Fire safety issues in underground spaces: a need for regulatory evolution – French, Swiss and Hong Kong SAR, China (Hong Kong) contexts

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Abstract. Current regulations and operational safety requirements impose onerous constraints that make it difficult to be fulfilled by practical design of underground projects acceptable to all stakeholders. The ACUUS working group on fire safety of underground spaces intends to gather and share information on the ways how fire safety is taken into account and managed in different countries. This article presents the first work carried out within this working group. Regulatory contexts in France, Switzerland and Hong Kong SAR, China (Hong Kong) are presented, highlighting the current limitations. With their similarities and differences, the French, Swiss and Hong Kong contexts reveal a need to improve and to develop their respective regulations to allow pragmatic solutions without compromising fire safety. Underlying principles that condition fire safety requirements are defined in order to develop new approaches to overcome the aforementioned limits.

1. Presentation of the ACUUS WG on fire safety issues of underground spaces

Underground space offers multiple possibilities for urban development especially in densely populated areas. Safety issues are among the prime concerns in the design, construction and operation of underground facilities. The safety regulations that are implemented to manage them are generally based on regulations previously developed for open air projects. As a result, current regulations and operational safety requirements impose onerous constraints that make it difficult to be fulfilled by practical design of underground projects acceptable to all stakeholders.

The ACUUS working group on fire safety issues in underground space intends to gather and share information on the ways how fire safety is taken into account and managed in different countries. In particular, it would be useful to identify the underlying principles that condition safety requirements and determine to what extent they affect or restrict the design of such spaces. The working group intends to provide international examples of underground projects, and report on the way the building codes and regulations have been adapted to tackle specific underground issues. Drawing on such work can lead to new performance-based approaches or proposed amendments to the regulatory framework.

This article presents the first work carried out within this working group. It focuses on the French, Swiss and Hong Kong regulatory contexts. Limits and constraints due to the different regulations are
highlighted. In these three places specific regulations exist for transport infrastructures such as road, rail and metro tunnels. However, complex projects involving multiple activities and users face great challenges in complying with the applicable regulations. Such underground projects are the focus of the ACUUS working group. Finally, the article defines the primary objectives of fire safety that are to be taken into account at the design stage.

It is important to quote that the fire protection concept is a cornerstone of an overarching safety concept in which all the aspects of the safety system are coupled.

2. Fire Safety Regulations in France

2.1. Presentation of the French context

In France, buildings are divided into different categories according to their specificities (dimensions, occupancy and activity). The French Building and Housing Code [1] applies to all categories. Specific regulations provide additional requirements for some building categories. Although French regulations are mainly inspired for open air buildings, requirements for underground spaces can be found in:

- the Labour Code (for buildings receiving workers, e.g. restaurants, hotels…);
- the regulation for buildings open to the public [2] (e.g. libraries, shopping centres, hotels…);
- the regulation for underground car parks [3];
- the regulation for metro stations [4].

These regulations list a full set of prescriptive requirements. Unfortunately, the principles and objectives behind these requirements are rarely explained. The main constrains and limitations for underground spaces due to the French regulations are presented in the next paragraph.

All French building codes and regulations are currently being reviewed and modified. It is aimed to define common objectives for all buildings in order to allow the use of a performance-based approach instead of applying the existing prescriptive requirements. A working group of the French national research project “Ville 10D” composed by the Centre for Tunnels Studies (CETU), Paris firemen (BSPP) and the central laboratory of the prefecture of police (LCPP) is reviewing the state of the art on French regulations on underground space.

Despite the current limitations, a couple of underground projects have been developed in France as the Forum des Halles, the Louvre museum and some Paris metro stations [5]. These projects are worth noticing as they consider a depth more important than the regulatory limit or present a complex and multimodal infrastructure. For each, a tailor-made approach has been carried out to allow for derogatory clauses which are approved by a local authority committee, provided that the required level of safety is guaranteed. This case-by-case approach is subject to local and unpredictable decisions; therefore it remains an obstacle for planners and investors.

2.2. Main limitations due to current regulations

2.2.1. Depth

Existing regulations are based on the principle of rapid and direct evacuation to the surface/open area and firemen operating with traditional means. This is why, according to the existing French regulations, no more than one underground level (6 m) is authorized for buildings open to public. Nevertheless, there are some exceptions for specific structures:

- underground metro stations up to 30 m deep provided notably that a place of safety (refuge area) is available for emergency evacuation;
- underground car-parks up to 28 m provided that a suitable space partitioning and specific equipment are foreseen.

