

# Tunnels and Caverns in Hong Kong

## Working Group on Cavern and Tunnel Engineering

*Hong Kong Institution of Engineers Geotechnical Division*

**Abstract:** Many tunnels and caverns have been successfully constructed in Hong Kong. These underground structures cater for water supply, mass transportation (such as railways and roads), drainage, conveyance of sewage and electrical cables, as well as for underground space development (such as concourse for mass transit railways, sewage treatment plant and refuse transfer station and explosives depot). This paper summarizes the historical and recent developments in relation to tunnels and caverns in Hong Kong. It also outlines the recent developments in risk management of tunnel works and the research being carried out by the local universities.

### 1 INTRODUCTION

The population of Hong Kong has increased steadily from about 2.2 million in 1950 to about 7 million today. Intense urbanization and infrastructure development, combined with limited land availability and a growing awareness of environmental issues has driven Hong Kong's need to develop its underground space. This has resulted in the construction of numerous tunnels and caverns.

In December 2003, the Hong Kong Institution of Engineers (HKIE) Geotechnical Division Committee (GDC) formed an interest group on cavern engineering. This subsequently developed into a group on cavern and tunnel engineering and was renamed as the Working Group on Cavern and Tunnel Engineering in March 2005. Membership of the Working Group include representatives from the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) of the HKSAR Government, the Kowloon-Canton Railway Corporation (KCRC), the MTR Corporation Ltd (MTRCL), consultants, contractors and the universities. The terms of reference of the Working Group are as follows:

- (a) Consolidate local and international knowledge, experience and practice in cavern and tunnel engineering.
- (b) Identify key issues on and actions required for appropriate use of caverns and tunnels in Hong Kong.
- (c) Promote awareness among professionals, clients and the relevant authorities of the potential and benefits of caverns and tunnels in Hong Kong.
- (d) Make recommendations to the HKIE GDC on follow-up actions to be taken for promoting cavern and tunnel engineering good practice in Hong Kong.
- (e) Promote technical exchanges between practitioners in Hong Kong and overseas.

This paper summarizes the historical and recent developments in relation to tunnels and caverns in Hong Kong. It is based largely on published papers, including those given in the proceedings of the 26<sup>th</sup> Annual Seminar of the HKIE GDC held on 12 May 2006 on Cavern and Tunnel Engineering, as well as information provided by members of the Working Group and client organizations. Because of its scope, this paper will only refer to some relevant literature without going into details.

For the purpose of this paper, 'tunnel works' comprise tunnels, shafts, caverns and associated underground facilities, however constructed. The rock and soil descriptions given in this paper follow the recommendations of Geoguide 3: Guide to Rock and Soil Descriptions (GEO, 1988), which is the standard commonly adopted in Hong Kong.

### 2 GEOLOGY

Volcanic and granitic rocks are found in about 85% of Hong Kong's landscape, with the former covering approximately 50% of the land area. The remaining 15% are sedimentary rocks, exposed mostly in the northern and northeastern New Territories. The abundance of massive hard crystalline volcanic and granitic rocks makes Hong Kong particularly suitable for tunnelling and underground development.

The near-surface rocks in Hong Kong have been subjected to chemical weathering, which has resulted in variable decomposition and solution of the rock-forming grains and minerals to more chemically stable components. This process is primarily promoted by the flow of groundwater in pre-existing discontinuities. Corestone development associated with a gradational weathering profile is common in widely jointed coarser grained rocks, whereas in finer grained rocks, which have relatively close discontinuity spacing, few corestones may be present and the rock-soil interface (rockhead) may be sharply defined. Microfractures associated with tectonic stresses and stress-relief or hydrothermal alteration can significantly affect the rock strength.

The geology and general pattern of the main inferred faults in Hong Kong is shown in Figure 1. The laterally persistent north-east to east-northeast trending faults strongly influence the present day topography of Hong Kong. Northwest-trending faults are generally shorter (up to 20m) and less continuous. Some major faults are associated with zones of deep weathering. The faults can play a significant role in controlling the engineering geological and hydrogeological properties of the rock mass, a good understanding of which is vital for the design and construction of tunnel works.

While weathering and structural geology govern the requirements for tunnel support to ensure ground stability, hydrogeology plays an important role in respect of assessment of groundwater ingress into tunnels during their construction, the drawdown of groundwater pressures outside the tunnels and the consequential settlement of the ground and the facilities that the ground supports. Due to the presence of joints, faults and other discontinuities in the rock mass, and its weathering characteristics, there can be significant uncertainty in the hydrogeology within the ground mass in Hong Kong.

The magnitude and direction of insitu stress in the rock mass can be important considerations in the design and construction of tunnel works in rock. For example, high horizontal stresses normal to the axis of a tunnel or a cavern are usually beneficial for stability of the roof. The results of selected insitu stress measurements carried out in Hong Kong indicate that the principal

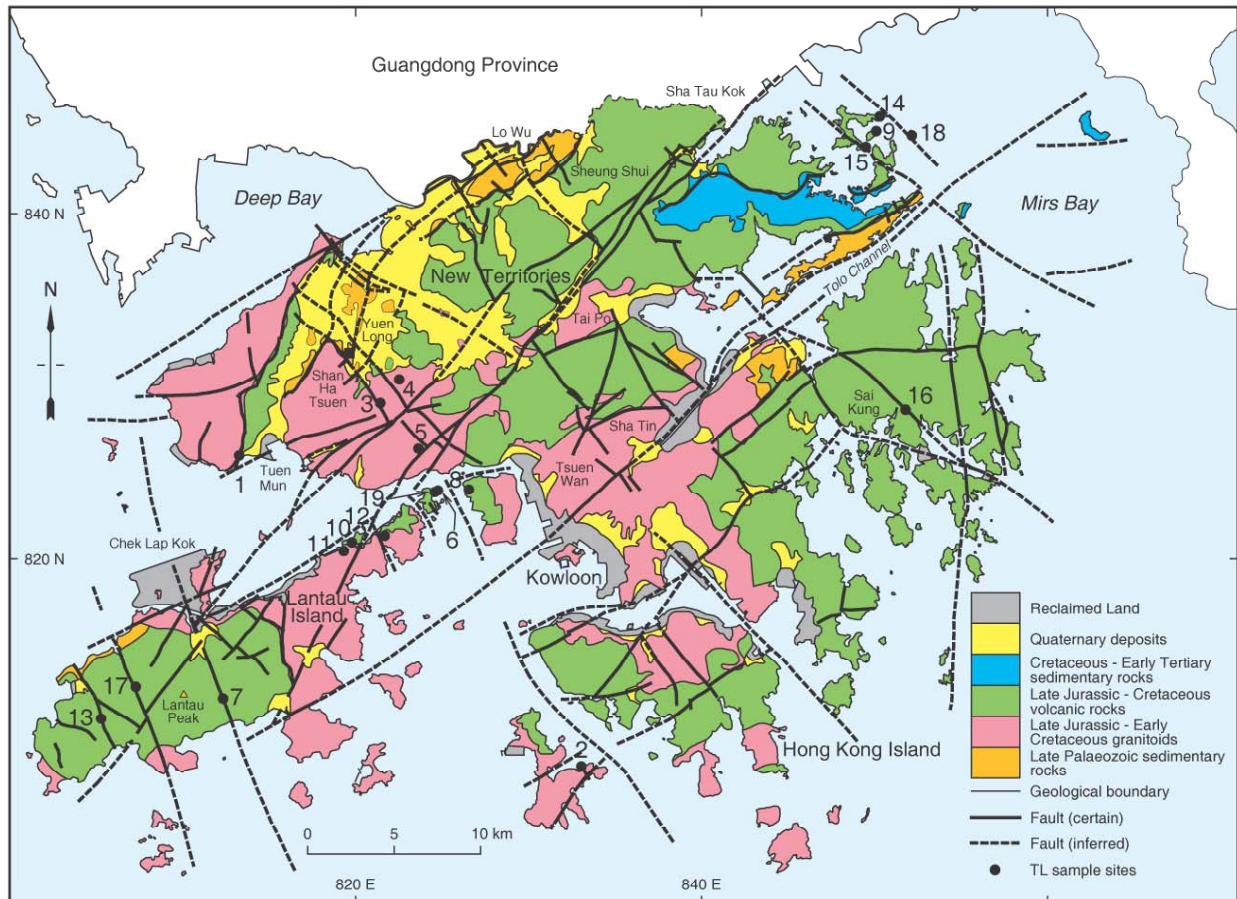


Fig. 1. Simplified geological map of Hong Kong (from Sewell et al., 2000)

horizontal stress in rock is in excess of the vertical stress at depths of less than about 150m (Klee et al, 1999; Free et al, 2000; Ng & Wardall, 2005). The scatter in stress ratio and orientation of maximum horizontal stress is due to factors such as the influence of topography at relatively shallow depth, locked-in stresses from different stress regimes over geological time, and proximity to major geological structures.

