LESSONS LEARNED FROM RECENT MRT CONSTRUCTION FAILURES IN ASIA PACIFIC

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ABSTRACT: Modern urban mass rapid transit systems (MRT) are frequently constructed underground. Since constructions are carried out mostly at depths of 15 to 30 m below ground surface, the risks are very high. This paper compiles major failures in underground MRT constructions since the year 2001 and classifies them in accordance with their causes of failure and consequences, with the ultimate goal of developing a system for managing risks involved in underground, particularly MRT, constructions. Basically, the classification system recommended by International Tunnelling Association is adopted for the purpose. Five major failures with disastrous consequences are discussed with their causes identified and consequences given. In consideration of the high fatality and huge economic losses involved in these failures, there is an urgent need for the construction industry to establish risk management policies, especially for underground works. Accordingly, the general principles of risk management are discussed

Keywords: MRT construction failures, Tunneling

INTRODUCTION

As metropolitan populations grow, rapid transit systems become a necessity for solving traffic problems and their benefits are widely appreciated. In this region, Japan has the longest history of MRT construction with its first route open for service in 1927, followed by China (Beijing) in the 60's, North Korea (Pyongyang), Korea (Seoul), Hong Kong in the 70's, Singapore in the 80's, Republic of China (Taipei) in the 90's, and Thailand joined the bandwagon in 2004. Most of the cities are still extending their existing lines and expanding their existing networks, and many new systems are to be constructed in the coming years. For example, there are MRT systems already in operation in 6 cities in China and new MRT systems have been approved to be constructed in 5 more cities by the Chinese government. In addition, 11 cities are applying or going to apply for approvals.

Most of these major Asian cities, with thick young sediments deposited at the surface, have ground conditions which are hostile to the underground works necessary for rapid transit systems, so failures frequently occurred during construction. This paper attempts to summarize major events, as listed in Table 1, which have occurred since the turn of the century, i.e., the year 2001 and onward. Information was collected mainly from 3 sources: (1) the authors' personal involvement, (2) available literature, (3) web pages. The list is by no means exhaustive as numerous events are unreported. Although it is intended to cover the entire Asia Pacific region, the information collected is rather limited to that related to MRT constructions in Guangzou, Beijing, Shenzen, Taipei, Kaohsiung, and Singapore. The authors will continue their efforts of collecting information from other cities and obtaining more details on individual events. The eventual goal of this exercise is to establish a database for risk management of MRT constructions.

CLASSIFICATION OF EVENTS

To facilitate statistical analyses for the purpose of establishing parameters for risk management, events are categorized according to the causes of failure and the consequences as a result of failure.

Classification of Causes of Failures

As listed in Table 2, there are 22 failure modes which are commonly associated with underground works, including open cut, cut-and-cover construction, shield tunnelling, mining (i.e., tunnelling by using the NATM method), and ground treatment. Failures are also frequently associated with rupture of underground utilities so this has also been included in the list. Codes are assigned to these failure modes so they can be defined consistently in the future to make statistical analyses easier.

Classification of Consequences

The guidelines, entitled "Guidelines for Tunnelling Risk Management, International Tunnelling Association, Working Group No. 2" (hereinafter called the Guidelines), proposed by the International Tunnelling Association (ITA, 2004) for classifying the consequences of potential hazards in tunnelling works provide an excellent framework for classifying the consequences of failures and the principles given therein are applicable for other types of underground constructions. The items proposed by ITA for classifying consequences are:

Injury to workers or emergency crew
Injury to third parties
Damages to third party property
Delay (to project schedule)
Economic loss to owner
Harm to the environment
Loss of goodwill

The last two items are not considered herein because of the lack of information. In addition to the remaining 5 items, the authors are of the opinion that disruption to traffic may lead to great social loss and is an important item to be considered in classifying consequences.

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It should be noted that the Guidelines are applicable to underground construction projects with a project value of approximately 1 billion Euros and duration of approximately 5 to 7 years. The construction of MRT lines, in general meet these two criteria, however, individual construction contracts are usually shorter in duration and lower in value.

Table 1 Significant events in MRT construction since year 2001

Event	MRT System	MRT Line	Clauses		Consequences					
						Classification				
			Code (Table 2)	Description	Description	Injury (Table 3)	Economic Loss to Third Parties (Table 5)	Total Economic Loss (Table 4)	Delay to Critical Path (Table 8)	Disruption to Traffic (Table 9)
1-02-14	Guangzou	No. 2	OT	Collapse of hand-dug caisson (depth = 17m), could be due to rupture of a watermain	1 worker died	serious	insignificant	insignificant	insignificant	insignificant
1-05-25	Shenzhen	No. 1	OC-1	Collapse of trench (width = 1.7m, depth = 2m)	1 worker died and 2 were injured	serious	insignificant	insignificant	insignificant	insignificant
1-08-20	Shanghai	No. 4	OC-1	Earth slip	4 workers died	severe	insignificant	insignificant	insignificant	insignificant
2-02-04	Beijing	No. 5	ST-3	Settlement/sinkhole over shield tunnel	3 residential houses collapsed	none	serious	serious	insignificant	insignificant
2-09-03	Nanjing		MG-1	Settlement/sinkhole over mined tunnel	sinkhole diameter = 4m, depth = 2.4m, rupture of watermain and sewer	none	considerable	considerable	insignificant	considerable
3-02-01	Taipei	Banqiao	ST-1	Leakage at tunnel eye	more than 100 residences were damaged	none	severe	severe	severe	considerable
3-07-01	Shanghai	No. 4	MG-6	Failure of crosspassage	refer to Section 3.1	none	disastrous	disastrous	disastrous	considerable
3-07-01	Nanjing		ST-2	EPB Shield machine encountered piles	Sinkhole of unknown size	none	considerable	considerable	insignificant	insignificant
4-03-17	Guangzou	No. 3	CC-1	Failure of retaining wall	1 worker died	serious	insignificant	considerable	insignificant	insignificant
4-04-01	Guangzou	No. 3	CC-1	Failure of diaphragm wall	area affected = 1000 m², 1 building (3-story) collapsed	none	serious	considerable	insignificant	insignificant
4-04-20	Singapore	Circle	CC-1	Failure of strutting system	refer to Section 3.2	severe	disastrous	disastrous	disastrous	disastrous
4-05-29	Kaohsiung	Orange	ST-1	Leakage at tunnel eye	refer to Section 3.3	none	disastrous	severe	severe	considerable
4-08-09	Kaohsiung	Orange	CC-3	Leakage of diaphragm wall	refer to Section 3.4	none	disastrous	severe	disastrous	considerable
4-09-25	Guangzou	No. 2	UT-1	Rupture of watermain led to collapse of retaining wall	area affected = 100m², 3 persons fell into the hole, one sustained minor injuries	insig.	considerable	insignificant	insignificant	insignificant
4-11-02	Taipei	Luzhou	UT-1	Rupture of watermain	sinkhole, diameter = 3m, depth = 4m	none	considerable	insignificant	insignificant	insignificant
4-12-05	Taipei	Hsinzhung	ST-1	Leakage at tunnel eye	Sinkhole of unknown size	none	considerable	considerable	insignificant	insignificant
5-01-24	Guangzou	No. 3	ST-3	Settlement/sinkhole over shield tunnel	sinkhole - 20 houses settled	none	considerable	considerable	insignificant	insignificant
5-07-07	Kaohsiung	Orange	CC-3	Leakage of diaphragm wall	refer to Section 3.4	none	considerable	considerable	insignificant	insignificant
5-11-30	Beijing	No. 10	CC-1	Failure of retaining wall	sinkhole 500m², 16m deep, rupture of utilities, estimated loss = US$ 0.4 millions	none	serious	serious	insignificant	serious
5-12-04	Kaohsiung	Orange	MG-6	Failure of crosspassage	refer to Section 3.5	none	severe	disastrous	disastrous	disastrous
6-01-03	Beijing	No. 10	UT-1	Rupture of sewer	sinkhole 350m², depth 12m	none	serious	insignificant	insignificant	considerable
6-06-27	Beijing	No. 10	CC-1	Failure of retaining wall at work shaft	Sinkhole 30m², depth 3m, 2 workers died	severe	insignificant	insignificant	insignificant	insignificant
6-08-02	Guangzou	No. 3	ST-3	Settlement/sinkhole over shield tunnel	1 worker died and 2 were injured	serious	insignificant	insignificant	insignificant	insignificant

