Cavern fire safety – overview of requirements and pragmatic solutions in Hong Kong

Julian SH Kwan¹, Leslie WH Tsang¹, Fred Ng², Johnny Cheuk² and Gary Au²

¹ Geotechnical Engineering Office, Civil Engineering and Development Department, The Government of the Hong Kong Special Administrative Region of the People’s Republic of China, 101 Princess Margaret Road, Kowloon, HONG KONG SAR, CHINA

² AECOM Asia Co Ltd, Grand Central Plaza, Tower 2, Shatin, HONG KONG SAR, CHINA

Abstract. Hong Kong’s steep hilly terrain limits the growth of surface urban areas. In response to the society’s needs for land to support social and economic developments, the Government of Hong Kong Special Administrative Region is actively exploring the use of caverns as one of the innovative measures to supplement Hong Kong’s land resources. The development of cavern space is an attractive option to meet the land demand not only for “not-in-my-backyard” (nimby) type public utilities but also for a wide spectrum of uses including commercial, industrial and community type facilities. The development of cavern fire safety design in Hong Kong evolved from the first cavern project in around 1980s. The design guideline “Guide to Fire Safety Design for Caverns” was jointly established by Building Authority and Fire Services Department in 1994, by referring to overseas and local experience consolidated in the Study of the Potential Use of Underground Space (SPUN) in 1990. This guideline however was developed with a focus on caverns for use by low population public utilities such as sewage treatment works and water service reservoirs where the fire load is generally localised, closely controlled and relatively low. Whereas, other prescriptive fire safety guidelines commonly adopted in the Code of Practice for Fire Safety in Buildings 2011 (FS Code) and the Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment (FSI Code) were developed for typical surface buildings only. The existing fire design guidelines are found to be not fully compatible with the recent expanding spectrum of cavern usage in Hong Kong. Each cavern development type has its unique site setting and fire safety characteristics under the proposed usage (e.g. government facilities, industrial and commercial facilities like concrete batching/rock processing/asphalt production plants, data centres, logistics/warehouse facilities, etc.). Strictly following the prescriptive fire safety requirements and the design guidelines for typical buildings to these usages in cavern will pose immense technical issues/challenges to cavern projects and could also lead to unwarranted impacts on their functional operations. A more coherent fire safety design approach for new cavern projects is therefore needed to facilitate project proponents to plan cavern projects in the future. This paper provides an overview of fire safety issues for cavern development, and also discusses the practical solutions in formulating the associated fire safety strategies which have been adopted in the latest cavern projects in Hong Kong, covering the technical issues on fire resisting construction, means of escape, means of access for firefighting and smoke management.
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 cavern has generally been limited in the past, mainly for accommodating nuisance ‘nimby’ type public utilities only. To unleash the full potential of cavern development, the Government of Hong Kong Special Administrative Region (HKSAR) has promulgated a strategic territory-wide Cavern Master Plan [1] and expanded the list of suitable land uses with potential for cavern development, including commercial, industrial and community type facilities, in the Hong Kong Planning Standards and Guidelines [2] with a view to expanding Hong Kong’s land supply in response to society’s development needs.

The development of cavern fire safety design in Hong Kong evolved from the first cavern project in around 1980s. The design guideline “Guide to Fire Safety Design for Caverns” (Cavern Guide) [3], which focuses only on low population public utilities in caverns, was established in 1994. Other prescriptive fire safety guidelines, the Code of Practice for Fire Safety in Buildings 2011 (FS Code) [4] and the Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment (FSI Code) [5], were developed for other typical surface buildings only.

Although the above guidelines have been adopted in a number of cavern fire safety designs, their applications diverged to other usages including industrial type facilities like rock crushing/concrete batching plant, and government facilities like archives centre. Some of the prescriptive requirements for surface buildings under the current guidelines have been found conflicting with the specific characteristics of cavern development, demanding respective deviations from these codes to be separately addressed by fire engineering approach. Also, it has been observed that the Cavern Guide [3] is only applicable to caverns with use for low population public utilities such as sewage treatment works and water service reservoirs where the fire load is generally localized, closely controlled and relatively low. Therefore, the existing fire design guidelines are not fully compatible with the recent expanding spectrum of cavern usage in Hong Kong, and strictly following the prescriptive fire safety requirements in the design guidelines would impose immense technical issues/challenges which could inhibit future implementation of cavern development.

