Structural geological input for a potential cavern project in Hong Kong

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ABSTRACT

Rock engineering requires an in-depth understanding of structural geology to assist with successful project outcomes. This paper examines how structural geological information can be incorporated effectively into a conceptual engineering geological model with reference to the proposed Sha Tin (Shek Mun) Strategic Cavern Area. It also examines the potential rock engineering implications and engineering geological uncertainties for the proposed Sha Tin Sewage Treatment Works Cavern site.

1 INTRODUCTION

Rock engineering requires an in-depth understanding of structural geology, as discontinuities govern the behaviour of many rock masses at the scale of most rock engineering projects. Consequently, the development of a conceptual engineering geological model by an experienced engineering geologist should be an early product for any rock engineering project. All too often the structural geological information for such projects is superficially evaluated and interpreted in isolation, without reference to an overall hypothesis or model. Given the variable and complicated nature of structural geological data, the lack of such an interpretative framework can result in misleading or incorrect interpretations.

The preferred approach (Baynes *et. al.*, 2005), is to develop a series of evolving engineering geological models (conceptual, observational and analytical), which explicitly and systematically include structural geological data. This paper demonstrates the use of conceptual engineering geological models in rock engineering, using as a case study the proposed Sha Tin Strategic (Shek Mun) Cavern Area in Hong Kong. The case study demonstrates how structural geological data from desk studies can be quickly, effectively and inexpensively incorporated into a conceptual engineering geological model. This in turn allows the establishment of a register of uncertainties and risks and demonstrates how key information can be quickly gathered in the early stages of a project, allowing better decision making. The paper also examines the required 'transforms' and appropriate methods of communication for conveying effectively the important aspects of these models and their associated uncertainties and risks to non-engineering geologists e.g. the planners and engineers involved in the design and construction. This approach ensures that the key points are understood by the project team and the model is re-evaluated during the later phases of the project. Finally, the paper discusses how the conceptual model can be used to develop the observational and analytical engineering geological models.

2. THE PROPOSED SHA TIN (SHEK MUN) STRATEGIC CAVERN AREA

The proposed Sha Tin (Shek Mun) Strategic Cavern Area (the 'cavern area') is one of five such areas identified in a recent report (GEO, 2011) and the location is shown in Figure 1. It is located under Nui Po Shan (Turret Hill), which lies to the south and east of the Shing Mun River Channel. As described by GEO (2011), the Sha Tin Sewage Treatment works, located on the opposite side of the Shing Mun River Channel (Figure 1), is considered to be a particularly suitable facility for relocation into caverns within the cavern area. As such, this facility has been selected as one of three preliminary feasibility studies (note that this paper is unrelated to these feasibility studies). Section 2 of this paper will discuss the geological structure of the cavern area in general, while Section 3 will focus on the engineering geological issues of the proposed sewage treatment works cavern site.

A desk study for the cavern area was carried out for the purpose of this paper, in which the relevant geological maps, memoirs, reference texts and published papers were consulted. This research was not as comprehensive as would be required for an actual feasibility study, as the aim of this paper is to demonstrate how basic structural geological information for Hong Kong can be relatively quickly and easily obtained and synthesized into a conceptual engineering geological model. The main limitations of this paper are: not all of the available reference material was consulted; a site specific aerial photograph interpretation (API) and site reconnaissance were not carried out; and, those features or aspects of features unrelated to structural geology, rock engineering and caverns were not considered. In particular, it is considered that a site specific API and reconnaissance (in particular a visit to Turret Hill Quarry) are critical to the development of a robust conceptual engineering geological model. Furthermore, it is recommended that a reinterpretation of the lineaments is made using high resolution LiDAR data and reference should be made to the records of the numerous water tunnels in the area. However, for the purposes of this paper the API and field mapping information from two unrelated studies at the cavern area were deemed to be sufficient to illustrate the concept. It should be noted that some geological observations are based on the 1986 edition of the 1:20,000 geological map, rather than the 2008 revised version. Finally, the cavern area extends to the south of the Ma On Shan fault, into volcanic rocks of the Repulse Bay Volcanic Group and Clearwater Bay formation. However, this area has not been considered for the purposes of this paper. A synthesis of the findings of the desk study is as follows.

