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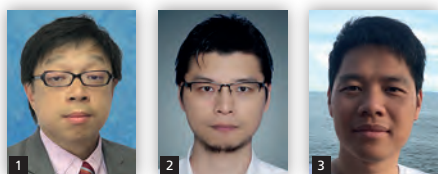
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Rock cavern development in Hong Kong: past, present and future

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The steep hilly terrain of Hong Kong is a significant constraint on surface development but offers great opportunities for underground rock caverns. With multi-dimensional planning vision, the Government of the Hong Kong Special Administrative Region has recently published a territory-wide *Cavern Master Plan*, broadened cavern applications and reappraised cavern engineering practice to enable future cavern development. For example, the recent project to relocate Sha Tin Sewage Treatment Works in 32m span caverns will release approximately 28ha of prime land for other beneficial uses. This paper gives an overview of the past and present cavern development in Hong Kong and discusses future cavern development from planning and engineering perspectives, with particular reference to the Sha Tin project.

1. Introduction

The hilly terrain and strong rocks of Hong Kong make the region highly suitable for rock cavern development. Notwithstanding this, the use of rock caverns has generally been limited, mainly for accommodating nuisance facilities. In view of limited developable land in the territory, enhancing the systematic use of rock caverns for wider application is providing a new opportunity for development.

Relocation of suitable facilities to rock caverns could release surface sites for other beneficial uses (e.g. residential and commercial development) and remove incompatible land uses. Placing 'not in my backyard' ('Nimby')-type facilities in caverns will minimise their nuisance to communities while enhancing the development potential of the released land and its surrounding areas.

Rock caverns can also provide space for new public and private sector facilities where there is a shortage of available surface land, thereby reducing further land take and providing lower cost accommodation, especially for land-intensive uses. These benefits, however, have not been actively reaped in the past. The search for future land in Hong Kong should therefore not be limited to a two-dimensional (2D) approach, but instead take a multi-dimensional perspective through optimising the use of these 'hidden' underground space resources.

To unleash the potential of cavern development, the Government of the Hong Kong Special Administrative Region has completed the *Enhanced Use of Underground Space in Hong Kong – Feasibility Study* (Arup, 2011) and more recently the *Long-term Strategy for Cavern Development – Feasibility Study* (Arup, 2018). These strategic studies led to the recent implementation of a suite of enabling measures by the government, including promulgation of a strategic territory-wide *Cavern Master Plan* (CEDD, 2017),

expansion of the list of facilities suitable for cavern development in the planning guidelines and reappraisal of the standard of cavern engineering practice in Hong Kong.

The relocation of Sha Tin Sewage Treatment Works to caverns is a pioneering underground development project started in 2019. After its completion, the cavern halls, with spans up to 32m, will be the largest cavern construction in Hong Kong and the region's leading example of cavern development.

Ho *et al.* (2016, 2018) provided a comprehensive overview of the long-term strategy of cavern development in Hong Kong. This paper aims to provide a further review of the past and present cavern development in the region and discuss the future direction of cavern development from planning and engineering perspectives. This includes the applicability of a rock reinforcement approach for future rock cavern projects, with particular reference to the Sha Tin project.

2. Cavern development in the past

Over the past decades, there have been only isolated cases of cavern development in Hong Kong. Its applicability was, however, mostly driven by lack of other surface land alternatives, and the real benefits of cavern development have not been properly explored and exploited.

In the 1980s, a few underground stations of the Mass Transit Railway (MTR) were constructed in rock caverns. In the 1990s and 2000s, several government facilities were housed in caverns, including Stanley Sewage Treatment Works (Oswell *et al.*, 1994) (Figure 1), Island West Transfer Station (Littlechild *et al.*, 1997), Kau Shat Wan Explosives Depot and Western Salt Water Service Reservoirs (Tam *et al.*, 2010). These schemes were primarily

driven by the difficulties in finding suitable surface sites at that time. During the 2010s, expansion of the MTR network again resulted in a number of large-span caverns being built for the purpose of metro stations, such as the expansion of Admiralty Station (Bezzano *et al.*, 2017).