Table 2 Classification of failure for underground works

Type of Work	Code	Failure Mode (see Note)
Open Cut	OC-1	Earth slip
	OC-2	Failure of base
	OC-3	Groundwater problems
Cut-and-Cover	CC-1	Structural failure of retaining system, Including failure of struts and walls
	CC-2	Failure of ground anchor
	CC-3	Leakage of wall
	CC-4	Failure of base soil
	CC-5	Groundwater problems, piping, uplifting
	CC-6	Settlement/sinkhole behind the wall
Shield Tunnelling	ST-1	Leakage at tunnel eye
	ST-2	Obstruction
	ST-3	Settlement/sinkhole over tunnel
	ST-4	Collapse of lining
Mining	MG-1	Settlement/sinkhole over tunnel
	MG-2	Earth slip at face
	MG-3	Failure of temporary support
	MG-4	Failure of permanent lining
	MG-5	Leakage of lining
	MG-6	Failure of crosspassage
Ground Treatment	GT-1	Ground heave/settlement
	GT-2	Damage to structure
Utility Problem	UT-1	Rupture of utilities
Others	OT	

Table 3 Classification of injury (ITA, 2004)

	Injury to Workers & Emergency Crew	Injury to third Parties
Disastrous	F>10	F>1, SI>10
Severe	1<F≤10, SI>10	1F, 1<SI≤10
Serious	1F, 1<SI≤10	1SI, 1<MI≤10
Considerable	1SI, 1<MI≤10	1MI
Insignificant	1MI	

Note: F = fatality, SI = seriously injured, MJ = minor injured

(a) Injury to workers, emergency crew and third parties

ITA differentiates injuries to workers and emergency crews from injuries to third parties, as shown in Table 3, with much less tolerance for the latter in comparison with the tolerance for the former. The argument is that the third party has no benefit from the construction work and should not be subjected to a higher risk than if the construction work not being carried out.

Table 4 Classification of economic loss (ITA, 2004)

	Economic Loss to Third Party	Economic Loss to Owner
	million Euros	million Euros
Disastrous	>3	>30
Severe	0.3 ~ 3	3 ~ 30
Serious	0.03 ~ 0.3	0.3 ~ 3
Considerable	0.003 ~ 0.03	0.03 ~ 0.3
Insignificant	<0.003	<0.03

(b) Economic losses to third party properties

For the same reason, the tolerance for economic loss to third parties is much less than that to the owner. As shown in Table 4, the former is one-tenth of the latter.

Economic losses (damages) to third parties include damages to adjacent buildings, infrastructures, utilities, etc. It is nearly impossible to know the damage caused by any event without being involved. It is even more difficult to estimate the value of the damage because buildings of the same type of structure and of the same quality, for example, will have very different values depending on where they are. Therefore, unless the actual costs have been estimated, damages to third parties are proposed to be classified by the nature of the damages and the importance of the object which was damaged. Accordingly, Table 5 is recommended to replace Table 4.

Table 5 Classification of damage or economic loss to third parties (This Study)

	Buildings	Infrastructure
Disastrous	Collapse of a 10-story or taller building Collapse of 2 or more 5~10 story buildings	Permanent damage to vital lifelines or public facilities
Severe	Collapse of a 5~10 story building Collapse of 2 or more 2~5 story buildings Heavy damage to many 5-story or taller buildings	Major damage to vital lifelines or public facilities Permanent damage to major lifelines or public facilities
Serious	Collapse of a 2~5 story building Collapse of 2 or more single houses (bungalows) Collapse of a luxury residence Heavy damage to many 2~5 story buildings	Minor damage to vital lifelines or public facilities Major damage to major lifelines or public facilities
Considerable	Collapse of a single house (bungalow) Heavy damage to many single houses (bungalows), shops	Minor damage to major lifelines or public facilities Major damage to minor lifelines or public facilities
Insignificant	Minor damage to single houses (bungalows), shops Collapse of temporary structures	Minor damage to minor lifelines or public facilities

Note: refer to Tables 6 and 7 for definitions of lifelines and damage

Table 6 Classification of lifelines (This Study)

	Definition
Vital	more than 10,000 people will be affected by failure
Major	1,000~10,000 people will be affected by failure
Minor	less than 1,000 people will be affected by failure

Table 7 Classification of damage to lifelines (This Study)

	Definition
Permanent damage	not repairable - replacement is required
Major damage	requiring more than 1 week to repair
Minor damage	requiring less than 1 week to repair

In Table 5, no attempt has been made to differentiate buildings by type, floor area, age, importance, etc. However, it is necessary to differentiate lifelines and public facilities by their importance and Tables 6 and 7 are proposed.

Strictly speaking, damage to lifelines as defined in Table 5 is not limited to the direct costs for repairing or replacing the damaged lifelines, but also includes the social costs to the public due to the loss of services or the inconvenience caused.

It is rather difficult to classify public facilities in a similar manner because there are too many types of facilities with different sizes and functions, and classification of damage to facilities can only be based on intuitive judgment using Tables 5 to 7 as guidelines.

Economic loss is not limited to damage to buildings, lifelines and public facilities. Frequently loss of ground led to sinkholes on public roads, and underground utilities may be damaged as a result. If a failure involved collapse of a section of road outside the site, the damage has been classified as "considerable" unless information is available to indicate more severe consequences. On the other hand, if a failure is totally confined in the boundary of the site, the loss is totally borne by the contractor and the loss to third parities will be classified as "insignificant".

(c) Total Economic Losses

It is recommended in the Guidelines that if it cannot readily be established whether additional costs are to be covered by the owner or by other parties, it should be assumed that the loss is defrayed by the owner. With limited information available, it is not possible to differentiate losses to owners and losses to contractors, therefore, total losses, no matter who is to bear them, are used in the classification.

