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<td>Citation</td>
<td>Pan, T. C., Tan, K. H., Li, B., Fan, S. C., &amp; Ma, G. (2010). An overview of the current research programmes in Protective Technology Research Centre at NTU. Design and Analysis of Protective Structures (3rd:2010:Singapore)</td>
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<td>Rights</td>
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An overview of the current research programmes in Protective Technology Research Centre at NTU

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Abstract

This paper presents a host of research activities currently conducted at the PTRC. The main objective is to introduce the research programmes to the protective engineering community in this conference. All of these works are sponsored by the Defence Science Technology Agency (DSTA), Singapore. The paper starts off with progressive collapse research which involves the testing and simulation of critical reinforced concrete structural elements to ascertain two reserve load-carrying mechanisms viz. catenary action and tensile membrane action when one or two perimeter columns are forcibly removed. These are the last line of defence mechanism just before progressive collapse kicks in. This paper introduces an experimental programme conducted on alternate load paths under two critical scenarios: External and penultimate column loss scenarios. Some test results involving slabs, beam-to-column joints, sub-frames and columns will be presented in the light of missing-column scenarios. The numerical capabilities of the centre will also be presented. These include (i) modelling of the break-up of uncovered and earth-covered RC magazine under internal high loading-density detonation, and (ii) concrete modelling for oblique perforation of slab by hard projectile. The last part of paper looks at the Underground Technology and Rock Engineering (UTRE) programme, which is a joint research programme between the Protective Technology Research Centre and DSTA. The UTRE programme aims to advance underground technologies in (i) rock dynamics research, (ii) discontinuous displacement analysis and manifold method, (iii) a comprehensive database for underground constructions; (iv) continuous health monitoring system for underground caverns and tunnels; (v) fire safety and evacuation research for underground structures. Due to the specialist nature of each research work, the paper omits most details but interested readers can refer to the references included at the end of this paper.

Keywords: Progressive collapse; Column loss scenarios; Membrane actions; Catenary action, Reinforced concrete structures; Penetration; Underground technology; Discontinuous displacement analysis; Manifold method; Health monitoring; Evacuation.

1. Introduction

The Protective Technology Research Centre (PTRC) is an inter-disciplinary research centre,
established on 29 September 1998 via a Memorandum of Understanding (MOU) signed between the Ministry of Defence (MINDEF) and the Nanyang Technological University (NTU). The centre is hosted in the School of Civil and Environmental Engineering (CEE) at NTU, and is primarily funded by NTU and MINDEF. On 9 September 2008, PTRC signed its second renewal of MOU with Defence Science and Technology Agency (DSTA). The Centre provides a platform for synergistic R&D programmes which involve NTU’s science and engineering colleges. The three-fold mission of PTRC is:

- To spearhead research efforts in developing advanced protective technology and homeland security
- To provide professional education/training and technology transfer
- To provide specialised advisory services to government ministries and local industry

PTRC has carried out many joint R&D projects with DSTA. This paper highlights the three main core R&D capabilities and research programmes of PTRC as follows:

- Progressive collapse on reinforced concrete structures in a post-blast event;
- Concrete constitutive models for concrete perforation and break-up;
- Underground technology and rock engineering (UTRE)

The paper begins with progressive collapse research which involves the testing and simulation of critical reinforced concrete structural elements to ascertain two reserve load-carrying mechanisms viz. catenary action and tensile membrane action when one or two perimeter columns are forcibly removed by a blast event. These two mechanisms represent the last line of defence against the onset of progressive collapse. This paper introduces an experimental programme conducted on alternate load paths under two critical scenarios: External and penultimate column loss scenarios. Some test results involving slabs, beam-to-column joints, sub-frames and columns will be presented in the light of missing-column scenarios.

It is noteworthy that despite the long history of studies conducted on progressive collapse, the majority of them were based on case studies of actual collapse, as well as numerical and finite element analyses. Clearly, these analyses require careful laboratory tests for validations before they can be used to conduct extensive parametric studies to investigate the complex interactions among the various design parameters. It was only in recent years that researchers began to investigate progressive collapse through controlled experiments, offering to fill the missing gaps in research.