Figure 1. Completed in 1995, the Stanley Sewage Treatment Works in Hong Kong is built within three 120 m long rock caverns

The limited use of cavern schemes in the past was not without reason. First, there was no holistic cavern development strategy in Hong Kong. The cavern option was occasionally adopted only as a last resort when surface land was not available. Second, there was a long lead time for cavern development compared to surface development due to various technical challenges such as environment and fire safety issues. Third, there was a lack of private sector involvement due to the long lead time for development as well as considerable front-loaded investment. The recent implementation of a suite of enabling measures aims to overcome these deficiencies in the current situation and facilitate cavern development in the long run.

3. Diversified cavern facilities

Many successful overseas examples have demonstrated that caverns are suitable to accommodate a wide spectrum of facilities (Figure 2). Considering the versatility of cavern development, the government has carried out a series of assessments to evaluate the technical feasibility of housing various facilities in caverns under the existing framework of regulations and requirements. The government has expanded the list of suitable land uses with potential for cavern development in the *Hong Kong Planning Standards and Guidelines* (Planning Department,

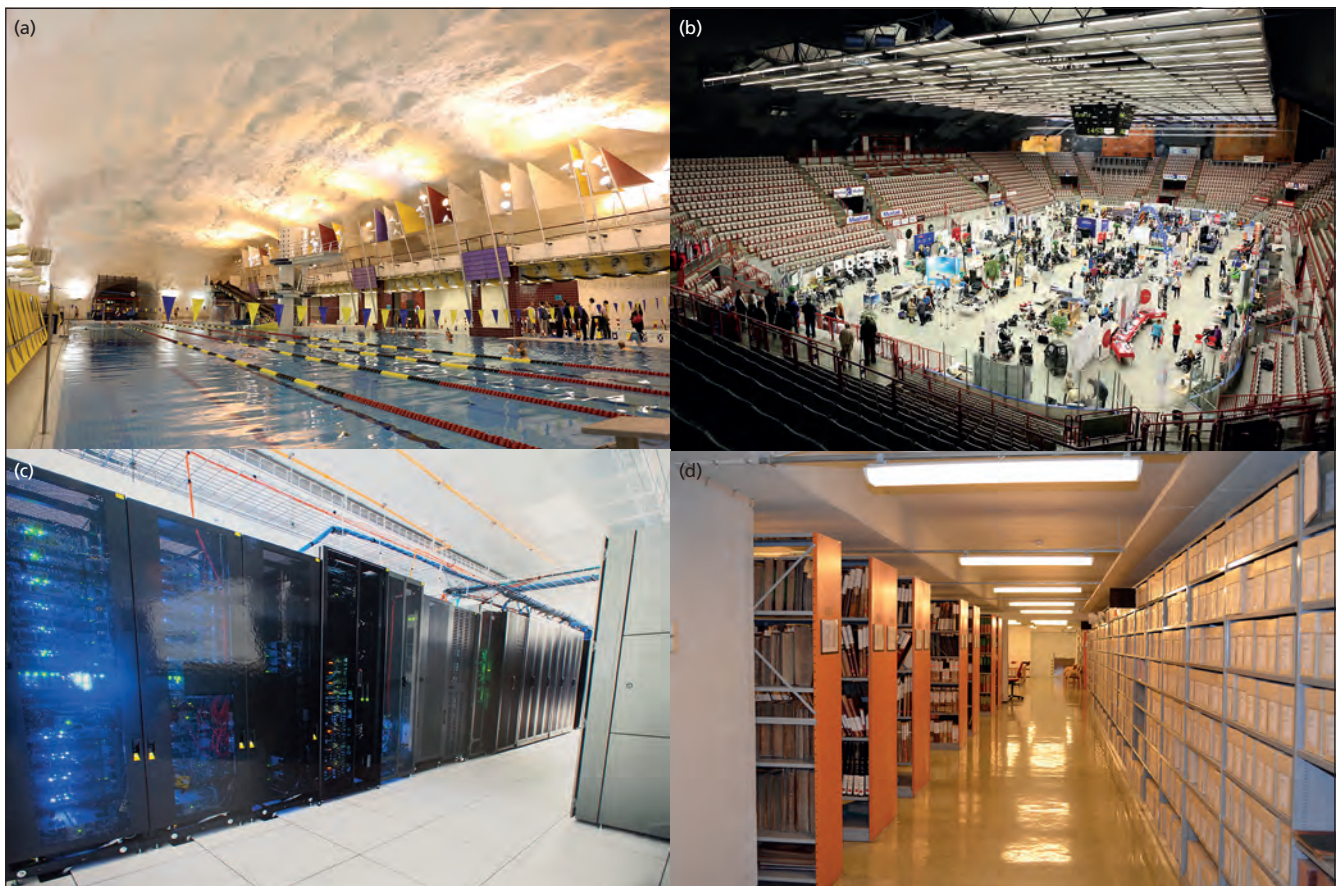


Figure 2. Various applications of cavern development from overseas examples (Ho *et al.*, 2018): (a) Itäkeskus swimming hall, Helsinki, Finland; (b) Gjøvik Olympic Stadium, Gjøvik, Norway; (c) Cavern Technologies Data Centre, KS, USA; (d) National Archives of Norway, Oslo, Norway

