A Review of Conventional and Innovative Permanent Support Systems for Rock Cavern Development in Hong Kong

Endicott L John, Franklin K L To*, Andrew K W Seto

AECOM Asia Company Ltd., Hong Kong, China

*Corresponding author

doi: https://doi.org/10.21467/proceedings.133.44

ABSTRACT

In recent years, the HKSAR government departments have been playing a leading role to study the feasibility of rock cavern development in Hong Kong. These studies include the relocation of existing surface sewage treatment works, service reservoirs, refuse transfer stations, archive centre and laboratory to rock caverns. After completion of the relocation, the previously occupied surface land can be released for other developments beneficial to the communities. Conventional permanent support systems comprise the cast-in-situ concrete lining with sheet waterproofing membrane. These have been applied in most of the highway and railway tunnels in Hong Kong. However, it involves the use of bulky steel shutter, heavy rebar fixing and an extra set of redundant temporary supports, which leads to very expensive and time-consuming construction. With the advance development in construction technologies, permanent rock reinforcements with sprayed waterproofing membrane could be a cost-effective engineering solution. With the integration of temporary and permanent supports, the tight daily drill-and-blast cycle and timely permanent support installation is greatly enhanced. This paper provides a general review of different conventional and innovative permanent support systems for rock cavern development with the purpose of achieving more efficient design and construction. It also discusses the application according to the unique requirements for various cavern facilities.

Keywords: Permanent Rock Support, Rock Caverns, Cost-effective Rock Support

1 Introduction

1.1 Rock Cavern Development Strategy in Hong Kong

Hong Kong is surrounded by hilly terrains, rural areas and statutory protected areas such as country parks and restricted areas. This provides limitations to the land development in Hong Kong. As such, only less than 25% of total land area in Hong Kong has been developed for the 7.5 million population. Traditional approaches of land development include flat land, open-cut site formation of moderately hilly terrain and large-scale reclamation. They have been playing an important role in Hong Kong’s continuous land supply. However, these approaches have caused the built-up areas to be largely concentrated within the foothills of natural terrain extending towards the shoreline or the reclaimed land.

Among the various rock types of igneous, sedimentary and metamorphic origins found in Hong Kong, over 80% of them comprises hard and massive igneous rocks, such as granite and various volcanic rock types. This brings favorable conditions for underground space development such as rock caverns as an alternative source for land supply. In recent years, the HKSAR government departments have been playing a leading role to study the feasibility of rock cavern development in Hong Kong. These studies include the relocation of existing surface sewage treatment works, service reservoirs, refuse transfer stations, archive centre and laboratory to rock caverns. After completion of the relocation, the previously occupied surface land can be released for other developments beneficial to the communities.

Proceedings DOI: 10.21467/proceedings.133; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-957605-1-0

A territory-wide Cavern Master Plan (CMP) is presented in Figure 1. It is prepared to guide and facilitate the planning and implementation of long-term cavern development. The CMP delineates 48 numbers of Strategic Cavern Areas (SCVAs) that are suitable for cavern development in terms of geological considerations and the current planning perspectives.

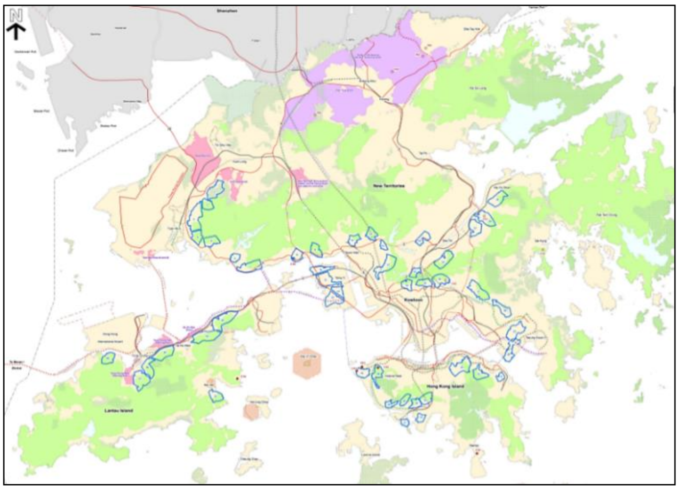

Figure 1: The Cavern Master Plan (CEDD and PlanD, 2017)

1.2 Permanent Cavern Support Systems

As suggested by GEO (2018), a cavern shall be designed and built in a way that can be maintained in a practical and economically viable manner during its service life, which could last for 100 to 120 years. The rock support elements shall be designed to be sufficiently durable and robust to guard against local deterioration of the rock mass over time, in particular at the weakness/fault zones. In consideration of the consequence of life, durability and maintenance problems, temporary supports such as rock dowels and shotcrete are usually not taken to contribute any of the long-term ground stability. The permanent support systems are installed in a later stage.

