SUSTAINABLE INFRASTRUCTURE IN EXCAVATED SPACES – A GEOTECHNICAL PERSPECTIVE ON HONG KONG PRACTICE FOR GROUND MODELLING AND ANALYSIS

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Abstract: Engineering practitioners in Hong Kong are well-versed in the challenges of designing and constructing infrastructure to account for the hilly terrain, building density and limited developable land. Hence, ongoing infrastructure development often involves "excavation" to create underground space for mass population transport or utility provision. In particular this excavation relates to tunnels and caverns – and it is also apparent that the use of underground excavated space offers the potential for enhanced sustainable infrastructure solutions. Excavations in Hong Kong invariably involve design by, amongst others, geotechnical and civil engineers. This paper discusses aspects of geotechnical (and geological) engineering related to underground excavations, with a view to highlighting some modern practices, possible ways forward for design methods in tunnelling and cavern construction, as well as citing some recent experience from Hong Kong and international projects.

To ensure the feasibility, constructability, economic viability and sustainability of specific underground excavations, engineers need to characterise and understand the predicted ground conditions. Such characterisation needs to be linked to the use of appropriate design methods and software tools – the more information and accuracy in designs, the less is the economic, safety and environmental risk. This paper discusses the use of 3-dimensional digital ground modelling methods for documenting and assessing ground conditions from the design stages into construction. Geology is not 2-dimensional – it is a 3-dimensional entity. An approach comprising the use of AGS data management, HoleBase, KeyHole, 3-Dimensional CAD and GIS is discussed, with recent examples for tunnel and cavern projects. The output provides a digital record of the interpreted ground conditions, which can be linked to Geotechnical Parameter and Construction Database, which in turn can be updated for Contract Re-measurement purposes during the excavation. Such "3-Dimensional Ground Modelling" allows design interrogation and cross-sectioning for design and works drawings. Once ground models are created, design of excavation support measures is undertaken via assessment, calculation and Tender/Construction Drawings – but the question of the correct design tools and methods arises. The more sophisticated the design method, the better the pre-construction design must be and the less risk there is to the project. Hence, this paper discusses an approach to the design of Temporary and Permanent support measures for tunnels and caverns that combines 3-Dimensional Ground Modelling, Barton's Q-System, the Universal Distinct Element Code (UDEC) software and Fast Lagrangian Analysis of Continua in Two and Three Dimensions (FLAC, FLAC3D). Experiences and lessons learnt from recent examples in the use of this combined and sophisticated approach are discussed.

1. KEY ISSUES FOR UNDERGROUND EXCAVATION

In Hong Kong and elsewhere in the world, there is a new drive to consider the use of excavated underground spaces to create development opportunities that also offer sustainable solutions to the mainstay alternative of above-ground development. Essentially this is driven by pressure of available land, particularly in densely-urbanised areas.

These potential sustainable underground spaces can be used for a variety of purposes. These include : underground water reservoirs, sewage treatment facilities, powerhouses in hydroelectric schemes, recreational sports centres, warehousing, extensions to building basements for parking, military and security purposes, nuclear waste repositories and even for residential purposes providing special climatic measures are installed.

There have been various past studies into the use of caverns in Hong Kong, as discussed by Chan and Ng (2006). These include the SPUN studies (OAP, 1990), the further cavern studies of CAPRO (OAP, 1991) and cavern area studies (Roberts, 1993). Notable past cavern projects include : Stanley Sewage Treatment Plant (1992 – 1994); Kau Shat Wan Explosives Depot on Lantau Island (1994 – 1997) and the Mount Davis (Island West) Refuse Transfer Station (1995 – 1997). A more recent example is the Hong Kong University Saltwater Reservoir Cavern (completion 2010). In addition, caverns have been constructed for Mass Transit Railway Corporation, including Taikoo Cavern station (completed 1985). It is notable that the use of rock caverns in recent times in Hong Kong has been limited.

Whilst underground spaces can include those formed in soils, or by cut and cover construction methods, for the purposes of this paper only discrete rock caverns are considered. Of course, developments based on rock cavern excavation will also require the construction of various access and ventilation tunnels or adits, as well as the associated infrastructure, such that “master planning” for underground spaces is key, although is beyond the scope of this paper. Instead, focus is given to the “design” of underground rock caverns, noting that in Hong Kong, rock cavern construction is relatively rare in comparison to other development projects. In terms of sustainable infrastructure, the following two aspects apply : (i) rock caverns offer potential environmentally-friendly forms of development in their own right, but in addition, (ii) the design tasks involved in optimising materials and specifications for construction are also of prime importance; this paper considers some aspects of modern cavern design, as a means to ensure constructional safety, optimised lining designs and sustainability and considers some recent examples.

2. UNDERSTANDING GROUND CONDITIONS FOR CAVERN DESIGN

2.1 Background and Previous Hong Kong Caverns

According to Chan and Ng (2005), in Hong Kong, the “first generation caverns” (Malone and Chan, 1993) constructed in the 1980’s were tunnel networks for water supply (e.g., valve chamber of Western District Aqueduct in 1984) or railways (e.g., MTR stations at Sai Wan Ho and Tai Koo in 1985). The three “second generation caverns” constructed in the 1990’s were purpose-built for environmentally unattractive facilities (Stanley Sewage Treatment Plant, Kau Shat Wan Explosives Depot and Mount Davis (Island West) Refuse Transfer Station). Figure 1 (extracted from Chan and Ng, 2005) compares the cross-sections of these Hong Kong caverns with the Olympic ice hockey cavern in Gjovik of Norway.

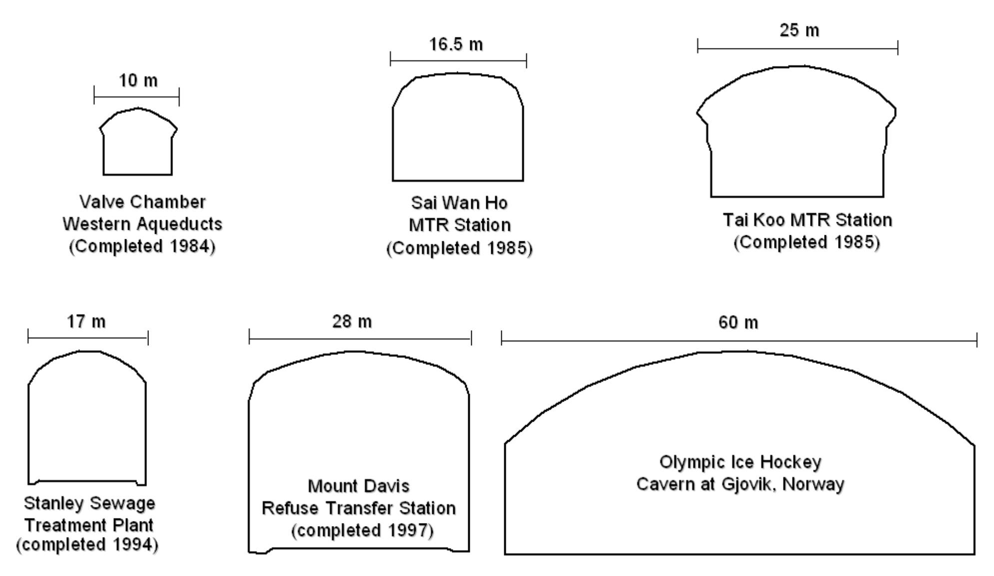


Figure 1 – Cross-section of Hong Kong Caverns and the Olympic Hockey Cavern in Norway (after Chan, K.S. and Ng, K.C. (2006).

There have been a number of other prominent caverns constructed internationally – some examples of these are presented in Figures 2a to d.

Figure 2a – Saltwater reservoir cavern at Hong Kong University, Hong Kong, 2008-2010.

Figure 2b - Muela Hydropower Station, Kingdom of Lesotho, 2005.

Figure 2c - Terminal 4 Station, Heathrow Express, UK.

