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Design and construction of shaft for rock caverns in Singapore

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Abstract. Access shaft is of critical importance to the construction and operation of underground rock caverns. It usually has a relatively large cross-section and penetrates through fill materials, soil layers, and weathered rocks before reaching the caverns excavated in solid bedrock. In this paper, the design and construction of vertical shafts are reviewed in terms of diameter, depth, geological conditions, and support structure. Three shaft alternatives, namely alternative I: vertical shaft with spiral roads, alternative II: upper shaft with spiral roads & lower tunnels, alternative III: plain shaft, are proposed based on a simplified geological profile of the Jurong formation, Singapore. The advantages and limitations of the three types of shafts are discussed. The key issues relating to shaft design and construction, such as the shaft sinking, water control, support structure, are also discussed with a series of solutions provided, such as the sequential excavation, pre-grouting and diaphragm walls.

Keywords: shaft; rock cavern; sinking; water control; support structure

1. Introduction

The demand for more space, especially in urban areas, is a world-wide challenge. Due to the fast growing population as well as the acceleration of immigrants from rural areas to urban areas, there is a need to create more spaces. In addition to the traditional solutions of land reclamation and high-rise buildings, the development of underground space has been recognized as an alternative. Singapore has a land area just over 700 km^2, the population increases rapidly from 4 million in 2000 to 5.4 million in 2013. As there are limits for taller buildings and reclaiming more land from the ocean, Singapore now sees underground space development as a key strategy for long-term sustainable urban development.

The first step in underground space development is to build a connection between aboveground structures and underground spaces. In mountainous area, the conventional horizontal or inclined tunnel can be used for access purposes. However, mega city like Singapore where the flat terrain is common, vertical shaft has to be considered as one of the major construction

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methods for accessing deep underground. The shafts will be used in construction, installation and operation phases.

Shaft facilitates construction and operation of underground space, and shall meet the demand of large amount of mucking transportation and different requirements for various underground space developments. The access shafts have the following unique characteristics and should be given special design considerations:

(1) The shaft usually has a relatively large cross-section.
(2) The shaft will penetrate through fill materials, soil layers, and weathered rocks before reaching the solid bedrock where underground rock caverns are usually excavated.
(3) A dry shaft is necessary to provide a safe, comfortable and cost-effective construction and operation environment.

The most important function for the access shaft is transportation (mucking, transportation of cargo, equipment and person etc.). Other functions such as ventilation, evacuation, placement of pipelines, etc., can be provided by access shaft or other small functional shafts. Table 1 summarizes the main required functions of shafts for several general types of underground facilities. For underground storage, ventilation and large volume of mucking are inevitable during excavation. The stored items (oil, gas, water, etc.) during operation can be transported through the installed pipelines. For developing warehouse facilities and underground city (i.e., for work and living), all the functions listed in Table 1 are necessary for safe construction and operation. As for the underground landfill, except for ventilation and mucking during underground excavation, it is generally seldom needed to get access to the underground space during operation and so as to the transportation.

Table 1 Required function of shaft for underground space construction and operation

Shaft function		General type of underground space			
		Underground oil storage	Warehouse facility	Underground city	Underground landfill
Construction	Ventilation	√	√	√	√
	Mucking	√	√	√	√
Operation	Person transportation	*	√	√	*
	Vehicle transportation	*	√	√	√
	Cargo transportation	-	√	√	-
	Ventilation	*	√	√	*
	Placement of pipelines	√	√	√	√
	Evacuation	*	√	√	*

Note: *indicates the function is needed in special conditions, e.g., person transportation of workers/firefighters for repairing/firefighting of underground storage; vehicle transportation of firefighting equipment for underground storage; trucks for the dispose in underground landfill

The size and layout of shafts in many cases are determined by the requirements for ventilation and mucking during construction and the transportation during operation. Ventilation and evacuation during operation are also critical if people are expected to stay in the underground cavern, e.g., the underground city and warehouse facility.

The rest of this paper is organized as follows. First, the vertical shafts constructed worldwide are briefly reviewed. Then three shaft design alternatives are proposed for underground cavern development. The main challenges on shaft construction in terms of shaft sinking, water control, structural support are discussed in the final part. A conclusion section is provided at the end of the paper.

2. Review of vertical shafts worldwide

As the development of large scale underground cavern is at the early stage, some researches relating cavern group have been implemented (Jiang *et al*. 2014, Zhang and Goh 2014, 2015, Zhang *et al*. 2012). But very few publications regarding the design and construction of main shafts can be found. Some large shafts are found in tunneling, sewage treatment, reservoir and hydropower projects (Vincenza *et al*. 2012). It would be beneficial to review these kinds of shafts for reference. Table 2 lists some of the typical shafts constructed worldwide.

Table 2 Vertical shafts constructed worldwide (DW is short for diaphragm wall)

Project's name	Diameter /(m)	Depth (m)	Geological conditions	Support structure
Access Shaft 3 of Jurong Rock Cavern, Singapore (Goldschneider *et al*. 2012)	18~24.5	132	Soil and rock	1.0 m thick DW to 27 m + cast in-situ linings or shotcrete walls with rock bolts
Punta Carrasco Shaft, Buenos Aires, Argentina (Vincenza *et al*. 2012)	40	34.5	Soil	DW to 55 m
Soacha Shaft, Bogotá, Colombia (Vincenza *et al*. 2012)	65 (68)	55	Highly fractured rock	DW
Surge Shaft, San Roque Project, Philippines (Funkhouser *et al*. 2004)	20 (23)	100	45 m of the poorly cemented conglomerate +55 m metavolcanics	concrete rings
Zeebrugge gas terminal - Construction of a circular shaft to take a gas reservoir, Belgium	90.5	28	Soil	1.2 m thick DW to 39.5 m
Sewage Treatment Plant of the Jumeirah palm Island, Dubai, United Arab Emirates (UAE) (Ryjevski 2008)	76	17	Soil	0.9 m thick DW to 25 m
Two pump shafts of influent pumping station (IPS) at Bandra, Mumbai, India (Antonio and Adams 2001)	37	46.5	Basalt and tuff breccia	Through-going grouted bolts

In the Harbor Area Treatment Scheme (HATS) in Hong Kong, 17 shafts were built in Stage 1 to construct the tunnels and to transfer the sewage from the coastal treatment works to Stonecutters Island Sewage Treatment Works. The diameter of these shafts varies from 2.5 m to 50 m and they reach down to a maximum depth of over 150 m. Table 2 includes two shafts in the HATS Stage 1 project, one is the production and drop shaft at Kwun Tong Pumping Station, and the other is the main pumping station shaft at the Stonecutters Island Sewage Treatment Works. Both two shafts are located in reclaimed land and in close proximity to the sea. The upper shafts in soils and weak rocks were constructed by diaphragm walling method and the lower shafts in rock were excavated by mainly drill and blast. The upper shafts and permanent shaft linings were designed using conventional methods and the primary support selection for the lower shaft was based on the 'Q' system developed by Norwegian Geotechnical Institute (NGI). Settlement monitoring and inclinometer measurements were undertaken during excavation to confirm the design assumptions (Pakianathan *et al*. 2004).

