1. **SCOPE**

1.1 This Technical Guidance Note (TGN) supplements the guidelines given in Geoguide 4 - Guide to Cavern Engineering.

1.2 Any feedback on this TGN should be directed to Chief Geotechnical Engineer/Planning of the GEO.

2. **TECHNICAL POLICY**

2.1 The technical recommendations promulgated in this TGN were agreed by GEO Geotechnical Control Conference on 4 January 2012.

3. **RELATED DOCUMENTS**


4. **BACKGROUND**

4.1 Geoguide 4 (GEO, 1992) provides the recommended standard of good practice for the civil engineering aspects of rock cavern applications in Hong Kong. It also serves as a reference document for non-specialists involved in the administration of cavern projects. The document gives guidance on good engineering practice, and its recommendations are not intended to be mandatory. It is recognised that experienced practitioners, on whose judgment the success of any underground excavation depends, may wish to use alternative methods to those recommended herein.

4.2 In March 2010, GEO commissioned a study on the Enhanced Use of Underground Space in Hong Kong. One of the requirements under the Brief of the study was to review Geoguide...
4. recommend areas for updating and outline major outdated information in the form of a Working Paper (Ove Arup & Partners Ltd., 2011). The major areas for updating are described below and summarised in Table 1 (Annex TGN 32 A1).

5. DEFINITIONS

None.

6. TECHNICAL RECOMMENDATIONS

Solid Geology (Section 2.2.1 of Geoguide 4)

6.1 GEO Technical Guidance Note No. 5 (GEO, 2009a) provides an update on the sources of information on geological and related maps and memoirs.

Sources of Information (Section 3.3.2 of Geoguide 4)

6.2 GEO Technical Guidance Note No. 5 (GEO, 2009a) provides an update on the sources of information for the planning of site investigation in Hong Kong and supersedes Appendix B: Sources of Information of Geoguide 2 (GCO, 1987).

Field Investigation (Section 3.6 of Geoguide 4)

6.3 References to ISRM (1981) which relates to the complete ISRM suggested methods for rock characterisation, testing and monitoring should be replaced by ISRM (2007).

6.4 Directional drilling is a major advance in the ground investigation for underground works that allows control of the direction of long drillholes along the tunnel axis. The technology makes it possible to drill in a forced straight line as well as controlling the drillhole in one or more curves, hitting the target with very high precision. Further discussion on directional drilling is given in GEO Technical Guidance Note, TGN No. 24 (GEO, 2009b) on Site Investigation for Tunnel Works.

Joint Orientation (Section 3.7.3 of Geoguide 4)

6.5 New and common methods available in Hong Kong include the Acoustic Televiewer and Optical Televiewer, which are becoming more commonly used compared with Impression Packers, Core Orientators and Closed Circuit Television Surveying as described in Section 3.7.3 of Geoguide 4.

Rock Stress Measurement (Sections 3.7.5 and 4.2.6 of Geoguide 4)

6.6 Since 1990, additional hydraulic fracture stress measurements to about 200 m depth were conducted in Hong Kong. The in situ tests were carried out by using the wireline hydrofracture technique. Klee et al (1999) reported that although the tests were performed both in fractured and un-fractured crystalline rocks and the drillholes are located in areas of
pronounced topographical relief, the results yield a consistent orientation of the  
maximum horizontal stress of N108°±28°. Above 150 m depth, the vertical stress \( S_v \) due  
to the weight of the overburden with given rock density is the minimum principal stress,  
while the limited amount of deeper data available suggests that the minimum horizontal  
principal stress is the least principal stress. Free et al (2000) provided a good summary of  
the general in situ stress measurements in Hong Kong and compiled the data from other  
references to depict the general major and minor principal stress states for rocks in various  
parts of Hong Kong. Figure 1 (Annex TGN 32 A2) shows the general relationship of in  
situ stress with depth that has been recorded. This is typical for rock masses at shallow  
depth over the majority of the world where due to removal of overburden, the near surface  
stresses are higher horizontally than vertically.

**Test for Drillability (Section 3.7.12 of Geoguide 4)**

6.7 An additional test that can identify the drillability of the rock is the Cerchar test (ASTM  
Standard D7625-10, 2010). This test is more commonly used in Hong Kong to assess the  
abrasivity and drillability of the rock and hence for assessment of the performance of  
Tunnel Boring Machines (TBM) (e.g. TBM penetration/advance rates, cutter wear rates,  
etc.).