Following a brief description of the progressive collapse study, the paper highlights the numerical work on (i) modelling of the break-up of uncovered and earth-covered RC magazine under internal high loading-density detonation, and (ii) concrete modelling for oblique perforation of slab by hard projectile. The last part of paper looks at the Underground Technology and Rock Engineering (UTRE) programme, which is a joint research programme between the Protective Technology Research Centre and DSTA. The UTRE programme aims to advance underground technologies in (i) rock dynamics research, (ii) discontinuous displacement analysis and manifold method, (iii) a comprehensive database for underground constructions; (iv) continuous health monitoring system for underground caverns and tunnels; (v) and fire safety and evacuation research for underground structures.

2. **RC Frame test**

2.1 **Objectives**

Under middle column removal scenarios, the mechanism of the remaining structure to sustain amplified gravity loads due to dynamic effect will be significantly affected by reinforcement detailing at the joint regions. This is because the bending moments at the joint regions just above the removed columns change reversely in sign and substantially increase in magnitude. The test results can be used to validate the effectiveness of the indirect method proposed in various codes. So far, catenary action which can only be mobilized after large deformations have taken place, is still not a well-known mechanism for engineers and has not yet codified. In the RC frame tests, the pertinent parameters which affect catenary action will be investigated.
2.2 Design of specimens

The specimens are located in the centre of a perimeter RC frame with multi-bays. To focus on the behaviour of two-bay beams and middle beam-column joints above the removed column, the RC beam-column specimens consist of a middle joint, a two-bay beam and two enlarged end column stubs, as shown in Fig.1. The specimens are designed in accordance with the ACI 318-05[1] code, which includes the integrity requirements for beams in perimeter frames.

2.3 Test setup

The test set-up is shown in Fig.1. To apply the axial restraints of intact frames onto the directly affected frame with a column removed, one end of the specimens is connected to a steel frame and the other end is connected to a reaction wall. A point load is applied at the top of the middle joint by using a hydraulic actuator, which is fixed onto a steel portal frame. A steel assembly is provided as a rotational restraint to the middle joints and two transverse frames are installed to prevent the out-of-plane failure of test specimens.

![Fig.1: The set-up for the simplified RC beam-column sub-assemblages](image)

2.4 Test results of a typical specimen

For a typical tested specimen, the top and the bottom reinforcement ratios are 1.24% and 0.49%, respectively. The bottom bars at the middle joint region are lap spliced. Fig.2 (a) shows that cracks were uniformly distributed along the beams and penetrated the whole beam sections, suggesting that large tension forces developed along the beams and catenary action was developed. Failure near the middle joint is shown in Fig. 2 (b). Near the joint interfaces at both sides, the top zone of concrete crushed severely and sections were physically separated with only the top layer of longitudinal reinforcement connecting the two beams together. Due to the lap splice detailing, wide cracks occurred at the sections approximately coincided with the starting or ending point of lap splice. Bottom reinforcing bars at one side of the middle joint fractured first, followed by the fracture at the other side.

Fig.3 illustrates the relationship of the applied forces and the middle joint displacement of a specimen. It shows that with increasing displacement, the applied force increases until the first peak value, which marks the capacity of compressive arch action. Thereafter, the applied force decreases until the onset of catenary action. Beyond that point, the applied force increases again. However, due to the fracture of reinforcement, the applied force drops suddenly at very large vertical displacements. Due to the development of catenary action, the ultimate resistance of the specimen is about 2.28 times the capacity of compressive arch action.
3. Beam-slab substructure test

3.1 Objectives

A penultimate column loss results in high potential for progressive collapse of reinforced concrete building structures since it leaves the associated slabs with horizontally unrestrained boundary condition. At large deformations, the slabs can develop membrane actions comprising a compressive ring of concrete around its perimeter and tensile membrane action in the central region to enhance the overall load-carrying capacity. The enhanced capacity is a key feature to prevent progressive collapse.