In the Stage 2A, the upgrading of Stonecutters Island Sewage Treatment Works is the construction of a new main pumping station (Fig. 1). The station is circular in shape, with a diameter of 55 m and reaching 40 m deep. The new main pumping station involves the construction of a 1.5 m thick diaphragm wall to act as the underground basement wall. Advanced construction machinery known as 'Hydromill' was deployed for the efficient and accurate excavation of 60 m deep diaphragm wall.

In Singapore, the Deep Tunnel Sewage System (DTSS) contains the design of the Influent Pumping Station (IPS) (Fig. 2), which consists of a wet well shaft providing coarse screening and distribution (Coarse Screen Shaft – CSS) (No. 4 in Table 2) through interconnecting tunnels to two lift stations (Influent Pumping Shafts – IPS1 & 2) (No. 5 in Table 2) which raise the raw sewage over 60 m so that it can pass through the Changi Water Reclamation Plant (CWRP) Liquids treatment facilities under gravity. The CSS has an internal diameter of 30 m and an excavation depth of 65 m, while the pump shafts are 37 m internal diameter with an excavation depth of 69 m. The performance of the circular diaphragm walls was monitored with a number of diaphragm wall panels with inclinometers and vibrating wire (VW) strain gauges. The performance monitoring of the diaphragm walls allowed the excavation of IPS shafts in 8 stages rather than originally planned 10 stages, reducing the critical construction time by approximately 2 months for each shaft. It also

Fig. 1 Photo of main pumping station shafts of HATS project
http://www.water-technology.net/projects/harbour-area-treatment-scheme-hong-kong/

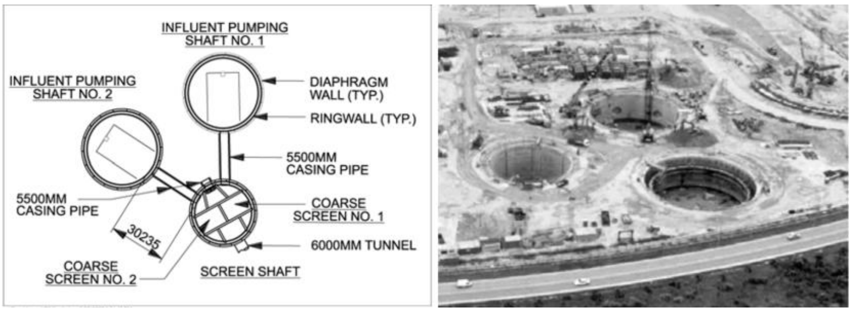

Fig. 2 Aerial view of IPS shafts, Singapore (Parashar *et al*. 2007)

Fig. 3 Photo of access shafts AS1

minimized a number of underpinning joints between successive stages of inner ring walls resulting in additional time and cost savings (Parashar *et al*. 2007).

Two access shafts AS1 (Fig. 3) and AS2 (No. 6 and No. 7 in Table 2) were built for the Jurong Rock Cavern, Singapore (Goldschneider *et al*. 2012). Before the excavation of the upper shafts in soil layer, 1 m thick diaphragm walls with cast in-situ ring beams at 4 m to 6 m intervals were used as the retaining system. The lower shafts were constructed in the highly weathered to fresh Jurong formation rocks. The cast in-situ linings or shotcrete walls with rock bolts were used to support the excavation after 1 to 2 m lifts.

The remaining shafts listed in Table 2 (No. 8 ~ No. 13) are not introduced in details and readers can refer the table for the diameter, depth, geological conditions, and support structure.

In addition to the typical circular cross section, the shafts can be designed in other shapes, such as rectangular, elliptical and multi-cell to fit for special conditions (Virollet *et al*. 2006).

Through reviewing typical vertical shafts, especially some large size shafts, some conclusions can be made as follows.

(1) Circular shaft is the most widely used shape.
(2) Diaphragm wall is widely used for the upper part of shaft in soil layers for water control and support.

(3) Diaphragm wall can also be used in rock layer by using the Hydromill-excavation method (case No. 3 in Table 2).
(4) Rock bolts or grouted rock bolts are widely used in the support of rock section of the shafts.
(5) Concrete liner (cast-in-place) or shotcrete walls or concrete rings (precast) are often employed as permanent structure in addition to diaphragm wall or rock bolts if needed.
(6) Optimization of excavation stages can be made by monitoring to ensure safety.

3. Three access shaft alternatives for rock cavern development

The proper design of access shaft can highly increase the efficiency and safety for the underground cavern construction, installation and operation. As shown in Table 1, the mucking and ventilation are the two main functions during the construction stage of underground facility. The efficiency and reliability are directly related to the construction time and consequently the cost. The transportation of person, vehicle and cargo, ventilation, evacuation as well as the placement of pipelines are the main functions during the operation stage. The proper design of access shaft will enhance the operation efficiency and safety of underground facility.

In this section, three access shaft design alternatives are proposed based on the simplified geological profile (Fig. 4) of the Jurong formation, Singapore. This formation has great potential for rock cavern developments. The Jurong Rock Cavern (phase 1) for oil storage has been built in the formation and two underground facilities are under planning - Warehousing and Logistics Facility at Tanjong Kling & Jurong Hill and Underground Science City at Kent Ridge.