Most of the constructed rock tunnels in Hong Kong for highway and railway purposes are permanently supported by conventional cast-in-situ concrete lining. Plain concrete lining is used in good rock conditions; while heavily reinforced concrete lining is used in poor/soft ground conditions. It involves the use of bulky steel shutter, heavy rebar fixing and an extra set of redundant temporary supports, which leads to very expensive and time-consuming construction. If design optimization for permanent supports is achieved, the overall construction cost and time can be significantly reduced. With the advance development in construction technologies, permanent rock reinforcements with sprayed waterproofing membrane could be a cost-effective engineering solution.

The use of single-layer rock support system has been applied in the overseas projects for many years. For example, a composite shotcrete lining can serve both the temporary and permanent support purposes. The system is continuously improved with the introduction of new technology and materials, such as machinery, explosives and shotcrete materials. With the integration of temporary and permanent supports, the tight daily drill-and-blast cycle and lengthy support installation is greatly enhanced to save the overall construction cost and time. Yet, in order to allow the use of single-layer rock support in Hong Kong, one of the key issues to resolve is the possible blast-induced damage and cracks development to the temporary shotcrete layer during excavation. The development of new shotcrete materials with vibration resistance could be one of the possible solutions.

The permanent structures for cavern can be designed as drained or undrained. A drained structure is designed with a groundwater pressure relief system to allow groundwater ingress into the cavern in a controlled manner; while an undrained structure is designed to withstand the full in-situ groundwater pressure by preventing any groundwater ingress. For drained caverns, the groundwater pressure relief system consists of groundwater inflow control and groundwater drainage system is installed. These arrangements ensure that the groundwater can be diverted effectively and prevent the built-up of groundwater pressure surrounding the rock mass.

A general review of different conventional and innovative permanent support systems for rock caverns development is carried out. The selection shall fit the unique requirements for various cavern facilities in order to achieve the purpose of achieving more efficient design and construction.

2 Conventional and Innovative Permanent Cavern Support Systems

2.1 Conventional Permanent Cast-in-situ Concrete Lining

For conventional cast-in-situ concrete lining, two independent sets of temporary and permanent supports are installed during the construction. Temporary support including rock dowels and a thin layer of shotcrete are first installed, then subsequently the casting of permanent support includes the cast-in-situ concrete lining with geotextile and sheet waterproofing membrane as shown in Figure 2. A movable steel shutter in form of scaffolding and timber formwork is used for concrete pouring.

Figure 2: Conventional Permanent Cast-in-situ Concrete Lining with Sheet Waterproofing Membrane

The use of permanent cast-in-situ concrete lining for large-span rock caverns has been successful in Hong Kong, such as the 24.2 m span cavern for MTR Island Line Tai Koo Station completed in 1985 as shown in Figure 3, and the 24.3 m span cavern for MTR South Island Line Admiralty Station completed in 2016.

Figure 3: Steel Shutter for the Construction of MTR Tai Koo Station

(http://dragageshk.com/project/tai-koo-mtr-station-and-tunnels/)

For permanent cast-in-situ concrete lining, the conventional “rock support” design approach is adopted in which concrete and reinforcement are used as structural materials to sustain all possible loadings. The design load involves an array of load combinations, including the overburden, groundwater and different internal facilities. They should be checked against the structural capacity of the lining such as axial, shear and bending moment accordingly.

2.2 Permanent Steel Fibre-Reinforced Shotcrete (SFRS) Lining

Steel fibre-reinforced shotcrete (SFRS) is sprayed concrete with steel fibres added as reinforcement. It has higher tensile strength than unreinforced shotcrete and is widely used for underground structure supports. The use of permanent SFRS lining has been successful at the Po Shan Road Drainage Tunnel (Lo et al 2009 and Chau et al 2011). The project consists of twin 3m-diameter bored tunnels and a series of sub-vertical drains. It was designed and constructed to form a robust system to control the groundwater levels for maintaining the overall stability of the Po Shan hillside within the Mid-Levels area. A horse-shoe shaped portal chamber of 8m (W) x 5m (H) was also constructed.