**Rock Classification Systems for Determining Rock Support Requirements (Sections  
4.1.4 and 4.5.2 of Geoguide 4)**

6.8 The Q-system was developed by the Norwegian Geotechnical Institute in the early  
1970s (Barton et al, 1974), and a major update was published in 1993 (Grimstad &  
Barton, 1993). Guidance on limitations and the proper use of Q-system is also given by  
estimates of rock support (Grimstad et al, 2003) is presented in Figure 2 (Annex TGN 32  
A3).

6.9 The Q-system incorporates the experience obtained from more than 1,000 case histories  
from existing tunnels, and an empirically based diagram showing the correspondence of  
Q-values and the support used in these cases has been constructed. The diagram also  
includes Reinforced Ribs of Sprayed Concrete (RRS), a design which is partly based on  
numerical modelling. RRS has been developed for use in very poor to extremely poor  
rock conditions for relevant cavern spans, as may be seen from the Q-chart. Situations  
where use of the Q-system may not be adequate and software tools may be used to assess  
the rock support requirements are discussed in Section 6.20.

**Groundwater (Section 4.2.5 of Geoguide 4)**

6.10 Reference should be made to Publication No. 12 of the Norwegian Tunnelling Society  

**RMR Method of Rock Classification (Section 4.5.3 of Geoguide 4)**

6.11 Bieniawski (1976) showed that the relationship between the RMR rating and the equivalent  
Q-values is given by the following equation:
6.12 Although this may be adequate for many cases, there are some cases where inaccurate results are found, up to ±50% from the actual value. It is therefore recommended that rather than using the correlation to derive the corresponding number, the value in the other classification system should be derived wherever possible by using the values or ratings of the input parameters for that system. It is more relevant to calculate the RMR values separately from the input parameters (and vice versa). Useful guidance has also been given by Hoek (2007) on the use of Q and RMR systems.

The Geological Strength Index (GSI) (New Item under Section 4.5 of Geoguide 4)

6.13 The GSI was introduced to provide a system for estimating rock mass strengths for different geological conditions as identified by field observations. The GSI ranges from 10 (for extremely poor rock mass) to 100 (for intact rock). The rock mass characterisation is straightforward and based on the visual appearance of the rock structure, in terms of blockiness, and the surface condition of the discontinuities as indicated by joint roughness and alteration. The combination of these two parameters provides a practical basis for describing a wide range of rock mass types. It should be noted that there is no input for the strength of the rock material in the GSI system. The GSI chart for jointed rocks (as proposed by Marinos & Hoek (2000)), is shown in Figure 3 (Annex TGN 32 A4). The figure provides a list of mechanical rock properties in tabular form, which can be used for modellling purposes.

The Rock Mass Index, RMi (New Item under Section 4.5 of Geoguide 4)

6.14 The rock mass index (RMi) is a volumetric parameter indicating the approximate uniaxial compressive strength of a rock mass. The RMi system was formulated by Palmström (1995) and has since been further developed and presented in several papers. It makes use of the uniaxial compressive strength of intact rock (sc) and the strength reduction effect of the joints penetrating the rock (JP).

6.15 The RMi value can be applied as input to other rock engineering methods, such as numerical modelling, the Hoek-Brown failure criterion for rock masses (Hoek & Brown, 1980), and to estimate the deformation modulus for rock masses (Palmström & Singh, 2001). It can also be used for estimating rock support using a support chart. Further details are shown in Figure 4 (Annex TGN 32 A5) (Palmström & Stille, 2010).

Numerical Models (Section 4.6.3 of Geoguide 4)

6.16 The development of computer hardware for numerical modelling has resulted in a situation where computational power and data memory is no longer a limiting factor in numerical analyses. The development of modelling software has also managed to successfully combine features from both continuum and discontinuum models allowing more complex and realistic models to be developed. Lists of currently accepted geotechnical computer programs, including those with applications in tunnel/cavern construction, for private and Government works, are respectively given at the following links: http://www.bd.gov.hk/english/inform/comprogram/agp.pdf and http://geosis.ccgo.hksarg
Different computer models may have respective strengths and weaknesses making them suitable for different geotechnical design problems. For input parameters to numerical models, the limiting factor is the heterogeneous nature of the rock mass material, which in a practical scale is impossible to investigate sufficiently in the field and to represent realistically in a model.