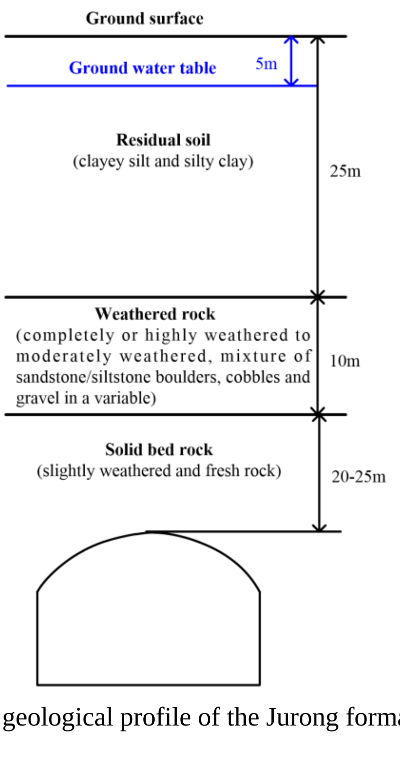

Fig. 4 Simplified geological profile of the Jurong formation, Singapore

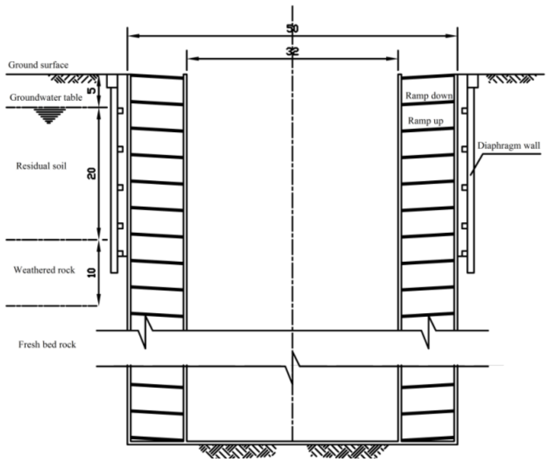

Fig. 5 Profile of the alternative I (Length unit: m)

Circular shape is chosen for all three alternatives as such cross section provides good geometry for airflow and good soil/rock stability characteristics. Diaphragm wall is used in soil layers and rock bolts and shotcrete are used as the rock support in the rock section. Concrete liner (cast-in-place) or shotcrete walls or concrete rings (precast) is used as permanent structure in addition to diaphragm wall or rock bolts.

3.1 Alternative I: Vertical shaft with spiral roads

In the alternative I, spiral roads (single one-way spiral road or double one-way spiral roads) are used for transportation in both construction and operation phases (Fig. 5). The central area of the shaft can be used as sunken garden, storage or other uses with one or more lifts installed for staff and passengers. If single two-way spiral roads or double two-way spiral roads are considered, the dimension of the shaft and vehicle speed of the spiral roads need to be evaluated.

For the shaft with the spiral road inside, the dimension of the shaft has to be sufficiently large, to ensure the turning radius of the spiral road for safety and transportation convenience. Minimum curve radius can be derived on the basis of sight lengths, the limit values of superelevation, the limit values of lateral acceleration and the limit values of Jerk (rate of change of acceleration) (KILINÇ and BAYBURA 2012).

(1) Minimum curve radius based on the limit value of superelevation

The minimum horizontal curve radius, based on the superelevation value, has been given by American Association of State Highway and Transportation Officials' A Policy on Geometric Design of Highways and Streets (American Association of State Highway and Transportation Officials 2001) as follows

$$\mathrm{R}_{\min} = \frac{V^2}{127(0.01n_{\max} + f_{\max})} \tag{1}$$

where;

$R_{\min}$: Minimum curve radius (m)

V : Vehicle velocity (km/s)

n_{max} : Maximum superelevation (m)
f_{max} : Maximum allowable side friction factor

(2) Minimum curve radius based on the limit value of lateral acceleration

The vehicles entering horizontal curve from the linear section of the road move under the influence of various forces, including centrifugal force, the force created by the weight of the vehicle, lateral friction force and lateral acceleration force.

The lateral acceleration is created by centrifugal force. Minimum curve radius can be derived through the limit value of the lateral acceleration (Baykal 2009)

$$\mathrm{R}_{\min} = \frac{V^2}{12.96(\sqrt{1+n_{\max}^2}a_Y + n_{\max}g)} \tag{2}$$

Where; a_Y : Lateral acceleration

According to German RAL guide (Richtlinien für die Anlage von Landstrassen) and Umar and Yayla (1997), the maximum lateral acceleration value tolerated by passengers inside a car is 1.47 m/s^2. Different values of lateral acceleration are also applied, e.g., a_Y = 2.45 m/s^2 (Schofield 2001).

(3) Minimum curve radius based on the limit value of lateral Jerk

The change of the acceleration with respect to time is called Jerk. The concept of Jerk is defined as the third derivative of distance (Schot 1978). Jerk is a value used to determine the voyage comfort and is known as comfort criterion while designing road.

The lateral Jerk is defined as the change of lateral acceleration created by the centrifugal force on the horizontal curve with respect to time. For the safety and comfortable driving, lateral Jerk must be lower than the predetermined limit values, which was defined as follows (Baybura 2001)

$$\begin{aligned} Z_y = \frac{bV}{\sqrt{u^2+b^2}}\Bigg\{ & 3k_y a_T + V^2\frac{d_{KY}}{d_l} \pm \frac{uV^2}{b\sqrt{1+W^2}}\frac{d_{KD}}{d_l} \\ & + \left(\frac{-k_Y V^2 u}{u^2+b^2} - \frac{g}{b} + \frac{gu^2}{b(u^2+b^2)} \pm \frac{k_D V^2}{b\sqrt{1+W^2}} \pm \frac{-k_D V^2 u^2}{b(u^2+b^2)\sqrt{1+W^2}}\right)\frac{d_u}{d_l} \\ & \pm \frac{-u^2V^2k_D W}{b(1+W^2)^{3/2}}\frac{d_w}{d_l} \pm \frac{2uk_D a_T}{b\sqrt{1+W^2}}\Bigg\} \end{aligned} \tag{3}$$

Where;
R_{min} : Minimum curve radius (m)
Z_y : Lateral Jerk (m/s^3)
V : Design speed (m/s)
b : Horizontal width of road platform (m),
u : Superelevation (m)
k_y : Horizontal curvature (1/m)
k_D : Vertical curvature (1/m)
g : Gravitational acceleration (9.81 m/s^2)
a_T : Resultant tangential acceleration (m/s^2)
W : Longitudinal slope
l : Horizontal length of road

The minimum radius can be determined as

$$R_{\min} = \frac{3V_{\max}\, a_T b}{\sqrt{u^2 + b^2} Z_y} \tag{4}$$

According to American Association of State Highway and Transportation Officials (AASHTO 2001), standard values of lateral Jerk ranging from 0.3 to 0.9 m/s^3 have been used for highways. Other values of lateral Jerk used for highways are as follows:

Z_y = 0.6 m/s^3 (for residential areas), Z_y = 0.3 m/s^3 (for rural highways) (Schofield 2001), Z_y = 0.6 m/s^3 (Umar and Yayla 1997), Z_y = 0.6 m/s^3 (Uren and Price 2006), Z_y = 0.5 m/s^3.