Thick colluvial deposits can also be present on the hillsides especially along the foothills. The strength, compressibility, permeability and consolidation characteristics of these materials, as well as the groundwater regime, can be of engineering significance if the tunnel works are to be constructed through or below them. Further discussion on material and mass weathering characteristics, development of ground models, and the key engineering geological issues related to tunnel works in Hong Kong is given in GEO (2006a).

### 3 TUNNELS AND CAVERNS IN HONG KONG

#### 3.1 Topography

About 47% of the land in Hong Kong is greater than 100m above sea level, and 12% exceeds 300m. The limitations on flat land have necessitated the construction of tunnels and caverns to support Hong Kong's built environment.

There are 32 peaks higher than 500m; three of these rise above 800m. Tunnels have been built through many of these hills including Beacon Hill (457m), Eagles' Nest (312m), Lin Fa Shan (578m), Lion Rock (495m), Ma On Shan (702m), Needle Hill

(532m), Smugglers' Ridge (337m), Tai Mo Shan (957m) and Tate's Cairn or Tai Lo Shan (577m).

In addition to the tunnels through the hills, many tunnels have also been constructed in the low lying urban and sub-sea areas.

#### 3.2 Water Supply Tunnels

Early settlements on Hong Kong Island relied on streams, supplemented from 1852 by wells. The first reservoir was opened in 1863 in the Pok Fu Lam valley. This was replaced by a larger one in 1871. Tai Tam Reservoir was constructed in 1889 and included a 2.2km tunnel to transfer water to Victoria (Surveyor General, 1884; 1885). The scheme was expanded, and Wong Nai Chung Reservoir was opened in 1899, with three further Tai Tam Reservoirs between 1904 and 1917, plus the Aberdeen Reservoirs in 1931 and 1932 (Ho, 2001).

In Kowloon, the first Kowloon Reservoir opened in 1910, and three more were completed between 1925 and 1931. The 2km long Shing Mun Tunnels were built in 1926 (Woodward, 1935).

During the early 1960s, the demand for water increased as several years of low rainfall led to water shortages and severe rationing. As part of the Shek Pik Scheme, 17km of tunnels were completed in 1963, and this included a 9.6km tunnel conveying water from the Shek Pik Dam on Lantau Island to Silvermine Bay. Concurrently, the 7.2km long Tung Chung Tunnel was built in 1963. The Tam Lam Chung Tunnels, about 24.3km long, were built in the period 1957 to 1974.

Plover Cove and High Island were dammed and filled with fresh water. During the period from 1965 to 1971, 38.4km of tunnels were constructed to augment the natural catchments with

water from adjacent watersheds under the Plover Cove Water Scheme (Ford & Elliot, 1965; Garrod, 1966). About 40km of tunnels were built in 1976 to divert fresh water to the High Island Reservoir (Tunnels & Tunnelling, 1971; Don et al, 1973; Vail et al, 1976).

In the 1980s, a number of aqueduct schemes were implemented. Agreement was reached between the Hong Kong Government and the Guangdong Provincial Authority for the water supply to Hong Kong to be increased by approximately equal annual increments from 220 million cubic metres in 1982 to 660 million cubic metres in 1994. This resulted in the implementation of the Western Aqueduct Tunnels under the project entitled "Future Increase of Water Supply from China, Stage 1". The tunnels, 13.8km long in total, were completed in 1986 (McFeat-Smith, 1982; McFeat-Smith, et al, 1999).

Under the Tolo Harbour Aqueduct Scheme, a 5.4km long tunnel, from Sai O to Pak Kong, was completed in 1988 (McMeekan & Yue, 1987). The 6km long Pak Kong to Tseung Kwan O Tunnel was completed in 1989 (McFeat-Smith, 1998; McFeat-Smith et al, 1999).

A 7km long tunnel, the Siu Ho Wan to Silvermine Bay Aqueduct, with a diameter of 2.7m to 3.56m, was built in 1996 (McFeat-Smith et al, 1999). This was the first time a Tunnel Boring Machine (TBM) was used for the construction of water tunnels.

In 2003, the 14.0km long, 2.7m to 4.9m in diameter, Tai Po to Butterfly Valley Fresh Water tunnels were completed. With a maximum ground cover of 600m, the main tunnel is the deepest tunnel below ground surface in Hong Kong. In this project, two hard rock TBMs and two pipe-jacked tunnelling machines were used, and there were two drill and blast drives (McFeat-Smith, 1998; World Tunnelling, 1999).

By 2006, about 199km of water tunnels, with diameter ranging from 1.5m to 9.14m, had been constructed by the Water Supplies Department (WSD) in Hong Kong.

Hong Kong's fresh water and salt water supplies are provided through a network of 7,600km of water mains. Most of these water mains are underground. About 45% were laid more than 30 years ago in step with urban development. They are approaching the end of their service life and have become increasingly difficult and costly to maintain.

In 2000, a systematic programme was launched by WSD to replace or rehabilitate progressively about 3,000 km of aged water mains in 15 years to improve the condition of the water supply network. The programme entails extensive use of different trenchless pipe replacement and rehabilitation techniques.

To overcome traffic and other constraints at surface level, the open shield pipe jacking technique with manual excavation has been widely used for laying water mains since the 1980s. This involves jacking a pipe sleeve from a launching pit to a receiving pit, with grouting from sub-horizontal holes drilled ahead of the excavation face carried out prior to jacking where necessary; the water pipes are subsequently placed inside the pipe sleeve. Swann et al (2003) presented a case history of pipe jacking for installation of a water main at Gloucester Road, Wan Chai.

In 2003, a 1.36km long water main was installed from Sham Tseng to Ma Wan Island using horizontal directional drilling (HDD) (Tam, 2000). The term HDD (or more appropriately directional drilling) is commonly used to include both horizontal and inclined drilling with directional control, and the drilling is carried out using a rig set up on the ground surface. In this project, a pilot hole was first drilled and the hole was enlarged using a back reamer. A 0.61m diameter steel casing was then installed and the 0.45m diameter water pipe was threaded through. This

was the first time HDD was used for forming a long, small diameter hole in rock (through granite and volcanic tuffs with rhyolite dykes) for the installation of a water main in Hong Kong.

### 3.3 Railway Tunnels

According to Philips (1990), five railway tunnels were constructed between 1906 and 1910 as part of the Kowloon-Canton Railway: Tunnel 1 - near Boundary Street - 46m long; Tunnel 2 - Beacon Hill - 2.2km long; Tunnels 3 & 4 near Ma Liu Shui - 100m and 52m long respectively; and Tunnel 5 at Tai Po Kau - 281m long. The 2.2km Beacon Hill railway tunnel was opened in 1910 (Eves, 1908; 1911). All of these tunnels, apart from Beacon Hill, were constructed to double-track dimensions. However, they were not wide enough to include overhead structures for power supply nor allowed adequate clearance, as required for upgrading works carried out in the late 1970s and early 1980s. As a result, Tunnels 1, 3 & 4 were opened out as cuttings, a new tunnel was constructed to replace Tunnel 2, while Tunnel 5 was repaired and a new single-track tunnel was built on the landward side.

