An Unprecedented Land Supply Means in Hong Kong: Underground Quarrying-cum-Cavern Development

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ABSTRACT

Cavern development is a viable source of land supply, which can provide solution space for a broad variety of land uses and preserve the valuable ecology and green environment at the ground surface. While most of the caverns are purposely built to house various facilities, underground quarrying-cum-cavern development at suitable sites is a viable means of creating a valuable cavern land bank. With thoughtful planning and prudent site selection, the operation of an underground quarry associated with concrete batching and asphalt production operations can be a self-financing or even profitable business in the short to medium term, while the cavern space created can be utilized for other strategic uses in the long term. To take forward this initiative, the Civil Engineering and Development Department has completed a technical study to establish the technical feasibility and possible implementation arrangement of underground quarrying-cum-cavern development in Hong Kong. A prototype reference design based on the site setting of the Lam Tei Quarry has been produced, considering factors including technical, operational and logistic considerations. This paper presents the findings of the study, including the reference design and implementation model, and discusses the prospect of the underground quarry-cum-cavern development as a land supply means in Hong Kong.

Keywords: Underground Quarrying, Cavern Development, Sustainable and Green, Cavern Land Bank

1 Introduction

The hilly terrain with strong rocks in Hong Kong is highly suitable for developing rock caverns. Ho et al. (2020) provided a comprehensive overview of the prospect of cavern development in Hong Kong. Relocation of suitable existing facilities to rock caverns can release surface sites for other development uses and remove incompatible land uses by placing 'not in my backyard' ('NIMBY')-type facilities in caverns. Rock caverns can also provide space to accommodate suitable new facilities, thereby lessening the high demand for surface land in Hong Kong. These benefits, however, have not been actively reaped in the past.

To unleash the potential of cavern development, Civil Engineering and Development Department (CEDD) completed a strategic study for cavern development (Arup 2018) and implemented a suite of facilitating measures, including the promulgation of the Cavern Master Plan (CEDD 2017). The strategic study identified many successful examples of underground quarrying in other countries, such as the Schollberg Underground Quarry in Switzerland (Plate 1) (Chan et al. 2017). In addition, there are other cases where the caverns formed by underground quarrying were subsequently utilized for a wide range of uses, such as cold storage, warehousing and archive facilities in the USA (Pelizza and Peila 1995), and also data centres in Norway (Saunavaara et al. 2022). These examples indicated that the underground quarrying-cum-cavern development could be a viable and cost-effective means of providing sustainable cavern space. Given that land is a scarce resource in Hong Kong and there is a

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pressing need for increasing land supply to sustain the city's development, this development model is of high reference value to Hong Kong.

Plate 1: Schollberg Underground Quarry in Switzerland; (left) rock processing plant; (right) underground quarry excavation

Despite the conceivable potential of cavern land supply by underground quarrying-cum-cavern development, this development model is unprecedented in Hong Kong. With this in mind, the CEDD has carried out a study to establish the technical feasibility and possible implementation arrangement of underground quarrying-cum-cavern development in Hong Kong. This paper aims to provide an overview of the prospect and technical issues of underground quarrying-cum-cavern development, focusing on a prototype reference design based on the site setting of the Lam Tei Quarry.

2 Benefits of Underground Quarrying

2.1 Green and Sustainable Cavern Land Bank

The main benefit of underground quarrying is the green and sustainable supply of cavern land bank. Hong Kong has a long history of quarrying, which supports the local construction industry through the production of aggregates and, at the same time, provides valuable surface land for development uses in the long term. With less environmental disturbance, the underground quarrying could be operated deep underground while preserving the valuable ecology and green environment at the ground surface. In addition, the caverns formed by underground quarrying can accommodate a wide range of uses in the long term, thereby realizing the full potential of the underground resource in different periods of time. The most prominent example is the underground quarry in SubTropolis, USA. The underground quarrying created over 5,000,000 sqm of cavern space involving a wide range of business and industrial activities, such as warehousing, light manufacturing, office and retail, run by more than 55 companies and over 2,000 employees (Plate 2).