The intersection of drainage tunnels and portal chamber has a span of ~17m but with an irregular shape. Under the conforming scheme, heavily reinforced concrete lining with the need of irregular formwork was required. The fixing of reinforcements at crown and formwork erection are known as high risk works activity. Alternatively, a 700mm thick steel fibre reinforced shotcrete (SFRS) lining with cast-in-situ kicker walls and base slab was adopted as the permanent support construction, which significantly shortened the construction period, lowered the construction cost and reduced the construction risks. The intersection is shown in Figure 4.

Figure 4: Intersection at Po Shan Road Drainage Tunnel with Permanent SFRS Lining

2.3 Permanent Rock Reinforcements in Hard Rock

The in-situ stress conditions for a rock mass at a specific depth below ground can have one or more origins. The major components usually comprise the gravitational stresses and tectonic stresses. According to GEO (2018), there is no evidence of high tectonic stresses in Hong Kong rocks. Local strong igneous rock has a typical uniaxial compressive strength (UCS) that ranges from 75 MPa to 200 MPa, which is much greater than structural concrete. Compared with the redistributed stresses after excavation, high stresses will not be a problem for local cavern construction at modest depths given the high strength of most of the rocks encountered.

An arched structural form has been widely used in civil engineering projects such as bridges and arched dams. This also applies to rock cavern engineering. After excavation, the overburden weight of loosened rock above the cavern crown is redistributed to the sidewalls. Hard rock is strong in compression but very weak in tension. With an arched roof, the best stress distribution is obtained to reduce the zone of tensile stresses in the cavern crown. This utilizes the “arching-effect” within the rock mass and therefore improves the ground stability, allows a more cost-effective support system and reduces the overbreak for excavation.

As such, the “rock reinforcement” design approach has been developed to offer a practical method to consider the hard rock as a structural material to self-support itself by utilizing the hoop stress within the arch of the rock above the roof of the cavern. Permanent rock bolts are installed as rock reinforcement to guarantee the formation of this arch, and permanent shotcrete supports the smaller rock wedges between adjacent bolts. The inherent strength of the rock mass is utilized by applying confining pressure from the rock bolts. The thrust capacity discussed by Bischoff JA and Smart JD (1977) is therefore increased and the theoretical rock arch formed around the cavern is capable to resist the hoop force and can stabilised the opening by supporting the ground above the excavation. The design load involves the field stresses in rock mass. The rock supports should be checked against individual failure modes.

The use of permanent rock bolts and shotcrete for large-span rock caverns has been successful in Hong Kong, such as the 15 m span cavern for DSD Stanley Sewage Treatment works completed in 1995 as shown in Figure 6, and the 27 m span cavern for EPD Island West Transfer Station completed in 1997. The on-going DSD project to relocate the Sha Tin Sewage Treatment Works to caverns involves the construction of a cavern complex with 7 parallel rock caverns up to 32m width x 33m height in order to handle a large sewage treatment capacity. Upon completion, the relocated STSTW will be the biggest cavern sewage treatment works in Asia.

Figure 5: Rock Bolt Installation in Hard Rock

Figure 6: Stanley Sewage Treatment Works in Caverns with Permanent Rock Reinforcements

For each class of rock support, the rock bolt length, diameter, and spacing, can determined by reference to NGI Q-system (NGI 2015), Geoguide 4 (GEO 2018) and other design guidelines. Guidelines are non-specific and are conservative, with suggested minimum values for requirements to be used. In particular for large-span rock caverns, design verifications using numerical modelling shall be adopted for the multi-stage excavation with site specific values for rock parameters. With sufficient design justifications, a less conservative approach could be adopted for a specific site and a specific use.

The guidelines for rock bolt length and spacing have largely been developed from large numbers of case histories. In theory, the bolts, together with shotcrete, provide a quantifiable support pressure. To some degree, rock bolt length could be shortened, and spacing decreased, resulting in the same support pressure being applied. However, rock reinforcement approach also requires a minimum thickness of theoretical rock arch, which would result in a minimum rock bolt length and spacing ratio proposed by Lang (1961), which might vary depending on the rock mass quality.