In 1981, the second Beacon Hill railway tunnel, 2.3km long and 30-40m to the side of the first Beacon Hill tunnel, was opened when the line was modernized by double tracking and electrification (Parrott, 1980). The original Beacon Hill tunnel is now being used for accommodating a major gas supply pipeline.

Many railway tunnels have been built by the MTRCL.

The MTR Initial System was conceived in a Mass Transport Study carried out in 1965-1967. The need for this system was later confirmed by further studies completed in 1970. Detailed design commenced in 1972, but subsequent to the withdrawal of a turnkey bid by a Japanese consortium, the size of the initial system to be constructed was reduced. The reduced system, the MTR Modified Initial System (MIS), was constructed on very congested sites (Edwards et al, 1980). This involved 15.6km of route, of which 13km is in tunnel (from Chater Road/Pedder Street in Central on Hong Kong Island to Choi Shek Portal in Choi Hung, including a siding section from Choi Hung to Kowloon Bay Depot), with 12 large underground stations.

Construction of the MIS commenced in 1975; the first section from Kwun Tong to Shek Kip Mei opened in 1979, and the remaining section opened ahead of schedule in February 1980. The tunnels were driven in different ground conditions. The soft and mixed ground tunnels were mainly constructed in compressed air with or without shields. Rock tunnel sections were excavated by drill and blast method. The lining types were selected based on the ground conditions encountered. Precast concrete or spheroidal graphite iron (SGI) segments were used in soft or mixed ground, and cast insitu concrete was used for the rock sections. The underground stations were constructed by cut and cover method with excavations of 17m to 25m deep, unprecedented in Hong Kong at that time. They were constructed by a variety of methods in mixed ground conditions comprising fill, marine deposits, and Grades I-V granite (often with corestones), with existing buildings of dubious integrity very close to the station boundary walls. The tunnels (with two MTR tracks) where they cross Victoria Harbour between Hong Kong Island and Kowloon comprise 14 twin immersed tube units.

The next phases of MTR development, the Tsuen Wan Extension (TWE, from Prince Edward to Tsuen Wan) and the Island Line (ISL, from Sheung Wan to Chai Wan), also comprised many running tunnels and underground stations. The TWE running tracks were in bored tunnels and the stations were constructed mainly by cut and cover methods. As for the ISL, the

concept of keeping surface disruption to a minimum was paramount and the majority of stations (which consist of platforms linked to off-street concourses constructed by cut and cover method) were built within bored tunnels (Cater et al, 1984; Caiden et al, 1986). The station platform tunnels on the ISL are 8m in diameter. Tai Koo Shing Station was constructed in a large rock cavern (Sharp et al, 1986; see also Section 3.8). TWE and ISL were opened in 1982 and 1986 respectively.

The MIS, TWE and ISL projects together gave a railway of 30 route kilometres, and involved construction of 40 km of bored tunnels through varied ground conditions. The running tunnels are 5-6m in diameter, with enlargements of up to 13m wide to accommodate crossovers and fan niches.

The Eastern Harbour Crossing was built in 1989 to provide a combined road and rail link from the ISL Quarry Bay Station to the eastern end of the MIS's Kwun Tong Line. The underground works included a cross-harbour tunnel of a 5-cell immersed tube (1.86km submerged length, with four road lanes in two ducts, a ventilation duct and two MTR ducts, see also Section 3.4). They also comprised new underground platforms and adits (in rock) at Quarry Bay Station, railway tunnels (in rock) from Kwun Tong to Lam Tin and running tunnels (also in rock) at Quarry Bay, constructed mainly by bored tunnelling, with the use of compressed air in soft ground and a short cut and cover section.

A high-speed rail extension, the Lantau Airport Railway, linking the central urban areas to the new Hong Kong International Airport at Chek Lap Kok was completed in 1998, with 9.3km of the railway in tunnels. These include three sections of rock tunnels at Lai King, Tsing Yi, and East Lantau. Also included are the third immersed tube railway tunnel underneath Victoria Harbour, the cut and cover tunnels in reclaimed land between Kowloon and Tai Kok Tsui, and tunnels in reclaimed land in Central and at Tung Chung. The rock tunnels have cast insitu concrete lining with a 5.4m wide horseshoe shaped section (Asia Engineer, 1996; Crighton & Budge-Reid, 1998; Hardingham et al, 1998).

The Quarry Bay Congestion Relief Works were completed in 2001 to relieve the serious congestion at Quarry Bay Station. This project included construction of new underground station platforms, two 2.2km long, 6.2m diameter tunnels built using two hard rock TBMs and over 15 cross platform adits (Costello et al, 1986; Matson, 1989; Cooper et al, 2001; Tam, 1998 & 2001; Yang et al, 2005). The crossovers, new station platforms and passenger adits were constructed using drill and blast method. Chemical blasting and mechanical rock excavation, including a substantial amount of hand drill and split excavation, were carried out to form the platform tunnels and passenger adits in rock, near vibration sensitive areas or in close proximity to operating rail tunnels. The existing running tunnels were extended from Quarry Bay Station to North Point Station, with overrun tunnels onto Fortress Hill, stopping short of Tin Hau Station.

The Tseung Kwan O (TKO) Extension project, completed in 2002, comprised the Black Hill Tunnels (consisted of four 6.3m diameter rock tunnels from Yau Tong to Tiu Keng Leng, a central siding and ventilation adits, giving a total length of 8km), the Pak Shing Kok Tunnels (consisted of four 6.3m diameter rock tunnels from Tseung Kwan O to Area 86 Depot and a reversed siding, giving a total length of 6.4km), and the Lam Tin to Eastern Harbour Crossing Tunnels (1.2km long, 6.3m diameter cut and cover tunnels). The majority of these were excavated using drill and blast. Other underground sections including the railway tunnels in reclaimed land and three partially underground stations were constructed by cut and cover method (Tunnels & Tunnelling International, 1999 & 2002; Ho et al, 2001; Pan et al, 2001; Hill et al, 2002, Wightman & Cheung, 2002).

In 2004, the Tai Yam Teng Tunnels (Disneyland Resort Line), comprising a 120m long, 6.6m wide by 6.1m high, cut and cover box section and a 750m long, 6.1m span by 6m high, horseshoe shaped, drill and blast tunnel were completed (Salisbury et al, 2006).

Frew & Ng (2006) have summarized some of the geotechnical and tunnelling experience gained in the development of the MTR.

A number of major tunnels were also completed by the KCRC as part of their railway network upgrading projects in the last few years. Of the 30.3km route alignment under the West Rail project, a total of 13.8km is built in tunnels. These comprise the 5.5km long Tai Lam Tunnel (the longest rail tunnel built in Hong Kong), the 1.7km long Ha Kwai Tsing Tunnels, the 1.78km Tsing Tsuen Tunnels and the 120m Tsing Tsuen cut and cover section, completed in 2003 (Asia Engineer, 2000; Stenning et al, 2001; Storry & Stenning, 2001; Gould et al, 2002). The Tsim Sha Tsui Extension Tunnels were completed in 2005 (Ng et al, 2004). The Lok Ma Chau Spurline Tunnels are due to open in 2007 (Storry et al, 2006a & b).

### 3.4 Road Tunnels

Hong Kong has an extensive and well-integrated transport network, but is a city with a very high number of vehicles per kilometre of road (540,000 licensed vehicles and 276 vehicles/km in December 2005). Tunnels have been built to overcome the obstacles posed by Hong Kong's hilly terrain and to provide a cost effective road transportation system for its dense urban development.

The first Lion Rock Tunnel, 1.4km long, was opened in 1967, connecting the New Territories and the urban area (Payne & Walker, 1962; Davis, 1963; Payne, 1963). This was the first road tunnel in Hong Kong. Apart from the vehicular traffic, it also carried three trunk water mains to Kowloon as part of the Plover Cove Water Scheme.

The integration of early urban development in Hong Kong was restricted by Victoria Harbour. The Cross-Harbour Tunnel, 1.9km long (1.6km submerged length), being the first immersed tube tunnel in Hong Kong (steel tubes with a reinforced concrete lining), was opened in 1972 to link up Hong Kong Island and Kowloon (Asian Building & Construction, 1976; Pratt, 1987; Chow, 1991; Yang et al, 2006).