2018) (Table 1) by making reference to overseas experiences and taking account of the latest technological developments.

The updated list of facilities includes data centres, research and testing laboratories, recreational complexes, archive centres and underground quarrying. A number of pioneer studies that cover some of these new types of facilities have been launched in Hong Kong. Examples of ongoing cavern development studies and projects are shown in Figure 3.

4. Revamped planning concept: multi-dimensional planning

To maximise the benefits of cavern development, it is necessary to revamp current planning practice. The conventional planning of land usually considers the surface networks, connections and interactions with adjacent areas. Yet such planning practice is very much confined in the context of two dimensions. In view of the limited developable land in Hong Kong, it is necessary to widen the planning perspective to the underground dimension and seek usable space from a three-dimensional perspective.

In suitable circumstances, there are also opportunities for adopting a four-dimensional (4D) approach, with ‘time’ being an integral consideration in planning the use of space. The strategy should no longer be restricted to a single permanent use only. Instead, the use of space in different phases in the future should be duly considered. With thoughtful planning, the land uses in both the near and far future can be properly distinguished, thereby conferring the underground space with different uses and values as time goes on.

Underground quarry-cum-cavern development is an excellent example to demonstrate the concept of a 4D planning approach. With proper planning and design, the operation of an underground quarry housing concrete and asphalt production plants could be a self-financing or even profitable business in the short to medium term, while the created cavern space can be utilised for other strategic use in the long term, thereby realising the full potential of the underground resource in different periods of time (Sum *et al.*, 2018). For example, an underground quarry in Springfield, MO, USA, is one of the successful cases, where the cavern space was turned into warehouse and logistic hub after work completed in the quarry (Figure 4).

5. Cavern Master Plan

A new multi-dimensional planning vision must be accompanied by a solid implementation framework to enable cavern development in Hong Kong. In 2011, under the feasibility study on enhanced use of underground space in Hong Kong, a cavern suitability map, mainly based on geological considerations, was developed (Wallace *et al.*, 2014) (Figure 5(a)). The map shows that approximately two-thirds of the land area of Hong Kong is suitable for rock cavern development.

However, aspects such as accessibility, infrastructure support and nearby land uses would also have a strong influence on the suitability of cavern development. In view of the above, the government has recently promulgated the *Cavern Master Plan*, with a host of planning and engineering factors considered in its development process (Figure 5(b)).

Table 1. Updated list of land uses with potential for cavern development in Hong Kong

Sector	Use
Commercial	Food and beverage Food/wine storage Retail
Industrial	Container storage Data centre Industry Liquefied petroleum gas bulk storage Oil bulk storage Research and testing laboratories Storage and warehousing
Government, institution, community and other specified uses	Archives Civic centre Columbarium, mausoleum and mortuary Cultural and performance venue Explosives depot and magazine Incinerator Indoor games and sports hall Indoor swimming pool complex Maintenance depot Recreational complex Refuse transfer facility Service reservoir Sewage and water treatment plant Slaughterhouse Transport connections and networks Underground quarrying Vehicle (including bus) depot Vehicle parking Wholesale market
Public utilities	Power station Public utility installation

In essence, the *Cavern Master Plan* provides a broad strategic planning framework with comprehensive user guidelines to facilitate public and private sectors in considering cavern options and implementing their projects. The objectives of the plan include

- facilitation of territory-wide cavern development – to delineate strategic cavern areas that could facilitate wider application of cavern development in the territory
- promulgation of information – to disseminate and publicise information on strategic cavern areas that could enable both government departments and private sector organisations to identify suitable cavern sites for their developments
- optimal utilisation of strategic cavern areas – to optimise the use of land resources through a pragmatic mechanism for managing cavern and other subsurface developments in strategic cavern areas, without compromising beneficial surface land use and developments.