Table 3 gives the minimum curve radius derived from different criteria (Lateral Jerk, lateral acceleration, superelevation) for highways with vehicle speeds ranging from 20 to 130 km/h.

For shaft spiral road design, the V, Z_y, a_y and e values shall be different from those for highway, and the smaller radius is expected. Eqs. (1), (2), and (4) shall be used to calculate the $R_{\min}$.

The design speed for spiral road in shaft can be similar to or a little higher than the design speed for the ramp garage, while much lower than that for highway. The general design speed for ramp garage is around 5 km/h.

The minimum horizontal curve radius for spiral road in shaft for a design speed of 8 km/h has been calculated respectively for the limit value of superelevation of 4% , the limit value of lateral acceleration of 1.47 m/s^2, and the limit value of lateral jerk of 0.9 m/s^3 (see Table 4). The final minimum horizontal curve radius should use the largest value (16 m) among the output of the three criteria. In the alternative I, the inner curve radius of spiral road in the shaft is taken as 16 m (Fig. 5).

Table 3 Minimum horizontal curve radius for highways (KILINÇ and BAYBURA 2012)

V (Km/h)	$R_{\min}$ (m)								
	Z_y (m/s^3)							a_y (m/s^2)	e (%)
	Z_y: 0.3	Z_y: 0.4	Z_y: 0.5	Z_y: 0.6	Z_y: 0.7	Z_y: 0.8	Z_y: 0.9	a_y: 1.47	e: 4
20	115	85	70	60	50	45	40	15	15
30	170	125	100	85	75	65	60	35	35
40	225	170	135	115	100	85	75	55	60
50	280	210	170	140	120	105	95	85	100
60	335	250	200	170	145	125	115	125	150
70	390	300	235	195	170	150	170	170	215
80	445	335	270	225	195	170	150	220	280
90	500	375	300	250	215	190	170	280	375
100	560	420	335	280	240	210	190	345	495
110	615	460	370	310	265	230	205	415	635
120	670	500	400	335	290	250	225	495	875
130	725	725	435	365	310	275	245	580	1110

$R_{\min}$: Minimum curve radius
Z_y: Lateral Jerk, Z_y: 0.3~0.9 m/s^3 (AASHTO 2001)
a_y: Lateral acceleration, a_y: 1.47 m/s^2 for highways (German RAL Guide)
e: Superelevation, e: %4 (AASHTO 2001)

Table 4 Minimum horizontal curve radius for spiral road

V (km/h)	R_{min} (m)		
	Z_y = 0.9 m/s^3	a_y = 1.47 m/s^2	e = 4 %
8	16	2.4	2.4

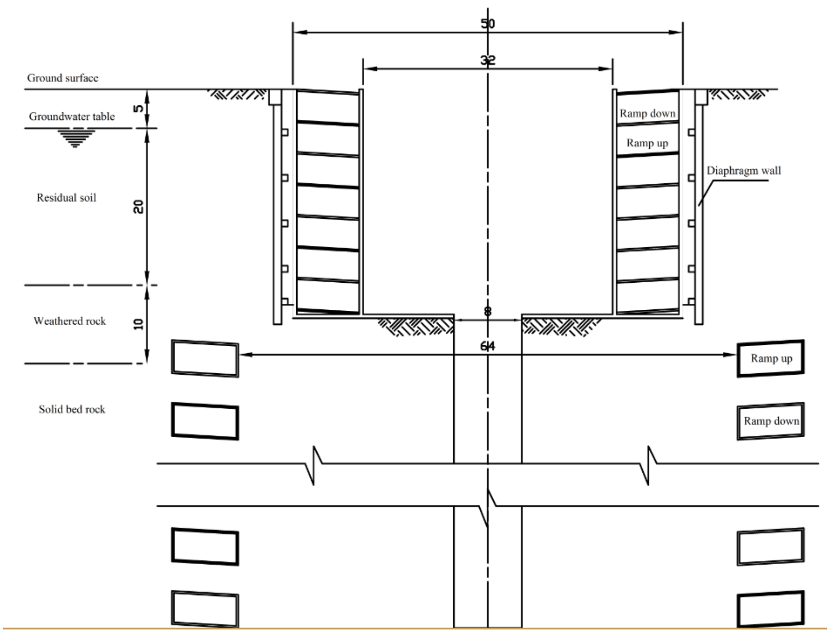

Fig. 6 Profile of the alternative II (Length unit: m)

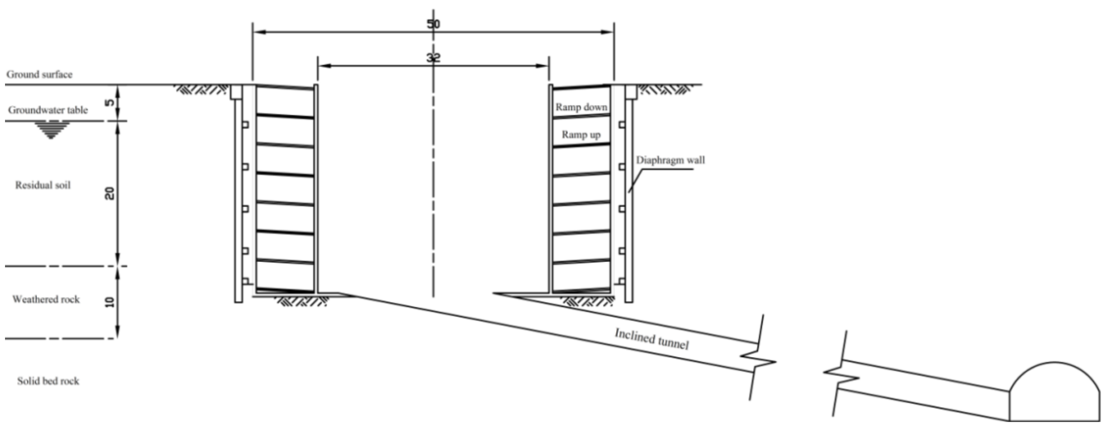

Fig. 7 Profile of the sub alternative II: shaft & inclined tunnel (Length unit: m)

3.2 Alternative II: Upper shaft with spiral roads & lower tunnels

Alternative II as shown in Fig. 6 is considered with the same shaft size as the alternative I. Spiral roads (single one-way spiral road or double one-way spiral roads) are used for transportation in both construction and operation phases. The shaft terminates at weathered rock and continues with small shaft, which is used for the installation of pipelines, small lifts, etc. Tunnels (circular curve, elliptical curve or inclined straight line shape (Fig. 7)) are used instead to enter the bedrock reaching the deep rock cavern.