(d) Delays

Delays can refer to delays to the critical path or delays of specific activity regardless of whether the activity is on the critical path. The two alternatives proposed in the Guidelines are given in Table 8. Alternative 1, with intervals in a factor of 10, is proposed therein in order to achieve only one risk matrix to cover all consequences, but the ranges proposed for "insignificant" and "considerable" are rather ambiguous. Alternative 2 is more meaningful and is therefore adopted herein. The critical path refers to the critical path for the pertinent construction contract, not the entire MRT line or the MRT network.

(e) Disruption to Traffic

Disruption to traffic may or may not involve heavy economic loss but will certainly cause inconvenience to road users. Closure of a major road, freeway, or MRT line may even cause political chaos. In the lack of precedents, the authors propose to classify disruptions to traffic in accordance with Table 9.

Classification of Events

The authors have collected information on 43 events, of which 23 events have at least one consequence classified as "considerable" or severer. These events are identified by the year-month-day of their occurrences and are listed chronologically in Table 1. The remaining 20 events were minor events with insignificant consequences.

Events can be classified by the highest level in the classification of consequences. An alternative which is frequently adopted is to assign a weight to each class, for example, 4 for disastrous, 3 for severe, 2 for serious, 1 for considerable and 0 for insignificant, and to classify events by summing up all the weights. Such a weighting system is inevitably arbitrary and is highly arguable. To avoid confusion, the former approach is adopted herein even though there is more than one consequence with the same level.

Table 8 Classification of delays (ITA, 2004)

	Alternative 1 months	Alternative 2 months
Disastrous	>10	>24
Severe	1 ~ 10	6 ~ 24
Serious	0.1 ~ 1	2 ~ 6
Considerable	0.01 ~ 0.1	0.5 ~ 2
Insignificant	<0.01	<0.5

Note: Alternative 2 is adopted herein

Table 9 Classification of disruption to traffic (This Study)

	Closure of a Major Road	Closure of a Freeway/MRT Line
Disastrous	> 3 months	> 1 month
Severe	1 ~ 3 months	1 week ~ 1 month
Serious	1 week ~ 1 month	1 day ~ 1 week
Considerable	1 day ~ 1 week	< 1 day
Insignificant	< 1 day	

Note: one level lower if a road is only partially closed

Table 10 Summary of events in the period 2001 to 2006

Code	Disastrous	Severe	Serious	Considerable	Insignificant
OC-1		1	1		1
CC-1	1	1	3		1
CC-3	1			1	1
CC-5					3
CC-6					3
ST-1	1	1		1	
ST-2				1	
ST-3			2	1	4
MG-1				1	
MG-3					
MG-6	2				1
GT-1					1
UT-1			1	2	4
OT			1		1
Total	5	3	8	7	20

As information is rather limited, classification of both causes and consequences requires much guesswork and judgment based on vague, sometimes even controversial, reports in news. In many cases, it is uncertain whether failures of retaining systems (ST-3) were due to rupture of utilities (water main or sewer) or the rupture of utilities was a result of ground movements behind retaining walls. Similarly, settlements/sinkholes over tunnels could be a result of rupture of utilities, but on the other hand, rupture of utilities must be due to excessive ground settlements over tunnels. In most of cases, failures were due to multiple reasons. Therefore, much guesswork is required in determining the cause of each event. The same can be said regarding consequences. The authors have had to make their best judgments to classify consequences based on indirect evidence.

The events listed in Table 1 have been classified accordingly and a summary is given in Table 10. As can be noted, of the 23 significant events listed, 5 are disastrous, 3 are severe, 8 are serious and 7 are considerable. Although not specifically listed in Table 1, the death toll of 14 is considered to be alarming bearing in mind the fact that non-geotechnical events are not accounted for.

MAJOR FAILURES IN RECENT YEARS

The five events with disastrous consequences are discussed as follows:

Event 3-07-01: Shanghai Metro (MG-06: Failure of Crosspassage)

The collapse of a crosspassage at the west bank of the Huangpu River led to the collapse of an 8-story building and 2 annexes attached to this building. A 20-story building and several others also suffered from serious tilting. A section of levee, 30m in length, settled by a few meters and eventually collapsed. Water rushed in from the river through the opening and caused flooding of streets in a large area. However, there are no reports on the traffic disruption or damage to public facilities.

The crosspassage, 7.8m in length, was constructed at a depth of about 30m below surface by mining. The surrounding soils were solidified by using the ground freezing technique. At the time of collapse, excavation was almost completed with less than a meter to go. According to information available on the web, the collapse was caused by thawing of the frozen soil as a result of power breakdown.

Other sections of Line 4 were opened for revenue service at the end of 2005 as scheduled. The section influenced, from Da Mu Qiao Road Station to Lan Cun Road Station, is unlikely to be ready by the end of 2007, therefore, the delay is estimated to exceed 2 years.

The loss was estimated to be US$80m (Wannick, 2006) but details are unavailable. Presumably it includes economic loss to the owner, the contractor and the third parties. Most of the loss is believed to be covered by insurance. It has been reported that insurance premiums for MRT works in China (for example, new lines in Guangzhou Metro and Beijing Subway) have doubled or even tripled subsequent to this event.

Event 4-04-10: Singapore MRT (CC-1: Failure of Retaining System)

The collapse of a section of cut-and-cover tunnel led to the death of 3 workers from the contractor and 1 supervisor from the Land Transport Authority (LTA). A 150-m section of Nicoll Highway, which is one of the arteries of the southeastern Singapore Island, was seriously damaged (COI, 2005). The highway, refer to Fig. 1, was closed for 7½ months and was rebuilt at a cost of S$3 millions (US$2 million). Several buildings nearby the site were affected by settlement but none of them collapsed nor was seriously damaged.

The site is located in a piece of land reclaimed in the 80's. As shown in Fig. 2, the subsoils at this site contain two thick layers of marine deposits (the upper marine clay and the lower marine clay) and are underlain by the Old Alluvium which is a competent base stratum. Figure 3 is a plot of the results of a cone penetration test carried out at the site. The excavation was supposed to be carried out to a depth of 33.5m and diaphragm walls with a thickness of 800mm (locally, 1000mm) were used. The collapse occurred on 20 April 2004 while the 10th dig was completed and excavation reached the depth of 30.5m on 16 April.