Depths around 50 m are encountered for the new metro stations of Grand Paris Express. This was only possible by a tailor-made approach and by allowing an evacuation to a place of safety.

Another limiting factor is the design of emergency facilities and especially the exit widths. These are determined by flat-rate calculations and exit width increases significantly with depth.
2.2.2. Multiple activities & reversibility of use

Current regulations prevent the development of a comprehensive fire safety strategy which would take into account multiple spaces and possible changes in activities and uses. French regulations are indeed very compartmentalized and specific according to the category of buildings. In these regulations, the approach is that each building must ensure its own safety and must have the necessary specific emergency equipment. As a result, complex structures including various activities (transport, shopping centre, library, public workspace…) face great challenges in complying with the different applicable regulations. Current regulations are also an obstacle to possible reversibility of the use of a building.

2.2.3. Compartmentalizing / Partitioning of spaces

All buildings and structures have fire compartments made of fire-resistant walls to contain fire and smoke. This partitioning aims to limit the volumes impacted by the fire, to facilitate the intervention of emergency services and to limit the extent of material damage. Nevertheless, in buildings open to public, the French regulation requires that the entire building must be evacuated in the event of a fire. Thus, if the regulation for buildings open to public is applied to underground spaces, emergency facilities will be over designed and the pooling of the emergency equipment (e.g. means of egress, smoke extraction…) of neighbouring structures will not be possible. Partitioning of underground spaces, evacuation strategy and more generally space management and monitoring should be rethought.

2.3. Example of French underground space: Forum des Halles

The Forum des Halles, now Westfield Forum des Halles, is an emblematic project in Paris. Established on 4 underground levels, plus a fifth one dedicated to the RER (Réseau Express Regional) platforms, it combines a vast shopping centre, cultural spaces (movie theatre, concert, hall, library…), sport equipment (swimming pool, sport hall…), metro and RER stations, car parks and roads. Derogations from the safety regulations were necessary to realize this project. They were accepted thanks to a specific configuration of the site and the implementation of facilities allowing for maximum safety of the public. To design these safety facilities and validate the derogations, the designers and local authorities relied on the requirements from two separate regulations: the regulation for buildings open to the public [2] (which is the category to the Forum des Halles) and the regulation for high-rise buildings [6].

An important difference between buildings open to the public and high-rise buildings is the emergency evacuation strategy. As explained before, everyone present in a building open to the public should be evacuated in the event of a fire. High-rise buildings are compartmentalized to allow a sequenced evacuation; the compartment threatened by fire is evacuated with highest priority. If necessary, all other compartments are evacuated but in sequence. An important consequence of this evacuation strategy is that the design of emergency routes and staircases are not over-designed and the pooling of the emergency equipment (e.g. means of egress, smoke extraction…) of neighbouring structures will not be possible. Partitioning of underground spaces, evacuation strategy and more generally space management and monitoring should be rethought.

The Forum des Halles is an underground shopping centre, library, public workspace, concert, hall, and cultural spaces. The French regulation requires that the entire building must be evacuated in the event of a fire. However, partitioning of underground spaces and the pooling of emergency equipment are not possible due to the requirements from two separate regulations: the regulation for buildings open to the public and the regulation for high-rise buildings.

An example of French underground space is the Forum des Halles, a shopping centre with four underground levels. The safety regulations were necessary to allow a sequenced evacuation of the building in the event of a fire. High-rise buildings are compartmentalized to allow for a sequenced evacuation, while underground spaces are partitioned to limit the spread of fire and facilitate intervention of emergency services. The Forum des Halles project was accepted thanks to a specific configuration of the site and the implementation of facilities allowing for maximum safety of the public.

The main regulatory derogations of the Forum des Halles concern:

- the depth of -17.50 m for the shopping centre and the admission of the public on several underground levels, whereas the regulation only authorizes 6 m depth and only one accessible underground level;
- the accessibility of emergency services (they access through level -2 although the regulations require accessible facades on the surface);
- the space management which considers independent compartments: this configuration required mobile arrangements (e.g. separating walls, vertically removable curtains, sliding fire-proof doors, removable smoke curtains…) to isolate the compartments and restore the 2-hour fire isolation in the event of a fire;
- the smoke extraction (only the damaged compartment is smoked out);
- the emergency evacuation strategy (only the damaged compartment is evacuated).
3. Fire safety regulations in Switzerland

3.1. Swiss regulatory context
The Swiss Building and Housing Code [7][8] applies in principle to all building types. Specific regulations provide additional requirements for some particular building categories. Buildings partly or entirely used as working spaces shall also comply with the Labour Code. The legal requirements resulting from the Labour Code are illustrated in several publications issued by the Federal Coordination Commission for Occupational Safety FCOS (EKAS) [10].