The second Lion Rock Tunnel, 1.4km long, was opened in 1978 to relieve traffic congestion due to the development of the Sha Tin New Town in the early 1970's.

More tunnels were subsequently constructed as part of the highway network as Hong Kong's vehicular traffic increased. The Kai Tak and Aberdeen Tunnels, 1.25km and 1.9km respectively, were opened in 1982 (Tunnels & Tunnelling, 1972; Chappell & Tonge, 1975 & 1976; Twist & Tonge, 1979; Cochrane, 1984). Tseung Kwan O and Shing Mun Tunnels, 0.9km and 2.6km respectively, were both opened in 1990 (Matson, 1984; Matson & Robinson, 1984; Highways Department, 1987; Bergfors & Coates, 1990; Larkin, 1990; Torpey & Larkin, 1990; Torpey & Hawley, 1991). Tate's Cairn Tunnel, 4km and the longest road tunnel in Hong Kong, was opened in 1991 (Martin, 1989; World Tunnelling, 1989; Matson & Porter, 1990; McFeat-Smith et al, 1999). Cheung Tsing Tunnel, 1.6km and the first 3-lane road tunnel in Hong Kong, was opened in 1997 (Tunnels & Tunnelling, 1994; McFeat-Smith, 1996; McFeat-Smith et al, 1999). The Route 3 Country Park Section Tai Lam Tunnel, 3.8km and 3-lane, was opened in 1998 (Endicott et al, 2000). The 200m long Ma On Shan Underpass was opened in 2004

(Yang et al, 2003; Ho & Li, 2006). Except for the Kai Tak Tunnel, these road tunnels are all dual tubes.

The 2.25km Eastern Harbour Crossing was completed in 1989 (the only cross-harbour tunnel with road and rail, see Taylor, 1990), and the 1.95km Western Harbour Crossing in 1997 (the first 3-lane cross-harbour tunnel in Hong Kong, see Leung, 1998; Robertson; 1998; Silva et al, 1998). Both of them are immersed tubes in concrete.

By December 2005, about 44km of road tunnels were constructed in Hong Kong.

### 3.5 Drainage and Sewage Tunnels

The Drainage Services Department (DSD) and the ex-Territory Development Department (TDD, which became part of a new department called the CEDD in July 2004) of the HKSAR Government have carried out a number of drainage and sewage tunnel projects.

The 1.82km Tseung Kwan O Sewer Tunnel, constructed by the ex-TDD, was completed in 1986. Drill and blast method was adopted, with temporary support provided by shotcrete, rock dowels and steel sets with lagging. Drill and blast was also used to construct the 9.1km long NWNT Sewerage Tunnel in 1992 (Construction & Contract News, 1992a; McFeat-Smith et al, 1999).

The Tolo Harbour Effluent Export Scheme implemented by DSD, which was completed in 1997, was the first use of a double shield hard rock TBM in Hong Kong by the Government for the construction of a 7.5km long 3.56m diameter effluent tunnel (Morris et al, 1992; McFeat-Smith, 1998; McFeat-Smith et al, 1999). The tunnel crosses about 12m below the Tate's Cairn Tunnel and about 4m above a water supply tunnel from the High Island Reservoir.

Open hard rock TBMs were also used for the tunnels (3.2-5.6m in diameter) under the Harbour Area Treatment Scheme (HATS) (previously known as the Strategic Sewage Disposal Scheme) Stage I project, which at depths of 75-145m below the sea level was unprecedented in Hong Kong (McFeat-Smith et al, 1999; Grandori et al, 2001; McLearie et al, 2001).

Trenchless techniques of tunnelling started to be used in Hong Kong in the late 1980s. Since then, more than 15km of sewers have been completed by DSD and the ex-TDD using different trenchless techniques, under different ground conditions.

The first major example was a tunnel for a 1.35m diameter sewer under the ex-TDD's Fanling South Trunk Sewer project in mid-1989 (McFeat-Smith & Woods, 1990; McFeat-Smith & Herath, 1994). This was the first time a sewer tunnel had been constructed using a pipe-jacked slurry shield TBM. The TBM was equipped with a cutterhead with 21 tungsten carbide bits to deal with sizeable boulders (up to 500mm in diameter). Bentonite slurry was used to balance the groundwater pressures (the tunnel soffit was at depths between 6m and 14m).

The same TBM was used by DSD in a number of other projects between 1991 and 1996. It performed satisfactorily in sands and clays, but had difficulties in ground with big boulders (larger than say 30% of the tunnel diameter), where the TBM became stuck and a rescue shaft had to be used. These sewers generally had a depth between 3m and 10m.

From 1993, there have been many drainage and sewerage contracts using pipe jacking with different types of shield TBMs and in different (open and/or closed) modes, with lengths extended to a few kilometres, e.g. the East Kowloon Sewer Tunnel (McFeat-Smith, 1994; McFeat-Smith & Herath, 1994), Central, Western and Wan Chai West Trunk Sewers (Mok, 2002) and the Aber-

deen, Ap Lei Chau and Pok Fu Lam Sewerage Stage 1B projects. In using the trenchless methods, pre-grouting of the ground ahead and excavation using pneumatic percussive tools or a mini-backhoe (if the size of the tunnel permits) were carried out inside the TBM to deal with old seawalls and artificial obstructions.

The 1.5km long, 4.4m diameter Kai Tak Transfer Scheme Tunnel, completed in 2004, saw the first use of a large diameter mixshield slurry TBM in Hong Kong (Salisbury & Hake, 2004). This second hand machine, originally built for the London Jubilee Line Extension project, was designed for mixed ground with a possibility of some strong rock. Progress was slow and there was a lot of cutter wear in the sections where Grades II/III granite of up to 145MPa was encountered and the thrust capacity of the TBM was found to be inadequate. Despite this, the TBM coped well with the remaining mixed ground conditions, during its operation at a depth up to 30m below the ground surface.

In the Wan Chai East and North Point Trunk Sewers project, completed in 2005, a 404m long 'S-curve' section of tunnel was achieved using a pipe-jacked slurry shield TBM for the first time in Hong Kong (Mok, 2006; Wang et al, 2006; Wong, 2006). The TBM was equipped with a compressed air chamber, allowing the cutters to be inspected and replaced.

By mid-2006, about 55km of drains and sewers had been constructed in Hong Kong.

### 3.6 Cable Tunnels

The normal practice for installation of underground electrical cables has been by cut and cover trench excavation on a section-by-section basis (typically 300m to 450m long). In order to reduce the number of cable joints in the system, the cables were laid after completion of the entire trench section, which often resulted in the trench being left open or decked over for some time before being reinstated.

In recent years, the HKSAR Government has strengthened control over excavation works in public roads, especially in carriageways, to minimize inconvenience to the public. In some cases trench excavations are not permitted, particularly along expressways, trunk roads and other busy roads. This has led to an increased use of cable tunnels and other trenchless methods of tunnelling to lay the cables. The benefits of using trenchless methods include minimal traffic disruption, reduced environmental impact and fewer expensive cable joints (Hui et al, 2002).

The Hongkong Electric Co. (HEC) Ltd has constructed a number of cable tunnels on Hong Kong Island and Lamma Island.

In 1988, a 3.1km long, 4.4m by 3.7m cable tunnel from Wah Fu to Bowen Road was built using drill and blast (McFeat-Smith et al, 1999; HEC website).

In 1993, an open hard rock TBM was used to construct a 5.5km long, 4.8m diameter cable tunnel from Nam Fung Road to Parker (Chai Wan Road) (Construction and Contract News, 1992b; McFeat-Smith, 1992, 1994 & 1998; McFeat-Smith et al, 1999; HEC website). The TBM had 32 single disc cutters of 483mm (19") diameter, with facilities for probing ahead at three positions. This was the first time such a hard rock TBM was used in Hong Kong.