3.3 Alternative III: *Plain shaft*

In the alternative III (Fig. 8), the shaft diameter is smaller than that in the alternative I and the upper section of alternative II, 20 m in the lower part (internal diameter) and 24 m in the upper part (internal diameter). The design diameter generally ranges from 20 m (minimum for efficient mucking during construction) to 40 m to meet the operational function requirements.

Plain shaft can access underground with a deep depth. Rock caverns excavated at different levels can share one plain shaft via linked tunnels. The support design of the conjunctions between shaft and tunnels are critical and should be paid special attention.

3.4 Comparison of the three alternatives

The proposed three alternatives are compared in terms of the mucking method, theoretical mucking capacity for underground cavern excavation, water control, and transportation integrity (see Table 5).

Mucking is of critical importance for the excavation of underground rock cavern. The mucking rate varies for different shaft depths. An average value is used for comparison as follows. In alternatives I and II, the transportation with double one-way spiral roads is reliable and has very

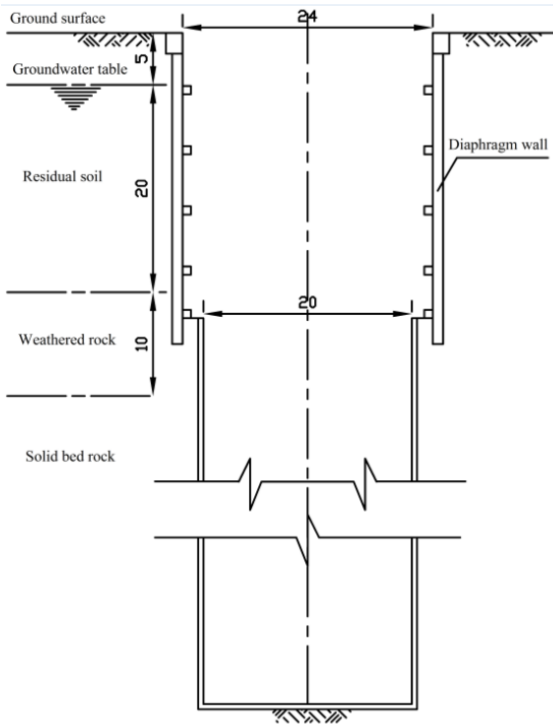

Fig. 8 Profile of the alternative III (Length unit: m)

Table 5 Comparison of different alternatives

	Alternatives	Mucking: Mucking method	Mucking: Theoretical capacity* (m^3/day)	Water control	Required volume of excavation	Transportation integrity
I	Vertical shaft with spiral roads	Single spiral road	14,400~24,000	Whole shaft section	High	√
		Double spiral road	No limit			
II	Upper shaft with spiral roads & lower spiral tunnel	Single spiral road	14,400~24,000	Upper shaft & Lower tunnel	Medium	√
		Double spiral road	No limit			
	Upper shaft with spiral roads & lower inclined tunnel	Single spiral road	14,400~24,000	Upper shaft & Lower tunnel	Medium	√
		Double spiral road	No limit			
III	Plain shaft	Single car-lift	4,800~7,200	Whole shaft section	Relatively low	—
		Double car-lift	9,600~14,400			
		Winders and hoisted buckets	Depend on the design			
		Conveyor belt	24,000			

*8 hours continuously working

good capacity. There is no theoretical limit but practically the capacity is limited by the truck performance. For single spiral road, the mucking capacity is highly dependent on the load capacity and moving speed of the truck, about 30~50 m^3/min. For an eight-hour shift with continuous mucking, the theoretical mucking capacity of the single spiral road is 14,400 ~24,000 m^3/day.

Car/truck lift, winders and hoisted buckets and conveyor belt are suitable for mucking transportation in plain shaft (alternative III). The single car-lift has a mucking rate of about 10~15 m^3/min, and the double car-lift has a mucking rate of about 20~30 m^3/min. The theoretical mucking capacity (8 working hours per day) of the single car-lift is 4,800~7,200 m^3/day, and of the double car-lift is 9,600~14,400 m^3/day. The mucking rate of the conveyor belt is about 50 m^3/min and the theoretical mucking capacity for 8 working hours per day is about 24,000 m^3/day.

Another advantage for car/truck lift is that it can also be used during operation stage without relocation (Fig. 9).

The maximum depths for the three alternatives are different. The maximum depth for alternative I and alternative II is controlled by the circular curve tunnels, as the driver/passengers may feel sick for driving in the circular ramp for a long period. The elliptical curve, irregular curve or inclined straight line shape for the tunnels in the bottom part of the alternative II can relieve the sick feeling and hence increase the access depth. For the alternative III, there is no limit for the access depth provided that the lift can reach the given depth.

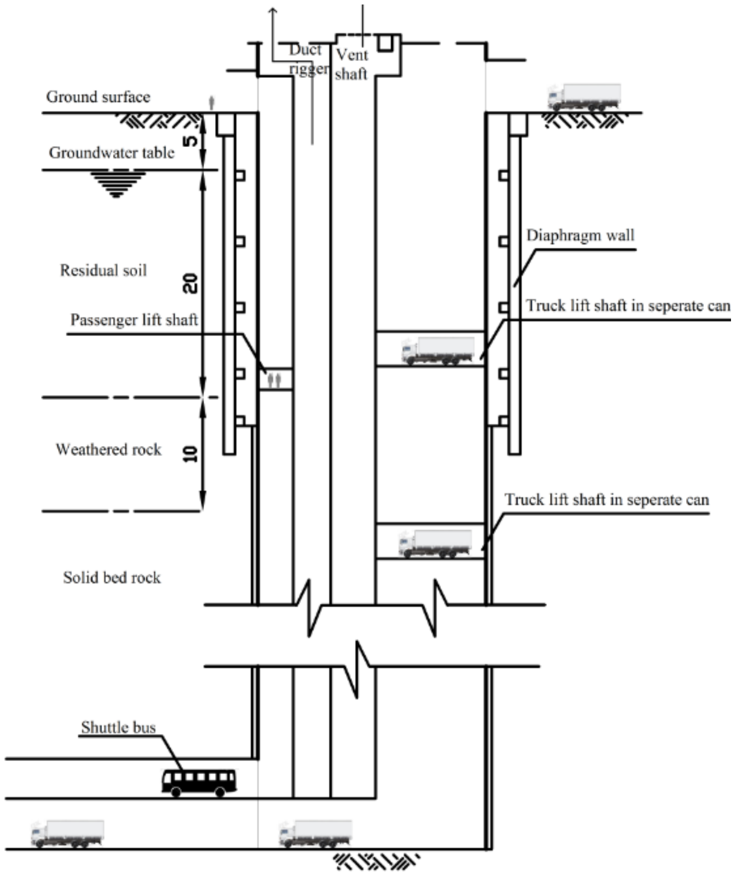

Fig. 9 Transportation of alternative III during operation

All three alternatives have their advantages and limitations and the proposed shaft design should be based on the conditions of local site and the requirements of the project. For example, if the overburden is thin and the rock cavern is shallow, the alternative I is a good solution as the direct vehicle transportation is required. When the rock cavern is deep buried, alternatives II or III can be considered depending on the transportation requirement.