An experimental programme will be conducted on ¼ scaled models of the beam-and-slab substructure subjected to large deformations. The purpose of this programme is to investigate the influence of the rotational restraint along the perimeter edges of the slab, reinforcement and aspect ratios, together with interior beams, on the development of membrane actions in laterally unrestrained slabs, and on the overall load-carrying capacity. Two series with 12 specimens will be tested in this programme. The experimental data is used to validate an analytical approach which is proposed for predicting the load carrying capacity of the beam-and-slab floors at large deformations.

3.2 Design specimens and test setup
Two series of beam-slab sub-assemblages, referred to as ‘PE’ series (Penultimate External column loss) and ‘PI’ series (Penultimate Internal column loss) are designed to study tensile membrane action of beam-slab systems under penultimate column loss scenarios. The dimensions of the test specimens are obtained by scaling down a prototype nine-storey building structure to ¼ size specimens. The building is designed for gravity loading in accordance with BS-8110-97.

Under penultimate column loss condition, the affected beam-slab substructures will behave as laterally unrestrained due to two discontinuous adjacent edges. A set of 8 perimeter columns with pin-ended support is designed to simulate the laterally and rotationally restrained boundary condition. The pin-ended columns allow perimeter edges of specimens to move horizontally since there are no adjacent slabs.

To simulate uniformly distributed load onto the beam-slab substructures under column loss condition, a loading scheme is designed based on existing laboratory constraints. A 200-ton actuator reacted against a steel frame is used to load the specimen through a set of loading trees (Fig. 5a). Ball and socket joints between steel plates and steel rods are used to keep the loading system as vertical as possible, when test specimens deform excessively.

To investigate the membrane actions in beam-slab substructures under a penultimate column loss, two variables of slabs are studied, viz. aspect ratio \( a = 1 \text{ and } 1.4 \) and bottom reinforcement ratio \( \rho = 0.22\%, \ 0.43\%, \ 0.57\% \).

### 3.3 Main experimental observations of PI series

![Specimen PI-01 during and after the test](image)

![Specimen PI-01 during and after the test](image)

Fig. 5: Specimen PI-01 during and after the test

Tensile membrane action was observed in the tests at one depth of RC slabs and continuously develops until the specimens completely failed to carry the applied load at a displacement of nearly 10% of span length. As vertical deformations increased, the central tension region expanded significantly, resulting in significant in-plane bending moments in perimeter beams which twist and displace inwards. The inward movement of perimeter edges which can be used to demonstrate the presence of tensile membrane forces is a very interesting phenomenon. While the movement along the short span continuously increased towards the final stage, the movement along the long edge attained a maximum value of nearly 10% of dimension of the column section and then reduced again.

Failure mode is the most important experimental observation as it can be used to propose a mechanical model for predicting the overall load-carrying capacity of the laterally-unrestrained beam-slabs under a column loss scenario. With a relatively low slab reinforcement ratio of 0.2%, the failure of compressive ring due to concrete crushing does not occur in the two specimens. However, the failure mode appears at the final stage with two full-depth cracks together with bar fractures of slabs and interior beams at the intersections of yield-lines in the slabs.

### 4. Exterior beam-column joint test
4.1 Objective

In the study of progressive collapse, although numerous damage scenarios can be assumed, one of the most probable scenario is the loss of exterior ground column. The loss of the supporting column changes the boundary conditions of the structure causing it to seek alternate load paths to redistribute loads, thus maintaining equilibrium. The key question is whether the remaining structural elements have reserve capacity for load redistribution as well as the ability to withstand any potential increase in load; otherwise, they will fail due to overloading resulting in progressive collapse. There is no known literature on controlled experiments relating to the performance of beam-column joints in a post-blast scenario under progressive collapse. It is important to understand that failure in joints will greatly affect the ability of the structure to redistribute loads.

4.2 Design of specimens and test setup

Beam-column sub-assemblages were tested to failure under monotonic loading. The test setup was specially designed to ensure that the boundary conditions were representative of the actual scenario (loss of exterior column), as shown in Fig.6. The amount of resistance the sub-assemblages could provide the damaged structure against progressive collapse and the associated failure mode will provide valuable information to the limited data on collapse potential of RC frame structures. Comparison between the as-built design and the improved design not only provides information with regard to the amount of improvement possible through incorporating seismic detailing but more importantly, their limitation towards progressive collapse mitigation. Furthermore, validation and calibration with test data will enhance the accuracy and reliability of finite element analysis.