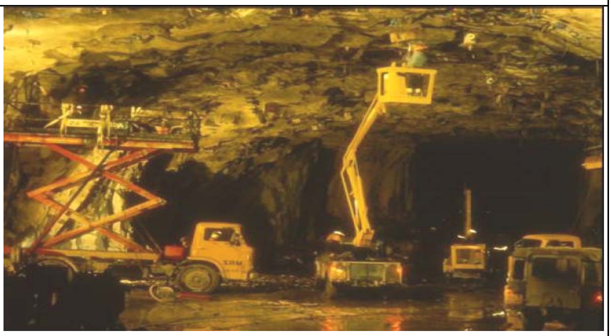


Figure 2d - Dinorwig Power Station, UK.

2.2 Cavern Designers

In order to form useable underground spaces a coordinated strategy amongst various professionals is required, which typically involves the following main parties : architects, civil engineers, geotechnical engineers and geologists, mechanical and electrical engineers, ventilation and fire safety engineers, traffic engineers, public liaison specialists, consultant and government planners, environmental specialists, consultants for design, contractors for constructability, quantity surveyors and specialists in contracts and procurement. Building a cavern or underground space is a complex undertaking.

Of the above-mentioned list, excavating and forming the space in a safe and sustainable manner is the primary first step and this is the focus of the paper herein. The designers of the excavation and the associated temporary and permanent support and lining systems are, by training, likely to fall into one of the following categories : civil engineer, geotechnical engineer, engineering geologist, rock mechanics expert, tunnel engineer or hydrogeologist. However, for reasons discussed below, it is apparent that rock cavern design is a specialist activity that requires elements of all of these disciplines to ensure a safe and optimal design. In addition, such design requires additional knowledge of ground investigation methods, ground settlement analysis, rock excavation and blasting, and cognisance of constructional constraints such as plant, machinery, excavatability and spoil processing and disposal. This paper considers some of these key aspects, recognising that there is then the fitting out and maintenance of caverns, which is beyond the scope herein.

As the main starting point to rock cavern design projects, it is fundamental to gain a detailed understanding of the ground conditions in which the complex and usually grand scale of the underground excavation is to take place. Practitioners will be familiar with geological and engineering geological plans and long- / cross-sections, as generated from borehole logs, in situ tests and associated laboratory testing. But for rock caverns, standard approaches may be insufficient, for the following primary reasons :

- The removal of enormous volumes of rock from a mass previously in a condition of equilibrium in situ stress means that rock wedge instability is difficult to predict and design out in the process of determining support measures and lining specification.
- Cavern construction often yields unusual and complex 3-dimensional geometries, such as cavern end walls, cavern-to-adit/tunnel junctions, construction adits, narrow rock pillars between vent adits and the cavern, and of course the internal excavation sequence of the cavern rock mass itself, which due to large spans will comprise numerous excavation stages.
- The potential hydraulic connectivity of large cavern voids can influence wide areas of developed surface land, both in terms of potential drawdown of the groundwater table and resulting consolidation settlement of soils and buildings in urbanised areas.

These three reasons are fundamental issues for the excavation design process to address and relate to ‘ground conditions’. If ground conditions are not well-defined then the construction of the underground space will be associated with enhanced or high risk. For these three reasons alone it is appropriate to apply state-of-the-art geological and geotechnical approaches to cavern design in order to reduce the risks of unexpected ground conditions to acceptable levels. Hence, there is a move in Hong Kong and elsewhere in the world to apply digital and “3-dimensional ground modelling methods” – commonsense tells us that geology and ground conditions cannot be represented adequately in two-dimensions. The recent GEO Publication

No. 1/2007, entitled Engineering Geological Practice in Hong Kong, offers some up-to-date guidance on mapping and assessment of ground conditions in Hong Kong (GEO, 2007). A three-step approach to providing a framework for input to engineering geological work is offered, comprising "geological", "ground" and "design" models. Essentially, the term "ground model for design purposes" can be adopted, which encompasses all available and relevant information, with appropriate interpretation, to represent the ground conditions. The use of geological models for foundation works design is further discussed in GEO (2006). GEO (2004) also stresses that "*the geological model assumed for design should be verified during construction and the verified information, including any amendments made to the design geological model during slope works, should be incorporated as part of the as-built records.*" This is quoted in respect of slope works design, but will apply equally to cavern design. The examples shown in Figure 3 are extracted from the GEO Publication No. 1/2007, as indicative of 3-dimensional models.

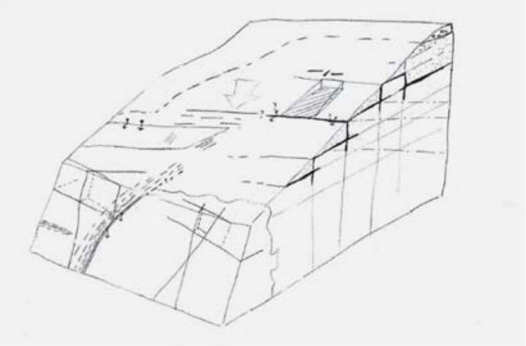


Figure 3a – Example of a geological model based on site reconnaissance (Parry et al., 2004b)	Figure 3b – 3-D models of a rock/soil interface based on logging of cuttings from drillholes for prereinforcement and grouting (models by Gammon Construction Ltd)

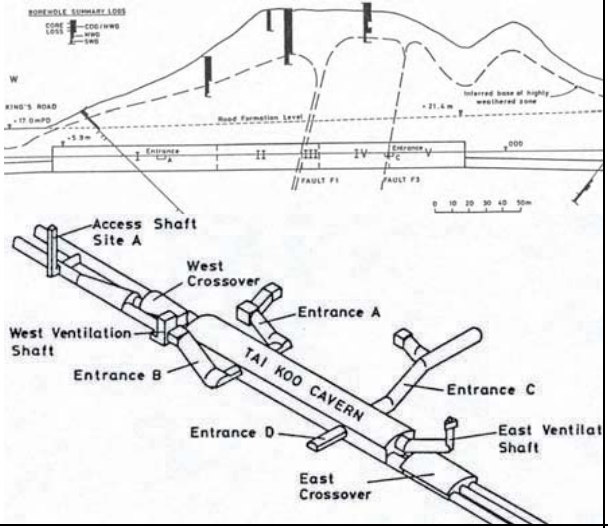
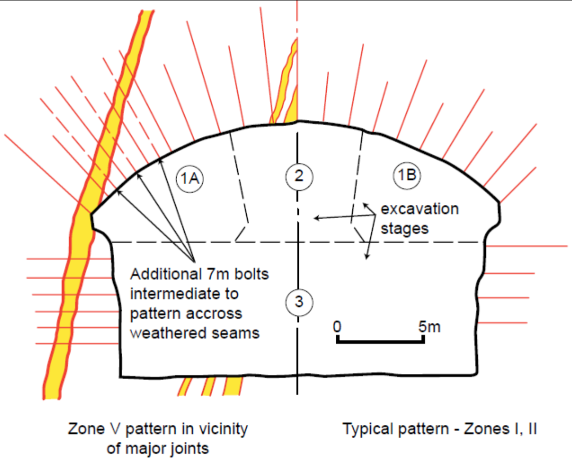
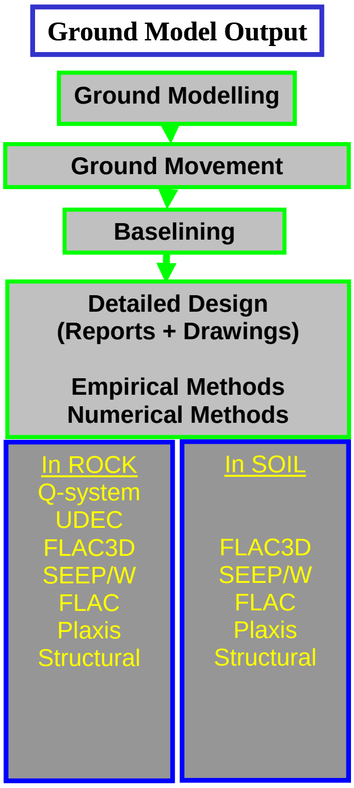

	

Figure 3c – Longitudinal section and plan of Tai Koo MTR cavern showing zonation (I to V) based on rock mass characteristics (Sharp et al., 1986)	Figure 3d – Typical cavern sections, excavation stages and rock reinforcement (after Sharp et al., 1986)

It is clear, however, that modern computerised and digital methods of ground modelling have moved the process on in recent times and that for caverns in particular, a more advanced procedure is required.