The purpose of this Paper is to review the current prevailing cavern fire safety requirements in Hong Kong and the concerns of major stakeholders by referring to a few recent cavern development cases with specific highlights on difficult issues. Discussions will be made on these concerned requirements that would lead to major technical constraints to respective design issues. Fire safety measures and strategies which have been adopted to address these requirements and the associated concerns will also be discussed.

2. Prevailing Prescriptive Fire Safety Design Requirements

2.1. Prevailing Codes of Practices/Guide
According to HKSAR Buildings Ordinance (Cap. 123), cavern is classified as “building” of which the fire safety design will be subject to the local Codes of Practices/Guidelines [3] [4] [5].

2.2. FS Code and FSI Code
In Hong Kong, the fire safety designs for typical buildings are governed by FS Code [4] and FSI Code [5]. As cavern development falls under the classification of “building”, the fire safety designs have to follow the prescriptive requirements under the said codes. The requirements for fire resisting construction (FRC), means of escape (MoE) and means of access for firefighting and rescue (MoA) to buildings are prescribed in the FS Code [4] whilst fire service installations (FSI) are prescribed in the
FSI Code [5]. The statutory authorities have been making use of the requirements as stipulated in the said codes to process the “building” application in general.

2.3. Cavern Guide
The development of cavern fire safety design in Hong Kong evolved from the first cavern project in around 1980s. The design guideline “Guide to Fire Safety Design for Caverns” was established in 1994 by referring to overseas and local experience consolidated in the Study of the Potential Use of Underground Space in 1990. The Guide was issued more than 20 years ago to address the fire safety requirements for caverns solely housing public utilities such as sewage treatment works, refuse transfer stations and water reservoirs characterized with:

- low population with mainly site workers who are familiar with the underground cavern;
- closely controlled, relatively low and localized fire load;
- no sleeping risk; and
- effective management scheme with satisfactory contingency plan.

2.4. Incompatibility of design guidelines
The FS Code [4] and FSI Code [5] lay down the fire safety requirements and performance intents for typical surface buildings only which often have been found to be conflicting with the specific characteristics and unique nature of cavern developments in terms of FRC, MoE, MoA, FSI, etc.

Unlike buildings on surface land, cavern developments have different orientations and dimensions due to its characteristic nature developing mostly in horizontal manner instead of building up vertically. Therefore, the control limits for buildings may not be relevant and consideration shall be given to different factors in formulating a pragmatic fire safety strategy for cavern developments.

The Cavern Guide [3] was developed mostly for low-populated facilities like service reservoirs, sewage treatment plants, etc. With wider application of cavern developments under planning, facility classifications according to more specific requirements should be introduced with different design controls assigned to individual type of facilities, rather than adopting one unified prescriptive specification for all types of facilities. Therefore, separating those with higher fire safety risks, such as facilities involving high fire loads or a larger number of people residing within the cavern facilities, from the rest would help to differentiate adoption of less restrictive requirements for the low risk type facilities and to develop tighter rules for other commercial and industrial uses with higher fire risks.

After four decades from the first cavern project, larger and more complex caverns with broader and complex uses are now under planning, thus it is high time that the Cavern Guide [3] shall be updated to become more practically applicable as each type of cavern development has its own unique fire safety characteristics/ considerations under its particular usage.