Plate 2: Underground quarry turned into a business and industrial complex in SubTropolis, USA

2.2 Housing Rock Processing, Concrete Batching and Asphalt Production Plants in Caverns

The land shortfall in Hong Kong has led to intense competition for land between the construction industry and other different sectors of industry. As construction-related activities involving rock processing, concrete batching and asphalt production could potentially cause adverse environmental nuisances such as dust and noise, it is challenging to locate suitable sites for these operations because of the potential environmental and visual impacts to the nearby sensitive receivers.

As the underground quarrying would typically be bundled with rock processing, concrete batching, and asphalt production, it can provide stable sites for these activities. In addition, there are several successful overseas examples of accommodating construction-related facilities inside caverns, such as the rock processing plants at Stendafjellet Rock Quarry and Ytre Arna Quarry, and also concrete batching plants at Hagerbach Test Facility (Plate 3) (Sum et al. 2018). These ancillary operations can be operated at the surface portal at the initial phase of the underground quarrying and then move into the caverns created by quarrying excavation at the later phase or even after the quarrying operation. As the quarrying period is normally 10-20 years, this creates an opportunity to provide long-term and stable sites for rock processing, concrete batching and asphalt production while reducing the environmental nuisance to the nearby sensitive receivers.

Plate 3: Underground concrete batching plant at the Hagerbach Test Facility in Switzerland

2.3 Supplement to Local Rock Production

Another add-on benefit is the potential to supplement the local rock production. Before the 1980s, the demand for rock materials by the Hong Kong construction industry was entirely met by local quarries. Since then, with the progressive closure of local quarries and the increasing demand for rock materials to meet development needs, the main source of rock material has been imported from Mainland China. Therefore, underground quarrying in Hong Kong can supplement the surface quarrying by supplying various rock products (Plate 4).

Plate 4: Example of rock products: marine works, railway ballast, concrete, asphalt

3 Site Selection Considerations

In a congested city like Hong Kong, the selection of a suitable site for underground quarrying is a challenging task. Therefore, the site selection process should carefully balance the below considerations.

3.1 Geotechnical Considerations

Sites with sizable rock reserves and good rock mass quality would be considered favourable for underground quarrying. This would generally apply to large volcanic or intrusive igneous bodies that have not been affected by faulting or dyke intrusion, and therefore less or even no rock reinforcement and grouting is required for cavern stability and groundwater ingress. Other geotechnical works unrelated to quarry production, i.e., site formation, natural terrain hazard mitigation and soft ground tunnelling, should also be kept minimal. Therefore, sites with available surface land immediately adjacent to the existing rock face would be highly preferable.

The suitability of the rock to be used as aggregate is also an important consideration. The sedimentary rocks in Hong Kong have been screened out primarily due to their lower rock strength and, thus, only intrusive or volcanic rocks should be considered further. Recognizing that there are measures that can be undertaken to counteract the impact of Alkali-Silica Reaction (ASR), the presence of rock that is potentially reactive has not been adopted as a fundamental criterion to rule out the feasibility of a site, although it is not as favourable as those sites with non-reactive rocks.

As the underground quarry and access tunnels would be excavated by the drill and blast method, lower explosive quantities per blast hole may be required if there are sensitive receivers within the blasting influence zone. This would result in a less efficient quarry operation and would therefore be considered less favourable.

3.2 Quarry Operational Requirements

At the commencement of the quarrying operation, rock processing plants, concrete batching plants and asphalt production plants have to be established on surface land in combination with offices and other ancillary facilities, which will enable the revenue earning facilities to be operational earlier. If there is sufficient surface area that can accommodate these associated facilities, the initial capital investment and overall operational costs can be reduced. Nevertheless, given the difficulty of finding an existing available surface land, an operational plant comprising rock crushing, concrete batching and asphalt production could be set up on a site as small as 2ha to 3ha. This could be considered as the minimum desirable surface land area.