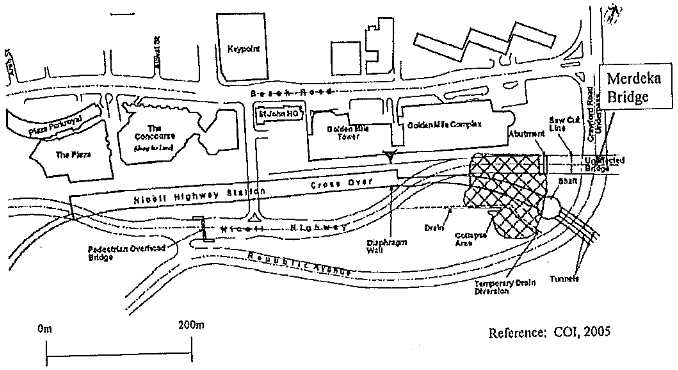
Figure 4 shows the wall deflection paths, which are the plots of maximum wall deflections versus depth of excavation in a log-log scale, for the two inclinometers installed on the two sides of the excavation (Hwang et al., 2007). Wall deflections on the two sides were about the same till 9 March, 2004, when excavation reached a depth of 25m, and deflections of 198mm and 215mm were recorded by Inclinometers I65 and I104, respectively. Subsequently, there was a period in which I104 was not read because it was damaged. When monitoring resumed on 26 March, the deflection of the southern wall was found to have increased by 67mm to 282mm while the readings for Inclinometer I65 on the north were fairly steady in this period. The readings for Inclinometer I104 kept on increasing while those for I65 remained to be steady subsequently, presumably, because of the asymmetry of ground conditions. In fact, I65 appeared to move outward by 27mm, from 202mm on 26 March to 175mm on 20 April, as depicted in Figs. 2 and 4. On the other hand, Inclinometer I104 moved inward by 90mm to 441mm in the 3-day period from 17 April to 20 April.

Failure started as the waling on the northern wall buckled at 9am on 20 April and by 3pm all the struts for a 100m section totally failed. As Nicoll Highway sank, gas, water and electricity cables ruptured, causing power to go out for about 15,000 people and 700 businesses in the Marina and Suntec City area. Tremors were felt at Golden Mile Complex. Tenants and residents in the building were also evacuated. One of the spans of Merdeka Bridge was demolished as a precaution and was rebuilt shortly afterward.

As a result of this accident, the completion of the construction contract was postponed by at least a couple of years from the original schedule. Nicoll Highway Station has been shifted about 100 m southward from the accident site to Republic Avenue. The original station was meant to be the southern terminus of the future Bukit Timah Line but this has now been shifted to Promenada Station.

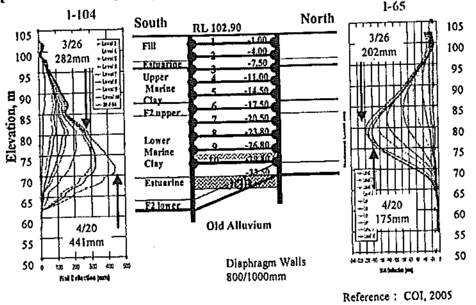
After the incident, the Singapore Government formed an independent Committee of Inquiry (COI), headed by a Senior District Judge, to look into the incident. After thorough investigations, in which 173 witnesses were interviewed and 20 experts offered their professional opinions, an Interim Report was released on 13 September 2004 and a very comprehensive Final Report was made available to the public on 13 May 2005 (COI 2005). Ministry of Manpower (MOM) also made a press release upon the publication of the Final Report and the key points made in the COI's report were quoted therein (MOM, 2005a, b).

The Committee identified critical design and construction errors, particularly the design of stiffeners on the walings at the connections between the diaphragm walls and the struts, that led to the failure of the earth retaining system. The Committee also found deficiencies in the project management that perpetuated and aggravated the design errors, including inadequate instrumentation and monitoring of works, improper management of instrumentation data, and lack of competency of persons carrying out specialized work.



Reference: COI, 2005

Fig. 1 Collapse of Nicoll Highway due to construction of the Circle Line, Singapore MRT



Reference : COI, 2005

Fig. 2 Ground conditions and retaining system at the MRT site.next to Nicoll Highway, Singa

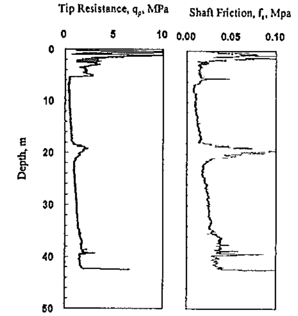


Fig. 3 Results of a cone penetration test next to Nicoll Highway, Singapore

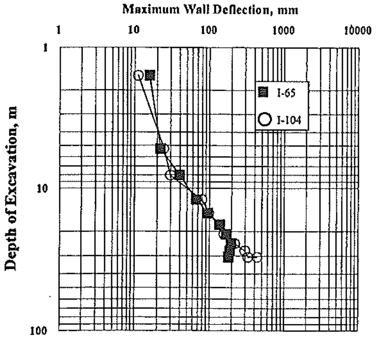


Fig. 4 Deflection paths for diaphragm walls at MRT site next to Nicoll Highway, Singapore

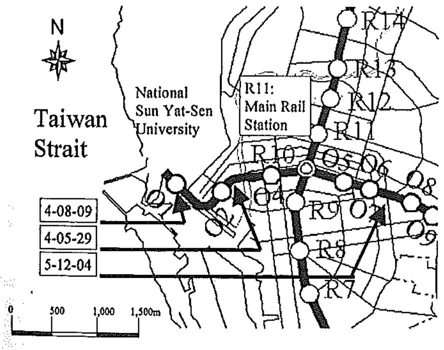


Fig. 5 Western segment of the Orange Line, Kaohsiung MRT

Event 4-05-29: Kaohsiung MRT (ST-1: Leakage at Tunnel Eye)

As the shield machine in the Up-track tunnel arrived at O2 Station and a portion of diaphragm wall was knocked out to make a portal at the tunnel eye, groundwater spurted into the pit (Lee et al., 2005). The site is very close to the seashore as shown in Fig. 5 and was a salt pan decades ago. It is located in a delta formed by the estuary of the Ai River. Groundwater table is very close to the surface and is influenced by the fluctuations of tides. The ground conditions at the site are shown in Fig. 6 and the N-values obtained in SPT tests at a nearby borehole are shown in Fig. 7. The properties of subsoils below the invert of the tunnel are given in Table 11. Although the SPT blow counts are in general greater than 15, subsoils consist predominantly of silts with natural water contents very close to their liquid limits. Such soils may easily be softened once disturbed or even liquefied when subjected to large hydraulic gradients.

Leakage started at the invert of the tunnel eye at 20:30 on 29 May 2004 and ground started to settle at 22:30 as the flow increased and sands were washed out. A sinkhole was finally formed and measurable ground settlements reached a distance of 50m. Seven 3-storey buildings in the vicinity were seriously damaged as the foundations settled by more than a meter and about 40 families were evacuated. The buildings were demolished shortly afterwards and had already been rebuilt by the time this paper was prepared.

The tunnel was driven using an earthpressure balance shield machine with a diameter of 6.3m. The axis of the tunnel is located at a depth of, roughly, 17m below surface. At the time the accident occurred, the portal had been completed and the cutter of the shield machine had intruded into the portal by 700mm.