Numerical modelling can be a powerful tool in geotechnical design. With recent software development, it has become more time and cost efficient to utilise numerical modelling. Despite this, the result of numerical modelling is only indicative of typical expected rock mass behaviour and the results must be subject to proper interpretation before it is incorporated in the design.

Universal Distinct Element Code (UDEC) analysis of jointed rock often produces conservative analysis as it is based upon 2D representation of the rock masses. The software tool is useful in understanding the stress changes and how rock blocks will react to the changes in stress around the excavation. In addition, it provides an essential tool in examining the rock bolt lengths and support requirements for large span excavations for which the empirical support charts are less reliable. An example of UDEC analysis for a large span cavern is shown in Figure 5 (Annex TGN 32 A6).

Other scenarios, in addition to large span excavations, where software tools should be used in assessing the rock support requirements include intersections/pillars supports, closely spaced cavern/tunnel openings, excavations in close proximity to foundations of existing buildings/structures, excavations under shallow rock cover and mixed ground conditions. Local case histories of using UDEC are described by Hardingham et al (1998) and Bandis et al (2000). A three-dimensional version of the program, 3DEC, is also available.

Planning the Excavation (Section 5.2 of Geoguide 4)

During the past 20 years, there has been a significant development of tunnelling equipment that should be taken into account during project planning. Typical standard equipment used during cavern and tunnel construction is described below.

Computerised drill jumbos are capable of drilling up to 3 m per minute in rock with uniaxial compressive strength up to 160 MPa. The largest currently available models can drill close to 200 m² faces from a single set up and have a maximum drilling height of 13 m. The computer controlled drilling performance automatically performs alignment for the next round and surveying of the previous excavated profile.

Mucking is performed by wheel loader and trucks. Diesel/electric loading equipment is applied to improve the environment at the tunnel face. A mobile crusher can be installed underground close to the face and connected to a conveying system. This can reduce the number of trucks significantly and as a result improve the air quality.
6.24 Support is performed by highly automated and computerised robots for sprayed concrete, whilst drilling for rock bolts is mainly done by a drill jumbo. For a large cavern complex, a dedicated rockbolting machine may be preferred especially where the total number of rockbolts is large. Scaling is normally performed by hydraulic hammers mounted on excavators, but final scaling by handheld bars is still used.

6.25 Rock mass grouting takes place using computerised units that can mix, agitate and deliver grout to several grout holes simultaneously upon pre-determined termination criteria in terms of intake volume, injection pressure or duration. Advances in grouting technology now allow for higher penetration into the rock mass creating a drier tunnel environment. This technology is just starting to be introduced to Hong Kong (Norwegian Tunnelling Society, 2011) and will need further experience before it can be used with confidence.

Concrete Lining (Section 5.6.8 of Geoguide 4)

6.26 Reference should be made to Publication No. 19 of the Norwegian Tunnelling Society (2010) on the choice of final support and the drainage design of concrete lining.

Blast Vibration Acceptance Criteria (Section 5.7.2 of Geoguide 4)

6.27 There have been further developments in the blasting limits set on soil slopes as outlined in GEO Technical Guidance Note No. 28 (GEO, 2010), which promulgates a new control framework for soil slopes subject to blasting vibrations.

Grouts and Grouting (Section 5.8.3 of Geoguide 4)

6.28 The practice of pre-grouting for rock excavations, which is an important construction element in cavern construction within urban areas, is presented by Garshol (2007). State-of-the-art grouting being introduced into Hong Kong has also been presented by the Norwegian Tunnelling Society (2011).

Construction Records (Section 5.12 of Geoguide 4)

6.29 For geological records, GEO has developed a standard electronic template for collection of tunnel data in the form of a Rock Mass Mapping and Classification Sheet (RMMCS). The RMMCS is available for downloading from the CEDD website at the following hyperlink: http://hkss.cedd.gov.hk/hkss/eng/download/rock-mass/GEO_Rock_Mass_Mapping_Proforma.xls. The standard template can be modified and used for geological records during cavern construction.