2.2 Digital 3-Dimensional Ground Modelling for Underground Works



The basic ground model process is iterative, going through the stages of data collation and manipulation, to preliminary analysis and baselining of parameters, and then through preliminary design before returning to the initial ground model for further appraisal – during the design process this loop can occur several times as the model is refined. Therein after, the final ground model may become embedded into the contract as part of the Geotechnical Baseline Report or other baselining documentation. A simplified procedure is shown in the diagram.

The production of a truly 3-dimensional and digital ground model requires the use of geotechnical data management software combined with Computer Aided Design (CAD) and a good measure of input by skilled personnel. Proprietary software includes Keycentrix's HoleBase and KeyHole for data management in AGS digital format, Surfer for 3-dimensional surfacing of strata, a CAD package capable of 3-dimensional meshing and rendering, and finally a Geographical Information System capable of storing and retrieving the information in a manner that can be added to or refined in the future. This approach requires a step change to the traditional approaches of 2-dimensional geological cross-sectioning and sketches. Many would consider that the ground model is a task done entirely at the start of a project, to facilitate later design of the works. However, by invoking the design process as a step in the development of the ground model, the model is "tested" and "validated" as being a reasonable representation of the most-likely-to-occur ground conditions. It should be appreciated that such 3-dimensional ground models can be refined at infinitum, such that to obtain a reasonable model with reasonable investment of time and cost should be done in conjunction with "Geostatics" and a Risk Assessment. In Hong Kong, the risk is usually addressed in Design Risk Registers and Construction Risk Registers, as items related to unforeseen ground conditions.

Ground models are built up as a series of data layers. The most important for rock excavations and caverns comprise : (1) the layout of the underground works, (2) incorporation of the GI data, (3) the rockhead, which delimits changes from hard rock conditions to mixed, weak or soft ground, (4) the main fault lineaments, and (5) the discontinuities within the rock mass (e.g., faults, joints, bedding planes, and any other natural or man-made fracture in the rock). These data inputs to the ground model are discussed below.

The Underground Works

Most ground models begin by defining the proposed excavation works in CAD and setting the boundaries of the model. Care needs to be exercised to include topography and ground investigation data points (e.g., existing or proposed boreholes) well beyond the extent of the works, to capture the full 'site setting'. An example of the basic CAD building blocks for a typical Hong Kong project is shown in Figure 4. The excavation, in this case for mass transit running tunnels and underground stations, are digitised and set within grid-referenced 3-dimensional space. In this example, the digital ground investigation data, in the form of borehole ‘sticks’, are also inserted in the model, showing the different geological and strata layers. It is important to build up such models using true grid coordinates - hence the model should be in true x, y, z space.

Ground Investigation Data

Well-established practice in Hong Kong, the UK and elsewhere is for borehole and ground investigation (GI) records to be created either during or shortly after GI takes place. The data is recorded in AGS format (The Association of Geotechnical and Geoenvironmental Specialists, AGS) by the GI Contractor. The purpose of the AGS Format is to provide a means of transferring geotechnical and geoenvironmental data between parties. From the outset the fundamental consideration was that potential users of the Format should be able to use standard software tools to produce the data file. These tools may range from simple text editors and word processors, through spreadsheet packages to sophisticated database systems. In order to ensure the widest possible level of acceptance it was also agreed that the Format should use the American Standard Code for Information Interchange (ASCII).

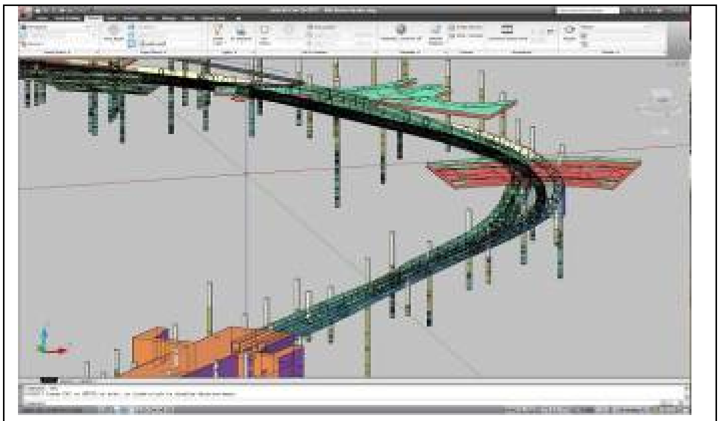


Figure 4a – Building the CAD Model of the Works (KTE Line, Hong Kong, MMHK Limited).

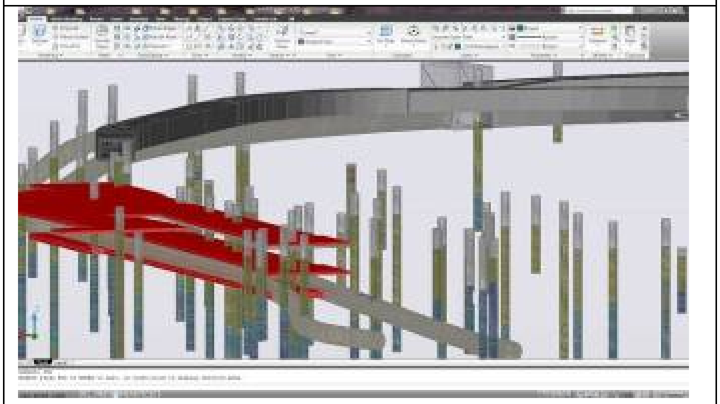


Figure 4b – Inserting the Borehole Data (KTE Line, Hong Kong, MMHK Limited).

Proprietary software such as HoleBase or gINT are available to make use of AGS data. In addition, guidelines for use in the planning of GI in Hong Kong include :

1. AGS-HK (2003), “Ground Investigation Guidelines”
2. GEO Geoguide 2 (1987), “Guide to Site Investigation”
3. GEO Geoguide 4 (1992), “Guide to Cavern Engineering”
4. GEO TGN24 (2009), “Site Investigation for Tunnel Works”

GI for tunnels and caverns, being laterally extensive structures, needs careful consideration. In Hong Kong it is common for boreholes to be drilled from ground surface vertically to intersect the rock and surrounds at and above scheme level. Sometimes a limited number of inclined boreholes may be drilled. It is also common for the results of such, perhaps limited, GI to raise as many queries as are answered – this may be due to gaps in the data, which results in uncertainly and risk of unexpected ground conditions. Hence, directional and horizontal drilling can provided a significant advantage (Figure 5).

Typical data output of directional drilling comprises : (1) Impression Packer Tests; (2) discontinuity data along the proposed tunnel alignment; (3) Q-value determination; (4) preliminary rock support requirements; (5) Water Absorption Tests; (6) permeability / conductivity of rock; (7) estimation of groundwater inflow conditions; (8) hydrogeological modeling data along the proposed alignment;


Figure 5 – Directional Drilling in Hong Kong.

Rockhead

Often the most important strata layer in a Ground Model is rockhead. In Hong Kong this usually equates to Grade III or better rock, as defined in Geoguide 3 (GEO, 2000), although the definition invariably needs expanding for contractual purposes, as the following example illustrates : *"Bedrock or rockhead is based on the criterion of 5 meters penetration into Grade III or better rock with a minimum total core recovery of 85%. Rockhead is equivalent to the top of Category 1(c) founding material defined in the Code of Practice for Foundations by Buildings Department of HKSAR. Bedrock is assumed to comprise 85% volume or greater of Rock."* Examples of 3-domensional ground models developed for recent Hong Kong projects are illustrated later in this paper.

