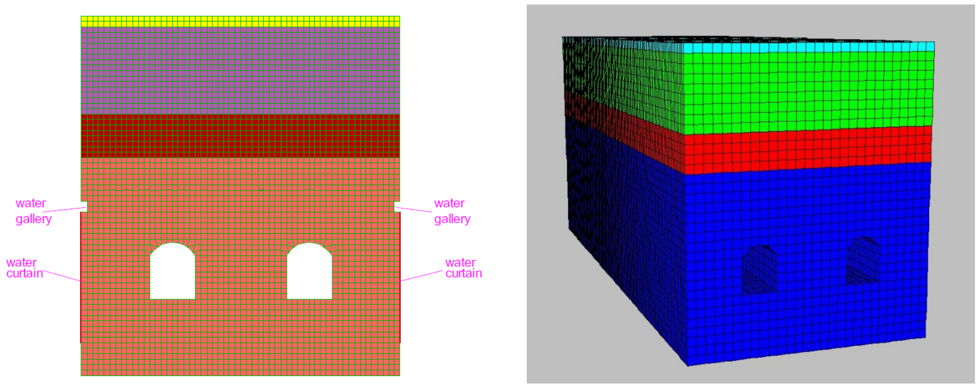

Fig. 11. Evacuation from a tunnel

## 3. The JRC research

Jurong Rock Caverns (JRC) is the first underground liquid hydrocarbon storage facility in Southeast Asia. It is located at a depth of 130m beneath Banyan Basin on Jurong Island (see Fig. 12).The storage capacity of the first stage caverns is approximately 1.47 million cubic meters, saving approximately 60 hectares of surface land space.

The permeability of the host rocks in liquid hydrocarbon storage caverns is the common issue for the cavern construction and maintenance. By review horehole hydraulic data from the technical report, as well as the probehole data collection, water pressure and water inflow data collection, 2D/3D seepage model using FLAC/FLAC3D have been built for seepage analysis (see Fig. 13 and Table 1). The effects of anisotropic permeability on water pressure, water quantities and criticalgas pressure have been considered in the model. The results indicate that most calculated results based on in situhydraulic tests with isotropic permeability assumption can be used safely in the underground oil storagecavern project (Sun and Zhao, 2010; Sun et al., 2011).


Fig.12.The location of JRC project




(a) 2D model (b) 3D model

Fig. 13. Numerical models of the oil storage unit.

Table 1. The simulated scenarios in 2D and 3D models

| 2D analysis | 3D analysis |
|---|---|
| Four hydraulic layers, one cavern unit | Four hydraulic layers, one cavern unit |
| Four hydraulic layers, anisotropic effect, one cavern unit | Four hydraulic layers, one cavern unit, fault zone |
| Four hydraulic layers, one cavern unit water bearing zone | Using a combined analytical/neural network model to consider anisotropic and heterogeneous effects |
| Four hydraulic layers, five cavern units | 140 m wide, 425 m long and 165 m deep |
| One hydraulic layer, one cavern unit, the effect of operation tunnel | |

## 4. The SEO project

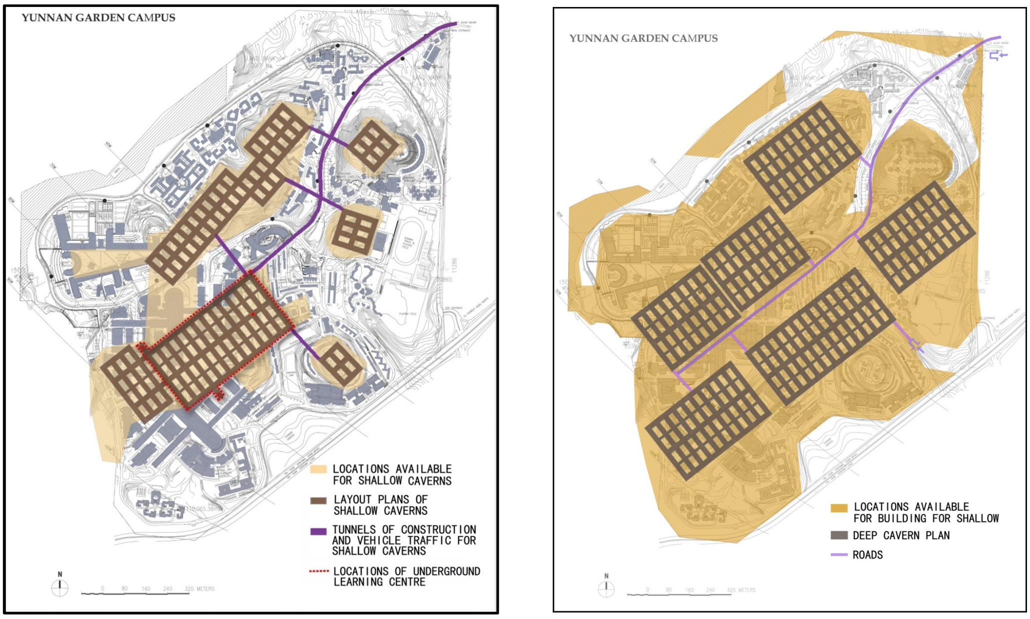
The study presents the first example in maximising space use in NTU campus and offers potential option by making use of underground space for its learning centre, sport hall, swimming pool as well as parking lots. The study shows that underground facilities provide more than 30,000 m$^2$ floor space for the learning centre alone. The geological condition is also found to be suitable for such a construction of these facilities.