3.3 Environmental Considerations

Although the quarrying operation deep underground should generally result in minimal environmental impact, there are inevitability some residual impacts to the surroundings due to the operation at the surface portal site. These impacts include air, noise, water, waste, ecology, land contamination, fishery, cultural heritage, landscape and visual impact. Therefore, the portals of the underground quarry should avoid being located close to the environmentally sensitive areas.

3.4 Planning and Land use Compatibility

The planning compatibility between the underground quarrying-cum-cavern development and the surrounding area has to be taken into account. While the after-use of the caverns created by quarrying could be finalized toward the end of the underground quarrying period, the conceptual after-use of the caverns should be preliminarily formulated with flexibility reserved for various other uses. The long-term use of the created cavern space is considered one of the benefits to the local community in terms of providing land for relocating some existing NIMBY-type facilities into caverns and thereby releasing land for other community welcome facilities. Careful selection of the underground quarry site and planning of the long-term use are required to foster public support for smooth implementation and operation of the quarry site. This would include sites that are remote from residential areas and sites with existing NIMBY-type facilities nearby that are suitable for relocation into the underground space formed by the quarrying operation.

3.5 Traffic Conditions

The underground quarry development will generate road traffic due to the transportation of raw materials to the site (e.g., imported rock, cement and bitumen) and the delivery of manufactured products to other construction sites (e.g., aggregates, concrete and asphalt). The transport route to and from the quarry should not affect roads that suffer from high peak traffic flow, which may restrict the allowable transportation hours of quarry products. Sites with good connectivity to road networks or waterfront with suitable barging facilities would be considered favourable.

4 Reference Design at Lam Tei Quarry

4.1 Site Selection for Reference Design

As underground quarrying is unprecedented in Hong Kong, a prototype reference design was produced for the purpose of investigating the operation parameters and establishing the technical feasibility of underground quarrying. The reference design was carried out based on the actual site setting of the Lam Tei Quarry (Figure 1), which has been operated for many years as a surface quarry and has proven to be suitable for quarrying operation. This site possesses a number of essential features for underground quarrying: sufficient surface area for ancillary operation, availability of sizable rock face and rock reserve; good rock quality suitable for concrete production; direct connection to existing road network; known local demand for rock products and the limited population at the surrounding area. This reference design can serve as a model that can generally be applicable to other similar underground quarry sites as identified in the territory.

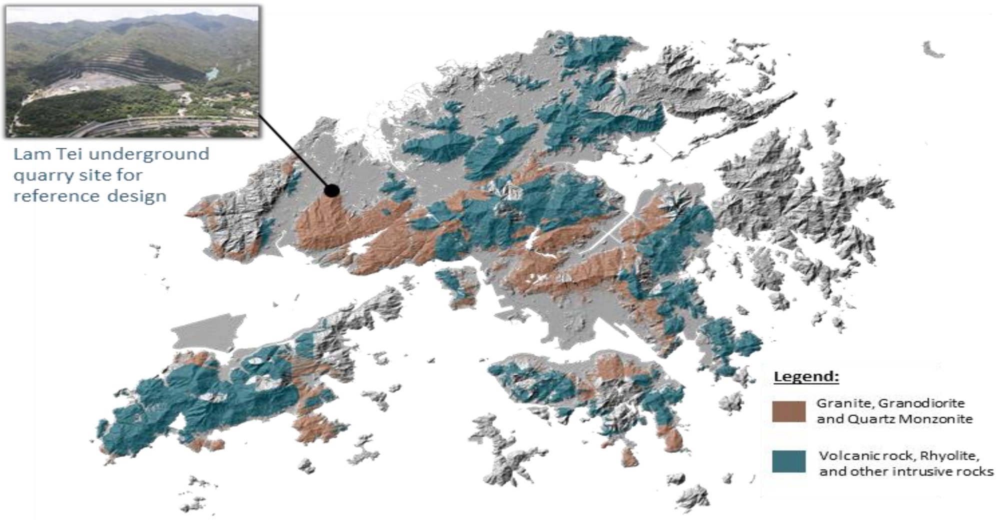

Figure 1: Selected site for reference design

4.2 Design Considerations

4.2.1 Operational and Logistical Arrangement

To facilitate a streamlined production with high efficiency, upstream procedures should be located near the rock reserve, while downstream procedures should be located close to the public road network. The portals of the underground quarry should be directly connected to the surface works area. The operation cost of an underground quarry should be optimized by providing a logistics-friendly overall layout,