3. Fire Resisting Construction (FRC)

3.1. FS Code
The FS Code [4] specifies the fire compartment area/volume and the fire resistance rating (FRR) based on different Use Classifications as shown in Table 1. In general, the maximum compartment area is 10,500m² and the FRR for element of construction and fire barrier should be in the range of 1 to 2 hours. When the buildings are used for storage purpose, an additional volumetric restriction of 28,000m³ is imposed. A further restriction is imposed when the buildings are used for storage, manufacturing of hazardous/dangerous goods. Basements which traditionally possess a higher fire risk and an expect longer duration for firefighting and rescue would require further enhancing the FRR to ≥4 hours for all elements of construction and all protected exits serving the basement regardless of the Use Classification.
Table 1. Fire Resistance Rating and Fire Compartment Limitation in FS Code

| Use Classification          | Compartment Area/ Volume | FRR (minutes) |
|----------------------------|--------------------------|---------------|
| 1. Residential             | Not limited              | 60            |
| 2. Hotel and similar Transient Accommodation | Not limited | 60 |
| 3. Institutional           | ≤2,500m²                 | 60            |
| 4. Commercial:             |                          |               |
| 4a. Business Facilities    | ≤10,500m²                | 60            |
| 4b. Mercantile Facilities  | <2,500m² but ≥10,500m²   | 120           |
| 5. Assembly:               |                          |               |
| 5a & 5d. PPE & Other assembly premises | ≤2,500m² | 60 |
|                            | >2,500m² but ≤10,500m²   | 120           |

| Use Classification          | Compartment Area/ Volume | FRR (minutes) |
|----------------------------|--------------------------|---------------|
| 5b. Educational establishments | ≤2,500m² but >2,500m² | 60            |
| 5c. Transport facilities   | ≤10,500m³                | 120           |
| 6. Industrial:             |                          |               |
| 6a. Industrial workplaces  | ≤10,500m³                | 120           |
| 6b. Bulk storage, Warehouses | ≤28,000m³ and ≤10,500m³ | 120          |
| 6c. Storage, manufacturing of hazardous/dangerous goods premises | ≤7,000m³ | 120 |
| 7. Carparks                | ≤10,500m³                | 60            |

3.2. Cavern Guide

In the Cavern Guide [3], it is stated that underground cavern is unlike a basement or aboveground structure, and is not fully dependent on the internal structure support. Hence, an FRR of ≥4 hours is not an automatic requirement. It further defines the requirement of FRR for cavern in the following context:

- Where the MoE does not involve ascent of stairs, in general an FRR of between 1 hour and 2 hours would be appropriate, depending on the fire load. Where MoE requires ascent of stairs, a higher FRR should be considered.

- In case of very low fire load such as a water service reservoir, and FRR of ≥1 hour would be adequate.

- For underground caverns with four or more levels, the likely duration of time to escape will affect rescue and firefighting and should be considered when deciding on FRR. However, in general an FRR of ≥4 hours would be appropriate.

Pursuant to Section 4.1 of Cavern Guide [3], the fire compartment size of underground cavern is restricted to specific volume as listed in Table 2. The caverns are generally subdivided into compartments with a volume of ≤28,000m³ each while for cavern use for warehouse/storage, the compartment volume shall further be restricted to ≤7,000m³. These compartmentation requirements are similar as those listed in the Code of Practice for Fire Resisting Construction, (the precedent code of FS Code [4]) in 1994 when the Cavern Guide [3] was published. When the access to the cavern space involves vehicular access tunnels, there is no restriction set for the compartment volume for the vehicular access tunnels.

Table 2. Fire Compartment Limitation in Cavern Guide

| Use                        | Compartment Volume |
|----------------------------|--------------------|
| 1. Warehousing             | 7000m³             |
| 2. Vehicular access tunnels | Not limited        |
| 3. All other uses          | 28,000m³           |