In 1999, another cable tunnel, 0.8km long and 4.0m wide by 3.7m high, was constructed from Tin Wan to Wah Fu. Again, this was excavated by drill and blast, with the tunnel at a maximum depth of 180m.

In 2003, a 0.83km long, 4.0m wide by 3.7m high, horseshoe-shape cable tunnel was excavated by drill and blast from Cyberport to Wah Wu.

In 2006, two 2.5m span by 3.2m high horseshoe-shape tunnel sections, 0.22km and 0.13km long, were excavated by drill and split methods from Lamma Power Station to Yung Shue Wan south and at Pak Kok Tsui respectively. Hydraulic splitters with chemical agents (Bristar) were used to form the tunnel sections. A mini-Jumbo was used for drilling the longer tunnel to increase the rate of progress.

CLP Power (Hong Kong) Ltd has also built a number of cable tunnels in Kowloon and the New Territories (Hui et al, 2002).

In 2005, the 1.1km long, 3.8m diameter Kwai Chung cable tunnel was completed using drill and blast techniques. In the same year, the 0.65km long Tze Wan Shan cable tunnel and the 0.3km Tuen Mun River Crossing were also completed, both 3.3m in diameter, using an air plenum TBM with precast concrete segmental lining.

In 2006, the 3.2km long, 3.2m diameter Chi Ma Wan cable tunnel was completed using an open hard rock TBM, with drill and blast to form joint bays and a dismantling chamber. In the same year, a 0.23km long and 3.0m in diameter cable tunnel was built using an Earth Pressure Balance (EPB) TBM, in addition to the cut and cover method, at KCRC's Hung Hom Freight Yard.

Other than cable tunnels, a number of cable duct crossings have been constructed over the years using trenchless methods of tunnelling such as manual or machine methods of excavation with lateral support (ELS), pipe jacking and HDD. Hand or machine-based ELS methods and pipe jacking are normally carried out to form tunnels of over 900mm in diameter (below which man-entry is generally not considered to be safe), and HDD has been used to form holes in the range of 330mm to 820mm in Hong Kong.

Hand or machine-based ELS methods are widely adopted for construction of cable duct crossings under busy roads or congested utility zones. The typical internal size adopted by HEC is 2.5m high by 2.0m wide. These tunnels can be constructed through various ground conditions with sub-horizontal channel planking or pipe piles driven ahead of the excavation face to form the tunnel wall structure and provision of lateral structural steel internal shoring, which is usually left in place. Depending on the ground and groundwater conditions, probing and pre-grouting of the ground ahead of the excavation face and some proof-drilling to check the grouting coverage achieved and to test the effectiveness of groundwater cut-off may be carried out before excavation.

Pipe jacking is carried out by jacking short pipe sections through the ground, from a jacking pit at one end to a receiving pit at the other end. The diameter of the pipes is usually 1.2m or more to facilitate construction. The largest pipe jacking project completed on Hong Kong Island for cable installation is 2.4m in diameter.

Similar to hand or machine-based ELS methods, in constructing cable duct crossings using pipe jacking, probing ahead of the excavation face is carried out and, where necessary, the ground pre-grouted to provide the necessary strength and stiffness, and to reduce any groundwater inflow, prior to excavation. Manual or machine excavation of the ground (and if necessary removal of boulders and other obstructions) is then carried out. The cable ducts are usually grouted up after the cables are fed through the pipe sleeve. Crossings constructed using pipe jacking are usually less than 12m below ground level.

Since the late 1980s, hundreds of cable duct crossings have been constructed using the above-mentioned hand or machine-based ELS methods and pipe jacking; hence it is not possible to mention them individually.

The HDD technique has been used to install cable duct crossings up to about 2km in length. It is a suitable method for construction of long tunnels for crossings under a river or the sea, but not for minor crossings due to high mobilization costs and the relatively large working space required on the ground surface.

In the application of HDD for cable installation, a small diameter pilot hole is first drilled along the required alignment, using an asymmetric drill bit powered by a down-the-hole motor and bentonite-based drilling mud. The pilot hole is then reamed (enlarged) to about 1.3 to 1.5 times the diameter required. A HDPE pipe (or a series of such pipes) with or without a steel casing is then pulled through the hole, and the cables are then fed through the pipe (or pipes).

Three such crossings have been completed using HDD since 2002. One is 0.7m in diameter, achieving a minimum radius of curvature of drilling of 330m, and another two are 0.6m in diameter. Two of the HDD operated at a maximum depth of 90m below the sea level (Tam, 2001). With accurate surveying tools and controlled steering, the maximum deviation of the pilot hole from the specified drilling alignment for HDD over a 1km distance can be limited to within about 2.5m (Hui et al, 2002).

### 3.7 Other Tunnels

Apart from railway and cable tunnels, a number of other private tunnels have been constructed. These include a few small private drainage and sewage tunnels, as well as tunnels for seawater cooling pipes for the Hongkong Bank Headquarters and for buildings in Queensway (Archer & Knight, 1986; Owen & Tam, 1989; Troughton et al, 1991). A 2.6km long 3.35m diameter man-accessible tunnel for a 600mm gas pipe was completed in 1994, through granite at Braemer Hill, using an open hard rock TBM (McFeat-Smith et al, 1999). A 600m long privately developed and operated tunnel, the Discovery Bay Tunnel Link, was completed in 2000. This was excavated by drill and blast.

In Hong Kong, such private tunnels are subject to geotechnical control under the Buildings Ordinance, Cap. 123, in which "building" is defined to include "cavern or any underground space adapted or constructed for occupation or use for any purpose including its associated access tunnels and access shafts". The Building Authority is responsible for enforcement of the Buildings Ordinance. The GEO provides geotechnical advice to the Building Authority on the submissions made to the Authority and observations made during site audits, in the interest of public safety.

HDD has been used by the Hong Kong and China Gas Company Limited (HKCGCL) to install gas pipes. In 1995, two steel gas pipes of 300mm diameter and 450m long were installed using HDD through marine deposits up to 15m below sea level, underneath a seawall at Ta Pang Po in north Lantau. In 2002, a 400mm diameter polyethylene gas pipe was installed inside a 0.55m diameter backreamed hole formed using HDD. In 2006, HKCGCL placed a 30m long 750mm diameter steel gas pipe inside a 1.1m diameter concrete sleeve pipe crossing constructed under the Tai Wan stream in Sai Kung, using the pipe jacking method. Also, a 40m long 400mm diameter polyethylene gas pipe was placed inside a 0.45m diameter casing installed using the pipe ramming method, underneath the Fanling Highway, with the casing driven from a launching pit to a receiving pit by a pneumatic hammer.

In 1996, two vehicular tunnels (one being 370m long and the other 500m) were constructed, using cut and cover method, for the new Hong Kong International Airport at Chek Lap Kok.

Both are in concrete and comprise triple tubes of 25-26m wide by 8m high, with one of the tubes for utilities.

A 1.15km long, main access tunnel and ten 27m long adits were built in 1997, for the Kau Shat Wan Explosives Depot managed by the GEO. In 1998, 100m and 80m long tunnels and deep shafts (76-89m deep, and 2.75m in diameter) were constructed for the glory hole construction under the GEO's project on rehabilitation of the Anderson Road Quarries (Lam et al, 2003). Both were excavated by drill and blast.

There are also a significant number of disused tunnels in Hong Kong.

As of January 2006, there are 92 disused tunnel networks known to the GEO (GEO, 2006b). These include air-raid tunnels built during the Second World War, and other tunnels built before or during the Japanese occupation of Hong Kong. While most of these old tunnels are unused, three tunnel networks are currently being occupied or used for different purposes: the bunkers at Shouson Hill are leased to a company as wine cellars, one network at Lei Yue Mun is being used as part of the Hong Kong Museum of Coastal Defence, and one network at Sai Ying Pun is being used by the Hong Kong Electric Co. Ltd for routing electric cable.