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minimizing the reinforcement needed for underground excavation, using aggregates from its own production, minimizing the provision of the groundwater drainage system and avoiding excessive provisions for fire safety and ventilation systems.

4.2.2 The Layout of Underground Quarry

Bord and pillar quarrying layout is proposed for the underground quarry. The main access tunnel surrounds the perimeter of the underground quarry and connects to two portals. The production caverns of various lengths are located further away from the portals. Adjacent production caverns are linked with connection adits at typically 50m spacing. All production caverns can be accessed at both ends via a sub-perpendicular main access tunnel. The formation level of the portals should match the level of the surface works area. A 1 in 100 longitudinal fall is assigned towards the portals to allow for the gravity drainage of groundwater seepage.

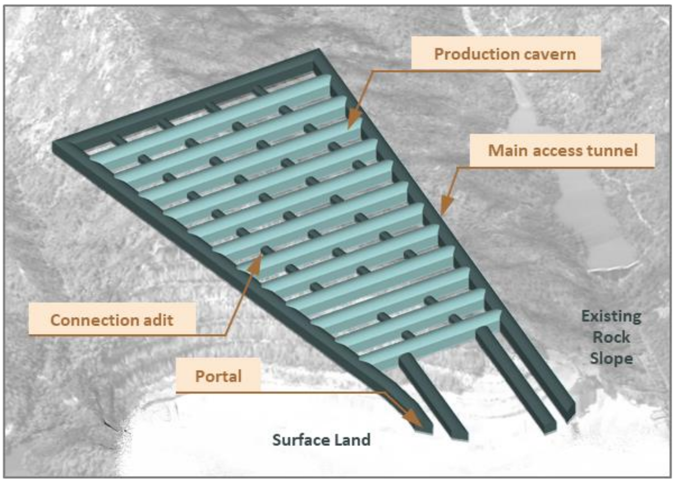

Figure 2: Layout of underground quarry

4.2.3 Spatial Requirements

The dimensions of the underground space created by the underground quarrying should take account of the potential types of after-use of the caverns to minimize any further modification works required. The dimensions of the main caverns were designed to be 20m (W) and 20m (H). Considering the space required for the installation of ventilation systems, utilities, fire safety provisions, structural slab and ceilings for the after use, the clear headroom of the caverns would be 10m to 15m, subject to the detailed design of the cavern usage. With the flexibility of further division into compartments, this size is generally sufficient for the operation of various potential after-uses such as logistics warehouses and data centres.

4.2.4 Geotechnical Stability

The preliminary design of the rock pillars and cavern reinforcement is according to the Geoguide 4 (2nd Edition) (GEO 2018). The orientation of production caverns is chosen to minimize any instability due to rock joints and rock stress. The rock pillar width is conservatively assumed to be equal to the cavern span (i.e. 20m), which can be further optimized when there is more available information about the rock mass properties. The roof and wall reinforcement should be generally derived from NGI Q-system (NGI 2015) and verified by design analysis. The support classes should be designed based upon the estimated Q-values and eventually assessed on-site based on face mapping. With a balanced excavation size and careful site selection for competent rock mass, the caverns should be formed with only minimal or without reinforcement elements in general.

4.3 Housing Ancillary Facilities in Caverns

While the ancillary facilities can be operated on the surface land at the portal of the underground quarry, a variation of this typical reference design was also developed to examine the details of housing rock processing, concrete batching and asphalt production plants inside the formed caverns. Such configuration is a very effective use of cavern land resources and is suitable for later stages or even after the quarrying operation. The three production caverns formed near the portal can be used for rock processing, stockpiling and concrete batching. The asphalt production plant should be placed in a separate cavern to cater for the operational need of asphalt production. The dimensions and functions of different types of caverns, tunnels and adits are summarized in Table 1.