For large rock cavern groups, using more than one of these alternatives is a good combination. Alternative I or II is good for direct vehicle transportation while alternative III is good for quick transportation via lift. Passengers can use lift of alternative III to get in and out of the cavern quickly. While large volume goods will be transported in and out by vehicle via ramp roads of alternative I or II. The ramp roads can also be used as escape road during emergency and fire engine access road during a fire.

Beside the aforementioned function comparison, quick shaft sinking is also very important. Because of the cavern excavation can only be started after the construction of access shaft. Among the three alternatives, the advance rate of alternative III is definitely the fastest due to its relatively small diameter. For alternatives I and II, large cross-sectional shaft rapid excavation methods such as sequential operation with different excavation steps conducted simultaneously in the pre-divided sections at the excavation face can greatly improve the efficiency.

4. Shaft construction

4.1 Shaft sinking

Mechanical excavation by excavator, hammer, or roadheaders can be used for shaft sinking without causing big vibrations. The new developed machinery of vertical shaft sinking machine (VSM) and shaft boring system (SBS) integrate process steps, allowing excavation, mucking and in some cases rock support to take place simultaneously (Frenzel *et al*. 2010, Puhakka 1997). Drilling and Blasting is suitable for variable rock conditions, shaft sizes and shapes. The introduction of new technologies, such as computer aided drilling, electronic delays and low-energy explosives, has made the reduction of vibration considerably easier. With these new technologies, good quality ground can be achieved drilling and blasting, and in most cases, with less cost compared to mechanical excavation.

Compared to these top-down methods, bottom-up methods (e.g., Raise boring, Alimak method and upward shield method) minimize the adverse effects of the excavation work on the environment, such as vibration, noise, and traffic congestion. Nevertheless, all the bottom-up methods require existing underground tunnel/cavern for transporting the excavation machine and the access to carry the muck to the surface. For the first production shaft or the single shaft without the existing underground tunnel/cavern, top-down excavation is the only choice. The characteristics and the applicable geological condition and shaft dimension of the sinking methods are summarized in Table 6.

In the recent study for excavation of Istanbul Kadikoy–Kartal metro tunnels in Istanbul, (Ocak and Bilgin 2010) compared with the impact hammers and roadheaders, the drill and blast method is most efficient in rock of high strength. Roadheader is proved to be more efficient than impact hammer in terms of machine utilization time and production rate.

The factors to be taken into account when determining the sinking method may include: the function of the shaft, its diameter and depth, soil and rock conditions, groundwater state, the proximity of other structures, the sensitivity to settlement, construction time and costs, etc. Selection of a proper method to sink the shafts is important to minimize the construction time and cost (Lashgari *et al*. 2011).

For all three shaft alternatives, the shaft passes through soil and weathered rock before it reaches the fresh bedrock and the shaft diameter is over 20 m. Only top-down method can be used for the upper part. It is suggested to use the excavator for shaft sinking in soil layer, the excavator / roadheaders, or the drilling and blasting in the weathered rock layer.

In the soil layer, excavation and mucking can be carried out in parallel after the diaphragm wall is constructed. Excavation was carried out by using tracked excavators to move spoil to the sides of the shaft. The excavated material was then raised to the surface for disposal by long arm excavators up to about 15 m deep, and in the deeper location by muck skips hoisted to the surface by crawler cranes.

The performance of the circular diaphragm walls can be monitored with a number of diaphragm wall panels which are instrumented with inclinometers or/and vibrating wire (VW) strain gauges. Optimization of excavation stages can be made by analyzing the monitoring data, for example, reducing the excavation stages if the performance is good. If ring walls are used as permanent structure in addition to diaphragm wall, a number of underpinning joints between successive stages of inner ring walls can be avoided and this may further save the construction time and cost.

Table 6 Comparison of different sinking methods

	Sinking method	Geological condition	Shaft dimension	Characteristics
Top-down	Hand excavation	Soil	No limits	Flexible; Unsafe if soil is not sufficiently stable.
	Excavator	Soil, weak rock	No limits	Avoid vibrations by drilling and blasting.
	Hammer	Weak rock	No limits	As above.
	Roadheaders (boom cutters)	Rock with moderate strength, laminated or Jointed rock	No limits	Overbreak can be limited; Minimise loosening of the surrounding rock.
	Vertical shaft sinking machine (VSM)	Soil, rock with moderate strength	Depending on rig (Diameter up to 12 m)	Fast and safe; Expensive.
	Shaft boring system (SBS)	Rock	Depending on rig (Diameter up to 10-12 m)	Fast and safe; Expensive.
	Drilling and Blasting	Rock	No limits	Flexible in rock conditions, shaft size and shape; Low capital cost; Serious vibration; Ventilation required.
	Pilot shaft method	Rock	No limits	Fast mucking; Existing underground openings required.
	Galloway stage	Soil and rock	Medium-sized (e.g., 4.6 m diameter)	
Bottom-up	Conventional Raise boring	Rock	Most economic for shaft diameter up to 6 m	minimize the adverse effects such as vibration, noise, and traffic congestion; Existing underground openings required; Require reasonably stable ground condition.
	Blind boring	Rock	Diameter normally range from 0.6 to 1.8 m	As above.
	Alimak Method	Rock	Practical diameter ranging from 1.8 m to 6 m	As above (Ventilation required).
	Upward Shield Method	Soil	Practical diameter limited	As above

Pre-grouting through the pipes embedded in the diaphragm wall/ continuous secant piles can be conducted for water inflow control near the boundary of soil and weathered rock.

In the lower part of alternatives I and III in rock layer, excavator and hammer can be used for weak rocks. When encountering moderate strength, laminated or jointed rock, roadheaders (boom cutters) can be used. These mechanical excavations can greatly reduce vibrations and overbreak, and can minimize loosening of the surrounding rock.