3.3. Current Limits / Constraints and Pragmatic Solutions

Unlike the usual circumstance, the FS Code [4] in terms of fire compartment size is considered to be less stringent than that of the Cavern Guide [3], in which the fire compartment size of general types of
buildings is restricted to \( \leq 10,500 \text{m}^2 \) with the exception of institutional and industrial uses which require to have less compartment area or have additional restriction to control the volume as shown in Table 1. Despite the Cavern Guide [3] has categorically indicated that cavern is unlike basement and has specified the FRR requirements under this context, it is still common in the latest cavern development projects that the statutory authorities would generally hold the view that all caverns should be classified as basement/underground facilities to have an 4-hour FRR as per FS Code [4]. Also, in view of uniqueness of cavern development where the vertical span of the space could reach as high as 10 to 30m dissimilar to typical buildings with limited floor height for one storey, complying the fire compartment following volumetric requirements as per FS Code [4] and Cavern Guide [3] will result in substantial number of fire compartments to be separated by fire rated walls, doors and/or fire shutters, which could seriously hamper the functional use of caverns. It would also pose huge technical difficulties to provide structural support for these large vertical span fire separation elements. Adopting the maximum compartment volume requirement of 7,000\( \text{m}^3 \) for storage facility in the Cavern Guide [3] could impose major obstacles to future design and operation for logistic warehouse or similar type of facilities.

In the interests of rationalizing fire safety requirements for caverns, the FRR requirements for elements of construction and fire barriers as well as compartment size could be reviewed to close the above gap in application of the FS Code [4] and Cavern Guide [3] referencing to criteria based on:

- Use Classification;
- Cavern height;
- Cavern depth;
- Number of storeys;
- Evacuation arrangement; and
- Fire service installations.

4. Means of Escape (MoE)

4.1. FS Code

FS Code [4] defines an exit route is a continuous path of travel from any part of a building to the ultimate place of safety. Occupants shall be allowed to reach the nearest protected exit within the prescribed travel distance and deadend travel distance in Table 3. After reaching the protected exits, they shall proceed along the protected exit which could be a required staircase, ramp or passageway enclosed by fire barriers to the ultimate place of safety. The ultimate place of safety is a place for final exit discharge where a protected exit terminates or provides access to an area clear of the effects of fire, where people may safely disperse. The ultimate place of safety is a street or an open area outside the subject building and connects directly with a street. The arrangement is shown in Figure 1.

| Table 3. Travel Distance Requirement in FS Code and Cavern Guide |
|---------------------------------------------------------------|
| Travel Option | FS Code | Cavern Guide |
| 1. Single direction | 18m to protected exit | 18m to place of safe passage |
| 2. Two or more choices of direction | 36m to protected exit | 72m to place of safe passage |

**Figure 1. Illustration of Exit Route Arrangement in FS Code and Cavern Guide**
4.2. Cavern Guide
The principle of MoE in the Cavern Guide is slightly different from that of FS Code [4]. In the event of fire, people in an cavern should be able by themselves to reach a place of safety (the open air) within the prescribed travel distance and deadend travel distance in Table 3, either directly or through a place of safe passage, before the fire affected cavern becomes untenable. The prescribed travel distance could also be allowed to be extended if it can be demonstrated that fire loads are low and escape route are extremely simple. Based on the exit time of 2.5 minutes in a fire compartment and a travel speed of 1m/s, a maximum travel distance of 150m may be acceptable. Even though there is a relaxation for travel distance, the Cavern Guide [3] limits the total horizontal distance to $\leq 750$ m in order to avoid people from getting unduly stressed by travelling such a distance.

Unlike protected exit in the FS Code [4], the place of safety passage is defined in the Cavern Guide [3] as escape stairs, corridors or another fire compartment adequately protected from fire and smoke and comprises the elements of the exit or route to be followed to reach a place of safety. Roadway is also acceptable to be a place of safety passage. The arrangement is shown in Figure 1.

4.3. Current Limits / Constraints and Pragmatic Solutions
Compared with FS Code [4], the travel distance in Cavern Guide [3] is considered less stringent, where the distance from any location to the nearest exit leading to a place of safety passage is limited to $\leq 72$ m rather than $\leq 36$ m when two or more choices of direction is available. The travel distance can be extended to 150m when fire loads are low and escape route are extremely simple. However, there is no guidance in the Cavern Guide [3] to define low fire load and extremely simple escape route. The limit of fire load and the geometry of the escape route to allow an extension of travel distance shall be clearly defined by making reference to appropriate international standards.