Table 1: Summary of Caverns, Tunnels and Adits

Types of Caverns, Tunnels and Adits	Span (m)	Height (m)	Functions
Main access tunnel	16	20	Primary access and evacuation route of the entire underground quarry
Production caverns	20	20	Where main rock extraction takes place; the main venue for after-use development
Connection adits	9	9	Evacuation route from production caverns
Concrete batching plant access tunnels	16	16	Separate access to the concrete batching plant
Rock processing cavern	20	20	Placement of the rock processing facilities
Stockpiling cavern	20	20	Stockpiling area
Concrete batching cavern	20	20	Placement of concrete batching plant
Asphalt production cavern	12	12 and 20	Placement of asphalt production plant

4.3.1 Rock Processing and Stockpiling

The rock processing equipment for the concrete batching can be housed in a production cavern with a size of 20m (W) x 20m (H). The stockpiling cavern is positioned next to the rock processing cavern and set up for the temporary storage of crushed rock and aggregates produced from the rock crushers before they are sent to the concrete batching plant. The crushed rock/aggregates products are transferred from the rock processing cavern to the stockpile cavern via conveyor belts through the connection adits.

4.3.2 Concrete Batching

The concrete batching plant can also be housed in the completed production cavern near the portals and next to the stockpiling cavern. Aggregates should be delivered to the concrete batching plant by conveyor belts and stored in different aggregate bins. Water should be supplied by pipeline and pumped to water tanks inside the cavern. Cement should be transported by trucks and transferred to the cement storage silos by pipeline. Each of the raw materials would be fed through weight hoppers to the concrete mixer for concrete mixing. An ice plant would be available for ice production if necessary. Such a layout arrangement aims to minimize vehicular traffic inside the caverns.

Considering there will be a relatively high traffic flow generated from the operation of the underground concrete batching plant, separate vehicular access tunnels should be provided. Two access tunnels independent from the quarry operation can form a one-way designated circulation of concrete truck traffic to and from the underground concrete batching plant. They connect the concrete batching cavern to the portals for the delivery of concrete produced. In addition, comprehensive dust control measures, such as materials delivery and storage by enclosed conveyor belts and tankers, together with an effective ventilation system, should be designed to mitigate the potential environmental and; occupational health and safety problems.

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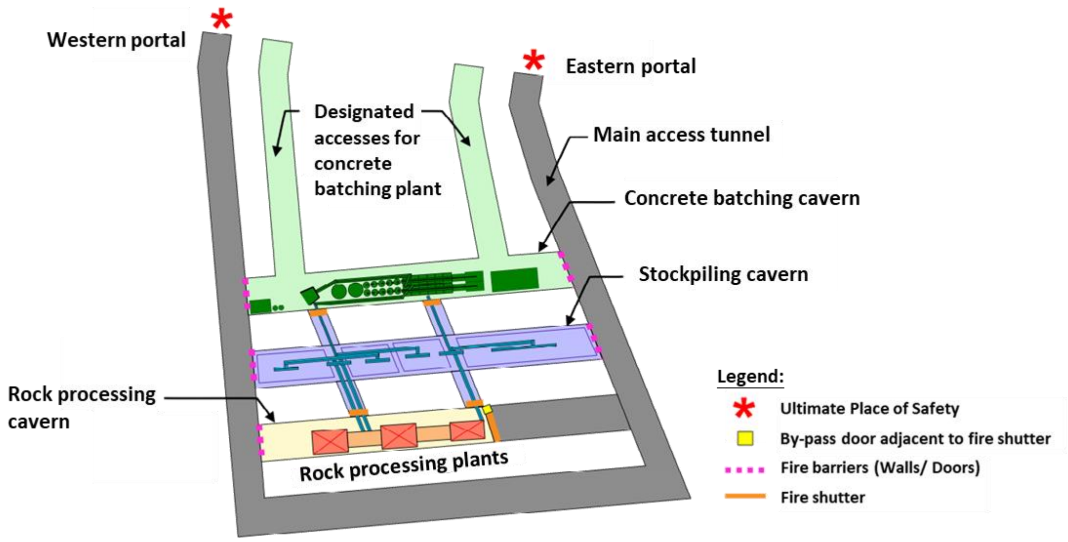