Fig. 6: Loading Frame - Full Configuration

Fig. 7: Observed crack patterns of exterior BC joint specimens
4.3 Observations

The failure modes of specimens are shown in Figs. 7 and 8. The following conclusions are obtained from the series of tests conducted on exterior beam-column joints:

a) In the study of progressive collapse, it is important to understand that all elements and joints are critical for load transfer and moment redistribution. Failure in any of the elements/joints will result in the increase in load and moment of adjacent members, which often result in collapse. In the context of the exterior beam-column sub-assemblage, with the onset of bar pull-out failure as observed in the NS series specimens in Fig. 7, significant amount of moment will be redistributed to the adjacent member/frame. If the adjacent members are not able to carry the increase in load and/or moment it will fail and possibly cause collapse. On the other hand, specimens of the improved design performed better and were able to redistribute a significant amount of moment within itself (between the beam and columns).

b) The increase in the percentage of transverse reinforcement in the joint region improved the shear strength of the joint through the development of the truss mechanism. However, test results from the specimens of the improved design (LS series) showed that joint shear failure was still the dominant failure mode and is independent of the amount of joint transverse reinforcement. Furthermore, it was important to note that undesired brittle failure mode (crushing of concrete struts) can result for overly reinforced joint as evidenced of Specimen LS03.

c) Limited seismic design detailing can significantly increase the global behaviour of the resistance of a RC structural frame subjected to a loss of its exterior ground column scenario. For instance, the yield strength, ultimate strength and ultimate displacement of interior BC joint (Specimen I4) (typical LS in Fig. 10) is larger than that of Specimen I1 by about 13 %, 17 % and 38 %, respectively. Moreover, Specimen I4 has a compressive stress in the joint major diagonal strut lower than that of Specimen I1 by about 18%.

d) Premature bond failure was observed in the bottom beam bars in all NS series specimens. It was suggested that additional bottom beam longitudinal reinforcement together with better detailing (i.e. smaller bar sizes thereby increasing effective bonding area) could prevent such failures.

e) Test results on the increase in provision of transverse reinforcement in the beam and column elements adjacent to the joint panel showed no significant influence on the strength of the exterior beam-column sub-assemblages. However, total deformations were significantly reduced.

5. Exterior column test
Columns are key load-bearing elements that hold up RC framed structures. Exterior columns are probably the most vulnerable structural components. Their failures could possibly trigger a progressive collapse of an entire structure. The post-blast residual axial capacity of an RC column is an important aspect to focus on, so as to determine if it could possibly trigger a progressive collapse of the entire structure. Numerical and experimental approaches were adopted to study the response and behaviour of reinforced concrete columns when subjected to blast loading. Numerical models obtained from analysis were used to produce a blast-damaged profile on actual column specimens within a laboratory through laterally mounted hydraulic actuators. Effects of parameters such as pre-axial loading and transverse reinforcement ratio are investigated in this study.

The performance of the tested column models and specimens subjected to blast or lateral loads was found to have enhanced appreciably by providing an increased ratio of transverse reinforcement. Pre-axial loading prescribed on columns were also found to have an effect on the blast-damaged residual deflected profile and residual axial capacity of the column specimens and models tested.

6. PTRC capability in numerical simulations

An accidental detonation in an ammunition magazine will lead to break-up of the structure and the debris throws. Quantitative assessment of this phenomenon is of great importance in safety studies. Performing field tests such as Kasun test is definitely the most valid and direct method of investigation, but is also of high cost and limited. A feasible alternative is to harness the power of the updated computing technology to conduct numerical modelling. The test data can be used to indicate which input parameters are important to obtain good numerical simulations as shown in Fig. 9(a) and (b).