Exposed Rock Surfaces (Section 6.3.2 of Geoguide 4)

6.30 Within the Stanley Sewage Treatment Plant, which was completed in 1995, there was an early issue with a minor rockfall incident at the start of the facility operation. Subsequently, remedial measures were proposed with the application of additional dowels and shotcrete that were applied over the majority of the exposed rock surfaces in the roof of the caverns. The original cavern support design was based on the Q-system (Barton, 1974) that required permanent support of systematic bolting in large areas of the cavern roof.
without shotcrete support. The extensive remedial works that were undertaken whilst the Sewage Treatment Plant was in operation could have been avoided had the requirement for rockfall protection been identified during the detailed design stage. The guidance already provided in Sections 5.6.2 (b) and 5.6.3 of Geoguide 4 should be further emphasized in Section 6.3.2 of Geoguide 4, stating that the extent of final roof support should be related to the future use, occupancy and psychological factors, in consultation with the owner.

7 ANNEXES

7.1 TGN 32 A1 – Table 1 – A summary of major updates or proposed new sections for Geoguide 4

7.2 TGN 32 A2 – Figure 1 – Summary of hydraulic fracturing test data on minimum horizontal stress ratio Kh (Sh/Sv) versus depth (Free et al, 2000)

7.3 TGN 32 A3 – Figure 2 – Updated Q-chart (Grimstad et al, 2003)

7.4 TGN 32 A4 – Figure 3 – GSI system (Marinos & Hoek, 2000)

7.5 TGN 32 A5 – Figure 4 – RMi system (Palmström & Stille, 2010)

7.6 TGN 32 A6 – Figure 5 – An example of UDEC analysis (for a large span tunnel showing support loading and displacement contours for staged excavation) (Ove Arup & Partners Ltd., 2011)
### Table 1 - A summary of major updates or proposed new sections for Geoguide 4

<table>
<thead>
<tr>
<th>Geoguide 4 (GEO, 1992)</th>
<th>Summary of Major Updates or Proposed New Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 2.2.1 – Solid Geology</td>
<td>GEO Technical Guidance Note No. 5 (GEO, 2009a) provides an update on the sources of geological information.</td>
</tr>
<tr>
<td>Section 3.3.2 – Sources of Information</td>
<td>GEO Technical Guidance Note No. 5 (GEO, 2009a) provides an update on the sources of information for the planning of site investigation in Hong Kong.</td>
</tr>
<tr>
<td>Section 3.6 – Field Investigation</td>
<td>References to ISRM (1981) for rock characterisation, testing and monitoring should be replaced by ISRM (2007). Directional drilling introduced as a major advance in ground investigation for underground works.</td>
</tr>
<tr>
<td>Section 3.7.3 – Joint Orientation</td>
<td>New and common methods available in Hong Kong include the Acoustic Televiewer and Optical Televiewer.</td>
</tr>
<tr>
<td>Sections 3.7.5 and 4.2.6 – Rock Stress Measurement</td>
<td>Summary of information on in situ stress measurements in Hong Kong.</td>
</tr>
<tr>
<td>Section 3.7.12 – Test for Drillability</td>
<td>An additional test that can identify the drillability of the rock is the Cerchar test.</td>
</tr>
<tr>
<td>Sections 4.1.4 and 4.5.2 – Rock Classification Systems for Determining Rock Support Requirements</td>
<td>A major update of the Q-system in 1993. The Q-chart for estimates of rock support (Grimstad et al, 2003) is presented.</td>
</tr>
<tr>
<td>Section 4.2.5 – Groundwater</td>
<td>Reference should be made to Publication No. 12 of the Norwegian Tunnelling Society (2004) on water control in tunnelling.</td>
</tr>
<tr>
<td>Section 4.5.3 – RMR Method of Rock Classification</td>
<td>Recommended to derive the RMR values using the values of the input parameters in that system.</td>
</tr>
</tbody>
</table>
### GEO Technical Guidance Note No. 32 (TGN 32)
**Updating of Geoguide 4 – Guide to Cavern Engineering**