Drill and Blast is the most flexible method with few limitations of rock conditions, shaft size and shape. Its application in urban areas is restricted due to vibrations. The introduction of new technologies, such as computer aided drilling, electronic delays and low-energy explosives have made the reduction of vibration considerably easier. Although more expensive than conventional blasting, excavation cost by blasting using these products and technologies in relatively good quality ground is believed, in most cases, to be less than the cost of mechanical excavation.

Pilot shaft method of top-down excavation is suitable for large vertical shafts with existing tunnel in the bottom, requiring an existing shaft to carry the muck to the surface. After the establishment of pilot shaft, the final shaft can be excavated by the drill and blast method or mechanical method. Mucking is faster from pilot shaft through existing tunnel / shaft than by other top-down methods.

Vertical shaft sinking machine (VSM), shaft boring system (SBS) and bottom-up method as listed in Table 6 may be used for excavation of small ventilation/evacuation shaft, and are not appropriate for the main shaft with relatively large cross-section.

The construction cost of a large cross-sectional shaft is tremendous. With the proposed shaft alternatives, the shaft diameter can be as large as 50 m with the cross-sectional area of up to 2000 m^2. Even for the relatively smaller shaft diameter of 20 m, the cross-sectional area is over 300 m^2. Well organized construction may considerably save the time and consequently the cost, while any delay in construction often requires excessive funding. It is particularly serious when the shaft also serves as the access for the construction of underground cavern.

In the soil layer, excavation and mucking can be carried out in parallel after the diaphragm wall is applied. For rock excavation, required rock support is installed simultaneously or after excavation and mucking. The drill and blast method in rock requires several working procedures, some of them are quite time consuming. Sequential operation with different excavation steps conducted simultaneously in the predivided sections at the excavation face can improve the efficiency, as what has often been done in foundation pit excavation. Fig. 10 shows the conceptual sketch of the proposed sections allocated for each construction step.

4.2 Water control

For underground engineering projects, the occurrence of water may greatly influence the design and construction method, and in the longer term, the durability of the structure and its maintenance cost (Li *et al*. 2014, Roman *et al*. 2013). It is even more challenging if the source of water is saline and infinite, which may lead to worse condition with serious corrosion problems particularly to the electric equipment underground. Therefore, water control is essential for a successful underground structure, and has to be considered for both construction and operation phases.

A shaft accessing to the deep underground rock cavern often passes through both soil and rock, and the preferable methods of water control for soil and rock shall be considered separately. Groundwater can be well controlled for shaft in soil by using the diaphragm wall or secant pile, which also bears the function for shaft support. Due to the better integrity for water prevention, diaphragm walls are used more often as shown in Table 2 and are the only form of structure for water control in present study. For shaft built in rock, pre-grouting based on geological prediction

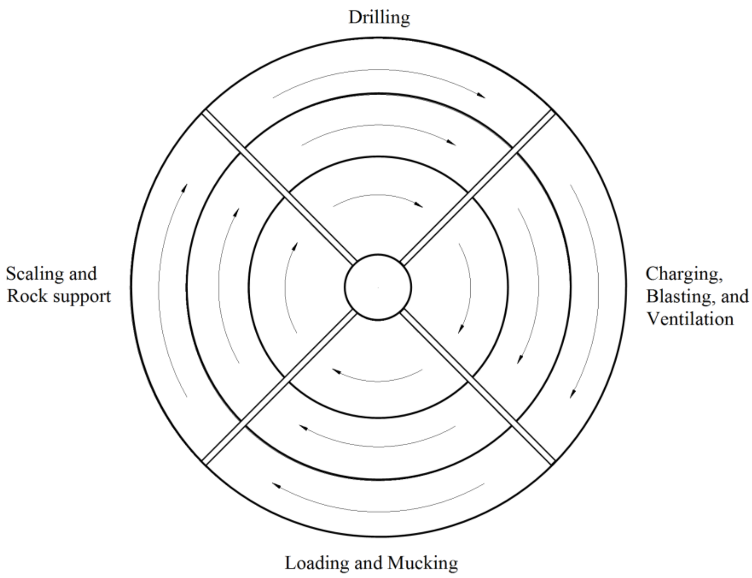

Fig. 10 Excavation initiating from the center radically out to the edge incorporated with sequential excavation

with probe drilling is an effective method. Special attention should be given to the transition zone at the top of rock layer where the rock is normally quite fractured. This paper will focus on water control in the rock layer.

Geological prediction ahead of the working face during excavation is crucial for mitigating risks associated with the potential hazardous geotechnical features including water inflow.

Support of diaphragm wall or bored contiguous pile in soil as suggested in the proposed shaft alternatives extends several meters to the rock layer. In the rest part of shaft, the rock support (e.g., rock bolts, shotcrete and concrete lining, etc.) is designed based on the rock mass quality and the in-situ stresses. Grouting may substantially mitigate the potential water ingress and improve the ground stability for underground excavation. Pre-grouting is often effective and should be considered as the most relevant water control method for rock excavation. If pre-grouting is difficult, e.g., due to high ground water pressure, post grouting may become an even bigger challenge (Garshol 2007). A study summing up some Norwegian projects indicates that the time and cost of reaching a specified result by post-grouting will be much higher than by pre-grouting (Stenstad 1998). The traditional water proof lining, with the polymer sheet membrane between the initial temporary shotcrete and the final cast-in-place concrete, is quite time consuming and costly

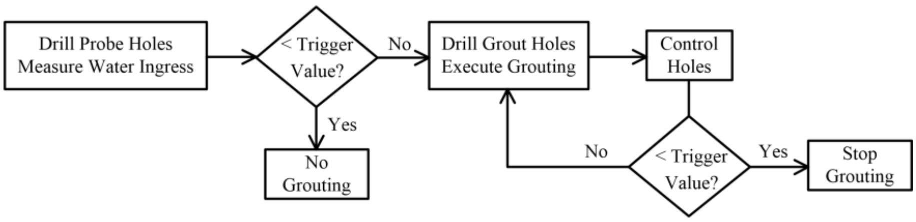

Fig. 11 Flowchart of simplified grouting procedure (Garshol *et al*. 2012)

and therefore is not recommended. It has been gradually realized that satisfactory exclusion of potential groundwater is achievable as far as the extensive pre-grouting is ensured, and the allowable rest water inflow into shaft can be pumped (Garshol 2013). This is some different from the conventional consideration on water control in rock, in which post-grouting is carried out as a supplementary to pre-grouting, to seal off possible spot leakages (Garshol and Lacerda 2007).