Major Discontinuities – Faults

Faults are usually the second most critical data layer. The position of these features within the model should be associated with a risk rating of uncertainty, since seldom are the dips and orientations of faults well defined – this in itself presents project risk. Most faults in Hong Kong are shown as sub-verticals fracture or weathered zones. Dip angles varying by plus/minus ten degrees can place a fault zone either on or off the works alignment at depth. Without some rationalisation, this could otherwise introduce significant error into the design and scheme. This is illustrated via a recent example from an MTR project (Figure 6). Faults are common in Hong Kong and these are generally shown indicatively on the Hong Kong Geological Map Sheets and via borehole data. A first pass in the ground model revealed the layout of faults as shown in the figure. Then, since all data in the 3-dimensional ground model was digital, the designers interrogated the possible dip angle variations of the numerous faults based on geostatistics and the confidence in data accuracy – the results are illustrated in Figure 7, whereby small variations in dip of 5 – 20 degrees results in offsetting of the fault to works intersection at depth, from vertical, of between 10 to 60 m.

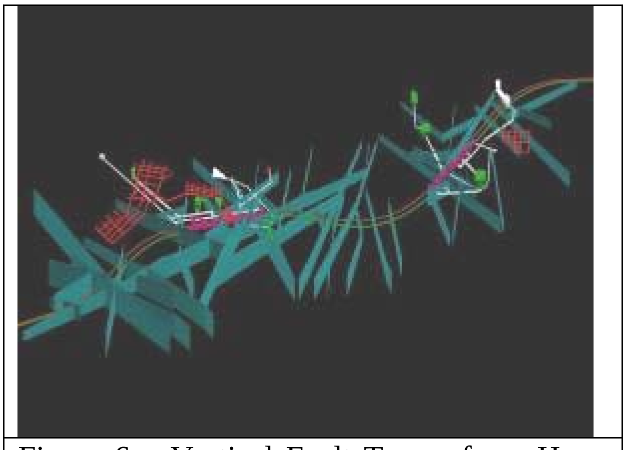


Figure 6 – Vertical Fault Traces for a Hong Kong Tunnel Scheme (MTR project, MMHK Limited, 2009)

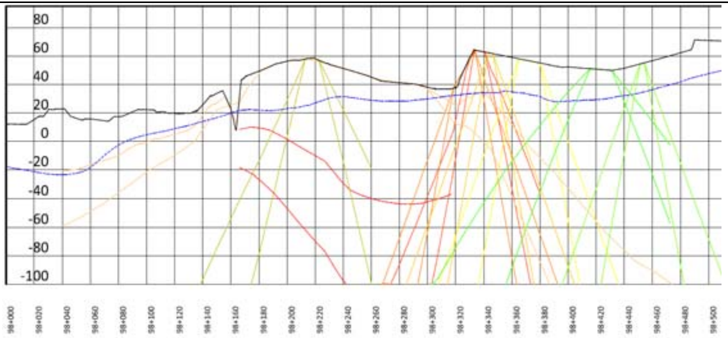
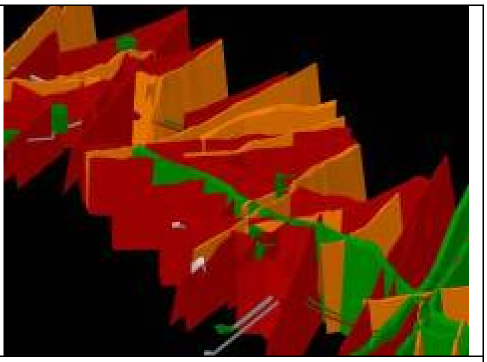
	

Figure 7a – Fault Trace Cones for Variable Dip, for a Hong Kong Tunnel Scheme (MTR project, MMHK Limited, 2009)	Figure 7b – Fault Cones Rendered in the Ground Model.

<u>Minor Discontinuities – Stochastic Discontinuity Parameters</u>

Discontinuities comprise the various types of fractures in a body of rock that dissect the mass into discrete rock blocks. The most common type of discontinuities are ‘joints’ and in most rocks these are ubiquitous but occur in sets of distinct orientation. As well as the *orientation*, other discontinuity parameters that must be assessed include the *spacing* and *persistence* of the discontinuities in the individual sets. These three discontinuity parameters are stochastic in nature and must be included in rock mass characterisation for underground works. The statistical distributions of these parameters are used directly in numerical analysis. In practice in Hong Kong, the source discontinuity orientation and spacing data tends to derive from borehole televiewer results, although persistence data cannot be derived in this manner.

The principles behind discontinuity data analysis and statistical interpretation are not new – in particular, a definitive book in the 1990’s was dedicated to the subject and offered practical advice on scanlines (Priest, 1993). This work came from ideas that included Fuzzy Set theory from the 1960’s and ideas developed by John Hudson at Imperial College and Priest in the 1980’s. Amongst the various practitioners, other schools of research into discontinuities are recognisable – these include Warburton on sterographics and persistence (Warburton, 1980) Baecher, with his classic paper on statistical analysis (Baecher, 1983), Dershowitz *et al* on fracture patterns from boreholes (Dershowitz et al, 1998), Kulatilake and Wu (1984) with their classic paper on discontinuity persistence (otherwise referred to as trace length) and methods developed at Berkeley University by Professor Goodman and others (Goodman and Shi, 1985).

For rock excavations, the realistic representation of anticipated discontinuity and jointing patterns is crucial for effective, optimised and therefore sustainable design of support and lining measures. The starting point is usually identification of joint sets via stereographic projection methods (Figure 8). This can be done manually or using software such as DIPS. v5 (available at www.rocscience.com).

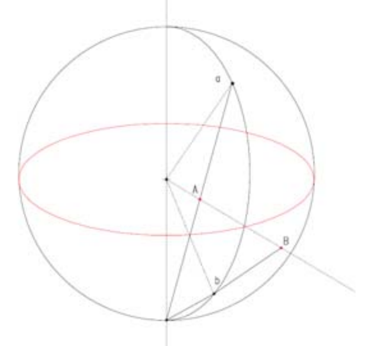


Figure 8 – Principles of Stereographic Projection

When joint sets interact with an excavation opening, rock blocks are created at the opening surface as well as those extending back into the rock mass around the opening. Some of these will be "detachable" or unstable, such that rock blocks may be removable via sliding, falling or toppling into the excavation.

It is important to note that due to the variation in orientation, spacing, persistence and other discontinuity properties, practitioners applying single values to these properties will underestimate the range of 'potential' detachable blocks (i.e., to use a single mean value for joint set orientation in particular is not advisable).

Good practice in discontinuity pattern assessment is the identification of structural domains in which the discontinuity patterns are relatively uniform. Invariably jointing patterns will vary across domains, different lithologies and even (in sedimentary rock) from one bed to another. Figure 9 illustrates an example of such variation within the same geometry, along a headrace tunnel for a recent hydro-electric scheme.