<table>
<thead>
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</tr>
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</tr>
<tr>
<td>Section 4.6.3 – Numerical Models</td>
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</tr>
<tr>
<td>Section 5.2 – Planning the Excavation</td>
<td>Significant development of tunnelling equipment/machines have taken place over the last 20 years.</td>
</tr>
<tr>
<td>Section 5.6.8 – Concrete Lining</td>
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<td>GEO Technical Guidance Note No. 28 promulgates a new control framework for soil slopes subject to blasting vibrations.</td>
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<td>Section 5.8.3 – Grouts and Grouting</td>
<td>The practice of pre-grouting for rock excavation and the state-of-the-art grouting are presented by Garshol (2007) and Norwegian Tunnelling Society (2011) respectively.</td>
</tr>
<tr>
<td>Section 5.12 – Construction Records</td>
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<tr>
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</table>
Figure 1 – Summary of hydraulic fracturing test data on minimum horizontal stress ratio $K_h$ ($Sh/Sv$) versus depth (Free et al, 2000)
Figure 2 - Updated Q-chart (Grimstad et al, 2003)

![Diagram of Rock Classes and Q-value calculation](image)

**ROCK CLASSES**

<table>
<thead>
<tr>
<th>G</th>
<th>F</th>
<th>E</th>
<th>D</th>
<th>C</th>
<th>B</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exceptionally poor</td>
<td>Extremely poor</td>
<td>Very poor</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
<td>Very good</td>
</tr>
</tbody>
</table>

**Span or height in m**

- 1.0 m
- 1.3 m
- 1.5 m
- 1.7 m
- 2.1 m
- 2.3 m
- 2.5 m

**Bolt Length in m for ESR = 1**

- 5.0 m
- 7.0 m
- 11.0 m
- 17.0 m
- 25.0 m

**Rock mass quality**

\[ Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \]

**REINFORCEMENT CATEGORIES:**

1. Unsupported
2. Spot bolting
3. Systematic bolting
4. Systematic bolting, (and unreinforced shotcrete, 4 - 10 cm)
5. Fibre reinforced shotcrete and bolting, 5 - 9 cm
6. Fibre reinforced shotcrete and bolting, 9 - 12 cm
7. Fibre reinforced shotcrete and bolting, 12 - 15 cm
8. Fibre reinforced shotcrete, > 15 cm, reinforced ribs of shotcrete and bolting
9. Cast concrete lining

**Reinforced shotcrete ribs:** 6 reinforcement bars in double layers in 55cm thick ribs with centre to centre (o/c) spacing 1.2m

Each box corresponds to Q-values of the left side of the box, as indicated.
### Geological Strength Index

<table>
<thead>
<tr>
<th>Structure</th>
<th>Surface conditions</th>
<th><strong>GSI</strong></th>
<th><strong>Rating</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Very good</td>
<td>Excellent condition</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>Good</td>
<td>Very good condition</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>Smooth surface</td>
<td>Decreasing</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Poor</td>
<td>Very poor condition</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Very poor</td>
<td>Very poor condition</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

#### GENERALIZED HOEK-BROWN CRITERION

\[
s_{1} = c_{1} + c_{2} + \frac{1}{2} \left( \frac{c_{1}}{c_{2}} + 1 \right) \]

- \(s_{1}\) = major principal effective stress at failure
- \(c_{1}\) = minor principal effective stress at failure
- \(c_{2}\) = uniaxial compressive strength of intact rock
- \(\alpha_{1}\), \(\alpha_{2}\), and \(\alpha_{3}\) are constants which depend on the composition, structure and surface conditions of the rock mass

### Figure 3 - GSI system (Marinos & Hoek, 2000)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Rating</th>
<th><strong>GSI</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocky - very well interlocked undisturbed rock mass consisting of cubic blocks formed by three orthogonal discontinuity sets</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>Very blocky - interlocked, partially disturbed rock mass, with multifaceted angular blocks formed by four or more discontinuity sets</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>Blocky / disturbed - folded and/or faulted with angular blocks formed by many intersecting discontinuity sets</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Disintegrated - poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Polished/terminally sheared - thinly laminated or foliated, tectonically sheared weak rocks, closely spaced extensively prevail over any other discontinuity set, resulting in complete lack of blockiness</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 4 - RMi system (Palmström & Stille, 2010)
Figure 5 - An example of UDEC analysis (for a large span tunnel showing support loading and displacement contours for staged excavation) (Ove Arup & Partners Ltd., 2011)