A simplified flowchart covering the pre-grouting procedure is shown in Fig. 11, and the basic steps include the following:

- Probe holes are drilled to measure the water inflow, which compares with pre-defined trigger value and the results to decide whether or not performing pre-grouting;
- Drill the grout holes according to the drill plan;
- Install packers into the holes;
- Grout all probe and grout holes;
- Drill control holes and measure water inflow from the holes;
- Decide about performing an additional round of grouting or progressing the excavation.

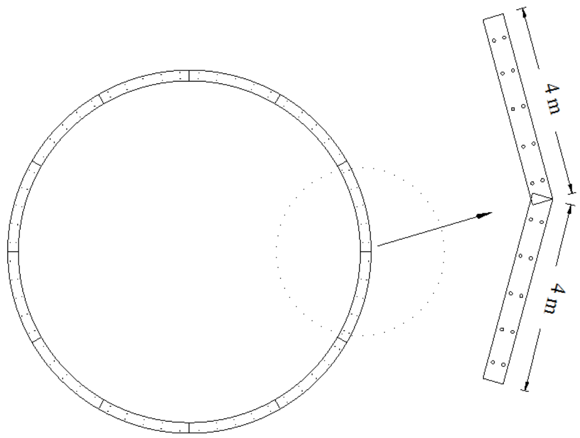

Fig. 12 Horizontal cross section of diaphragm wall with embedded grouting pipes

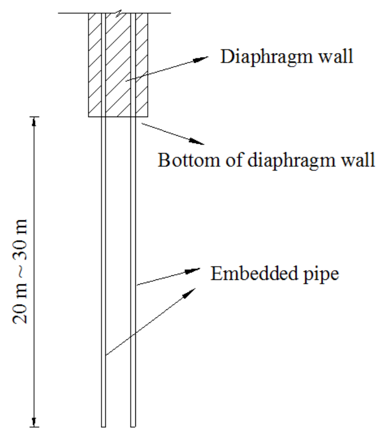

Fig. 13 Vertical cross section of diaphragm wall with embedded grouting pipes

In terms of water control during the shaft sinking, the transition zone in the weathered rock where the diaphragm wall / pile wall ends can be most challenging. Application of pre-grouting in this zone requires special attention. Pre-grouting may have to be carried out through steel / plastic pipes pre-embedded in the diaphragm wall /pile wall to seal off the potential water seeping (Garshol 2013).

Fig. 12 illustrates the conceptual layout of the embedded pipes for diaphragm wall. The whole diaphragm wall is distributed with the grouting pipes. Arrangement of double rows of pipes in the wall enhances the grouting quality. The distance between the two rows depends on the thickness of the diaphragm wall and the protective course. The distance of adjacent pipes within one row can be in the range of 70~120 cm, e.g., 4~5 pipes per row for a 4 m long segment. The pipe dimension should accommodate the drilling rod. Fig. 13 shows the vertical cross section of the diaphragm wall with the embedded pipes. The drilling hole may need to extend 20 m~30 m beyond the bottom of the diaphragm wall to ensure water proof, and pre-grouting is preferably to be conducted by sections with the section length around 10 m.

4.3 Support structures

For the soil layers in the upper part of the shaft, available methods include plate and anchor wall by underpinning, vertical soldiers and horizontal lagging, king post method, sheet piling, contiguous bored piling, secant piles, diaphragm wall, soldier pile tremie concrete (SPTC) method, ground freezing. Diaphragm wall is the most commonly used method nowadays and especially suitable for large diameter shaft (Virollet *et al*. 2006).

In the lower portion of the shaft - the rock layers, support structure should take the rock mass properties into account. Shotcrete, rockbolt, steel rib or their combinations can be used based on the rock mass classification and rock mass properties.

The stability of underground excavations depends on the rock mass quality and the stress induced in the rock. The strength of the rock mass is the key issue for the stability of deep underground excavations while the structure of the rock mass is the key issue for the stability of shallow underground excavations. The design of structures and support in rock should take both the rock mass quality and in-situ stress into consideration. Rock mass classification and rock mass strength are widely used for rock mass quality assessment. Numerical simulations are very useful tools for the analysis of rock support. The Finite Element Method (FEM) and the Discrete Element Method (DEM) are used to calculate the stress, strain and the potential failure for the proposed design. Optimization hence can be made. For example, DDA can be used to simulate the joint rock mass and rock bolt support (Zhao *et al*. 2012) and the PFC can be used to simulate the failure processes of rock (Zhang *et al*. 2015, 2017).

The Q-System is widely used for rock mass classification. On the basis of an evaluation of a large number of case histories of underground excavations, the Norwegian Geotechnical Institute proposed a Tunneling Quality Index (Q) for determination of rock mass characteristics and tunnel support requirements (NGI 2013). This method was once used for primary support selection of shaft design in Hong Kong SAR during the construction of the Harbor Area Treatment Scheme Stage 1 (Pakianathan *et al*. 2004) and shaft design in the Jurong Rock Cavern Project in Singapore. In the Q-system, some parameters such as ESR are specially given to consider shaft sectional shape (e.g., circular, rectangular/square), shaft at intersections with one, or two widely separated openings and with multiple openings close separated. All these are practical and may often be encountered in the construction of rock cavern.

5. Conclusions

The present study has proposed three access shaft alternatives and discussed the construction methods for shaft sinking, water control and support structure. Some important conclusions are as follows:

(1) The main shafts usually have a relatively large cross-section for transportation requirement during the cavern construction and operation. They will penetrate through fill materials, soil layers, and weathered rocks before reaching the solid bedrock. The proper design, rapid excavation and water control are the key aspects for consideration.

(2) The alternatives I and II with the spiral roads can be used for transportation in both construction and operation phases. The alternative I and alternative II with circular curve tunnels have a depth limit, and special arrangement for the tunnels in the bottom part of the alternative II can relieve the sick feeling and hence increase the access depth. There is no limit for the access depth for the alternative III.

(3) A sequential excavation is proposed for large shafts to improve the efficiency of excavation. This method with different excavation steps has great advantage of speeding up the excavation.

(4) Diaphragm walls are used in soil layers for the water control and support structure of the three alternatives. Pre-grouting is often effective and should be considered as the most relevant water control method for rock layer. In the transition zone between soil layer and rock layer, pre-grouting may have to be carried out through steel / plastic pipes pre-embedded in the diaphragm wall to seal off the potential water seeping.

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