Legal requirements for underground spaces/ caverns can be found in:
- the regulations for buildings open to public [7][8],
- the Labour Code,
- the regulations for specific underground infrastructures, such as road or rail tunnels.

Specific regulations apply for underground construction works [11]. These are applicable during construction and maintenance of underground structures, such as tunnels and caverns. The construction and maintenance of caverns is included, as well as the underground extraction of rock, as in underground quarries.

Underground car-parks are treated as special buildings, for which specific requirements apply. Underground rail and metro stations are treated as buildings. Rail and road tunnels are treated separately, e.g. in the SIA tunnelling norms [12].

3.2. The Swiss Building Code
The Swiss Building Code is developed and maintained by the Swiss Association of Cantonal Fire Insurances VKF/AEAI/AICAA. The code consists of:
- a general norm defining the general principles and requirements [7],
- specific guidelines providing further details on specific topics, such as construction materials, emergency exits, fire extinguishing systems etc. [8] and
- documentations providing further details on specific building categories, such as school buildings, car-parks or high-rise buildings.

The main objective of the Code is the protection of persons, animals and things against the dangers arising from fires and explosions. They are applicable to new buildings and existing buildings, in case of significant modifications (structure or operation) or in case of particularly high risks for persons. The treatment of underground components is very limited.

The Building Code has generally prescriptive character. The fire safety goals can be achieved following standardized fire protection concepts, based on structural and extinction measures. There is no need for additional investigations as long as the prescribed regulations are respected.

Deviations from the regulations are allowable in the following cases:
- Specific fire-protection solutions are allowed for specific buildings, if they can be proved to provide an equivalent level of protection. The competent Authority decides on a case-to-case basis if the proposed concept can be considered equivalent.
- In case the risk level in a specific building is significantly higher or lower than usual.

In both cases all safety objectives stated in the fire-protection norm [7] must be achieved.

More relevant deviations from the Building Code are allowed under specific conditions discussed in the next section.

3.3. Specific fire protection concepts
A specific guideline of the VKF/AEAI/AICAA Building Code is devoted to special buildings, where the prescriptive approach is not applicable. This procedure is regulated in a specific section of the Building Code [9]. This defines a form of performance-based fire engineering design and is the fundament for the feasibility of extensive underground facilities such as the Test Gallery Hagerbach.

The procedure is allowable for the evaluation of fire threats and risks or for adopting alternative fire-protection concepts under the following conditions: all safety objectives stated in the Fire Protection
Norm [7] shall be achieved and a holistic approach, considering all relevant safety-relevant aspects, shall be applied. The safety objectives [7] are stated as follows:

- The safety of persons and animals is ensured
- Fires and explosions can be prevented, and the propagation of fire, heat and smoke is limited
- The propagation of fire to neighbouring structures is prevented
- Effective fire-fighting operations are enabled and the safety of the first responders is ensured.

The guideline specifies the formal requirements and contents of the procedure to be applied at different design and construction stages. The safety concept must be approved by the competent Authority and the boundary conditions adopted in the approval process are binding. The operator of the facility takes full responsibility for this.

3.4. Issues and limitations

Despite national differences, the Swiss Building Code in its prescriptive part has limitations similar to the corresponding codes in other countries. This can be illustrated based on the prescriptions applied to emergency exits. The applicable maximum total escape length to a vertical escape or to the exterior are:

- The maximum permitted distance to the next safety exit is generally 35 m.
- Distances up to 50 m are acceptable if more than one escape direction is available. This distance can be exceeded if the room height exceeds 6.0 m after verification with the competent Authority.

Analogous limitations apply e.g. to fire compartments. It is clear, that such prescriptions represent a serious limitation for large, multipurpose underground developments. However, a distinct advantage of this framework, if compared e.g. with the French regulations, is its relative lack of compartmentalization and specificity according to the category of buildings. The basic regulations are common for all kinds of usage and are further specified for different usages at a lower level.