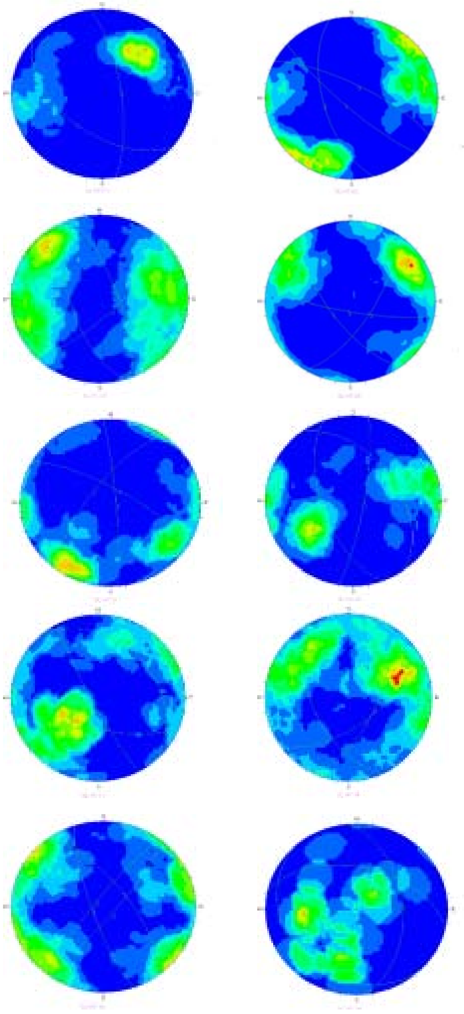


Figure 9 – Joint sets along a 1 km length of headrace tunnel, Bunji Hydroelectric Scheme, Pakistan, MMHK Limited.

In respect of detachable blocks, Goodman and Shi (1985) developed the concept of "Key Blocks", which is seldom applied in excavation design but perhaps should be utilised far more. An example of the stereographic method to determine so-called removable blocks is shown in Figure 10.

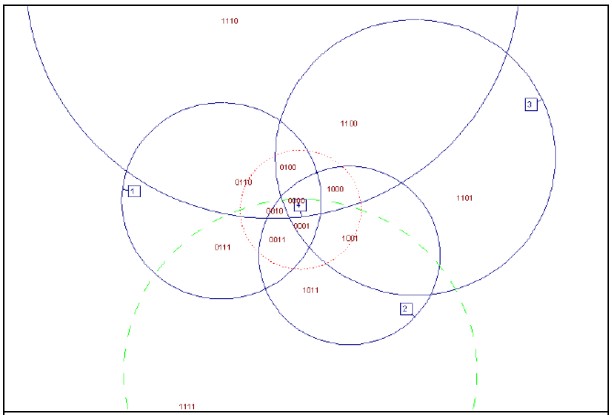


Figure 10 – Key Block Theory and Removable Blocks using Stereographic Projection

Fortunately, as an alternative to manual methods, software is available that can generate these plots (e.g., ROCK3D) – these determine identify and analyses all the blocks that may form under each kinematic mode. Key block theory is an important concept to optimise design and during-construction stabilisation of excavations – it enables near-surface blocks to be stabilised in such a manner that results in stabilisation of often much larger removable blocks.

It is also worth noting that in the author's experience, the key to obtaining useful discontinuity data is to impose rigorous scanline survey approaches, whereby data is acquired in a systematic manner along a physical scanline set up on the rock mass being mapped or through "televiewer" methods along a borehole. In addition, modern practices of automated mapping of rock exposures have been developed using laser and photogrammetric methods, although these have yet to be fully embraced by industry.

3-Dimensional Ground Models

Traditional geological cross-sections are generated for most construction projects, including in Hong Kong (Figure 11). For linear Works such as tunnels, a 2-dimensional representation may be sufficient for preliminary design, but will be insufficient for detailed design, or for the case of a widespread project area involving intersecting tunnels, adits and caverns.

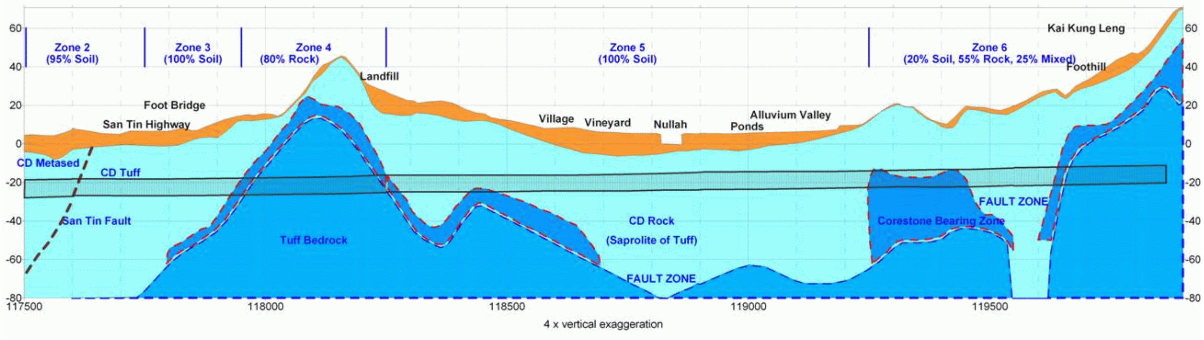


Figure 11 – Traditional 2-dimensional Geological Cross-section (Express Rail, Hong Kong, 2009).

Dipping rockhead, groundwater flow and topographic effects of in situ stress are but a few of the effects due to 3-dimensional geology and topography. For instance, understanding that a rockhead dipping across a cavern profile will affect a cavern design profoundly will reduce safety risk and increase certainty on contract costs. Hence, for an optimised and sustainable design with reduced safety and commercial risk, a mind shift from geology in 2-dimensions to one of 3-dimensions is advocated as a way forward for Hong Kong underground excavation.

In accordance with the above, a suggested 'recipe' for ground modelling comprises the following :

3-Dimensional Ground Model = *AGS data + HoleBase + KeyHole + HoleBase Reporter + Surfer + CAD-3D + GIS + Constructional Database*.

Recent examples of typical design output from 3-dimensioal digital ground models on Hong Kong projects are shown in Figures 12 and 13. In Figures 12(a) and 12(b), a possible fault zone and depressed rockhead lineament are seen crossing one of the station boxes. In 2-dimensions, this was not apparent and the results would affect design feasibility (i.e., open cut or cavern excavation).

Figure 12a – Probable Rockhead Profile for Proposed Ho Man Tin Station (view from above), MMHK Limited, 2009.

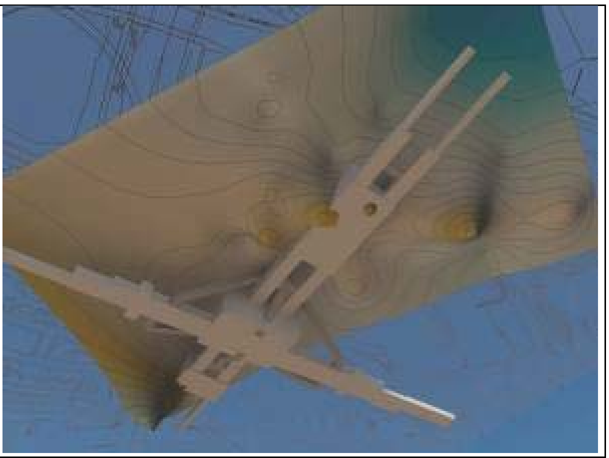


Figure 12b – Probable Rockhead Profile for Proposed Ho Man Tin Station (view from below), 2009.

In Figures 13a to 13b, an extract from the ground model for part of West Island Line (WIL) Contract 704 (Sai Ying Pun to Kennedy Town) is shown. The Ground Model was used for design interrogation, as a replacement and upgrade of approach to conventional cross-sections. This formed the basis for defining ground conditions in the Geotechnical Base Report and a Construction Database for Temporary Support Measures.

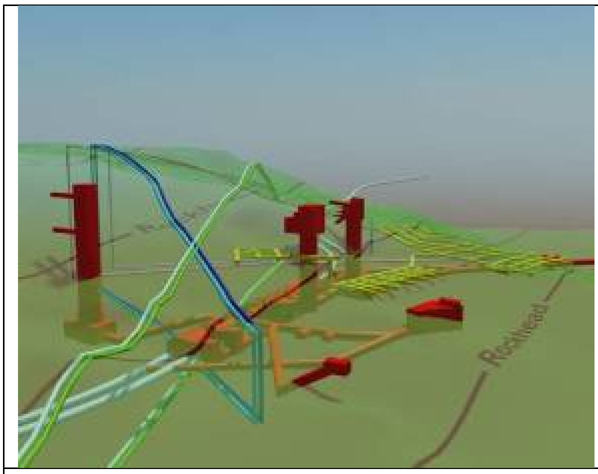


Figure 13a – Typical rockhead profile in 3D, with faults shown. WIL, 2009.