2.1 Solid geology

To the north of the Ma On Shan Fault, the cavern area is situated in the Shui Chuen O Granite of the Cretaceous Cheung Chau Suite and the Sha Tin Granite of the Jurassic Kwai Chung Suite (underlying the upper, steeper slopes of Nui Po Shan). Some minor sections of the cavern area also fall within the Cretaceous Tei Tong Tsui Quartz Monzonite of the Lion Rock Suite. It is interpreted that the Needle Hill Granite was the first pluton intruded in the region (which also belongs to the Kwai Chung Suite). This in turn was intruded by the Sha Tin Granite. These units were subsequently intruded by the Shui Chuen O Granite during the Cretaceous. The final significant phase of intrusion in the area was the intrusion of the NE trending dykes of the Tei Tong Tsui Quartz Monzonite. It is clear that all of these intrusions are strongly controlled by a NE trend, with the intrusions being elongate in this direction, having been controlled by transtension (probably dominantly extensional) associated with deep crustal structures. Tectonic activity has continued after the intrusion of these rocks, which have subsequently been faulted, jointed and intruded by dykes, again following the NE orientation, which is the dominant structural trend in Hong Kong (the Lianhuashan Fault Zone) and which includes the Lai Chi Kok – Tolo Channel Fault (Sewell *et. al.*, 2000), discussed in the following section.

2.2 Structural geology

A consideration of faulting is of importance in determining the regional structural trends, which can help in interpreting joint trends. Figure 1 shows the locations of the faults and lineaments interpreted in the region of the cavern area. This interpretation is based on a combination of faults and photolineaments interpreted on the 1:20,000 and 1:100,000- scale geological maps, Lau & Kirk (2001) and a site specific interpretation of a 1:5,000-scale digital elevation model (DEM) by the authors. The main trends in general decreasing order of magnitude are NE-SW, NW-SE, ENE-WSW and WNW-ESE (the regional dyke swarms also follow these trends, with NE also being the dominant trend of the minor intrusions and dykes). As a result of the previous tectonic and igneous activity, structures will exist at all scales from microstructures, through joints and to faults of varying magnitude.

There is no indication from this basic desk study of major fault zones crossing the proposed cavern area and this is probably one of the reasons that this region has been selected for consideration. However, a number of lineaments, many of which probably represent moderate and minor faults are present (faults in this paper have been tentatively classified as *deep seated, major, moderate* and *minor* on the basis of Table IV in Burnett & Lai, 1985). Therefore, knowledge of the faulting pattern can be used to minimise the risks posed by unidentified faults to underground excavations in the cavern area and to reduce the risk of encountering unforeseen ground conditions. It also allows early optimisation of the cavern orientation with regards to the joint sets and potential instability.