The effective bolt length should exclude the allowance for the expansion shell and face plate portion embedding into the shotcrete layer as shown in Figure 7. By adopting appropriate numerical modelling to validate the proposed rock bolt length and spacing, it is considered that there may be opportunity to optimize rock bolt lengths to suit either material supply, or site working practice. For example, one opportunity would be to reduce the length of systematic rock bolts such that the bolt holes could be drilled in one pass, without the need to add extension rods during the drilling process. By adopting shorter bolts, the time saved per bolt is the time taken to add a drill rod before continuing to drill. However, if the design validation proves that shorter systematic rock bolts will constitute to the increase in rock bolts quantities, the total number of installations is indeed increased. This would be doubtful if there would be an overall saving of time. A further detailed study shall be carried out with approval from relevant authorities.

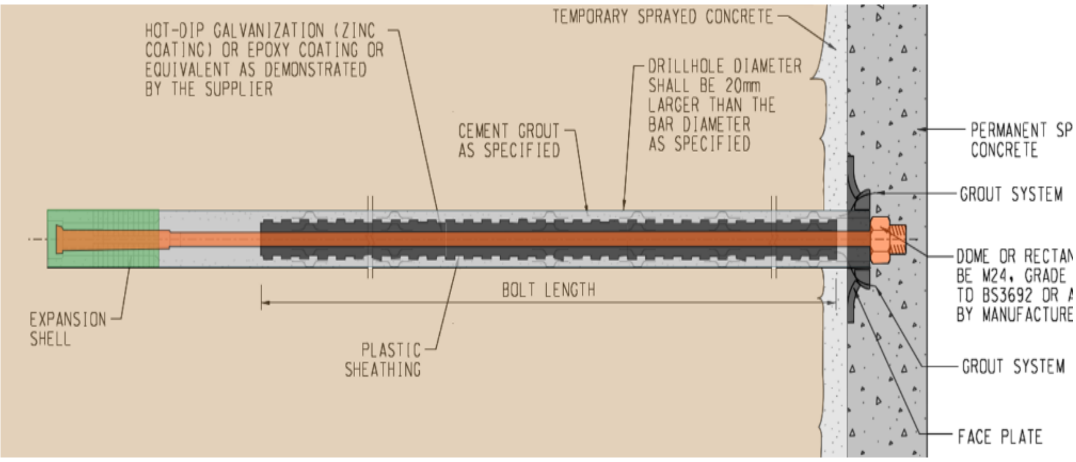

Figure 7: Typical Arrangement of Cement Grouted Permanent Systematic Bolts with Expension Shell

2.4 Integration of Permanent Cavern Supports & Internal Structures

From a structural engineering perspective, the internal structures of cavern facilities can be integrated or even replace the permanent cavern walls support. This allows a cost saving on construction materials. An example is shown in Figure 8 where the cavern sewage facilities with water tank walls and rock support walls coexist adjacently. However, if the excavation works and internal structures are carried out by two Contractors under separate contract; or the rock supports are designed by the Engineer but the inner facilities (such as special hydraulic and E&M equipment) are designed by the Contractor, the contractual issue would cease the feasibility for the integration.

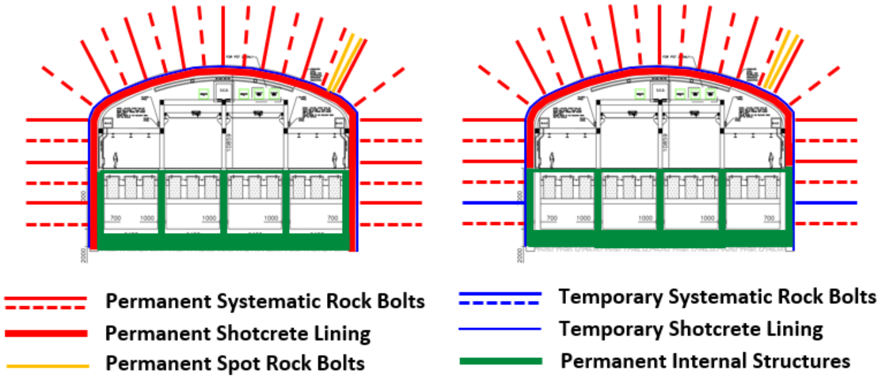

Figure 8: Integration of Cavern Support and Internal Structure (left: not integrated; right: integrated)