As shown in Figs. 6 and 8, the ground behind the diaphragm wall was treated by installing JSG piles, with a spacing of 1.6m center to center, in November 2003 as a precautionary measure. Treatment was carried out for the full face in the 4.71m section immediately next to the diaphragm wall, but was carried out partially, leaving a soil

Table 11 Properties of subsoils below the tunnel at the eastern end of O2 Station, Kaohsiung MRT (Lee et al, 2005)

SPT Sample	Depth m	Soil Type	Sand %	Silt %	Clay %	water content %	Liquid Limit %	Plasticity Index
S-14	20.55	ML	19	76	5	22.4	27	4.1
S-15	22.05	SM - ML	48	52	0	25.6	21.4	0.8
S-16	23.55	ML	15	82	3	24.4	27.5	1.2
S-17	25.05	ML	4	86	10	19.5	35.2	6.4
S-18	26.55	ML	20	74	6	21.7	26.5	3.3
S-19	28.08	CL	6	56	38	42.9	43.9	20
S-20	30.00	ML	15	84	1	25.1	26.1	1.2

Table 12 Chloride contents at O1, O2 and O3 Stations of the Orange Line, Kaohsiung MRT (Lee et al. 2005)

	Chloride Concentration (ppm)
Groundwater	10,442 12,546 13,796 11,197 *17,000 15,300
Soils	*3,000 *8,500

Notes: * by Mass Rapid Transit Bureau, Kaohsiung

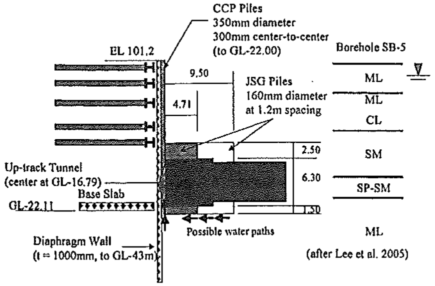


Fig. 6 Collapse of tunnel portal, O2 Station, Kaohsiung MRT

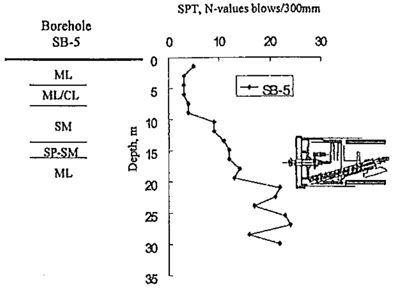


Fig. 7 N-values obtained in Borehole SB-5 next to O2 Station, Kaohsiung MRT

core in the middle, in the remaining section away from the wall. As a normal practice, six water tests were carried out to determine the quality of the treated ground. Minor leakages occurred and ARON and LW grout was injected to seal off water paths. The attempt obviously failed to achieve the purpose.

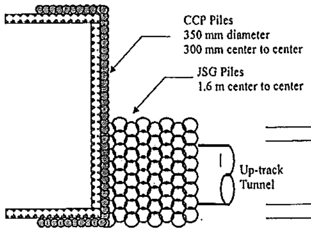


Fig. 8 Ground treatment at tunnel eye portal, O2 Station, Kaohsiung MRT

Failures of trenches occurred frequently in this area during the installation of diaphragm walls. Therefore, one row of CCP piles of 350mm in diameter was sunk in November of 2002 to prevent the trenches from collapsing prior to the installation of diaphragm wall panels. Subsoils at the site have high chloride contents as depicted in Table 12. According to CNS13961 for concrete mixing, the chloride contents of water are limited to 250ppm while, as depicted in Table 12, the chloride contents in the groundwater exceed 40 times this limit. Since the CCP piles were intended to serve only for temporary purpose, Type I Portland cement was used. Therefore, it is suspected that, as a result of chloride attack, the CCP piles had already deteriorated by the time JSG was performed a year later and could be cut into fragments by JSG. The presence of these fragments might have led to poor quality of the treated soils at the interface between CCP piles and JSG piles and water paths might have been formed as a result, allowing groundwater to seep into the pit. It is also possible that the quality of the ground treatment was poor at the bottom as the soils were much disturbed at the tip during JSG operation and they were not well mixed with cement (Lee et al. 2005) as the grouting pipe was raised. In case this was indeed the cause of failure, it will be a good idea in the future to sink grout pipes to, and to start the injection of grout at, different depths to avoid forming a continuous blanket with high permeability at the bottom.

The attempt to recover the shield machine was abandoned and the shell of the shield was left in the up-track tunnel. At the time the incident occurred, the shield machine in the down-track tunnel was still far away from the station. To prepare for its arrival, a steel chamber was installed at the portal so compressed air could be applied to stop water flow should a similar incident occur again. Since the ground was much disturbed, additional grouting was carried out to solidify the ground. However, the ground was then too hard for the shield to go through because of over-treatment, therefore the shell was also abandoned in the down-track tunnel. A new shield machine had to be purchased for other sections of tunnels to be driven.

One of the two lanes of the street next to the site was closed for a few months. Because the local traffic is not heavy, the disruption to traffic was not serious. The completion of the construction contract was delayed by 8 months.

Event 4-08-09: Kaohsiung MRT (CC-3: Leakage of Diaphragm Wall)

Water spurted from the bottom of the excavation in front of Panel S60M, refer to Fig. 9, on the southern wall at 13:20 on 9 August 2004 as excavation reached a depth of 15m at O1 Station which is located near the seashore as shown in Fig. 5. A sinkhole of 3m maximum depth was formed behind the diaphragm wall and the area affected was around 500m^2. Four 3-story buildings collapsed in less than an hour and were demolished overnight. Several low-rise shops were severely damaged and were demolished sometime later.

The site is located right at the mouth of the Ai River and the ground conditions are extremely poor. Figure 10 shows the soil profile obtained at Borehole WB-11. The pit was retained by diaphragm walls, 800mm in thickness and 39m in length. As mentioned in Section 3.3, subsoils on the west coast of Kaohsiung City can easily be softened once disturbed, or liquefied when subjected to large hydraulic gradients and, therefore, failures of trenches during installation of diaphragm walls were quite common. In many cases, mini-piles and/or micro-piles were installed to prevent trench collapse. Even so, necking frequently occurred and reduced the sectional areas of diaphragm walls. Furthermore, groundwater has extremely high chloride contents and the quality of diaphragm walls deteriorates quickly as a result of chloride attack. Ground treatment frequently had to be applied behind defective diaphragm walls to stop ingress of groundwater into pits.

Subsoils at this site, being closer to the sea, are even worse than those at O2 Station so the incident was not a surprise. One row of CCP piles was used along the perimeter of the area to be excavated for maintaining the stability of trenches prior to the installation of the diaphragm walls. After the incident, coring was carried out at the end of September 2004 and it was found that Panel S59F was defective with pockets of rock fragments and soils at depths ranging from 15.95m to 16.55m below surface. One row of 11 bored piles was installed behind Panels S58M to S60M. Pumping tests were performed in November 2004 to see if there were other defective panels. A total of 3,285 cubic meters of water was drawn from 6 wells and water levels inside the excavation closely monitored at 60 wells. The groundwater table inside the excavation dropped; on an average of 2.2m as a result of pumping. The recovery of water levels was monitored for more than 10 days, however, the desired purpose was not achieved as the locations of leakages could not be identified (Ho et al., 2007).

To be on the safe side, one row of JSG piles was added along the entire perimeter of the station. Furthermore, the joints between JSG piles were treated by using CCP piles. Pumping tests were again performed subsequently to confirm the effectiveness of these measures. The results were not satisfactory as the rate of recovery of groundwater inside the excavation was only slightly smaller than that obtained previously (Ho et al., 2007). It was decided to add more JSG piles at the back of Panel S58M. Three new piles were installed without problem. As No. 4 pile, refer to Fig. 9, was installed on 7 July 2005, groundwater brought a large quantity of soil into the pit. A nearby hospital was endangered and the patients in the hospital were urgently evacuated as a precautionary measure. It however survived with only minor damage. The sinkhole was about 1m in depth and settlement spread over an area of about 1,000m^2.