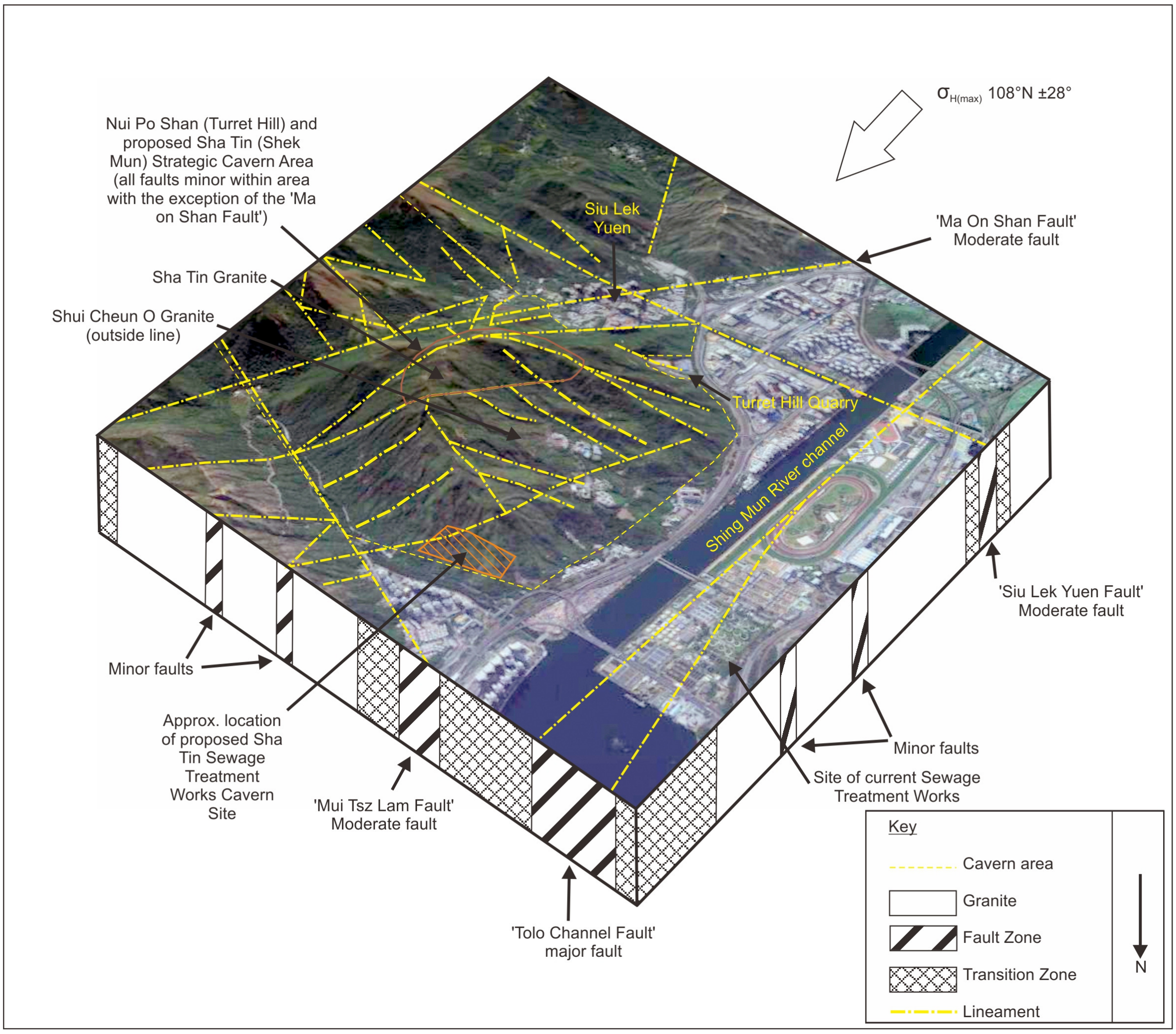

Figure 1: Proposed cavern area – location and regional conceptual engineering geological model (Image © 2011 Google, © GeoEye, ©2011 DigitalGlobe)

NE-SW trend: This is the main structural trend in Hong Kong, forming a component of the Lianhuashan Fault Zone. A NE trending major fault zone, the Lai Chi Kok - Tolo Channel Fault (Burnett & Lai, 1985, henceforth referred to as the Tolo Channel Fault) is located to the immediate north of the cavern area (and may affect the northernmost part of the cavern area), running through the Sha Tin urban area and parallel to the Shing Mun River. The fault zone has probably been periodically active since the late palaeozoic and may have continued to be active until 3-4 Ma. The NE trending moderate Ma On Shan fault is located in the southern part of the cavern area and is mapped as downthrown to the south. The Tolo Channel Fault and, to a lesser extent, the Ma On Shan Fault are considered to be subvertical, trending 050° (approx.) with crush zones of several to tens of metres wide (30m width has been found on the Tolo Channel Fault), comprising, cataclasite, breccia, slickensides, sheared granite, fault gouge, closely jointed zones adjacent to the fault and significant kaolinization and chloritization of the host granite. There may also be mafic and quartz monzonite intrusions locally. Minor faults of this trend, if encountered in the cavern area, would be expected to have related albeit much less well developed characteristics. Adjacent faults of this trend appear to be 1.5 to 2 km apart (Lau & Kirk, 2001).