The plan delineates 48 strategic cavern areas that are well placed for developing rock caverns to meet the existing or future needs of the adjoining districts. All the strategic cavern areas identified are located in close proximity to existing urban areas

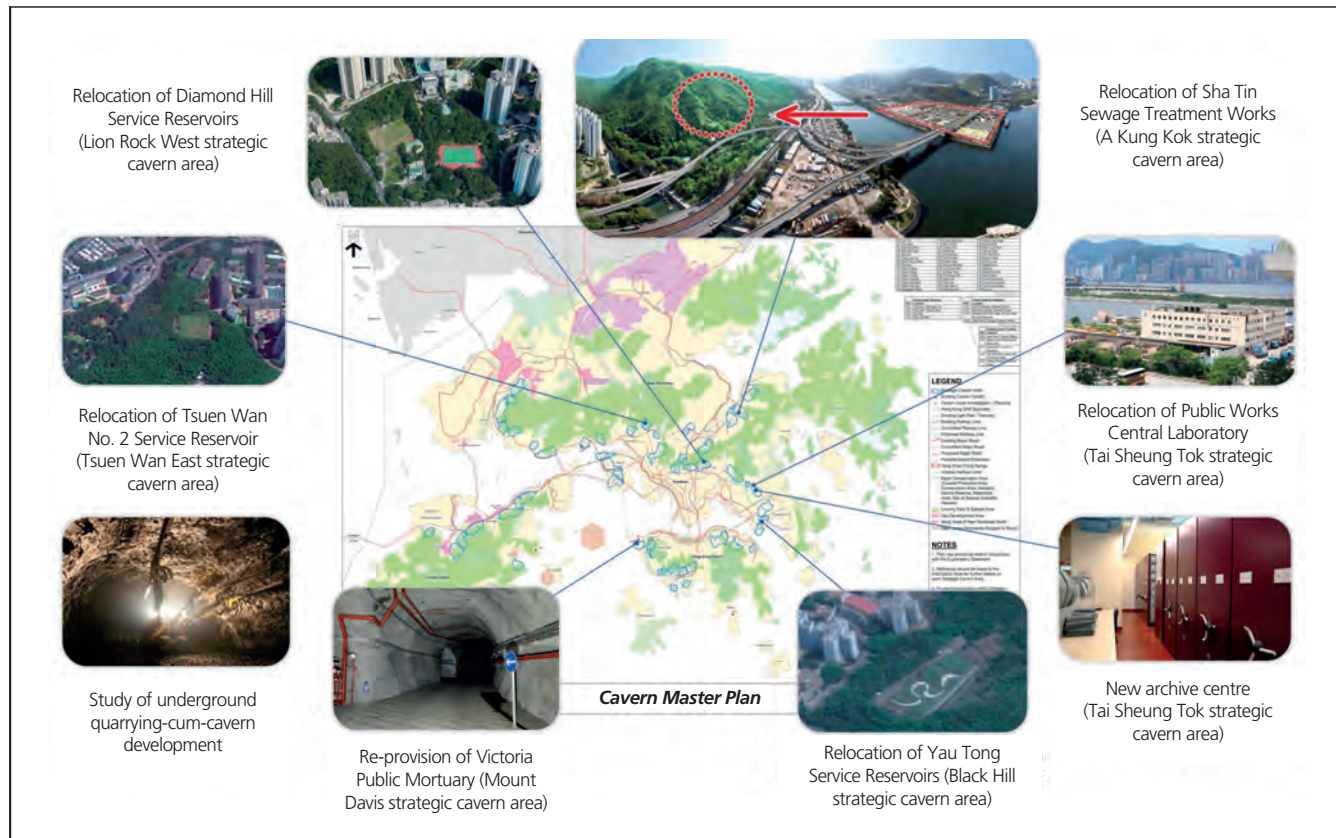


Figure 3. Examples of ongoing cavern development studies and projects in Hong Kong

with a good supporting infrastructure network and are sufficiently large to enable the accommodation of multiple cavern facilities. These areas offer an additional source of solution space that is versatile for a wide range of land uses, such as for accommodating new commercial, industrial, community or municipal facilities, subject to the needs of the society.