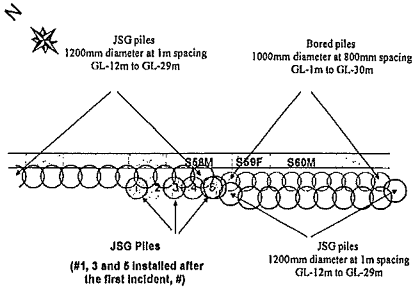


Fig. 9 Ground treatment prior to July 7, 2005, O1 Station, Kaohsiung MRT

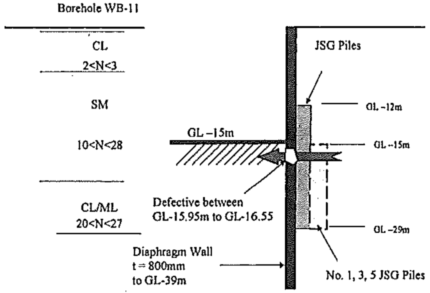


Fig. 10 Soil profile and ground treatment behind Panel S58M prior to July 7, 2005, O1 Station, Kaohsiung MRT

Excavation was again halted for investigation. The Concessionaire of the system, i.e., Kaohsiung Rapid Transit Corporation, engaged a team of geotechnical specialists to be stationed at the site to represent the Concessionaire and ensure that the excavation could be carried out safely. With additional grouting carried out behind the wall, excavation resumed in December 2005 and took 6 months to reach the bottom.

Event 5-12-04: Kaohsiung MRT (MG-6: Failure of Crosspassage)

As excavation was carried out at the bottom of a crosspassage, refer to Fig. 5 for the location of the site, for constructing a sump, water started to spurt out at 5pm on 4 December 2005 and the flow soon became uncontrollable because of the huge water pressure. The center of the crosspassage is located at a depth of about 26m below the surface and excavation was supposed to go down to a depth of, roughly, 33m for constructing the sump as depicted in Fig. 11. Excavation for the sump, with an outer diameter of 3.9m, was carried out in 7 stages, each 0.5m in thickness, as shown in Fig. 12. The sidewall of the excavation was protected by shotcrete as temporary lining. At the time the incident occurred, excavation had reached the last stage and half of the area had already been completed.

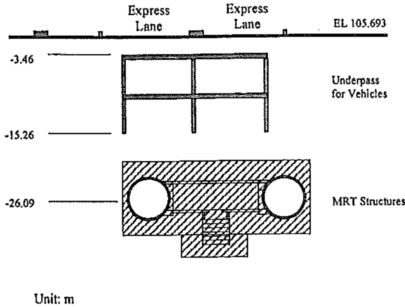


Fig. 11 Section at the location of the crosspassage and the sump

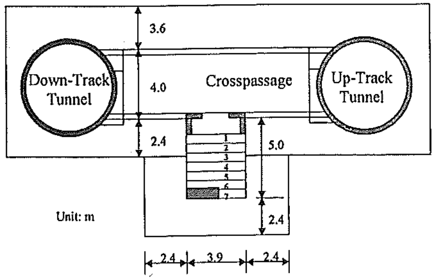


Fig. 12 SJM treatment for excavation for the crosspassage and the sump

The soils surrounding the crosspassage and the sump had been treatment by using the JSM (Superjet Midi) grouting method prior to the commencement of excavation as depicted in Fig. 12. The quality of ground treatment might have been affected by the fact that grouting had to be carried out mostly in inclined holes because of the presence of an underpass running in parallel with the tunnels. Water tests were carried out to confirm the effectiveness of the treatment. Additional grouting was carried out to seal off water paths when seepage was noticed. This however did not prevent the failure from happening.

The situation was aggravated by the rupture of 300mm and 600mm water pipes. The tunnels, together with the underpass above the tunnels, about 100m in length were totally damaged as a result. The tunnels and the underpass will be rebuilt by using the cut-and-cover method of construction with diaphragm walls to depths exceeding 60m. Ground freezing technique will be applied at the two ends of the damaged section to seal off the gaps between the diaphragm walls and the tunnels and to solidify the sludge in the tunnels to become plugs to enable excavation to be carried out. Finally, these plugs will be removed and damaged segments replaced.

Ground freezing work started on 27 June 2006 and the rehabilitation of the tunnels is expected to be completed by mid-2007. The economic loss is estimated to exceed US$50 million which is considered to be the biggest loss in the Kaohsiung MRT construction. Other than the underpass, damage to third parties was small because the sinkhole is located in a park and there were no buildings nearby. Although the underpass will be closed till the end of 2007, fortunately, space is available to divert some of the traffic at surface to lessen the impact.

LESSONS LEARNED

Lessons learned from failures contribute to the advancement of technology and reduce fatalities and economic losses in future construction. The recent failures quoted above indicate that:

Water Is a Prime Cause of Failures

Water is a prime cause of major failures in underground construction. For example, four of the five disastrous events, discussed in Section 3, were associated with ingress of groundwater. Therefore, works must be carried out with great care whenever and wherever excavation is carried out in water bearing strata. This is particularly true if openings are to be made on underground structures at great depths, for examples, for making tunnel portals through diaphragm walls.

In the first stage construction of the Taipei Rapid Transit Systems (TRTS) carried out in the 90's, all the top four failures with disastrous or severe consequences were also caused by ingress of water and two of them occurred at tunnel portals. There exist the Chingmei Gravels, which is practically an underground reservoir with extremely high permeability, at depths varying from 35m to 60m below ground surface in the Taipei Basin, and it will be very difficult to stop the flow once water finds its way to seep into any openings. Learning from failures in these 2 cases and near-failures in several other cases, bulkheads were provided in a few contracts in the subsequent constructions to enable the portals to be sealed off once the flow became uncontrollable. In some cases, ground freezing, in lieu of or in addition to grouting, was adopted to solidify surrounding soils and to seal off any fissures or cracks. Ground freezing was adopted more frequently in the second stage TRTS construction because excavations go deeper and also because the technique has gained popular confidence.

Construction of crosspassages in sandy strata is also a very dangerous operation, particularly under rivers. It is very popular to adopt ground freezing to solidify surrounding soils for excavation to be carried out safely. An alternative is to use double-O-tube (DOT) shield machines which, to the authors' knowledge, have been used successfully in 13 projects in Japan and 5 projects in Shanghai. The Department of Rapid Transit Systems of Taipei City Government is also evaluating the feasibility of adopting DOT machines in some of the sections in the future extensions of TRTS.

Defective retaining walls may also lead to severe consequences as groundwater may seep its way into the pit/excavation, leaving large cavities behind the walls. Leakage in diaphragm walls has frequently occurred in the coastal area in the Kaohsiung City in the past because the subsoils consist predominately of silty sands and sandy silts with water contents very close to their liquid limits, making it very difficult to maintain the stability of trenches and resulting in necking of walls. In many cases, micropiles or minipiles were installed to stabilize trenches, but even this did not fully solve the problem. Grouting was frequently carried out at the back of the walls which were suspected to be defective, but failures still occurred. The results of on-going research indicate that the silty sands in the Kaohsiung area are unique with strange behavior once disturbed. This, however, is beyond the scope of this paper.