The adoption of object-specific fire protection concepts according to [9] is an extremely powerful and flexible tool which fully overcomes such limitations. There is however a price to be paid for this flexibility. The engineering analysis required for achieving this can be extensive and complex. The prescriptions provided in [9] are very generic and technical guidance for carrying out the analysis and for proving that the intended goals are achieved is very limited. Furthermore, the requirements to the approval process by the competent Authority are only specified in very general terms. This can result in a very long approval process, whose outcome can be uncertain.

3.5. Example of Swiss underground space: Test Gallery Hagerbach

A prototype for a number of heterogeneous underground applications is the Test Gallery Hagerbach (Figure 1). The complex, expanding network currently encompasses over 5.5 km of galleries built over the past 50 years for different purposes, ranging from research, fire and material testing to training facilities, meeting and seminar rooms, a restaurants and large-span event spaces. The maximum number of allowable persons within the facility is currently around 500.

Safety is a global issue for all occupants and potential threats arising from labs or excavation cannot be allowed reducing the safety of visitors sitting in the restaurant or working in a meeting room. Potentially dangerous activities must be fully separated and contained by means of appropriate fire compartments.

The operation of the Test Gallery is based on a specific fire protection concept, approved by the competent Authority, which is adapted whenever relevant structural or operational modifications occur.
4. Fire safety regulations in Hong Kong

4.1. Code of Practice for Fire Safety in Buildings
In Hong Kong, the fire safety designs for buildings are governed by Code of Practice for Fire Safety in Buildings (FS Code) [13] issued by the Buildings Department (BD) and Code of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment (FSI Code) [14] issued by the Fire Services Department (FSD). BD and FSD are responsible for approving the fire safety designs for underground space development projects. Besides underground space developments underneath buildings, the other projects are mostly related to cavern developments beneath the hillside. According to the Building Ordinance (Cap. 123), cavern development falls under the classification of “Building”, thus the fire safety design shall follow the prescriptive requirements following these codes. Despite public cavern developments undertaken by Hong Kong government could be exempted from compliance of the Building Ordinance, the fire safety designs still follow the aforementioned codes under normal circumstances. Recent applications of the said codes to the latest cavern developments have identified many challenges. These Codes of Practice lay down the fire safety requirements and performance intents for typical buildings and are sometimes found to be not fully compatible with the specific characteristics and unique nature of cavern development in terms of fire resisting construction, means of escape, means of access and fire service installation etc.

Unlike building development on surface land, cavern development has different orientation and dimension due to its special nature e.g. developing mostly in horizontal manner instead of building up vertically. Therefore, different factors would need to be considered for fire safety management.

4.2. Cavern Guide 1994
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 1994) [15] was jointly established by the Building Authority and the FSD in 1994, by referring to overseas and local experience consolidated in the Study of the Potential Use of Underground Space (SPUN) in 1990. The Guide was issued more than 20 years ago to address the fire safety requirements of caverns solely used for public utilities such as sewage treatment works, refuse transfer stations and water reservoirs characterized by low population; users on site are mainly employees and are familiar with the underground caverns; fire load is generally localized, closely controlled and relatively low; and occupancy will not involve sleeping risk.
Furthermore, this Guide was developed mostly for low-populated facilities such as service reservoirs and sewage treatment plants, and it needs updates to align with the latest trend of cavern development covering other potential uses, such as industrial facilities. With wider application of cavern developments in project planning, facility classification defined with specific requirements rather than adopting one blanket specification should be introduced to suit different types of facilities e.g. warehouses and logistic centres where high fire load and high population are involved. It would also help to introduce less restrictive requirements for the low-risk type facilities such as service reservoirs and the like and to devise different requirements to suit other commercial and industrial developments.

4.3. Fire Safety Strategy in Underground Quarrying (UQ) Development

As cavern usages are now being diversified, it has been shown that strict compliance with the current two regulatory design codes could impose heavy provisions on fire safety design. Very often, a cavern would be treated as a basement under the “Building” classification of the FS Code 2011, taking precedence over the Cavern Guide 1994, rendering the fire safety design too conservative. One very recent cavern development project could demonstrate the challenges posed to the cavern designers.

Recently, the Civil Engineering and Development Department (CEDD) has commenced the “Technical Study on Underground Quarrying in Hong Kong – Investigation” (Technical Study) in 2017. One of the prime objectives of the Study is to ascertain the technical feasibility of housing the rock processing, concrete batching and asphalt production plants in caverns typical for underground quarry operation.