The plan is accompanied by an explanatory statement and a set of information notes. The explanatory statement is intended to provide the key information, including a list of land uses with potential for development in rock caverns by various users. It sets out the objectives of the plan, outlines the rationale and methodology of delineating strategic cavern areas (such as geological suitability, land use planning, environmental constraints and fire safety requirements) and highlights key issues for implementation.

The information note for each strategic cavern area describes the characteristics and development potential as well as constraints of the area. It includes details of the geological, planning, environment and traffic characteristics and other key issues and constraints on cavern development. The *Cavern Master Plan*, explanatory statement and information notes are available for the public to download on the government's Civil Engineering and Development Department (CEDD) website (CEDD, 2017).

6. Cavern support design

In Hong Kong, cast in situ lining has been the most dominant form of permanent support for rock caverns, in particular for



Figure 4. Underground quarry turned into a warehouse and logistic hub in Springfield, MO, USA

underground MTR stations due to functional requirements. Yet the rock reinforcement approach in the form of pattern rock bolts and sprayed concrete offers significant benefits compared to conventional cast in situ lining in suitable ground conditions.

A review has been carried out regarding the suitable permanent support form for future cavern construction. The most common rock types in Hong Kong are granitic and volcanic igneous rock. Fresh and slightly weathered igneous rocks are easily

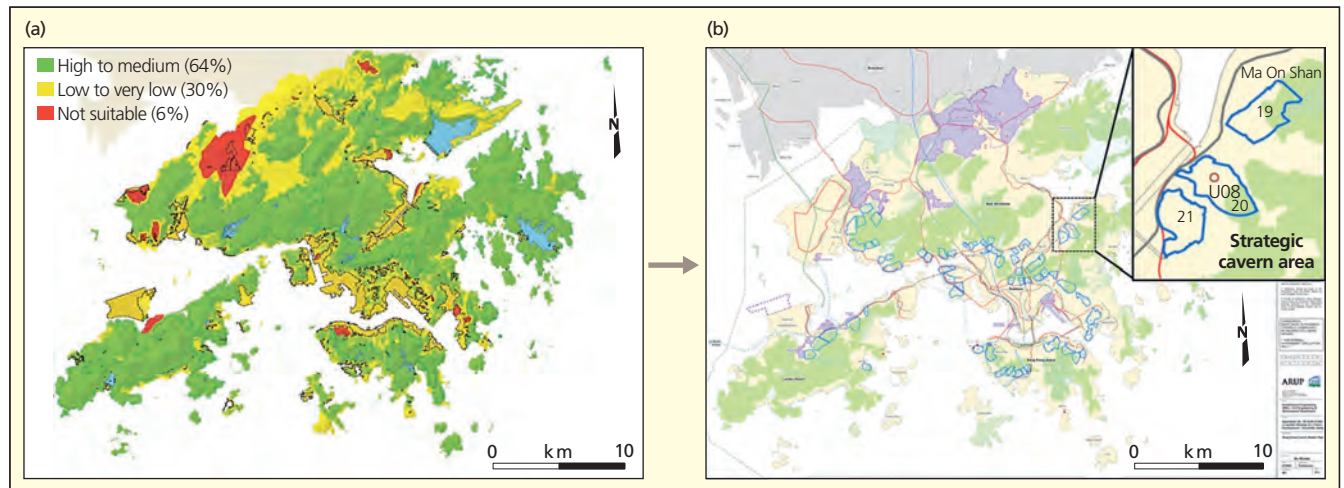


Figure 5. The geologically focused 2011 cavern suitability map for Hong Kong (a) has been replaced by the more holistically based 2017 Cavern Master Plan (b)

accessible inside most of the hillsides at the urban fringe by short access tunnels. Their uniaxial compressive strength is typically 100–200 MPa or more, which is greater than concrete, and they can be considered as structural material in the design of underground excavations in rock (GEO, 2018).

However, a rock mass is seldom free of discontinuities or weakness zones. The essence of a cavern design lies in the recognition of weaknesses in the rock mass and the provision of adequate reinforcement to conserve and improve the rock mass so that the rock supports itself.

The rock reinforcement approach has many proven advantages. First, as the rock is designed to utilise its inherent strength of the rock mass to support itself with the aid of rock bolts, the amount of structural elements installed in the rock reinforcement system is normally less than that in the cast in situ lining system, especially for situations in which the rock quality is good and competent, thereby providing an economic design solution. Second, the rock reinforcement installed in the rock mass for temporary support could eventually also be used as the permanent rock stabilisation elements. Hence it involves less construction effort as compared to the use of a separate cast in situ lining for permanent support.