The integration of permanent cavern supports and internal structures have been successful at the Western Salt Water Service Reservoirs at the University of Hong Kong. It is the first service reservoirs built in rock caverns (Mackay et al 2009, Toh et al 2011 and Yeung et at 2011). The permanent support system comprises cast in-situ concrete along the sidewalls and shotcrete across the crown as illustrated in Figure 9. The cavern roof is permanently supported by a steel-fibre reinforced shotcrete lining with a plain shotcrete smoothing layer. The shotcrete arch roof was first constructed during the top-heading excavation and supported on an elephant foot founded on sound rock before full excavation of bottom beaches. SFRS lining is able achieve a quantifiable tensile strength depending upon the quantity of steel fiber reinforcement added. It doesn’t require the use of formwork for installation. The shotcrete lining is rested on recesses at the crown base with additional reinforcement to the side walls using 32mm diameter rock dowels.

In order to fulfill the watertight requirement, the cavern permanent linings were designed as water retaining structures. Waterproofing layers were laid at the external face of cavern profile to avoid groundwater ingress into the salt water service reservoirs as shown in Figure 10. The service reservoir structures are monolithic reinforced concrete structures. With these mitigation measures, the possibility of groundwater leakage into the cavern would be minimized such that the contamination problem could be avoided. The permanent lining was designed as drained with a groundwater relief system.

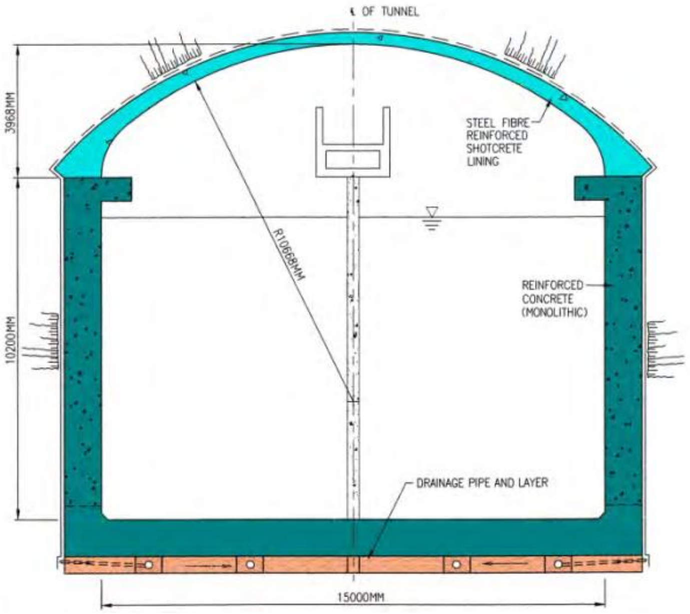

Figure 9: General Arrangement of Western Salt Water Service Reservoirs at HKU

Figure 10: Construction of Western Salt Water Service Reservoirs at HKU

2.5 Modular Integration Construction (MiC) and Design for Manufacturing and Assembly (DfMA)

Modular Integrated Construction (MiC) with reinforced concrete structural components cast off-site under factory conditions adopting Design for Manufacturing and Assembly (DfMA) methods which allow elements to be imported and erected and in position can prove to be time saving for site works and can be a cost saving method of construction. Normally, cost for modular constructions might contribute savings of up to 10% of the total costs for outdoor greenfield structures but there are more constraints for caverns.

The choice of elements to be included for modular construction should be those highly repetitive members that could be pre-casted and delivered to site. An example for a rock cavern accommodating sewage treatment facilities is discussed. Internal structures such as the top slab of sewage treatment tanks, large tank covers, columns and beams, and internal buildings could be considered for modular construction. Water retaining structures requires high standard of workmanship to ensure the water tightness. They may not be as appropriate as a mandatory component for modular construction given the number of pre-cast units and constructions joints that will be involved. For large metal tank covers and mesh flooring system, they could be prefabricated off-site. The cavern facilities usually involve many E&M equipment to be installed. These could also be considered for modular construction.

Construction inside a rock cavern is limited by headroom, working space and internal access. This limits the Contractor's choice of plants for lifting operations and size of prefabricated elements. These factors will eventually contribute to the construction costs, hence undermine the cost-effectiveness of modular constructions.