The principle of MoE in the cavern development should be further refined in the future. As long as the roadway satisfies the fire safety requirements for place of safe passage, the Cavern Guide [3] allows occupants to evacuate to another fire compartment and roadway other than required staircases and protected corridors only as required in the FS Code [4]. However, it is common for the statutory authorities to request protected corridor(s) along the roadway as an additional fire safety enhancement in recent cavern developments. A recent concrete batching plant development in cavern for underground quarry operation is a typical example where pressurized protected corridors are provided next to the roadway which has already been fully protected with smoke extraction provisions.

![Figure 2. Fire safety designs in underground quarry caverns](image)
Also, it is recommended that the MoE design for cavern developments shall be formulated with consideration of design basis of a single fire scenario at one location at one time, i.e. a fire occurring inside an incident fire compartment not affecting other non-incident fire compartments. The connecting roadway which is designed as a place of safe passage will serve as a safe passage to allow occupants to leave the incident fire compartment and proceed to the open air. Scenario-based analysis shall be conducted to provide a basis for determining the availability of exit routes and assessing the need of protected corridors along the roadway. This could allow a better cavern design and optimize cavern space usage.

Some cavern spaces are planned to be built with great depth within the hillside from the open surface to accommodate the geological and topographical conditions of the site, and also aim at developing more usable lands with larger cavern size. At present, the Cavern Guide \[3\] sets the limit of the total horizontal distance of \(\leq 750\)m in order to avoid people from getting unduly stressed by travelling such a distance to open air in the evacuation. This limit becomes a critical issue which could potentially constrain the extent of future cavern development. One recent example is a relocation project of an existing sewage treatment works to caverns where the evacuation routes exceed this limit. In addition to having wider evacuation routes with high headroom or having appropriate resting facilities to relieve the unduly stress during long travel, other mitigation measures or innovative ideas such as introducing a two-stage evacuation plan (i.e. provision of refuge chambers as a temporarily shelter for evacuees prior to proceeding further evacuation) shall also be explored to effectively reduce the horizontal travel distance.

5. Means of Access for Firefighting and Rescue (MoA)

5.1. FS Code
Emergency vehicular access (EVA) should be provided to serve at least one major façade of the building. For this purpose, a major façade of the building refers to the façade having not less than one-fourth of the total length of all the perimeter walls of the buildings. For buildings under Use Classification 6: Industrial, the requirement of EVA is even more stringent that it should serve two opposite façade that are remote from each other.

5.2. Cavern Guide
The Cavern Guide \[3\] suggests that vehicular access tunnel to the cavern spaces should be used as EVA with adequate carriageway, headroom, loading, gradient and turning facilities to permit smooth maneuvering of major emergency appliances. Also, a setting down point should be provided within the cavern. Such provisions should normally be provided at the end of access tunnel just before the entry into the cavern. This setting-down point should provide an area of the highest absolute safety for firefighting and rescue purposes and should have an FRR of \(\geq 4\) hours.

5.3. Current Limits / Constraints and Pragmatic Solutions
The requirements in the FS Code \[4\] are obviously relevant to typical buildings above ground with façade facing the EVA. For developments which are present within cavern space without building façade, the prescriptive requirements in the FS Code \[4\] fully articulated its incompatibility to the cavern development. More appropriate specification suited to the cavern facilities should be made in the Cavern Guide \[3\]. Recently, it becomes more common to have multiple levels of accommodation within cavern space to achieve a better space utilization. The situation warrants fireman’s lifts and firefighting and rescue stairways to be required within the cavern space which should also be properly formulated to facilitate the firefighting and rescue operation.

Cavern space is always developed with portal building at the surface to house essential facilities to support the operation of the cavern space. There is no explicit guideline to determine when the vehicular
access tunnel (also serving as EVA) to the cavern spaces is required to facilitate the firefighting and rescue. Sometimes, for cavern space close to ground surface, the sole use of pedestrian access route for the MoA may be sufficient subject to liaison with relevant stakeholders. When the vehicular access tunnel (also serving as EVA) is required, the arrangement of setting down point should be clearly defined as to what provisions should be required for the area to be treated as setting down point such as ventilation requirements, fire services installation provisions, protected lobbies for access openings, etc.