There are comparative assessments indicating the financial benefits of the rock reinforcement approach in the literature. According to Garshol (1997), the ratio of cost between a concrete-lined tunnel and one with fibre-reinforced sprayed concrete was approximately 500:225. In another paper by Aagaard *et al.* (1997), the cost ratio was reported to be 4:1 for poor rock mass and 4:3 for exceptionally poor rock mass. The research by Grøv (2013) concluded that the Norwegian tunnelling method, which basically adopts the principle of the rock reinforcement approach, was 20–40% cheaper than the traditional cast in situ lining in terms of total cost. The financial benefit of the rock reinforcement approach over cast in situ lining is obvious, particularly when the rock quality is competent.

The concept of the rock reinforcement approach in cavern design relies on the formation of a rock arch at the cavern crown. Lang (1961) demonstrated the effectiveness of pattern bolting by means of a model of a self-supporting plate of bolted gravel. The rock

arch will support loads primarily by axial compressive thrusts, with negligible bending moment in the arch. From the model developed by Bischoff and Smart (1977), the system of rock bolts and other rock reinforcement elements will increase the thrust capacity by providing confinement to the rock arch that is structurally equivalent to an internal cavern support system (Figure 6).

Apart from rock bolts, sprayed concrete is another important element in the rock reinforcement system. The prime function of sprayed concrete in the system is to protect the exposed rock face from deterioration and prevent the falling of small blocks between the rock bolts. Typically, there is only a thickness requirement for sprayed concrete in the rock reinforcement approach and it is seldom used to withstand bending moment by way of increasing the axial load in the member, as in other well profiled arch-type linings.

Barrett and McCreath (1995) have developed a deterministic design approach and proposed six potential failure modes of sprayed concrete, including adhesive, flexural, direct shear, punching shear, compressive and tensile (Figure 7). Uotinen (2011) has developed a design framework for sprayed concrete linings according to

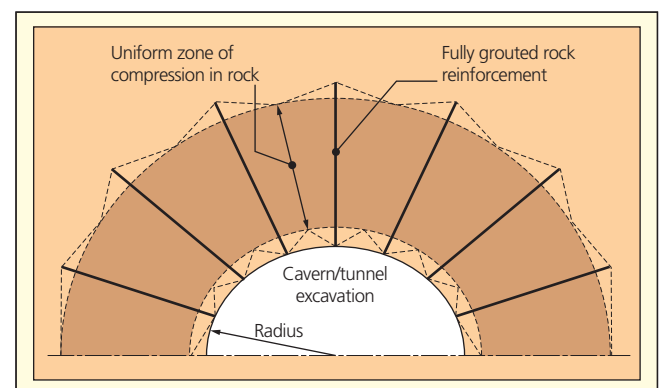


Figure 6. Rock reinforcement arch (modified from Bischoff and Smart, 1977)

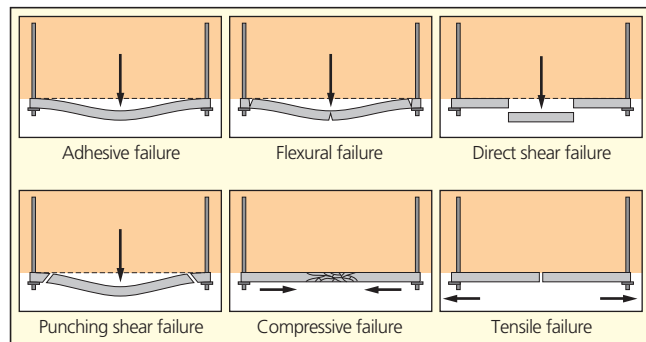


Figure 7. Potential failure modes of sprayed concrete linings (modified from Barrett and McCreath, 1995)

Eurocodes. Based on Uotinen's work, Kong and Garshol (2015) supplemented further details in relation to the design of sprayed concrete in the rock reinforcement system.

The design framework of the rock reinforcement approach has been well established over the years. Benchmarking with international practice, it is recommended that a rock reinforcement system should be widely adopted in the future as the typical rock cavern permanent support form in Hong Kong.