NW-SE trend: This is the second most important structural trend in Hong Kong and these are considered to be moderate faults in accordance with Burnett & Lai (1985). In the region these faults dip steeply and trend between 310° to 340°. A NW trending fault is probably located to the immediate west of the cavern area running parallel with Siu Lek Yuen Road. Another, NW trending fault (interpreted to downthow to the NE), and possibly of greater magnitude as it has a greater topographic expression, is located to the immediate east of the proposed cavern running along the well-defined Mui Tsz Lam Valley. Both of these faults may affect the areas at the boundary of the cavern area. In a few locations mafic dykes are intruded along faults in the region with this trend. Some quartz veins with mineralisation are associated with faults with a similar trend to the west. These faults are of compressive-shear or tensile-shear type, with a narrow crushed zone. They are thought to have been active since the late Mesozoic (possibly active up to 33,330+/-2700 years BP according to Ding & Lai (1997). Present river systems, estuaries, channels and sections of coast are commonly influenced by faults of this orientation. A lineament of this trend has been identified in the NE part of the cavern area. These faults are often found to be cross-cut and offset by the NE-SW trending faults (Lau & Kirk, 2001).

WNW-ESE trend: Several WNW-ESE trending lineaments have been identified within the cavern area. The orientation of these features indicate a probable structural origin and they appear to be the least persistent lineaments. This might correspond with the findings of Lau & Kirk (2001) who indicate that most faults in the region with this trend are minor faults that are 0.5 to 1km in length. Where faults of this orientation have been described in Lau & Kirk (2001), they vary in width (they can be many metres wide), vertical or inclined and may be weathered to considerable depths. Quartz mineralisation (hydrothermal) is commonly associated with the faults.

ENE-WSW trend: There is less published information on the nature of the ENE-WSW trending faults as these are typically minor faults. There is a group of faults of this orientation to the north of the Tolo Channel Fault that strike about 060° to 080°. These faults are intensely brecciated and are associated with sericitisation. Movements on these faults are relatively minor, the main effect being to form a minor graben on the northern side of the granite outcrops. Minor zones of mylonite and narrow shear zones occur striking 065° to 075° (Addison, 1986). Several lineaments of this trend have been identified crossing the cavern area.

The following information on the joints is mainly derived from information from two unrelated study reports which have been carried out within the cavern area. Note these two studies were located in the Shui Chuen O Granite and the joint patterns in the Sha Tin Granite may differ. The subvertical joints are likely to be tectonic joints, formed in relation to the faulting. However, the possibility that some of these joints might have originated as cooling joints cannot currently be discounted. The engineering properties of joints are controlled by their mode of formation and subsequent history. Therefore, establishing the mode of formation of the joints can significantly assist with rock mass characterisation and subsequent rock engineering analysis (Hencher et. al. 2010).

Sheeting joints: Where recorded during the studies it was found that the sheeting joints dip 20° to 50° towards 260° to 305° (average 25°/285°), subparallel to the slope faces (note that the orientations of sheeting joints will vary across the cavern area and these values are unlikely to be applicable elsewhere). The joints are typically associated with increased weathering and typically have 1 m to 3 m spacing (reducing to as low as 0.5 m near the surface). These joints are best developed near the ground surface and spacing is expected to increase with depth, with sheeting joints probably confined to within 30m of the surface (Hencher *et. al.* 2010). These joints have wavy, rough undulating surfaces, are occasionally dilated (<15 mm) and infilled with kaolin. Seepages along these joints have been reported.

NE-SW trending steeply dipping to subvertical joints: This set dips 55° to 90° towards 325° to 345° (pole concentration at 80°/150°). This joint set has a persistence >10 m length on some rock slopes and the joints are typically smooth planar to rough planar, and close to medium spaced, but can be widely spaced.

NW-SE trending steeply dipping to subvertical joints: This sets dips 75° to 90° towards 220° to 250° (average 75°/225°). These joints are occasionally slickensided (one measurement plunging 53°/347°), indicating that they may occasionally form minor faults, given the NW-SE trend and presence of slickensides and associated quartz veins. This joint set is tentatively considered to be widely spaced (considered to have an average spacing of 1 m, but ranging from 0.6 m to 2 m) and the joints are described as smooth planar to rough planar. A drainage line within the proposed cavern area also appears to be controlled by an extremely persistent discontinuity dipping 75° towards 230°.