The underground space design in NTU campus consists of three parts, 1) the deep basement, 2) shallow caverns and 3) deep caverns. The underground space at various depths can be used for different purposes, for example, the shallow and deep caverns can be used for student learning centres and sport complex, and the deep basements are suitable for parking lots.

We have identified 5 possible shallow cavern locations and their general layout plan is shown in Fig. 14(a). Shallow caverns are in general 70m below ground level or 26m below the deep basement. The shallow caverns connect to the surface through portal tunnel and connect to deep caverns through spiral ramp.The orientation of the shallow caverns is laid North-East stretching from administration building to the student service centre. It is notable that the orientation and layout of cavern is also related the orientation of rock joint and the convenience of the access to linked tunnel.

We have identified 6 possible deep cavern locations as shown in Fig.14(b), typically 120m below the ground level or 26m below the shallow cavern or 76m from the deep basement. The deep caverns connect to the shallow cavern through portal tunnel as well as access shaft. Similarly it also has spiral ramp connecting to shallow cavern.

Typical 2D cavern cross-sections are shown in Fig. 15; they are 20m width and space at 20m. The cavern roofs are semi-circular cross sections and the total cavern height is 24m. The shallow caverns are at 70m below the ground level, while the deep caverns are at 120m below ground. The depth of the caverns reflects symmetrical section between shallow cavern and deep cavern with identical cross section as well.




(a) Shallow caverns location (b) Deep caverns location

Fig. 14 Shallow and deep Cavern Locations

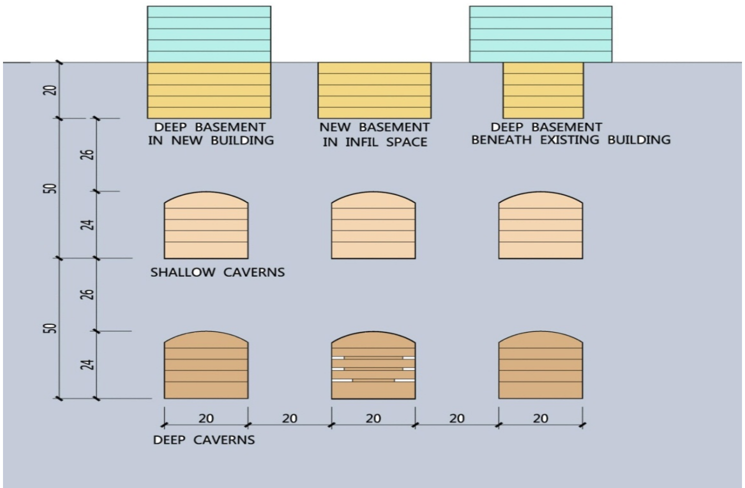



Fig. 15. 2D Sections of basement and caverns at defferent depths

## 5. Conclusions

The present paper gives an overview of the research done related to rock engineering and underground space creation technology in Nanyang Technological University, Singapore. Numerical tools based on the discontinuous deformation analysis (DDA) and the numerical manifold method (NMM) have been developed to analyze the stabilities of jointed rock mass. Another numerical tool has been established to simulate the emergency evacuation from underground space based on cellular automaton. A 3DGIS software called 3DRock+ has been developed, incorporating 3-D data models and relational database for borehole information. A digital elevation model (DEM) in 3-D of the whole of Singapore's main island and the surrounding seabed has been created. Built on top of the DEM is the 3-D surface geological model of Singapore which established the framework to model subsurface geological structure. 2D/3D seepage models for the JRC caverns has been developed and successfully used in Jurong Rock Cavern (JRC) project. A conceptual master plan of underground space development in the NTU campus has been showed to demonstrate the integrated underground space development concept. The study presents the first example in maximizing space use in NTU campus and offers potential option by making use of underground space

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