7. Sha Tin Sewage Treatment Works project

The relocation of Sha Tin Sewage Treatment Works to caverns by the government is a showcase cavern project in Hong Kong. It is also the leading example of the application of the rock reinforcement approach for permanent cavern support design.

The existing plant is the largest secondary sewage treatment works in Hong Kong. It serves an existing population of about 630 000 in Sha Tin and Ma On Shan districts, which produce 250 000 m³ of sewage per day. The relocation of the plant to caverns at Nui Po Shan of A Kung Kok will release approximately 28 ha of existing land for housing and other beneficial uses (Figure 8).

In addition to creating new land resources to meet the development needs, the project will help to remove land uses that are incompatible with the surroundings, thereby benefiting the community and environment. The sewage treatment facilities will be concealed inside caverns, with minimal impact on the surrounding environment. Coupled with appropriate environmental and odour control measures, the surrounding rock of the caverns will serve as natural barriers to minimise the impact of odour on the surrounding communities.

The proposed cavern halls in this project will span up to 32 m and have a height of up to 28 m, making them the largest caverns of their type ever built in Hong Kong. Based on ground investigation results, most of the rock within and in the vicinity of the cavern footprint at Nui Po Shan has been assigned as slightly decomposed granite (grade II), with bands of moderately decomposed granite (grade III) and very localised bands of highly decomposed granite (grade IV).

Given the overall favourable ground condition, it is suggested that the rock reinforcement approach would offer a more cost-effective solution for hard rock excavation in this area.

The initial design of the support was undertaken using the empirical design chart formulated by NGI (2015) to determine



Figure 8. Relocation of Sha Tin Sewage Treatment Works to caverns will release 28 ha of surface development land

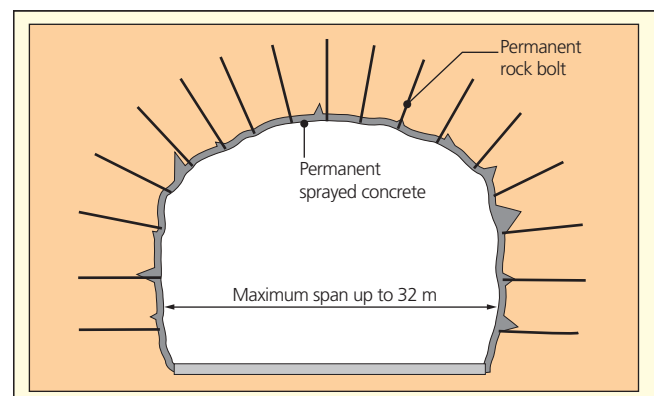


Figure 9. Schematic design of Sha Tin cavern halls

the required systematic rock bolt spacing and sprayed concrete thickness. The length, size and spacing of rock bolts were then verified using a numerical modelling approach according to the method proposed by Hoek (2011). The design considered failure of the rock mass against stress concentration around the opening.

In addition, kinematic analyses were carried out to check against the rock stability around the underground openings. All rock bolts and sprayed concrete were designed as permanent rock stabilisation measures with a design life of 100 years.

The schematic permanent design of the cavern hall is shown in Figure 9. The design of this relocation project was completed in phases since 2017/2018 and the stage 1 construction works of the project were started in February 2019.

8. Conclusion

Cavern development is one of the innovative land supply sources in the long run to meet the challenge of creating developable land to sustain the population and economic growth of Hong Kong.

In the past, Hong Kong has reaped the benefit of utilising rock caverns mainly for the accommodation of nuisance facilities on an individual project basis. Based on overseas experience, it is clear

that the applicability of caverns can be extended to a wider variety of uses.

With the recent launch of the *Cavern Master Plan*, numerous cavern projects for different land uses are being implemented in various strategic cavern areas. The direction of city planning has moved from the 2D approach to a more visionary multi-dimensional perspective, with a view to utilising underground space resources over different periods of time.

The relocation of Sha Tin Sewage Treatment Works to caverns marks an important milestone in cavern development in Hong Kong. It showcases the use of rock caverns to unlock precious land resources in the congested urban area. The adopted rock reinforcement approach also serves as a paradigm shift towards a more rational and economical design concept for future cavern projects.

Moving on to a new era, the *Cavern Master Plan*, together with the enabling measures, will form the key strategy to steer broader application of cavern development in the territory. By adopting a proactive and holistic approach, Hong Kong will continue to make use of underground space in a smart, balanced and effective manner for sustainable city development.

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