The response of reinforced concrete structure under internal blast loading is complicated due to the high dynamic effects, material breaching and large deformations. A coupled solid-fluid scheme is usually required to tackle the sophistication of this type of problem. The cracking of the concrete elements are of primary interest because they ultimately form concrete debris which is the main objective of this research. Because of its complexity, it is still a challenge to fully model the break-up process. Past research works have shown that using “element erosion” can effectively simulate the formation of concrete debris. However, its application is somewhat limited to internal blast loading-density of less than 2.5 kg/m³. Most of the concrete elements were vanished under higher loading conditions and hence unable to capture the break-up of the reinforced concrete.

A project was done to simulate the structural break-up modelling for both uncovered and earth-covered reinforced concrete (RC) magazine under internal high loading-density detonation up to 30 kg/m³. It takes into consideration of different charge stack formats (centred or distributed). The structural break-up simulation is achieved by adopting a viable combination of two numerical algorithms (element erosion and nodal splitting). The break-up process as shown in Fig. 10 involves the application of fluid-solid interaction (FSI). The characteristics of overpressure, impulse, structural break-up and debris launching velocity in each scenario are investigated. All these will lead to different debris dispersion patterns, which are used subsequently to determine the hazard zone.

The RC structure break-up and debris launch conditions are solved by using the computer code LS-DYNA. The simulation of debris flying and the final debris dispersion are achieved by using an in-house program, namely ‘DeThrow’. Fig. 11 shows the simulation results of a typical debris hazard zone pattern.
6.1. Concrete model for oblique perforation of slabs by hard projectiles

‘Hydrocodes’, which are actually computer coding for solving wave-propagation problems, have become more sophisticated, and its use in the investigation of stress-wave propagation in fluid and solids is increasing. In the commonly used hydrocodes, numerical models are available to simulate many physical phenomena including the highly dynamic events – perforation of concrete panel by hard projectile. However, constitutive modelling for concrete material remains the major hindrance when it comes to obtaining accurate predictions. A project is done to develop a dynamic plastic-damage material model for concrete, and then apply it to simulate the perforation of a steel projectile through concrete panels at 30 degrees obliquity. The simulation results were found in reasonably good agreement with the experimental data.
A multi-surface stress-state model, which is a dynamic plastic damage material model, was developed to model the concrete target. Prior to failure, the multi-surface strength model is based on a modified Unified Twin Shear Strength (UTSS) theory (Fig. 12), which takes into account the effect of intermediate shear stress. The UTSS theory together with some empirical formulae leads to the initial yield surface, loading surfaces and the failure surface. Beyond failure, damage parameters are introduced and residual strength surfaces are constructed to define the damaged material. The damage scalar depends on an equivalent plastic strain. The model is incorporated into the commercial software AUTODYN through its user-defined-function. The results obtained from the 3D numerical simulation agree well with available experimental results (Fig. 13).

7. Research and development in rock engineering – the UTRE programme

The Underground Technology and Rock Engineering (UTRE) programme is a joint research programme between the Protective Technology Research Centre, Nanyang Technology University (NTU) and the Defence Science and Technology Agency (DSTA), Singapore. The UTRE programme aims to advance underground technologies in the following areas: 1) to build up the capabilities in rock dynamics research in the international society for rock mechanics; 2) to make UTRE one of the strongest research groups in discontinuous displacement analysis (DDA) and manifold method (MM); 3) to develop an integrated digital rock modelling system which creates a comprehensive database compiling pre-, during- and post-construction information for underground constructions; 4) to research on automatic data acquisition and continuous health monitoring system for underground caverns and tunnels; 5) to perform advanced fire safety and evacuation research for underground structures.

The phase I of the UTRE programme is from 2003 to 2009, and the phase II started in June 2009, with duration of 4 years. Main achievements during the last five years are summarised in this section under 4 areas.

7.1 Rock dynamics and material properties

7.1.1 Studies of Rock Mechanics and Material Properties under Dynamic Loads

A computer program based on the SPH method has been developed to simulate the fracture process in brittle materials under dynamic loads by considering the material heterogeneity (Fig.14). An advanced non-linear elasto-plastic constitutive model has been implemented based on the extension of widely-accepted Unified Strength Theory, which can better reflect the failure mode of brittle materials.
A statistical approach based on Weibull distribution law was utilized to model the material heterogeneity. The program has been calibrated and used to simulate the Brazilian splitting test and compression test for rock materials.