Mining activities in the past have left underground networks of tunnels and workings in different localities. Four mines had been particularly important in the economy of Hong Kong, including the Ma On Shan Magnetite Mine, Li Ma Hang Lead Mine, Needle Hill Wolframite Mine and West Brother Graphite Mine (Roberts & Strange, 1991; Strange & Woods, 1991; Williams, 1991; Woods & Langford, 1991). At Ma On Shan, which was closed in 1981, there was a 2.2km haulage drive at the 110mPD level. During site investigation for the design of the Shing Mun Tunnels (Route 5) it was found that the mine workings at their lowest level were approximately 1m above the crown of the proposed tunnel (Torpey & Larkin, 1990). The civil contract for the project required that before the tunnels reached this area the water had to be pumped out of the abandoned works and the void back-filled with concrete and cavity grouted. The contractor was also required to probe ahead of the main tunnel drives to assess whether any pre-excavation ground treatment would be necessary. At West Brother Island, by 1964 the mine workings had reached 90m below sea level and serious water inflow problems were encountered. The island was levelled in the mid-1990s to provide for a navigation facility for the International Airport at Chek Lap Kok.

### 3.8 Caverns

The development of caverns in Hong Kong is summarized by Chan & Ng (2006). Since 1982, the GEO, in collaboration with the relevant Government departments and regulatory authorities, including the Planning Department, the Buildings Department, the Fire Services Department and the Lands Department, has conducted a series of studies on the planning, design, construction and regulatory control on the development of underground caverns in Hong Kong. The outcome of these studies has been incorporated into the Buildings Ordinance, the Hong Kong Planning Standards & Guidelines, Geoguide 4: Guide to Cavern Engineering (GEO, 1992) and the Guide to Fire Safety Design for Caverns. The GEO also assisted Government departments in considering and processing cavern development proposals for some infrastructure projects. The current state of practice is that established in the mid-1990s.

A number of major rock caverns have been constructed in Hong Kong. The "first generation caverns" are those constructed

in the 1980s (Table 1). These were part of the tunnel networks for water supply (e.g. valve chamber of the Western Aqueduct) or railways (e.g. MTR Island Line substation and station at Sai Wan Ho and Tai Koo respectively). The three "second generation caverns" constructed in the 1990s were purpose-built for environmentally unattractive facilities. They include the caverns for a sewage treatment plant at Stanley, an explosives depot at Kau Shat Wan and a refuse transfer station at Mount Davis (Cheng et al, 1999). All were constructed using drill and blast techniques.

Table 1. Major rock caverns in Hong Kong

Type of Facility	Approximate Dimensions	Year Completed
<b>FIRST GENERATION CAVERNS</b>		
Valve Chamber (Western Aqueduct)	20 m long, 8 m high, 20 m wide	1984
MTR Substation (Sai Wan Ho)	18 m long, 13 m high, 16.5 m wide	1985
MTR Station (Tai Koo)	250 m long, 16 m high, 24 m wide	1985
<b>SECOND GENERATION CAVERNS</b>		
Sewage Treatment Works - Main Cavern (Stanley)	130 m long, 17 m high, 17 m wide	1994
Explosives Depot (Kau Shat Wan, Lantau Island)	20 m long, 6.8 m high, 13 m wide	1997
Refuse Transfer Station - Tipping Hall (Mount Davis)	60 m long, 12 m high, 27 m wide	1997

Other than providing the direct benefit of housing an environmentally objectionable or unattractive facility, the cavern option also:

- releases the surface land for other uses thereby reducing pressure for land and development cost, especially at prime sites,
- provides for a solution for safety and security-sensitive facilities,
- helps to contain landslide risks in the long term as the need for site formation close to steep hillsides could be correspondingly reduced,
- releases the pressure for extensive reclamation for developable land, and
- provides a source of rock products such as aggregates for concrete, seawall armour rocks, etc.

## 4 RISK MANAGEMENT

### 4.1 Recent Developments

Systematic identification and management of construction risks is becoming increasingly common practice in many areas of the construction industry and, in some jurisdictions, has become a regulatory requirement as part of construction site safety requirements. In Hong Kong, the "Tang Report" (CIRC, 2001) on Construct for Excellence pointed towards the need to adopt similar practices in Hong Kong's construction industry.

With regard to tunnel works, a review was carried out by the HKSAR Government in 2004 to examine the implementation issues of the HATS Stage I project, after experiencing the construction problems associated with major water inflows (Gran-

Table 2. Typical examples of geotechnical hazards and construction-related risks in tunnel construction

Examples of Geotechnical Hazards	Risk Treatment Option
Variable rockhead and mixed ground conditions	Avoid/reduce the risk, e.g. by selecting a suitable tunnel alignment based on adequate site investigation
Presence of buried obstructions (e.g. corestones, boulders, disused piles, old seawalls and other artifacts)	
Presence of foundations and other subsurface installations	Reduce the risk, e.g. by specifying or selecting appropriate tunnelling method(s) with adequate additional site investigation during construction
Presence of permeable zones that may be subject to high groundwater pressure or that may convey large quantities of inflow	
Presence of weak or compressible ground (e.g. weak/fractured zones, faults, fissures, clay-coated discontinuities, granular soils and soft/ compressible soils). Ground under very high or very low insitu stress.	Treat the risk, e.g. by specifying appropriate ground support (e.g. precast segmental linings with back grouting), ground strengthening, groundwater control and containment measures, and implementing preventive or protective works
Presence of explosive or poisonous gas (e.g. methane) or other aggressive chemicals	
Salinity of groundwater	
Contaminated ground, e.g. due to ingress of leachate from landfill	

Examples of Construction Method-related Risks	Associated Tunnelling Method
Excessive ground settlement/lateral displacement due to ground loss (including rock falls within the tunnel and tunnel face collapse) caused by unsuitable tunnel construction method/equipment/control measures, resulting in adverse impacts on life or property	All methods
Excessive ground settlement/lateral displacement due to groundwater inflow/drawdown caused by inadequate tunnel construction method (e.g. pre-grouting not carried out in difficult ground), or inadequate ground treatment or groundwater control or inadequate consideration of changes in ground stresses or groundwater regime, resulting in adverse impacts on life or property	All methods
Excessive ground vibration, causing damage to adjacent facilities	All methods that use vibratory equipment, or that could induce ground vibration such as drill and blast
Ejection of rock and protective material (e.g. blast door) at the tunnel portal or areas with a thin ground cover, due to explosion and/or gas pressures, causing dangerous occurrence	Drill and blast
Blowout or ground heave for tunnelling under high compressed air or slurry or grouting pressure, resulting in dangerous occurrence	All methods that create pressure in the ground, e.g. compressed air or slurry TBM and grouting

dori et al, 2001; McLearie et al, 2001). The review was led by the Environment, Transport and Works Bureau (ETWB) with input from Government departments including DSD and GEO. During this process, the GEO carried out a review of the technical literature on the subject of risk management of tunnel works. This indicated that many problems in tunnelling, particularly those that resulted in a direct impact on the public, were due to inadequacies in the management of geotechnical risks. These geotechnical risks were either, as Barton (2004) has suggested, often a result of an unexpected combination of factors or the unexpected magnitude of a single factor. Such incidents resulted in significant losses to clients, contractors, consultants and the insurance companies worldwide.

Internationally, because of the tunnel failures experienced in recent years, the insurers' perception was that the tunnelling industry had an inconsistent approach to risk management, to the extent that it threatened to withdraw the provision of insurance coverage to the tunnelling industry as a whole (Mellors et al, 2004). As a way forward, the insurers worked with the tunnelling industry to develop a "Joint Code of Practice for Risk Management of Tunnel Works", which was published by the Association of British Insurers and the British Tunnelling Society in 2003. This became the forerunner of the international code entitled "A Code of Practice for Risk Management of Tunnel Works"

published by the International Tunnelling Insurance Group (ITIG, 2005) in late 2005.

The Code of Practice emphasises the importance of risk management in all stages of a project, i.e. project development, contract procurement, design, and construction stages. It promotes identification of hazards and the associated risks during all four stages, preparation of risk registers, cascading the registers throughout the project to ensure that all parties are aware of the previously identified hazards and risks, continuous review and updating of the registers throughout the project, and identification of a party to be responsible for managing each element of risk. It highlights the need for the project client to take proactive action and responsibility in risk management. It also requires the project client to carry out adequate site investigation and to prepare (or have prepared on its behalf by a competent agent) "ground reference conditions" for projects involving tunnel works.