Figure 2: Fire safety designs in UQ caverns

In this project, the height of each cavern space (i.e. rock processing cavern, stockpiling cavern, concrete batching cavern, driveway and asphalt cavern) ranges from 12 m to 20 m. Due to the large cavern height, following the Cavern Guide 1994 by restricting the fire compartment size to be not more than 28,000 m³ would result in a substantial number of fire compartments, and such compartmentalization for the operating cavern space would seriously affect its functional performance. To this end, the entire cavern follows the fire compartment size limiting to 10,500 m² as required by the FS Code, including the driveway for which the fire compartment size is not restricted in Cavern Guide 1994.

Fire barriers with a fire resistance rating (FRR) of no less than -/120/120 (i.e. Stability fire resistance rating (in min)/Integrity fire resistance rating (in min)/Insulation fire resistance rating (in min)) are provided to separate the main driveways and the caverns in accordance to the FS Code. The caverns are also separated from each other by fire shutters also with similar FRR. On occasions, requirements on FRR could be more stringent than those for buildings on surface land, as cavern development is regarded as “basement” which would demand more stringent control.
Although the Cavern Guide 1994 requires that it is necessary to have suitably designed mechanical means to prevent the ingress and accumulation of smoke and does not explicitly require mechanical smoke extraction systems to be fully provided in all cavern spaces, again it follows the use classification of industrial basement according to FSI Code, and mechanical smoke extraction systems should be fully provided except for general plant rooms with a compartment volume less than 7,000 m³.

The main driveways will serve as a Place of Safe Passage before exiting to an open-air area, which fully satisfies the requirements as per Cavern Guide 1994. However, as the Cavern Guide 1994 is developed for very low-risk public utilities, the provision of pressurised protection corridors along the main driveways leading to the tunnel portals is required to further enhance the level of fire safety. In the absence of Emergency Vehicular Access (EVA) provided along the building façade, as required by FSI Code, which is normally achievable for buildings, the main driveways are also designed as EVA routes as a compensation measure so that the operating caverns can be reached directly by emergency vehicles.

5. Discussion and further works
Despite some national differences, the French, Swiss and Hong Kong regulatory contexts are quite similar. Existing regulations are mainly prescriptive, with a list of requirements that could constrain the development of underground space. These regulations are not compatible with deep underground space developments including various activities and users. However, a case-by-case approach and a performance-based approach with the use of fire safety engineering make some underground space projects possible. Nonetheless, these approaches have some drawbacks. They require detailed studies and complex analyses. The approval process can be long and challenging and often depends on the practice of local authorities, with an uncertain outcome. The requirements and objectives to be met are not always clearly defined.

The analysis of the French, Swiss and Hong Kong regulations underlines the need for a regulatory evolution regarding fire safety in underground space. The main objectives of fire safety design should be clearly and systematically defined at a national or regional level. These objectives should then be developed to set up the appropriate measures and criteria to be complied with in order to ensure an appropriate level of fire safety. The later could be ultimately justified either by following prescriptive measures or by carrying out a performance-based approach. A performance-based approach is the key to designing a fire safe underground space overcoming the limitations imposed by the current regulations.

The ACUUS working group is currently working on defining the main objectives of fire safety. Four principles have been drawn and should be further developed:

- **Limiting the occurrence and spread of fire;** this brings up the subject of continuous and efficient space management and the implementation of a fire safety management system. This includes the designation of someone in charge of the fire safety of the entire space, coordination of all owners and operators, designated uses and monitoring of space, maintenance of equipment, adoption of active and/or passive partitioning, use of advance construction materials, etc.

- **Evacuation of people;** a specific evacuation strategy should be devised to suit a complex underground space, with a clear definition of the perimeter to be evacuated, the design of emergency evacuation routes (maximal escape distances allowed, lighting, smoke control, etc.), the place(s) of safety to go to (which would not be necessarily outside), their design (fire resistance, emergency equipment, etc.) and the maximal time allowed for people to reach these places of safety.

- **Access and operation of emergency services;** the complexity of an underground space and difficulties of orienting oneself without a view of the outside emphasize the importance of training to be familiar with the space. The conditions of access for emergency services and the specific equipment to be installed on site should be described.

- **Protection of assets;** mainly translated by the structural fire resistance.
The ACUUS working group welcomes any members who would like to share their national experience in order to broaden the presented overview of international fire safety regulations and practices. This will help to refine and consolidate the objectives mentioned above. The next step will be to develop these objectives in detail taking into account the specificities of underground space and looking at all aspects of fire safety: operational organisation, space management, passive and active protection measures and structural concepts. Challenges in applying fire safety engineering approach to achieve these objectives will also be discussed.

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