A computer program based on two-dimensional numerical manifold method (NMM) has also been developed. The NMM has been extended to tackle complex cracks such as multiple branched and intersecting cracks, and their growth. The mathematical covers completely cut by the crack surfaces are split into several physical covers attached with independent cover functions, thus the displacement discontinuity across crack surfaces away from the crack tips are modelled in a straightforward manner. Each of the mathematical covers partially cut by the crack surfaces form a singular physical cover enriched with asymptotic crack tip functions, thus the displacement discontinuity across the entire crack surface can be modelled and the crack tip singularities can be better captured. The NMM proves to be superior over other widely used methods, such as the XFEM and the GFEM for such problems. By incorporating proper contact detection, modelling algorithm and domain form of interaction integral considering the tractions along the crack surfaces, the frictional contact problems of complex cracks can be modelled. The NMM seems a promising approach to tackle the whole failure process from crack initiation, propagation, connection, formation of a failure surface, and then large movement between discrete bodies. Fig.15 shows some examples of the use of 3-dimensional NMM.

7.1.2 Behaviour of Rock Fractures under Dynamic and Impact Loads

Based on the SHPB test and wave separation methods, the dynamic properties of rock joints with filling materials and the wave propagation across a single filled rock joint are investigated (Fig.16). Meanwhile, a three phase medium model for the filled rock joints is proposed for cases where the filling materials are sand and clay with different water contents and void ratio. An equivalent visco-elastic model for rock mass with parallel joints is also suggested, which uses a continuous method to calculate
the wave propagation across a set of parallel joints.

Recently, an analytical method for plane wave propagation with arbitrary impinging angles across a single rock joint, when the behaviour of the joint is linear and nonlinear, such as BB-model and Coulomb slip for normal and shear properties of the joints, respectively, is under study.

7.2 Modelling, Design and Construction of Underground Structures

7.2.1 Development of Numerical Modelling for Underground Structure

A computer program based on the discontinuous deformation analysis (DDA) has been developed, with a comprehensive user manual and a simple pre- and post-processor. The relevant theoretical development on the DDA includes: an accurate stress evaluation scheme based on nodal stress equilibrium; a new corner-corner contact algorithm; an algorithm for an efficient FEM/DDA coupling analysis; an efficient DDA block generation; a numerical study on the accuracy of the DDA in wave propagation problems (Fig. 17). The developed DDA code has been used to investigate various rock engineering problems, including: cavern stability analysis with/without rock bolts; fracture process of rock under static and dynamic loads; drill/blast simulations; stress wave propagation over fractured rock mass.

7.2.2 Rock Mechanics and Engineering for Caverns and Tunnels

The first part of this module was under the care of PI Prof. Zhao Jian from 2004 to 2005, which included general underground technologies and site investigations. The second part of this module was carried out under PI Zhao Zhiye from January 2007 to March 2009. The main development work for the
second part of this module included two areas: 1) Development of design guidelines for caverns under dynamic loads, where a peak particle velocity (PPV) criterion was proposed to assess the rock damage zone. Empirical formulas and charts are presented to provide valuable information on the cavern stability. 2) A literature review on the drill/blast method for tunnel/cavern has been carried out, to provide a general assessment on the various methods used for the grill/blast design. The LS-Dyna and the DDA were used to determine the impacts of various drill/blast parameters on the rock fragmentation.

7.2.3 Comprehensive Monitoring of Underground Structures during Construction and Operation

This project is aimed at developing a piezoelectric and fibre optic sensors based system for underground structural health monitoring. Firstly, electromechanical impedance models have been developed to associate the structural damage and loading level with the PZT admittance signature, followed by experimental tests on the calibration of PZT and FBG sensors on metal, rock and concrete specimens. Subsequently, practical issues such as long term reliability, temperature, bonding thickness, protection and installation have been studied. A temperature compensation algorithm for the PZT signature has been developed. The bonding thickness between the PZT and structure has been recommended to be less than 1/3 of PZT thickness. A sensor protection method has also been proposed. Finally, based on the theoretical and experimental studies, an automatic and continuous monitoring system consisting of an impedance analyzer, a switch box, operation software and PZT/FBG sensors for continuous monitoring of excavation support structures has been developed. The system has been installed and tested at Telok Blangah excavation site for about one year (Fig. 18). Comparison with the conventional measurements showed good performance of the system.