Nonetheless notwithstanding the above concerns on MiC in caverns, some of the Contractors could be more capable than others in overcoming constraints inside caverns by using special machinery, while some Contractors would prefer conventional ways of cast in-situ construction depending on their availability of resources and their costs in securing materials at the time of works. Therefore, one of the cost-effective options could be to leave the option for precasting and prefabrication open for the Contractor. Moreover, if the designer/procurer of the structures are to be carried out by the Contractor, they could then decide the most cost-effective way to construct the facilities, which will be subject to a competitive tendering process and promote this consideration.

Figure 11: MiC and DfMa for Rock Cavern Facilities

2.6 Groundwater Relief System and Water Tightness Requirements

The permanent cavern support system can be designed as drained or undrained. A drained structure is designed with a groundwater pressure relief system to allow groundwater ingress into the cavern in a controlled manner; while an undrained structure is designed to withstand the full in-situ groundwater pressure by preventing any groundwater ingress. For drained caverns, the groundwater pressure relief system consists of groundwater inflow control and groundwater drainage system is installed. Drainage layer comprising crushed rock will be laid at the invert of the caverns and tunnels. The drainage layer will divert the groundwater to the public drainage system. These arrangements ensure that the groundwater can be diverted effectively and prevent the built-up of groundwater pressure surrounding the rock mass.

A rock cavern network is usually proposed under hillside and above the seawater level. Therefore, the probability of excessive groundwater inflow into the caverns is very insignificant. Considering the majority of the caverns shall be relatively dry, it is proposed that groundwater pressure relief system shall only be installed in areas with observable groundwater inflow instead of applying the systems along the entire caverns and tunnels.

A three-tier groundwater system for rock caverns is considered as a cost-effective solution:

i. During the probing from rock face, carry out permanent pre-excavation grouting (PEG) if excessive groundwater inflow is recorded;
ii. For any small groundwater inflows observed after excavation, install drainage measures to direct the flow path to the drainage layer at the cavern invert; this flow path would become embedded within the permanent sprayed concrete;
iii. In sensitive areas where equipment needs to be free from water (e.g. E&M plant rooms), install a systematic grid of groundwater drainage measures, and spray waterproofing membrane over the entire cavern roof and upper walls, covering the drainage measures. This waterproofing layer would then be covered by the final layer of permanent sprayed concrete support.

For caverns constructed in sound granite rock material, it has very low permeability and groundwater circulation can only circulate through fissures where present. Where mass weathering is extensive, such as close to rockhead, water can also seep through the decomposed zones. However, this is not expected as sufficient rock cover is required when proposing a rock cavern location. Ground investigation with rock coring shall be carried out. Limited localised flow is expected through minor rock fractures. Only at locations of faults with higher fracture frequency, these zones may have potential for higher groundwater inflow rates.

The appropriate means of dealing with potential inflow of water is to probe ahead of the excavation to identify zones where large inflows would occur and to stem these by pre-excavation grouting. By this means flows of water immediately after excavation would be limited. Where any minor seepages are subsequently observed, seepage water should be collected and drained, such as by means of band drains that conduct the water from the zone of seepage down to the drainage system at or near the invert of the tunnel or cavern. This approach is discussed in ITA tech Report No.2, section 3.3 which describes a localised drainage system option for zones made up of mainly impermeable rock. The report considers whether a waterproof membrane may be added after the primary shotcrete and invert drainage system has been applied. However, the invert drainage system is equally applicable whether a waterproof membrane is required in addition to the final shotcrete lining or not. Therefore, for very good and massive rock, there is no need for systematic weep holes and systematic circumferential band drains to be applied for zones made up of mainly impermeable rock. Localised adhoc band drains maybe required where minor seepage occurs. The actual provision and spacing shall be subject to review and agreement with the resident site staff spacing.

Figure 12: An example of Massive Granite. It can be "bone dry", no groundwater weep holes are needed

3 Conclusions

A general review of different conventional and innovative permanent support systems for rock cavern development is carried out. These include the use of conventional cast-in-situ concrete lining, steel fibre-reinforced shotcrete (SFRS) lining, rock reinforcements in hard rock. Two innovative systems including the integration of permanent cavern supports & internal structures as well as modular integration construction (MiC) and design for manufacturing and assembly (DfMA) are also discussed. The selection shall fit the unique requirements for various cavern facilities in order to achieve the purpose of achieving more efficient design and construction.

It is essential that civil engineering works are designed and built to the required standards of safety. However, it is also important to ensure that design of civil engineering projects is not unduly conservative; whilst recognizing the inherent geological risks associated with major underground construction works.

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