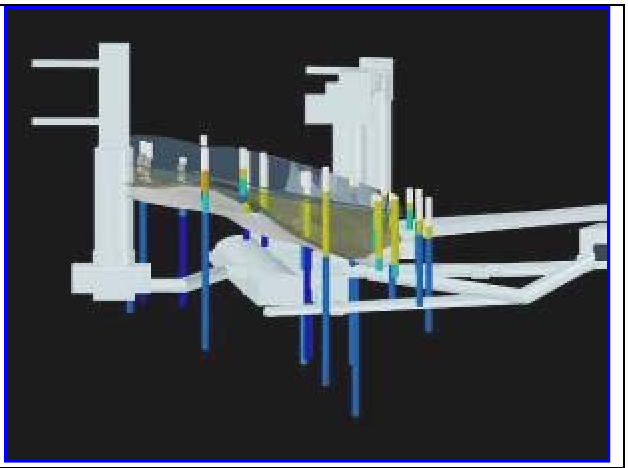


Figure 13b – 3D model allows interrogation of strata surfaces and boreholes, WIL, 2009.

3. ASPECTS OF OPTIMSED AND SUSTAINABLE 3-DIMENSIONAL CAVERN DESIGN

Barton provides a view on the development and current status of numerical modelling in rock excavation design (Barton, 2006), stating that *"in the late 1960's, there was a move in some rock mechanics circles to try to move beyond the confines of continuum modelling, and focus on the possible effects of jointing on the performance and reinforcement needs of rock excavations …"*. In addition, Barton describes the start of the development of UDEC and 3DEC, by Cundall since the early 1970's, and the need for experience, time and budgets for such work, before going on to state, "*Presumably as a result of time and budgetary pressures, and also the developing need to model large-scale mining problems, there has been a* *'backwards' movement into the use of conventional continuum codes, which also have particularly good graphics presentations*."

For the design of rock excavations and besides the general use of Barton's Q-System, there are six proprietary numerical analysis software packages available to practitioners in Hong Kong, as follows : (1) FLAC, (2) Plaxis, (3) Phase2, (4) FLAC3D, (5) UDEC and (6) 3DEC. In addition there are various ancillary proprietary software packages commonly used in Hong Kong, including TunSet, UnWedge, and for structural lining design, SAP2000. However, the point here is that (1) to (4) use continuum modelling and only (5) and (6) model discontinuous rock masses; these latter two software programmes are rarely used, even now over 30 years on from the first versions of UDEC. Modellers prefer to use either use the continuum models of either Phase2 or FLAC, or a combination of both, with the former providing rock bolt/dowel designs and the latter providing shotcrete and concrete designs. Most designers will then go on to use SAP 2000 to check bending moments and mass-structure interaction. In some cases, Phase2 and SAP 2000 is deemed sufficient. The note of caution to raised is that this latter minimal and continuum route for the design of rock caverns may be inappropriate – generally, and from experience of recent Hong Kong projects, an appropriate and workable methodology may comprise the following sequential steps :

- ***Step 1*** : Ground Model Output – Generation of design cross-sections and long-sections using a 3-dimensional ground model.
- ***Step 2*** : GBR – Review and benchmark ground conditions and geotechnical design parameters.
- ***Step 3*** : Q-System – Apply the latest 2002 version of the Q-system, as a benchmark for temporary and permanent support and lining design.
- ***Step 4*** : Structural Design – Carry out structural design, using SAP 2000 for example.
- ***Step 5***: UDEC Modelling – Use representative cross- and long-sections from the 3-dimensional ground model and commence support and lining designs using UDEC. The UDEC results may be used in a two-fold manner : (a) as a check for the Q-based design in good rock and (b) as the precedent-design for poor rock conditions and complex staged excavation. For highly complex excavations or critical design elements, the use of 3DEC may be justified – usually the use of this is latter software would be initiated to model rock mass "arching" in a more realistic and advantageous manner, since UDEC is only two-dimensional.
- ***Step 6*** : FLAC3D Modelling – apply this software to derive stress and strain conditions at 3-dimensional junctions and complex excavation geometries. Often the results show the locations of tensile and compressive stress concentrations that can inform the design of linings. It should be noted that effectively, FLAC3D will yield a design for the lining and not the temporary support from rock bolts and dowels in a rock mass excavation. Being continuum modelling software, it is possible to simulate a zone of strengthened rock mass, but true representation of a ubiquitously jointed rock mass is not possible. Hence UDEC or 3DEC is preferable.
- ***STEP 6*** : Ground Movement Analysis – On projects involving major excavations, a crucial aspect of design will involve assessment of potential ground settlement. This may be due to void space strain or consolidation settlement due to inflow into the excavation and drawdown of the groundwater table. The resulting settlement may affect buildings or other existing structures or infrastructure at surface or sub-surface. This analysis is not straightforward and usually involves significant time input using a combination of analysis approaches and software, such as FLAC, Plaxis, and UDEC for ground movement, and SEEP/W for inflow and permeability determinations. With

respect to inflow, common practice is to use SEEP/W, but it is important to recognise that this approach only considers homogeneous rock and soil masses in terms of permeability. Far more important to rock caverns is the concept of “hydraulic connectivity” due to discontinuities. For design purposes, this can be assessed empirically, from existing Lugeon test data, or by numerical modelling using UDEC with internal programme functions or linked to fracture simulation software such as FracMan.

Further details and examples of these key steps are illustrated below.

Rock Mass UDEC – BB (Step 5)

The first thing to reiterate is that UDEC numerical analysis software has been around for a few decades now. Although in 2010 the programme is at version 4, the process has remained command-driven rather than menu-driven; this can result in the perception of UDEC being user-unfriendly. Nonetheless, it is the only proprietary “discrete element” numerical analysis programme software available. It requires experience to use, detailed geotechnical knowledge, rigorous parameter selection and sufficient time and budget to achieve useful and realistic results. On this latter point, it is worth pointing out that practitioners may be faced with needing to inform clients about numerical analyses and the benefits thereof, but the bottom line should be : “why use outdated methods, when validated modern software is available ?” Like construction methods and technology, design methods must move forward.

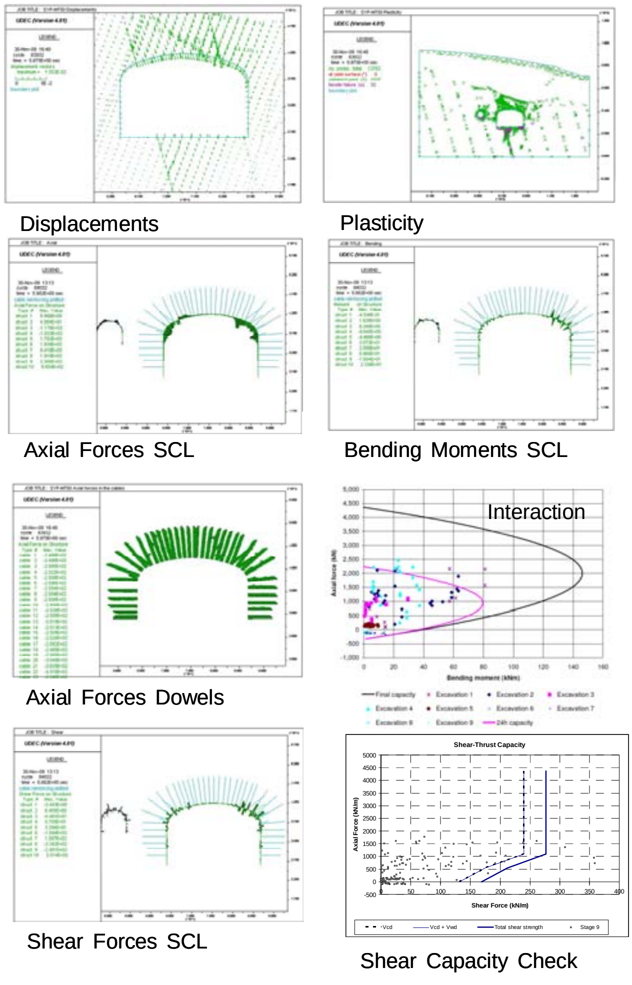
The principles of discrete element numerical analysis are similar to Finite Element and Finite Difference methods, in that boundary conditions need to be well-defined, meshing of the model needs to be applied and the parameters to allow stress and strains to form realistically need careful selection. But simply put, discrete element analysis allows a model to be cut into individual blocks that can slide and rotate. It is possible to apply various ‘constitutive models’ to dictate how the discontinuities interact and shear and blocks deform. Experience from recent projects undertaken on Hong Kong projects suggests the following :