The sheeting joints are considered to have been formed by stress relief close to the land surface, although they may have developed along pre-existing microstructures and joints (possibly related to cooling). The subvertical joints are most likely tectonic joints related to the faults. However, some of the steeply dipping or subvertical joints might also represent cooling joints roughly subparallel to the flanks of the Shui Chuen O Granite and Sha Tin Granite intrusions.

3 IMPLICATIONS FOR THE PROPOSED SHA TIN SEWAGE TREATMENT WORKS CAVERN

The preceding information is of importance to the rock engineering aspects of the proposed cavern, but its use is limited if the key points are not communicated effectively to the project team. One of the engineering geologist's roles is to take the kind of geological information presented in Section 2 and 'transform' this into a form that is of use to those who will use the data, typically, but not only, engineers (Baynes, 1999). This transformation requires a synthesis of the information into text, maps/plans, sections, block models, uncertainty and risk registers. In the case of this paper, the text of Section 2 along with Figure 1 constitutes a basic conceptual engineering geological model for the cavern area. Figure 2 provides a larger scale model for the proposed Sha Tin Sewage Treatment Works Cavern site, which is located within the NE corner of the cavern area as shown on Figure 1. In addition, Tables 1 and 2 are intended to communicate some key items of engineering significance and uncertainties for the proposed sewage treatment works cavern site. Note that a full conceptual engineering geological model would provide a much more comprehensive account.

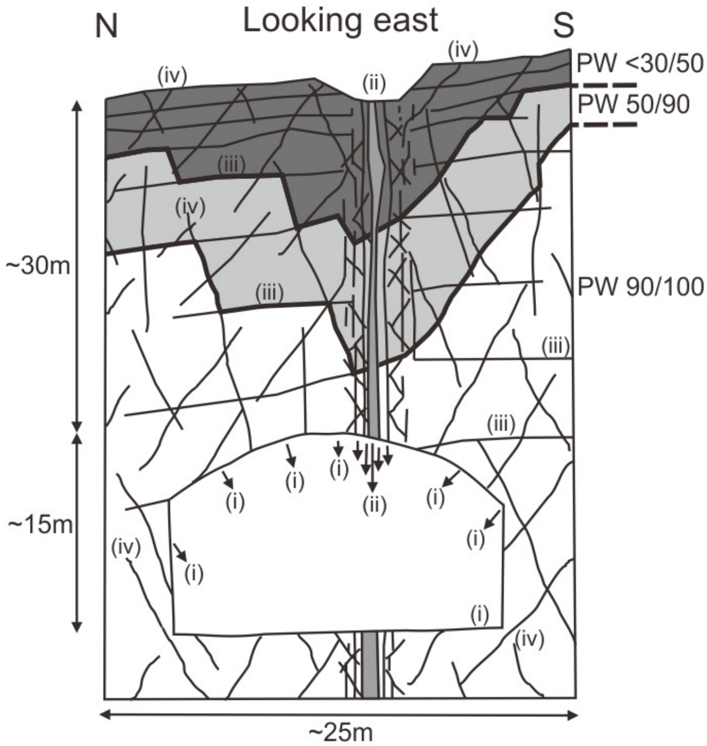

Figure 2: Proposed Sha Tin Sewage Treatment Works conceptual engineering geological model, (Note: Roman numerals refer to Table 1)

Table 1: The possible engineering significance of the structural geology – conceptual engineering geological model stage (Note: parameter values are conceptual estimates and are not intended for use in design)