6. Smoke Management

6.1. FS Code and FSI Code
Dynamic smoke extraction system is required for any fire compartment with a volume of $\geq 7,000m^3$ where the designed fire load is likely to $>1135\, MJ/m$. For industrial basements, dynamic smoke extraction system is required even if the fire compartment volume is $<7,000m^3$. The design of dynamic smoke extraction system in the FSI Code [5] is generally using the air change basis. The minimum extraction rate shall be equivalent to not less than eight air changes per hour of the total compartment volume. The design volume shall be considered to be 7,000$m^3$ for any compartment of 7,000$m^3$ or less. When the cavern space is considered as a basement in the FSI Code [5], separate systems shall be provided for each compartment and each system shall comprise at least two independent plants and ductwork i.e. for a proportion of the area and extract/supply volumes.

Whenever firefighting and rescue stairways are required for cavern with multi-levels structure, the lobby to the firefighting and rescue stairways and the access staircase in firefighting and rescue stairway shall be protected using pressurization system to control the ingress of smoke into the stairway or lobby.

6.2. Cavern Guide
The Cavern Guide [3] provides only a broad requirement for the smoke control arrangement. Under this guide, it is required that the smoke control should be made by mechanical means and smoke extraction rate should be based on design fires with designated smoke clear height to limit the lateral and vertical movement of smoke, to extract smoke and hot air, to aid rescue and firefighting operations and to ensure that the escape routes are free from smoke and heat.

Pursuant to item (a) of Clause 5.5.1 in Cavern Guide [3], it is stated that pressurization should be provided for place of safe passage. If it is not practicable due to large volume or if the design of the place of safe passage is connected to open air, a suitable smoke extraction system should be installed.

6.3. Current Limits / Constraints and Pragmatic Solutions
The design of dynamic smoke extraction system could have a variety of issues rendering the matter difficult in statutory approval and inspection. Neither FSI Code [5] nor Cavern Guide [3] has provided any detail for the dynamic smoke extraction system design arrangement for cavern developments on items such as:

- Design fire size;
- Minimum smoke clear height;
- Maximum number of smoke zone/compartment to be served by one smoke extraction system;
- The location of fan plants;
- The redundancy/backup requirement of smoke extraction equipment;
- Extent of protection; and
- Extent of exemption.

In the absence of detail on dynamic smoke extraction system design requirements to be accepted by relevant statutory authorities, the designers may make over-provisions. In some cases, all areas within the cavern would be protected by dynamic smoke extraction system regardless of the fire load and fire
risk level with provision of separate system for each individual fire compartment and simultaneous operation of all systems regardless the situation and necessity. Such provisions could substantially affect the cavern planning in its sizing and would also impact its overall project cost and financial viability. On the other hand, lean provisions could potentially undermine the level of fire safety. Due consideration on the provision of dynamic smoke extraction system should also be made for areas with very low fire risks such as compartment housing water reservoir/water tanks or general mechanical plant rooms with a volume of <7,000m³ having adequate fire suppression system.

Moreover, statutory authorities would generally request FSI plantrooms to be located outside of cavern as full assurance on reliability in case of fire incident even though the plantrooms, if accommodated within the cavern space, could be properly protected by fire barriers. Compliance with these requirements will demand huge land-take in the portal building and also substantial space provisions along the access tunnel to house the respective plant and equipment.

7. Conclusion
This Paper has reviewed and discussed the current cavern fire safety requirements based on the prevailing codes of practice and the Cavern Guide [3] referencing to recent cavern development projects in Hong Kong. It has been observed that there are gaps in the requirements between these documents and there are also considerable limitations when applying them as they are not fully suitable for the specific nature and characteristics of cavern developments. While the development of cavern space has been confined to limited functions for ‘nimby’ type public facilities, it is anticipated that the use of cavern space will be extended to a wider spectrum including commercial, industrial and community type facilities to meet the acute land demands in Hong Kong. For the future planning of these land uses, a practical fire safety strategy has to be developed to address appropriately these specific issues. It is also high time that the prevailing fire safety regulations shall be revisited and updated in order to promulgate the wider application of cavern development in Hong Kong.

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