- The larger the model, the longer the cycle time and less stable the model may be. Large models can run (cycle) for a few days and then a single block may yield or the model does not come to equilibrium. Hence, the “lesson learnt” is to reduce the scale of models, whilst retaining the ‘representativeness’ and the ‘usefulness’ for design.
- Select discontinuity spacings with care. The closer the spacing, the more cycle time is required.
- Consider the water pressures – UDEC can include water pressure via FISH function programming or from commands.
- Consider the exact location of joints relative to the excavation, when the model is cut (or “cracked”). Stresses and strains will be related to particular block movements and therefore locations around the excavation, unlike continuum models – this can cause problems with the models coming to equilibrium, or may produce localised stress concentrations that affect the specification (e.g., thickness) of lining designs.
- The excavation sequence must be modelled in its entirety, from no excavation, to individual headings – each stage of excavation is modelled and the support requirements installed into the model before the next stage is cycled.
- Carefully consider which constitutive model for discontinuity behaviour to use – in UDEC, the Coulomb slip model is perhaps most-commonly used, which allows for limited dilation during shear, but there is also a displacement-weakening model

referred to as the Barton-Bandis model, whereby progressive damage is simulated along joints during shearing.

- It is found from experience that the definition of corner-to-corner and corner-to-edge block interaction is important in avoiding non-convergence of models.

So the question arises : What does UDEC provide in the design process ? The answer is : (a) a comprehensive design for Temporary support during excavation, that includes rock bolts and dowels (numbers, diameters, lengths, loads) and shotcrete (thickness and specification), and (b) Permanent lining designs. Both are supplemented as appropriate via the Q-system approach, structural analysis using SAP 2000 or similar and analysis for individual large blocks, using UnWedge or similar.


Displacements

Plasticity

Axial Forces SCL

Bending Moments SCL

Axial Forces Dowels

Shear Forces SCL

Shear Capacity Check

Figure 14 – Typical Suite of UDEC Output (MMHK, 2009).

The images in Figure 14 show a typical suite of UDEC design output for temporary support and lining design associated with a recent cavern construction project in Hong Kong. The top four plots comprise the main UDEC design elements for the final stage shotcrete design - displacement, plasticity check (only a few blocks attain yield, at the base), axial forces check (with dowels in place) and bending moments calculation (with dowels in place). In the two lower left images the axial forces on the dowels and the shear forces in the shotcrete are shown. Finally, the two lower right images show the rock mass-structure interaction diagram that confirms the design elements are within capacity and the design is acceptable, and a final check on shear capacity (which must be done in addition to the interaction calculation). The results show a workable and optimised design, via distinct element modelling, is attained. It should be noted that the model boundaries are set well beyond those shown – the images in the figure are zoomed-in extracts of the model.

Cavern Excavation and Support Sequence

For the purposes of designing the excavation, support and lining of large rock caverns there is a significant difference in the approaches and rationale for Temporary Works versus Permanent Works. Fundamentally, temporary support is designed to allow a certain degree of deformation and 'convergence' – this allows the rock mass itself to take loading in response to the creation of the void, principally by 'arching', mobilisation of full joint shear strength at relatively large strains and interlocking of rock blocks. Temporary Works are designed to control to deformation to a point of 'zero convergence' (i.e., no movement) and excavation stability. Thereafter, the permanent support can be installed – these permanent support and lining works generally take lower stress levels than the temporary works and do not have to cater for rock mass strain, other than localised rock wedges.

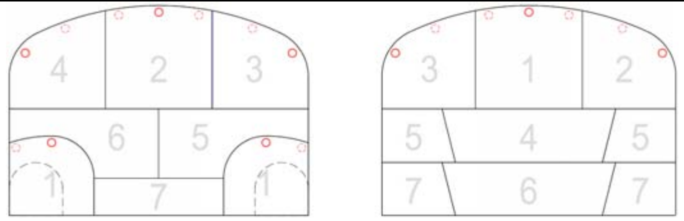


Figure 15 – Typical excavation sequences for cavern construction and temporary works design

In view of the above, it is clear that the design of temporary support and the lining systems for rock caverns must account for the sequence of proposed excavation (Figure 15). In a sense, it becomes apparent that, with the above-mentioned demarcation between temporary and permanent works in Hong Kong, the temporary works design is often more involving than the permanent works design. Furthermore, it is incumbent on designers, who are usually consultants, to work closely with contractors, since the latter will have clear views on methodology for excavation based on plant availability, construction and contractual restrictions (blasting, inflow, ground movement, groundwater drawdown) and programme, not to mention the contractor's experience and preferred methodologies.

Junction and Complex Geometries – FLAC3D

One of the most challenging aspects of cavern design relates to junctions between the cavern and connecting adits or tunnels, be these permanent or for construction purposes. These are 3-dimensional structures and do not lend themselves readily to 2-dimensional analysis. In 3-dimensions the effects of arching can be considered more fully such that the design is optimised and not overly-conservative. In addition, the extent of stress concentration zones can be visualised and the design of support modified accordingly. There are two approaches advocated herein, which relate to the finite difference method of Itasca's FLAC3D and the discrete element approach of Itasca's 3DEC. Few practitioners have experience of 3DEC and there is limited track-record on the use of this software – a substantial investment of budget and time is required to 'truth' this approach to the site-specific conditions. An alternative approach, that has substantial track record in tunnelling, is to use FLAC3D – this can be used in conjunction with Phase2 and correlation to the results from 2-dimensional UDEC and the Q-system (with the Q system normally applying a factor of 3 to the Jn value to account for support requirements at junctions).

The FLAC3D approach yields a standalone design for the shotcrete or lining elements of a support system (Figure 16) – typically, this approach will not account for rock dowels or bolts directly.