Feature	Engineering significance and rock mass behaviour
General rock mass (i)	For the purposes of this paper it is assumed that the proposed sewage treatment works cavern site is typically situated at 30m depth or greater in moderately to slightly decomposed Shui Chuen O Granite (although weathering in Hong Kong can easily extend to these depths or greater and therefore the proposed caverns may need to be deeper). The orientation assumed is as shown in the GEO (2011) report. It is further assumed that the sheeting joints (see below) will be less well developed or absent below this depth (Hencher *et. al.*, 2010). Based on the approach suggested in Chapter 5 of Palmstrom & Stille (2010) the granite at the cavern depth might generally be classed, depending on the extent of weathering along joints, between *'jointed rocks or blocky materials – Class B – rocks intersected by joints and partings - jointed homogenous rocks'* and *'jointed rocks or block materials - Class C – jointed rocks intersected by seams or weak layers – prominent weathering along joints'.* Consequently, it is assessed that the main issues associated with the typical rock mass will be block falls and areas of water inflow. Based on an assessment of the information in Section 2 and the conceptual engineering geological model, the following parameters have been derived as estimates for initial consideration: Strength (100 – 250 Mpa); block dimensions might typically range from 0.1m to 2m, perhaps with 0.5m being an average; GSI (50 to 80, assessed typical value – 75); Q (best – 37.5 [RQD 100, Jn 4, Jr 1.5, Ja 1, Jw 1, SRF 1]; typical – 4.5 [RQD 90, Jn 6, Jr 1.5, Ja 2, Jw 1, SRF 2.5]; worst – 1.1 [RQD 75, Jn 9, Jr 1, Ja 2, Jw 0.6, SRF 2.5]. RMR (best/typical/worst – 77 (good rock)/ 67 (good rock) / 49 (fair rock). RMi (best/typical/worst 87 (very high) / 33 (very high) / 3 (high).

Faults (ii)	Descriptions and orientations as per Section 2.2. No major or moderate faults have been identified crossing the proposed sewage treatment works cavern site, although some lineaments, possibly representing minor faults, cross the proposed cavern site, particularly at the southern end. Possible materials in the minor fault zones include breccia and minor areas of fault gouge. Adjacent to the faults, the frequency of tectonic joints may increase markedly and the rock may be comminuted or very closely jointed with well-developed joints. The faults may also be partially (quartz lenses) or fully silicified and/or intruded by dykes. Unless replaced by secondary mineralisation the fault material will be 'weak'. Consequently, these features may result in increased overbreak, block falls, cave-in and water inflow. In addition, whilst more unlikely, the possibility of running ground, raveling and water inburst should be kept in mind. Depending on the nature of the material, fault zones can act as an aquiclude or an aquifer. Some types of mineralisation (e.g. sulphides) can cause problems with concrete. If the fault zone is silicified it may present some difficulties with tunneling, such as increased bit wear. Blocks along fault zones are likely to be small and crushed and may occur as clasts in a finer matrix. In any case block sizes will be smaller than the assessed range for unfaulted rock. Assessed parameters for consideration: GSI (10 – 30, assessed typical value - 20). Q, RMR and RMi can be assessed for faults, but it is recommended that these classification systems are used with great care in these circumstances and that it is better to assess faults in detail as individual features.
Sheeting joints (iii)	Orientations possibly as per Section 2.2, although orientations will vary with slope aspect, possibly towards the NE and E at the proposed cavern site. Unlikely to be encountered at the depth of the cavern (i.e. assumed >30m), or where encountered may be widely spaced and weakly developed (Hencher *et. al.* 2010). For certain cavern depths, these may form surfaces to which block falls would fail back to, or sliding planes for sidewall blocks depending on cavern orientation. Sheeting joints may have a basic angle of friction of 40° (Hencher & Richards, 1982) to which a roughness angle of the surface *i* can be added (assumed to be 2° for initial assessment purposes), giving an effective friction angle of 42°. However, this could be much less if some sheeting joints are dilated, weathered and/or have significant kaolin or other infill. Joint Roughness Coefficient (JRC, Barton, 1973) values might range between JRC 10 and 20.
Steeply dipping to subvertical joints (iv)	Orientations as per Section 2.2. These primary joints will typically control the stability in the proposed cavern. It may be possible to optimise the cavern orientation with respect to the average orientation of the primary joint sets. In the absence of other information the angle of friction of these joints could be considered to be 40° (Hencher & Richards (1982), although this could be much less where joints are slickensided or weathered. No surface roughness angle is applied due to lack of information and typical description as rough planar. JRC values might range between 5 and 10.

On the basis of Section 2 and Table 1, a simple uncertainty register has been prepared (Table 2). Those uncertainties which have engineering significance to the project should be transferred to a risk register and proactively managed.