Figure 3: Layout of housing rock processing and concrete batching plant in caverns

4.3.3 Asphalt Production

For the asphalt production plant, it is placed in a separate cavern with a limited length from the portal (< 30m) to allow for good ventilation, which is required to mitigate the heat generated from bitumen processing and the potential hazards due to the fume emission during the production process. Bitumen is stored in heated tanks while awaiting delivery to the drum. When the hot asphalt mix is required, bitumen should be delivered to the asphalt drum by pipeline for mixing with the aggregate, which is first heated in the dryer drum. The output of hot mix asphalt is discharged to the storage silos for final loading onto trucks. During the production of the asphalt mix, a baghouse should be provided to remove fine particulate matter from the dryer exhaust gases, and additional silos should also be provided for storing mineral filler or special additives that are added to the hot mix.

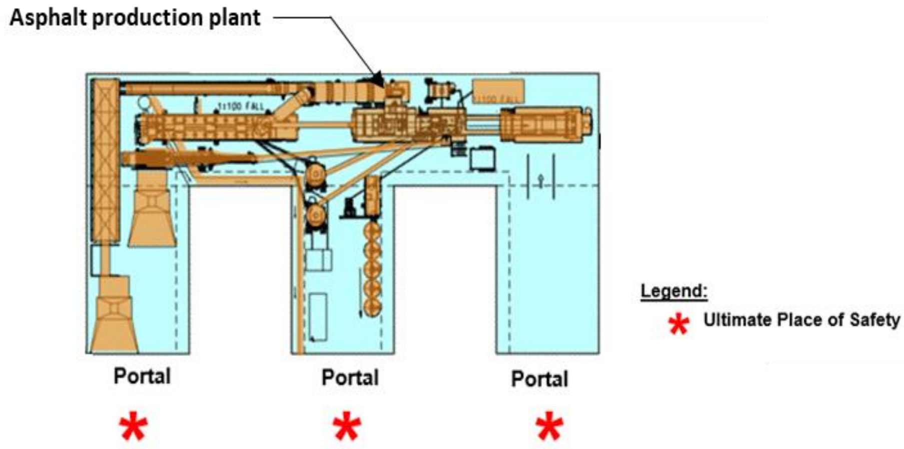

Figure 4: Layout of housing asphalt production plant in cavern

4.4 Fire Engineering

A comprehensive fire safety design has been devised with reference to the Guide to Fire Safety Design for Caverns 1994 and the fire engineering approach to suit the special nature and functional requirements of the caverns. Computational fluid dynamics have been conducted to verify the key performance of the design. The key features of the fire safety strategy for fire resisting construction, means of escape/access, smoke control strategy and fire service installations (FSI) for the proposed caverns housing the rock processing plant, concrete batching plant and asphalt production plant are summarized as follow:

4.4.1 Fire Resisting Construction

Each of the rock processing caverns, stockpiling cavern and concrete batching cavern should form a single compartment with a compartment area limited to 10,500m^2. All elements of construction should have a fire resistance rating (FRR) of 240/240/240. Fire barriers and fire shutters should have FRR not less than -/120/120.

4.4.2 Means of Escape/Access

In case of fire in one of the main caverns, occupants should be evacuated to the Place of Safe Passage (i.e. main access tunnel) and proceed to the Ultimate Place of Safety (Figure 3). The travel distance to the Place of Safe Passage is limited to 72m. In case of fire at the main access tunnel, occupants will evacuate from the incident smoke zone to the non-incident zone within 72m and further proceed to the Ultimate Place of Safety. The main access tunnel is designed as Emergency Vehicular Access (EVA) route so that the areas within the caverns can be reached directly by the emergency vehicles. A clear space of 7.3m (W) x 4.5m (H) should be designed along with the EVA, which allows passage of the emergency vehicles.