Failures resulting in sinkholes also frequently occurred as soils were washed away when utilities (watermains, sewers, drains, etc) ruptured as a result of large ground deformations. Such incidents should not have happened because movements of ground and utilities should be closely monitored and precautionary actions should be taken.

Another factor supporting the view that water is a prime cause of major failures is the lack of them during construction of the MRTA Chaloem Ratchamongkhon Line in Bangkok from 1997 to 2004. The soil profile in Bangkok means that at typical excavation levels of 15 to 30 m below ground surface, the strata are firm to stiff clays, and dense silty sands in which the ground water level is already drawn down by about 20 m. Thus the very high water pressures which existed and caused problems in Taipei and Kaohsiung are not present in Bangkok.

Design Codes on Ground Treatment Require Revision

Ground treatment is routinely applied to solidify the surrounding soils and to seal off any fissures or cracks, when openings are to be made in underground structures. In four of the five cases quoted above, failures could have been avoided if ground treatment had served its purpose. Even for the case of the collapse of the Nicoll Highway in Singapore, refer to Fig. 2, a grouted slab was placed below the 9th level of struts and served as a temporary support and another grouted slab was placed below the bottom level of excavation. Although it was concluded that the poor quality of these slabs was not directly responsible for the failure, it is arguable whether failure would still have happened if they had done their duty.

To the authors' knowledge, ground treatment in this region is either designed in accordance with Japanese codes or designed to codes which were developed mainly based on Japanese codes/experience. This has been proven to be inadequate as the quality of the treatment is highly dependent on the equipment used and workmanship. The equipment used in this region may not be as capable as those used in Japan in cutting soils and forming piles and the workmanship may not be compatible with that in Japan. One of the factors attributing to the differences between this region and Japan is the prices awarded to the specialist contractors. The price of grouting in this region is far below that in Japan and it is thus unreasonable to expect the workmanship to be the same as that in Japan. It is therefore important to develop local codes based on local experience to account for these differences. Furthermore, most, if not all, of the codes of practice on grouting fail to deal with the situations with steep hydraulic gradients. Therefore, they may be inadequate for excavations with depths of, say, 15m or greater, or making openings in underground structures at similar depths.

As shown in Fig. 6, the treatment was thicker above the crown of the shield than that below the invert. For shield tunneling, close-in of surrounding soils toward the shield machine is only a minor concern. Therefore there is no good reason for the treatment to be thicker above the crown. On the contrary, the treatment below the invert should have been thicker because the water pressure was greater. For the same reason, it is reasonable to expect the treatment below the bottom of the sump shown in Fig. 12 to be thicker than that below the bottom of the crosspassage.

Treated ground tends to be brittle, and cracks may develop as geo-stresses are changed as a result of excavation. These cracks may be undetected during water tests. For tunnelling using the mining technique, it may be a good idea to treat the ground to form circular (or annular), instead of rectangular, sections. The treated ground will then behave as a compression ring and cracks, if any, tend to close up as the core is excavated while tension cracks are likely to develop at the mid-spans of the four sides if rectangular sections are used.

If the treatment is to serve a long-term purpose, say, more than 6 months, the effects of chemical content in groundwater on the quality of ground treated by grouting should not be overlooked and the cement used should be sufficiently resistant to the chemical attacks.

As excavations go deeper and deeper, revision of codes is urgently needed with water problems properly addressed. Before such a time, to compensate for the deficiency in quality, it is suggested extra thickness of treatment be provided. This will effectively increase the lengths of water paths, if any, and reduce the potential of piping.

Quality Control of Ground Treatment Is Vital

It is difficult for supervising engineers, even experienced geotechnical engineers, at sites to be sufficiently knowledgeable to perform their duties of ensuring the quality of the works because even minor details in handling the machines will affect the quality of the product and only skillful technicians know the techniques. Commercial pressures mean that it is natural for the specialist subcontractor to save time and material by speeding up the operation and/or adding more water to the mix, and the effects on strength are very difficult to monitor.

For treatment to be carried at great depths, the tips of grout pipes (or freezing pipes) could easily be off their intended locations by a few hundreds of millimeters as the alignments of pipes deviate from the vertical. It is even more difficult to ensure the alignment for inclined holes which are necessary because of site constraints or because of the presence of obstacles. The case shown in Fig. 11 is an example in which grouting had to be carried out mostly in inclined holes due to the presence of vehicular underpass structures. In cases like that, grout piles may not overlap each other as they are shown on design drawings and the gaps between piles are likely to become seepage paths for water. Therefore it is necessary to be extraordinarily cautious whenever and wherever risks are evident. In critical cases, inclinations of grout pipes must be measured and the tips of grout pipes located to see if grout piles indeed interlock as desired, and at least 2 rows of grout pipes are necessary to ensure that gaps, if any, between the grout piles will not be continuous.

Check boring is normally specified for confirming the quality of treatment but, more often than not, the importance of strength of treated ground was over-emphasized while uniformity was overlooked. Usually, the best parts of the cores are tested for determining the strengths of treated ground but, in fact, it is the poorest parts that lead to failures. Therefore, test results are not representative of the entire body of treated ground nor are they meaningful for practical purposes. Instead of strength, the uniformity of the treatment should be the key in judging the quality of treated ground. Although the use of core recovery ratio and rock quality designation as indices for the quality of treated ground is challenged by many engineers, it remains the most practical approach until better ways have been found.

Computer Analyses Shall Not Be Trusted Blindly

The advancement in technology for the design and installation of retaining systems has indeed reduced failures drastically in recent years. For example, the adoption of performance-based design, instead of capacity-based design has reduced wall deflections, and hence settlements behind walls, by a factor of 3 as proved by comparing the inclinometer readings obtained during the construction of the Taipei Rapid Transit Systems in the 90's with those obtained previously. This becomes possible because of the availability of advanced computer codes which enable complicated geometry and nonlinear soil behavior during excavation to be modeled. Yet, a disastrous failure occurred (refer to Section 3.2) in the construction of the Singapore MRT System as a result, mainly, of inadequate design of the retaining system based on erroneous computer analyses due to the adoption of a wrong soil model. Failure did not occur without warning as wall deflections exceeded their design values in the very early stages of excavation. Back analyses were carried out, but with improper procedures, to predict what would happen in the subsequent stages and tolerances were relaxed accordingly as the results appeared to indicate that the retaining structures would still be safe.

As engineers rely on computers more and more for their daily works, they have lost engineering sense and can no longer judge the reasonableness of the results obtained because they no longer have to go through the procedures step-by-step and understand the mechanism involved. In fact, most failures could be attributed to improper use of computer codes, rather than improper codes. While the reliance on computer codes is an irreversible trend, the profession is urged not to ignore the fundamentals of geotechnical engineering and not to abandon empirical approaches totally. The results of computer analyses should always be checked against experience until the day computer codes are confirmed to be truly reliable and are easy to be used by all the engineers without misconception.