7.3 Subsurface Infrastructure Planning and GIS

7.3.1 3-D Geological Information System for Subsurface Infrastructure Planning

For subsurface development, information in the third dimension – the depth – is important and thus the need of 3D GIS could not be over-emphasized. It is both useful and essential for the planning, design and construction for subsurface infrastructural development. Under Phase I of the UTRE programme, a 3D GIS software called 3DRock - customisation of the Virtual Geographic Environment GIS (VGEGIS) software of Wuhan University – had been developed incorporating 3D data models and relational database for borehole information. A Digital Elevation Model (DEM) in 3D of the whole of Singapore’s main island and the surrounding seabed had been created. Building on top of the DEM is the 3D surface geological model of Singapore which establishes the framework to model subsurface geological structure.
Subsurface modelling and analysis and multi-layered surfaces and cavern had been successfully implemented in 3D Rock (Fig. 19). A project to update the 1976 geological map of Singapore had also been incorporated under this Phase I programme. A recent update of the Singapore Geological Maps and the geological report had been launched in March 2009 by DSTA [2]. Moving forward, there is a need to research into better harnessing of geological information in 3D modelling, analysis and visualisation techniques for underground space development. The aim to develop Digital Rock Engineering which integrates GIS, site investigation, construction, instrumentation, construction management and numerical modelling is targeted under Phase II of UTRE programme. By incorporating the requirements of the concept and through collaborative research, the 3D Rock software will be enhanced to facilitate the design, construction and maintenance of rock cavern and subsurface infrastructures.

7.4 Safety, Health and Environmental Issues and Structural Monitoring

7.4.1 Fire Safety in Underground Caverns and Tunnels

Based on better understanding of fire safety in underground tunnel, a zone model was developed to simulate tunnel fire. The theoretical background of this zone model is the conservation of mass and energy in fire compartments. It takes into account of heat release rate of combustible materials, fire plume, mass flow, smoke movement and gas temperatures. It relies on some assumption concerning the physics of fire behaviour and smoke movement suggested by experimental observation of real fires in compartments. Compared with computational fluid dynamics, the zone model developed is a very efficient numerical tool. The geometry of a compartment including its dimensions and the locations of openings can be modelled easily (Fig. 20).

In order to assess the safety level of an underground basement, a numerical model for evacuation modelling was proposed. This model stands on the concept of cellular automaton that consists of a regular grid of cell. To determine the movement direction of an evacuee, two factors, viz. spatial distance and occupant density are used to evaluate the safety grade of a particular cell. The proposed model is built on a flexible platform which can adopt various features such as 3-dimensional geometry, tenability condition and multi-velocity, etc. In this model, human behaviour such as the effect of familiarity, inertia and unadventurous traits are considered. Tenability analysis is also incorporated into the model to simulate how smoke affects an evacuation process. At current stage, the model can be used to make comparison between different designs of various evacuation schemes (Fig. 21).
Fig. 20: Illustration of a zone model

Fig. 21: Evacuation modelling

Acknowledgements

All the research works presented in this paper are supported by funding from Defence Science & Technology Agency (DSTA). The authors would like to acknowledge the following researchers for their respective research works and contribution to this article, namely, Mr Yu Jun and Mr Pham Xuan for the progressive collapse programme, A/P Zhao Zhiye, A/Prof Tor Yam Koon, A/Prof Yang Yaowen, Dr Yuan Weifeng and A/Prof Robert Tiong for the UTRE programme. The authors would also like to acknowledge the following personnel from DSTA for their invaluable contributions to these works, namely, Dr Zhou Yingxin, Mr Lim Shiyi, Mr Lim Heng Soon, Ms Venetta Ng and Dr Seah Chong Chiang. The financial support of DSTA is also gratefully acknowledged.

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