The KCRC has followed the key recommendations of the Joint Code of Practice in the implementation of its Kowloon Southern Link project, which is currently under construction. The project involves construction of 3km of running and station tunnels, using both cut and cover methods and a large diameter slurry TBM. KCRC has incorporated relevant provisions of the Code into the contract documents for this project.



In 2005, a technical guidance document, TGN25, on geotechnical risk management was issued by GEO (GEO, 2005). The preparation of this TGN had significant input from members of the HKIE Working Group. TGN25 refers to, and has incorporated the essential elements of, the International Code of Practice for Risk Management of Tunnel Works. It also refers to an administrative instruction issued by the HKSAR Government, ETWB TC(W) No. 6/2005, on Systematic Risk Management, which applies to public works projects with cost estimates exceeding HK\$200M (US\$25.6M); geotechnical risk management for tunnel works being an integral component of the systematic risk management for the overall project.

In the same year, the ETWB also issued ETWB TC(W) No.15/2005 on Geotechnical Control for Tunnel Works. Under this circular, the GEO audits the geotechnical aspects of design submissions on government tunnel works and the adequacy of the project's site supervision and geotechnical risk management provisions. The GEO will also conduct site audits on the implementation aspects. The scope of these audits is on risk to public life and property. This parallels the GEO's existing role to provide a geotechnical advisory service to the Building Authority on private tunnel works controlled under the Buildings Ordinance.

From the HKSAR Government's perspective as a regulator, a key aim of geotechnical risk management in tunnel works is to ensure that the works do not affect adversely public life or property. To help achieve this, it becomes the responsibility of the project client, with due advice from the project manager and an experienced geotechnical professional, to ensure that adequate resources are provided and an adequate system is in place for the management of geotechnical risks in the construction of such works. The implementation details should take into account the level of risk to life and property.

Compliance of the Code of Practice is effectively mandatory if the client wishes to transfer some of the contract risk to the insurance market. TGN25 advises that insurance of the risk does not remove the need, or reduce the responsibility of the client, to ensure safety is properly managed. In complying with the Code, insurers expect availability of ground reference conditions. These may be put together by the geotechnical professionals preparing the contract, or by the tenderers as part of tender submissions.

Apart from those arising from geotechnical hazards, some geotechnical risks are construction method-related (Table 2). Consequently, evaluation of the tunnel alignment, layout design and construction methods is an important step in managing such risks, in that exclusion of particular layout designs or construction methods could avoid specific risks. In some cases, the contract may need to exclude designs or construction methods that are not acceptable based on risk management considerations.

The background to the recent developments in the geotechnical control and risk management for tunnel works in Hong Kong is given in Pang et al (2006).

#### 4.2 Current Practice

In Hong Kong, the current practice is that the geotechnical risks of a tunnel works project with respect to public safety are examined in a geotechnical assessment or geotechnical risk assessment report. A blasting assessment report is also prepared if rock blasting is to be carried out. The risk of ground collapse and the risks associated with excessive ground deformation, ground vibration and/or groundwater inflow and drawdown, as well as effects on life and property are assessed. The geotechnical risk assessment is conducted from the early project planning stage, so

that adequate funding and time are allocated to manage the risks during design and construction.

The geotechnical risks during construction are managed by careful contract specification. The contract would have to specify the performance measures and limits, allow for the major items of risk mitigation works anticipated and contingency measures, and require a quality management system with experienced supervision personnel to ensure timely provision of ground support and ground treatment, and monitoring and review of the construction effects and risks to life and property. For works for which the design responsibility is assigned to the contractor (e.g. Design and Build contracts), the pre-tender reference design is required to be carried out to a good level of detail. The design would have to deal with the geotechnical risks, and provide for robust risk mitigation works to be carried out should these be found to be necessary by the Engineer or Supervising Officer during construction.

In undertaking the geotechnical risk assessment, existing buildings, structures and other facilities affected are surveyed, studied and classified in terms of their condition and time of construction, and for buildings and structures an assessment of the potential damage is undertaken. KCRC has adopted the 'slight damage' category (Burland et al, 1977; Boscardin & Cording, 1989) in their contracts for the Kowloon Southern Link project. The contracts require that the allowable limits set by the authorities and major owners should not be exceeded. Contract performance/action limits, normally expressed in terms of Alert, Action and Alarm levels with corresponding actions defined under the contract, are also specified together with the methods of measurement. The validity of these limits is subject to confirmation by the responsible design professional, for risk control purposes.

The assessment of ground settlements due to construction of the tunnels and the associated temporary works, and its effects on adjacent buildings and other facilities, is usually carried out using the three-stage risk assessment approach recommended by Burland et al (2001). Different degrees of geotechnical input and analyses are applied depending on the level of risk and the stage of the project.

The assessment of piezometric drawdown and its effects is carried out where the tunnel is to be constructed under a groundwater table. This is done using conventional consolidation theory. The aim is to arrive at allowable piezometric drawdown levels and allowable water inflow limits along the tunnel alignment. Account is taken of the site-specific data on hydrogeology and structural, stability and maintenance conditions of the sensitive receivers. Reference is made to the known past fluctuations in groundwater pressures and ground settlement and vibration levels.

Local data on settlements due to construction of bored tunnels (including the temporary walls) and their effects were reported by Davies & Henkel (1980), Morton et al (1980a & b), Howat & Cater (1983), Cater et al (1984), Budge-Reid et al (1984), Cowland & Thorley (1984), Cater & Shirlaw (1985), Cowland & Thorley (1985), Cater et al (1986a & b), Thorley et al (1986), Stenning et al (2001), Norcliffe et al (2002), Salisbury & Hake (2004), Mok (2006) and Wang et al (2006). These cover a wide range of ground conditions and construction methods. Guidance is also given in GCO Publication No. 1/90 (GCO, 1990) on the assessment of ground movements due to wall construction, dewatering and bulk excavation in the construction of deep excavations.

In the case of drill and blast, the assessment of the effects of ground vibration is carried out using available attenuation relationships of blasting waves, site-specific data on ground and

groundwater conditions, and information on the structural, stability, and maintenance conditions of the facilities affected. Local data on blasting wave attenuation were reported by Smith & Morton ((1986), Clover (1986), Troughton et al (1991), Sekula & Johansson (1998), Zou (2002) and Murfitt & Siu (2006a & b). For slopes, blasting effects on slope stability are assessed. The guidance given in GEO Report No. 15 (Wong & Pang, 1992) is commonly used.

#### 4.3 Contract Risk

Other than management of geotechnical risks with respect to life and property, the tunnelling industry and client organisations in Hong Kong have recently been reviewing the contract risk sharing mechanisms in tunnel contracts, including the sharing of geotechnical risks. The current situation is that the geotechnical risks in tunnel contracts are largely allocated to the contractor. The industry is looking for more equitable risk sharing to be achieved. There is currently much discussion on whether the client should provide interpretive geotechnical reports and ground reference conditions to the tenderers. The use of Geotechnical Baseline Reports and, if they are to be used, what parameters should be used for setting the baselines, and what methods of measurement should be adopted to achieve consistent and repeatable remeasurement of cost and time when differing geotechnical conditions are encountered during construction, is being further debated.

It is of interest to note that in the tunnel contracts for the MTR Modified Initial System, borehole information together with details of the assumptions made by the Engineer in preparing the outline (reference) design were provided to the tenderers. This included assumed positions of soil/rock interfaces, the approximate locations where soft marine soils would be encountered and the need for compressed air and/or ground treatment (Haswell et al, 1980).

In some of the past rock tunnel projects, the costs of major items of tunnel support and groundwater control works are re-measured and paid for, e.g. the Tseung Kwan O Tunnel (Matson & Robinson, 1984), the Tolo Harbour Effluent Export Scheme (McFeat-Smith, 1992) and the CLP Kwai Chung cable tunnel.