4.4.3 Smoke Control and Fire Service Installations

A smoke control system should be provided to the main access tunnel, concrete batching, and rock processing/stockpiling caverns in order to limit the smoke spread and help to maintain a tenable environment for evacuation and firefighter's access. A linear heat detection system, water spray system, and other FSI should be provided at designated locations to detect and control the fire.

4.4.4 Fire Safety Management Plan

A comprehensive fire safety management plan has been developed to mitigate the inherent fire risk associated with the nature of the underground quarry (e.g., checking of vehicle engine temperature before entering the caverns, a limited number of workers inside the caverns, proper fire safety training to the workers, etc.)

4.5 Quarrying Method and Sequence

4.5.1 Quarrying Method

Similar to traditional surface quarrying, drill and blast is the most productive and cost-effective excavation method for hard rock. Before the blasting, probing and grouting would be carried out if necessary. The blasting operation starts with marking up the blast pattern on the tunnel face and reviewing the rock characteristics. Then the blast holes should be drilled in accordance with the blast design in terms of hole depths and locations. Explosives would then be delivered to the site, and the blast holes would be charged and connected up. Following the blast, the shotfirer would check to confirm that there have been no misfire and site activities around the blast area can recommence in a safe condition. The excavated rock can be mucked out by truck loaders and backhoes.

Due to the considerable height of the tunnels and caverns to be excavated, a heading and bench sequence of excavation is necessary for the underground quarry. Top heading excavation should commence first at the upper half of the caverns, followed by lower bench excavation. The cross-section of excavation with top-heading and bench is shown in Figure 5.

After every round of excavation, geological mapping of the exposed rock face is conducted by geologists to assess the rock quality around the excavation. Reinforcement elements in the form of sprayed concrete and rock dowels are installed if necessary, corresponding with the rock quality. The next excavation cycle follows when all reinforcement elements to the excavation are installed as required.

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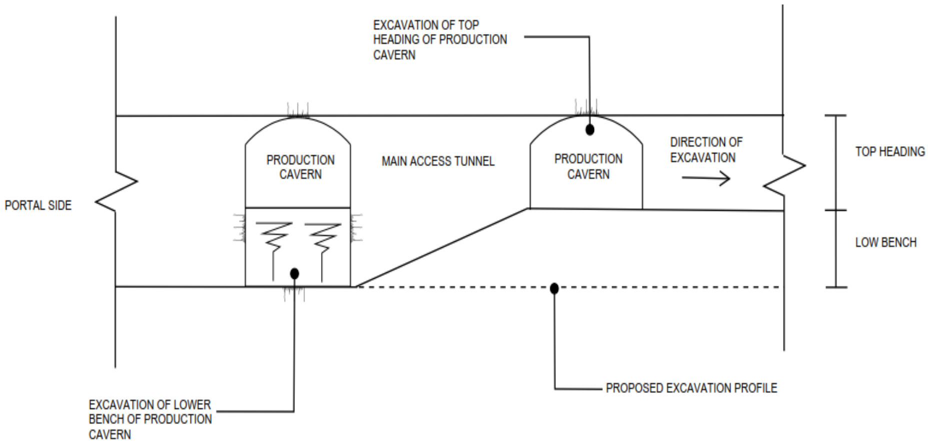

Figure 5: Excavation sequence of top heading and lower bench

4.5.2 Quarrying Sequence

Before any production from rock excavation, the initial set-up phase would take typically one to two years, including the period required for procurement, delivery, installation and license application for plants. The top heading of the main access tunnel is excavated first to provide utilities and services. Then the excavation of the top heading proceeds to caverns from the near end to the far end of the portal. The excavation of the low bench of access tunnel and caverns follows the top heading excavation at a distance. An inclined floor to the low bench will be provided at the transition of top heading and lower bench excavation for access. This sequence offers fast access and fast delivery of excavated rock. Each quarrying area shall be further divided into portions for excavation to limit the active working area within the quarry. Excavation portion by portion can prevent recirculation of air and maintain the required airflow along the main access tunnel during the excavation stage of the quarry. There should be two to three excavation faces at each time within an active working area. A typical excavation rate is estimated to be about 5 blasts per week with an average production rate of 500m^3 to 600m^3 per blast based on the site setting of Lam Tei Quarry.