Table 2: Uncertainty register for structural geological features – conceptual engineering geological model stage

Uncertainty (related to structural geology)	Description and importance	Suggested actions
Location and properties of faults	Faults can be critical to the stability, safety and success of projects involving tunnels and caverns. Faults and related issues, such as significant water inflow, are the most likely 'unforeseen' (rather than unforeseeable) ground conditions to affect the proposed cavern site.	Carry out site specific API and LiDAR interpretation to identify all possible lineaments, carry out a site reconnaissance, followed by carefully planned and targeted field mapping and then GI, preferably involving several stages of investigation, with the observational model being constantly updated. Where encountered, faults should be described in detail using a scheme such as Chapter 5 of USBR (2001) combined with GeoGuide 3 terminology.

Properties of joints	Joints will control the most commonly encountered instability mechanisms underground in the vicinity of the proposed sewage treatment works cavern site.	The rock mass of the area should be split into engineering geological and structural domains, the joints divided into sets and if possible the formation mechanism of the joint sets should be established (sheeting, tectonic or cooling joints) as this will greatly assist with the description and characterisation of these joints (Hencher *et. al.* 2010). *Full* description of joint sets should be carried out in accordance with GeoGuide 3. This will require several phases of mapping and GI (including the detailed discontinuity logging of orientated core and comparison with field mapping and televiewer data) along with field testing and laboratory testing. Mapping and orientated core should be the basis of the joint characterisation, not televiewer results. Note that the joint patterns may be different in the Shui Chuen O Granite and the Sha Tin Granite.
Optimum cavern location and orientation	There is an opportunity at the earliest stages of a cavern project (i.e. when the conceptual engineering geological model is developed) for engineering geology to have a significant input to the selection of the orientation of the caverns, potentially saving much cost and time with regards to rock support. However, later in the project this opportunity is typically not available as the cavern orientation will have been set by a myriad of other factors.	If possible the proposed sewage treatment works cavern site should not be located in an area crossed by faults or lineaments (particularly major or moderate faults), and it appears that this aspect has already been taken into consideration with the selection of the proposed site. The information on the primary joint trend could also be used to make an initial estimate of the best cavern orientations to reduce block fall and overbreak. However, this assessment is exceedingly coarse given the information available and much more data and analysis is required, although enough information is available to make initial considerations. There are many other factors that would need to be considered such as *in-situ* stress (approximately 108°-288° +/- 28° in Hong Kong, Free *et. al.* (2000)), access points, mucking out, operational requirements of the cavern etc.

4. CONCLUSIONS

The following conclusions can be drawn from this basic assessment:

- The main fault trends in the region of the proposed cavern area, in general order of decreasing magnitude, are NE-SW, NW-SE, ENE-WSW and WNW-ESE.
- Minor faults or lineaments are interpreted to cross the southern end of the proposed sewage treatment works cavern site, although unidentified minor to moderate faults may be present (classification of faults in accordance with Burnett & Lai, 1985).
- There may be scope to optimise the orientation of the proposed sewage treatment works cavern site in relation to identified lineaments, primary joint trends and *in-situ* stress.
- The primary joint trends near the cavern site are NE-SW and NW-SE with sheeting joints likely to be present, predominantly within 30m of the surface, orientated subparallel to slopes.
- These are not the conditions that will be encountered during future investigations or construction, they are only a possible model of the conditions that may be encountered.

Clearly the uncertainties that remain and the risks associated with these for the proposed cavern area are not insignificant and hence considerable additional research, investigation and analysis is required. It is hoped that this brief paper, which constitutes a basic conceptual engineering geological model, has demonstrated the advantage of such models for reducing the risk of unforeseen ground conditions, along with facilitating early decision making (such as cavern location and orientation), cost estimates and planning the optimum development of the observational engineering geological model (as in providing key features, uncertainties and risks to be targeted by mapping and GI). It also anticipates and assists with the development of the analytical engineering geological model (providing assumptions and parameters which can be investigated, tested, refined or discarded). Finally, it is hoped that this paper shows how easily structural geological data can be obtained and synthesized for Hong Kong, given the information available.

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