On the KCRC's Kowloon Southern Link contracts, KCRC provided all geotechnical data available (Geotechnical Data Reports), interpretations (Geotechnical Basis of Design Reports) and risk assessments (Existing Buildings and Structures Reports, Ground Movement Prediction Reports and Geotechnical Instrumentation Reports) to the tenderers. The tenderers are required to provide their geotechnical interpretations and risk assessments which were then reviewed in the tender assessment exercise of each contract.

## 5 RESEARCH

Three universities in Hong Kong are conducting research in the area of tunnelling. They are The University of Hong Kong, Hong Kong Polytechnic University and Hong Kong University of Science and Technology.

The University of Hong Kong has two study areas. The first study area is related to investigating the hydrogeological behaviour of a highly fractured water-bearing rock mass. The piezometric drawdown and ground settlement data collected during the construction of a deep sewage tunnel in Hong Kong were used in the study (Kwong, 2005). The shape of the drawdown cone followed closely that of a classical dewatering well. The study demonstrated that the only credible cause of the drawdown and

settlement was due to this deep tunnel intersecting a system of rock fractures. From the 2-D numerical seepage modelling, it was found that a high mass permeability of about  $4 \times 10^{-5}$  m/s was needed in the rock for the predictions to match observations (piezometric drawdown profile, settlement and water inflow).

The study found that once significant inflow occurred, a steady state seepage condition was established very quickly. The marine deposits overlying the rock created a confined aquifer condition, and prevented the replenishment of water from the sea above into the depressurised rock layers. The pore pressure reduction in the alluvial deposits and completely decomposed volcanic (CDV) layers between the marine deposits and the underlying rock was slow because the drawdown cone spread out laterally more than usual due to anisotropy in the rock mass permeability (higher in the horizontal direction). Ground surface settlement due to pore pressure reduction was mainly attributed to the underlying alluvial clay and sand and the CDV layers.

The second study area is related to investigating the blast-induced vibrations from construction of tunnels, with particular emphasis on its effects on nearby slopes. Site-specific vibration monitoring data from the drill and blast construction of a road tunnel were collected to derive a site-specific attenuation equation appropriate for underground blasting works at that site. Numerical dynamic modelling is being carried out, taking into account the geology encountered and the measured dynamic properties of the rock mass and the completely decomposed granite layer above. The objective is to assess the feasibility of using numerical modelling technique to predict the tunnel blasting vibration at the nearby slopes by comparing the predicted values with the monitoring data collected.

Physical modelling has been carried out by The Hong Kong Polytechnic University on the time-dependent damage around a tunnel opening in a non-persistent jointed rock mass (Wong et al, 2000, 2001 & 2002). Understanding of the failure mechanisms of the disturbed/damaged zone in such a rock mass is important in tunnelling because improper use or overestimation of its strength can lead to catastrophic failure.

Experiments were carried out using a mixture of plaster and water (100:60). To study the failure process, loading was applied on a block of such material (the test specimen) and then an opening was drilled at the centre of the block to simulate tunnel excavation (diameter of the opening was 20mm, representing a 4m tunnel in prototype scale). The development of the failure process and the growth rate of cracks were observed and strain gauges were installed to measure the strains induced around the tunnel opening. The experimental technique was verified by comparing the results obtained with the observations made in a real project.

The study found that the initial growth rate of cracks was slow but the growth rate increased progressively some time after the tunnel was completed. The time of 'creeping failure' around the opening (when fragments detached from the two sides and the roof of the opening and there was a sudden change in strain levels around the opening) depended on the initial vertical stress level.

Both centrifuge modelling and three-dimensional (3-D) numerical modelling are being carried out at the Department of Civil Engineering of the Hong Kong University of Science and Technology (HKUST). For centrifuge modelling, the HKUST centrifuge with a 4-axis robotic manipulator (Ng et al, 2002) for in-flight simulation of various construction activities was used. For three-dimensional numerical modelling, the ABAQUS computer program was used. The subjects studied or being studied include:

- (a) centrifuge modelling of multiple tunnel interaction caused by advance of a new NATM tunnel close to an existing tunnel in sand, in which the settlement profile and the bending moment distribution and deformed shape of the existing tunnel were studied (Ng et al, 2003),
- (b) 3-D elasto-plastic coupled consolidation finite element analyses of ground settlements due to tunnelling to investigate the role of  $K_0$  and stiffness anisotropy of the soil (Lee & Ng, 2002),
- (c) 3-D parametric study of use of soil nails for stabilising tunnel faces, in which it was found that the soil nails reduced the magnitude of stress relief at the tunnel heading during excavation, and in turn minimises soil yielding and excess pore water pressure generation in the soil around the heading (Ng & Lee, 2002),
- (d) 3-D analyses of twin tunnel interactions in NATM tunnelling, in which it was found that the lagging distance between the twin tunnel has a stronger influence on the horizontal movement than on the vertical movement of each tunnel, and it significantly affected the shortening of the horizontal diameter of the tunnels and led to generation of highly non-symmetrical pore water pressure distributions around both tunnels (Ng et al, 2004), and
- (e) 3-D numerical modelling to investigate the effects of advancing an open face tunnel on an existing loaded pile, in which it was found that the tunnel excavation induced complex distributions of relative subsurface settlements and both positive and negative side shear stresses along the pile but did not significantly affect the existing bending moment and axial load distribution within the pile (Lee & Ng, 2005).

In the last four cases, stiff clay (London clay) is being modelled.

Further research needs identified include development of improved methods for:

- (a) characterising the hydrogeological behaviour of fracture rock masses, identifying where the water inflow problems lie and predicting ground settlement, through systematic collection and synthesis of instrumented field data,
- (b) modelling multiple tunnel-tunnel and tunnel-foundation interaction in local soils and rocks, taking into account the construction sequence and the structural stiffness of the facilities affected,
- (c) assessing the effects of blasting vibration on existing slopes, foundations, underground facilities and support systems (such as anchors, bolts and dowels), taking into account the frequency content of the vibration waves and the facilities affected,
- (d) assessing the effects of gas pressures generated by blasting on nearby slopes,
- (e) instrumentation, monitoring, risk control and risk mitigation, and
- (f) economic construction.

Given the large number of tunnel projects under planning in Hong Kong, researchers will need to discuss with the major stakeholders to understand the future project needs in order to prioritise their research efforts and use appropriate research methodology, if they wish their results to be useful and value-adding to these projects in due course.

## 6 PROJECTS AHEAD AND LIKELY FUTURE DEVELOPMENT

At the time of writing, the construction of the Eagle's Nest, Nam Wan and Sha Tin Heights Tunnels, which are part of the Route 8 project, have just been completed for opening in 2007. The

Kowloon Southern Link railway tunnels and the Po Shan Road drainage tunnels are being constructed. Design of some major urban drainage and sewage tunnels is on-going, and planning is being carried out on a number of mass transit railway, road and water tunnels. The current and planned projects involving tunnel works in the next eight years amount to project estimates of over HK\$50 Billion (US\$6.4 Billion).

With continuing demands for new and replacement public and private facilities, there is potential for significant tunnel and underground space development in Hong Kong in the future. The future development of projects is likely to be influenced greatly by factors such as availability of suitable surface land for new and replacement facilities, and environmental, traffic and transport impact considerations.

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## APPENDIX

Current membership of the Hong Kong Institution of Engineers Geotechnical Division Working Group on Cavern and Tunnel Engineering include:

Richard Pang, Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government (Chairman, from 2003 to August 2006)

Joseph Lo, Maunsell Geotechnical Services Limited (Chairman, from September 2006)

David Salisbury, Ove Arup & Partners (Hong Kong) Ltd

Derek Arnold, Black & Veatch (Hong Kong) Ltd

Peter Cheng, Nishimatsu Construction Co., Ltd, Hong Kong Branch

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 Joseph Lo represents the Association of Geotechnical and Geoenvironmental Specialists (HK) Ltd and the Institute of Materials, Minerals and Mining (Hong Kong Branch), and David Salisbury represents the Hong Kong Tunnelling Society, respectively.

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