5 Possible Implementation Model

Based on the operation parameters of the reference design, a possible implementation model is broadly examined. The underground quarrying-cum-cavern development can be implemented in 2 stages: (1) underground quarrying by an operator; and (2) long-term use of cavern space by end-users.

5.1 Underground Quarrying Stage

The first quarrying stage can be operated by a revenue-earning quarrying contract, which should be sufficiently long to provide a stable site for operation. The underground quarrying should be bundled with the revenue-earning business of rock processing, concrete batching and asphalt production, as well as recycling of imported rock. The establishment of ancillary operations on surface land (Figure 6) at the beginning can enhance the business model of the underground quarry by starting up these revenue-earning facilities to be operational as early as possible. With a compact site set up, a surface area of about 2ha to 3ha at the portal location is considered necessary for setting up facilities, including ancillary operations to support the underground quarrying operations. The reference design also demonstrated that these ancillary operations could be moved into the caverns at the later stage of the underground quarry period.

Rock reinforcement costs will be kept to a very nominal level by carefully sizing the excavations and prudent site selection. For the operation cost, the quarry layout should be designed to allow for multiple and flexible work fronts to optimize the blasting operation and the utilization of plants and equipment. During the quarrying stage, the quarry operators should also be allowed to use the cavern space for other revenue-earning activities to optimize the use of the space formed in the interim term, provided that the regulations and contractual obligations of the underground quarry are not be compromised. The operation of an underground quarry associated with concrete catching and asphalt production can be a self-financing or even profitable business.

Figure 6: Typical ancillary facilities at surface portal site for underground quarrying

5.2 Long-Term Use of Cavern Space By End-Users

After the completion of the quarrying stage, the cavern space should be handed over to the government for construction of public facilities or disposed of/leased to the private sector for private development, depending on the nature of the future land uses of the cavern space. As the major excavation works would already be completed in the quarrying phase, the underground quarrying-cum-cavern development is a very cost-effective means for cavern land supply for various uses. According to many overseas experiences, the uses of underground spaces are often an afterthought development after the formation of underground spaces. A recent example includes the Lefdal Mine Data Centre in Norway (Saunavaara et al. 2022), which was converted from an abandoned olivine mine. Conversion works on the site started in mid-2015 and the data centre was officially opened in May 2017. The layout and dimensions of the caverns can be developed based on a conceptual after-use, with flexibility reserved for various other uses to minimize any modification works of cavern development required in the future.

6 Conclusion

This paper presents the concept of underground quarrying-cum-cavern development. This development mode can supplement the local rock products supply, accommodate various construction-related activities in the interim term and provide green and sustainable cavern space in the long term. The site selection for underground quarrying should carefully balance the considerations of geotechnical, operational, environmental, traffic, planning and land use compatibility. The prototype design presented in this paper established the technical feasibility of this unprecedented land supply means in Hong Kong. A viable implementation model based on the referenced design is also devised for future reference.

With proper planning and design, the underground quarrying-cum-cavern development could be a self-financing or even profitable business in the short to medium term, while the created cavern space can be utilized for a wide range of strategic use in the long term, thereby realizing the full potential of the underground resource to support the development of Hong Kong.

7 Declarations

7.1 Acknowledgements

This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development Department of the Government of the Hong Kong Special Administrative Region. More information on the cavern development mentioned in this paper can be found on the website (www.cavern.gov.hk).

7.2 Publisher's Note

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