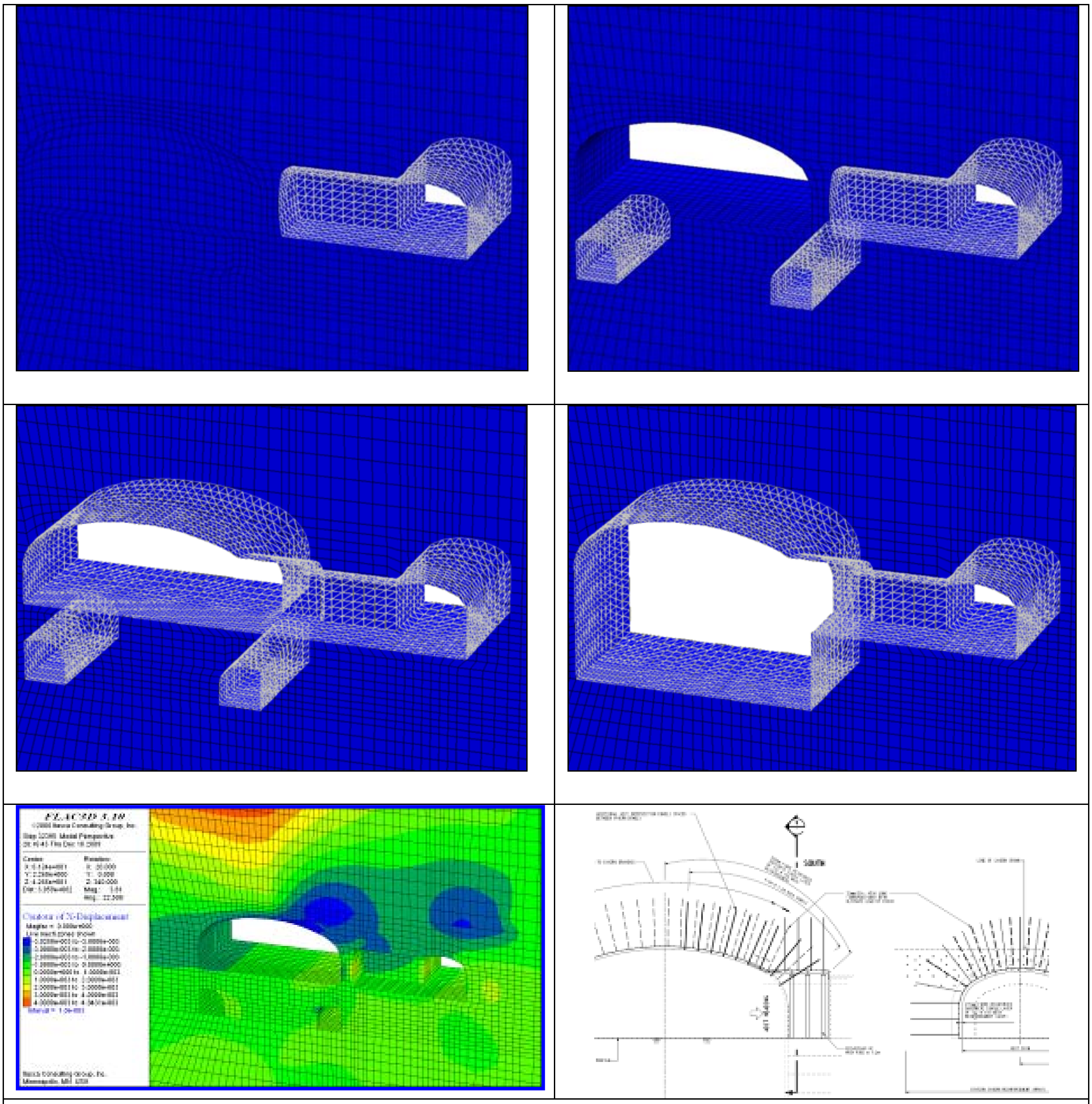


Figure 16 – Typical sequence of excavation in FLAC3D. *Note: lower left image shows design output of compressive stress concentrations (in blue) and lower right image shows a typical 3-dimensional junction temporary works design.* (MMHK Limited, 2009).

Inflow, Groundwater Drawdown and Settlement

The design of temporary works in particular needs to account for groundwater inflow into the excavation. It most cases for Hong Kong projects, maximum groundwater drawdown permissible due to the proposed works is limited and specified under the contract. Regarding rock cavern excavations at depth, within the deep rock mass, such issues are still critical, since the rock mass discontinuities may connect to overlying perched water tables in soils and superficial deposits, and of course the permanent groundwater table may be present within the rock mass itself.

The literature on groundwater inflow prediction is extensive. Forth and Thorley (1995) discuss ground and building settlement due to tunnelling in Hong Kong, referencing the works of Peck in 1969. More recently, Hewitt (2005) provides experiences of rock tunnel excavation and groundwater control in Sydney, citing the classic Heuer groundwater inflow analysis approach (Heuer 1995 and 2005), amongst other methods. Indeed, the Heuer method is utilised routinely in Hong Kong for inflow estimation. If time allows on projects, UDEC can be used to estimate hydraulic groundwater flow in discontinuities within the rock mass – this sophisticated approach is further discussed by Gattinoni etc al (2009).

From recent experience, a practical approach to assessing ground settlement over extensive project areas may be as follows :

- For estimation of the movements induced by the excavation of the underground openings, numerical analysis software FLAC2D and UDEC can be used to calibrate PLAXIS2D results (Figure 17a) and estimate ground movements repeatedly at sections along the works.
- The groundwater drawdown is predicted using a background permeability approach, employing the rock mass permeability, which accounts for the typical fracture network of the rock. These predictions are based on the analyses undertaken by using the software SEEP/W 2D (Figure 17b) and the associated ground settlements are estimated using elastic theory.
- Drawdown calculations are based on the 3-dimensional Ground Model.
- The analysis stages should include : (a) calibration of piezometric levels and hence pore water pressures according to the field measurements of the groundwater table by using reasonable boundary conditions and modelling the underground openings as "zero pore pressure" regions; (b) a steady state calculation stage can be undertaken to estimate the drawdown.
- Greenfield settlements are calculated using steady state drawdown results, which is undertaken using a specified permeability profile.
- For existing buildings (EBS) : (a) The damage classification for EBS is undertaken according to the building and structure risk categories (for example, for MTR projects this would be as per MTRCL DSM Table 4.2.5.T1); (b) the zone of influence of ground movements is defined (e.g., by 10mm predicted ground surface settlement contour); (c) analyses of the structural and geotechnical capacity of any pile foundations (e.g., using the OASYS©. Software suite) is analysed for single and group pile effects.

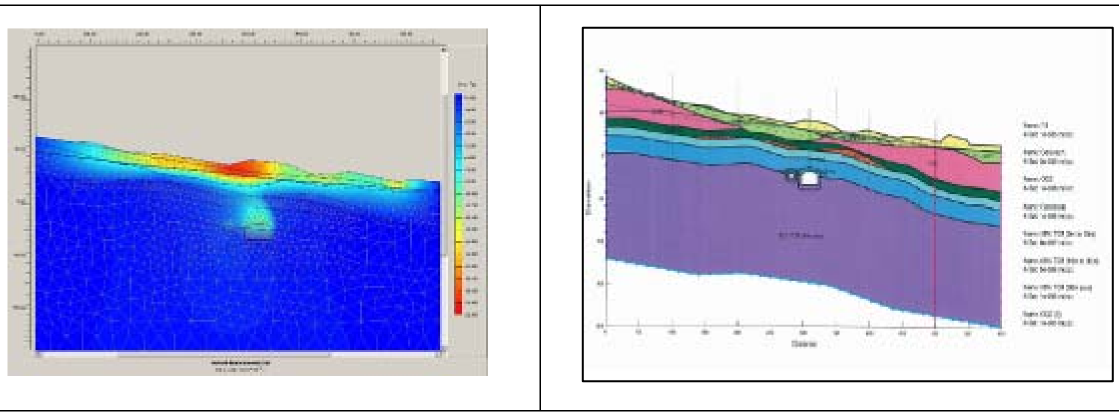


Figure 17 – Groundwater and Settlement Analysis - Typical output from Plaxis and SEEP/W

4. CONCLUSIONS

This paper is aimed at drawing attention to two aspects of sustainability that apply directly to infrastructure development in Hong Kong. These are :

a) The use of underground caverns as alternative locations for development, utilities and infrastructure, and
b) The role of and the tools available to practitioners to optimise designs and therefore facilitate sustainable developments – namely the use of 3-dimensional digital ground models and numerical analysis.

For the former, Hong Kong clearly has limited surface land availability for development, so underground spaces may be an option. Although the use of caverns is limited currently, there may be opportunity for such structures to form part of a sustainable strategy for the future. On the latter, the author considers the measures that designers should perhaps be adopting more widely with respect to using modern numerical analysis techniques to interrogate and optimise designs. It is perhaps fair to say that numerical analysis is seldom used to date owing to the complexity of the programme and the investment in time and budget. However, for wide-span and complex structures such as rock caverns, such approaches should be encouraged. Recent examples of the utilisation of UDEC and FLAC3D for Hong Kong projects are presented, with this numerical analysis approach having been applied within the context of well-established digital 3-dimensional ground models.

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