Most Failures Could Have Been Avoided

With modern technology, poor ground conditions should not be an excusable reason for failures to occur. Most failures could have been avoided if potential risks were managed properly. As mentioned in Section 3.2, a Committee of Inquiry was formed by the Singapore Government to investigate the cause of the collapse of the Nicoll Highway. After interviewing 173 witnesses and 20 experts, the Committee concluded that "The collapse did not develop suddenly. A chain of events preceded the collapse" and "The Nicoll Highway collapse could have been prevented".

There is a growing awareness of the importance of risk management. However, although various measures have been adopted in nearly all the major construction projects for reducing potential risk and for ensuring construction safety, it is desirable to establish a system so that risks can be managed properly and the efforts spent can be optimized.

RISK MANAGEMENT

Since the investigation conducted by COI was carried out to an unprecedented depth and the Singapore Government has taken many positive measures to prevent similar events from happening, the case can be considered as a milestone for underground construction and the measures taken set new state-of-the-art standards for managing risks involved in underground constructions.

The COI made specific recommendations on the following issues (COI, 2005):

(1) Effective Risk Management
(2) Managing Uncertainties and Quality
(3) Management and Monitoring of Geotechnical Instrumentation and Data
(4) Robustness of Design
(5) Design Review and Independent Check
(6) Numerical Modeling in Geotechnical Design
(7) Jet Grout Piling (JGP)
(8) Codes and Specifications
(9) Stop Work
(10) Emergency Preparedness
(11) Competence of Professionals, Contractors and Sub-contractors
(12) Contract and Tender Evaluation System
(13) Safety Culture
(14) Chain of Command
(15) Independence of QP
(16) Building Control Functions

These issues are essentially the major elements in risk management programs and the recommendations given in the report can readily be adopted to form the framework of risk management programs.

In response to COI's recommendations, a Joint MND-MOM Review Committee was convened to examine safety standards in the construction industry. In respect to geotechnical engineering, the Singapore Government, inter alia, has adopted the following measures (MND, 2005):

Reform of Occupational Safety and Health (OSH) Framework

- Contractors will be required to have a comprehensive safety and health plan for every worksite, which includes a structured risk assessment, names of persons responsible for safety for each aspect of work, and contingency planning. The risk assessment must also address the potential risk/impact of the work to members of public. There must be emphasis on translation of the plan into ground action.
- Developers as a key stakeholder will in future also be required to ensure that the designers they appoint also assess and address any major design risks.
- Contractors' safety and health plans must consider the flow of safety information among parties. Their risk assessments must clearly set out the triggers for stopping work.

By MND-MOM Review Committee

- Requirement for OSH management certification (OHSAS18001 standards) will be extended to all contractors in BCA's Contractors Registry System.
- Tougher penalties for professionals (PEs and architects) who do not perform their duties with due diligence. The maximum period of suspension for moderate contraventions should be raised from 1 to 2 years.
- Licensing will be introduced for specialist contractors engaged in critical geotechnical work such as soil investigation and instrumentation.
- PE(Geotec) will be responsible for instrumentation and monitoring for TERS in deep excavations, including data interpretation and specification of review trigger levels.
- AC(Geotec) will have to conduct field reviews and site inspections, including review of data interpretation and trigger levels.
- It will be mandatory for PE(Geotec) and contractor's Technical Controller to stop works when the relevant trigger levels are exceeded.
- Construction of all temporary structures will have to be supervised and certified by a PE before being subjected to its intended loading. The PE for the permanent works should be consulted where appropriate.
- AC(Geotec) will be required to undertake independent review of design.
- AC(Geotec) has to meet prescribed requirements in terms of qualifications and experience in geotechnical works.
- AC(Geotec) has to be appointed independently by the owner and not the contractor, as with the AC in permanent works.

By Land Transport Authority (LTA)

- LTA has set up comprehensive risk registers for each site. The risk register identifies the hazards/risks involved in each construction activity with associated risk index and describes the risk mitigation measures to be undertaken to bring the residual risks to an acceptable level.
- On each contract/project there will be weekly design review and instrumentation and monitoring meetings.
- Design and quality shortcomings as well as instrumentation breaches of alert and work suspension levels are to be immediately reported to higher management.
- For new projects, LTA will be engaging specialist instrumentation contractors to carry out the instrumentation and monitoring works.
- For ongoing projects, where there are existing contracts, LTA has instituted quality control of the instrumentation contractors.
- LTA has engaged external independent consultants / QP (Supervision) to check the design of temporary works prepared by the contractor.
- To ensure the independence of the PE (Temporary Works), LTA will require that the PE (Temporary Works) engaged by the contractor shall not be an employee of the contractor or have economic interest in the firm.

Note: The abbreviations quoted above are:
BCA = Building and Construction Authority of Ministry of National Development
PE = Professional Engineer
AC = Accredited Checker
TERS = Temporary Earth Retaining Structures
QP = Qualified Person = Person-in-Charge

Safety related instrumentation works are now directly tendered out to specialist contractors by LTA, and these specialist contractors will report to LTA, instead of contractors. Late in 2004, LTA also engaged an independent party to carry out the geotechnical services, refer to Section 8.2, for the Circle Line and such a practice is expected to continue in the future. The Government has also legislated a new category in professional registration for geotechnical engineers and requires underground works to be certified by Professional Geotechnical Engineer. It is also compulsory that designs of underground works be checked by accredited checkers.

FUNDAMENTAL ISSUES

The collapse of Nicoll Highway mentioned above is by no means an isolated case. As listed in Table 10, there have been 5 disastrous events, 3 severe events and 8 serious events associated with the constructions of rapid transit systems in this part of the world since year 2001, resulting in deaths, serious delays and heavy economic losses.

It should be noted that consequential loss could be many times the direct loss to a project, if failure extends beyond the site boundaries. Furthermore, the frequent occurrence of accidents reduces the confidence of the public in construction safety, and property owners become more and more resistant to construction carried out near their properties. This not only hampers the progress of projects but also indirectly jacks up construction costs.

While there are numerous factors to be considered in risk assessments, there are several fundamental issues which are more influential than others:

Quality Shall Be Emphasized Over Prices

The fundamental elements for poor quality of works are budget constraints, construction period and mentality of all the parties involved. For example, the policy of awarding projects to bidders with lowest prices will certainly reduce the quality of works. Because of the competition, whoever wins the contract will inevitably takes more risks than he should and cut corners to remain profitable. This issue is addressed in the COI Report that "A strict weightage system should form part of the contract and tender evaluation system. The weightage system should include non-technical and non-commercial attributes such as safety records and culture of the bidder, and its core or corporate competency. Such a weightage system should apply even if the tenderer is a joint venture or a consortium" (COI, 2005). MND-MOM JRC responded to this directive by stating that "Use of current price and quality (including safety) attributes in tender evaluations will be formalized for public sector projects through the Price-Quality Method (PQM). This is recommended as the preferred method of procurement for public works." (MOM, 2005b, MND, 2005). LTA also states that "For all its major projects, LTA adopts a prequalification process to evaluate, assess and pre-qualify potential bidders based on their technical competencies shown in past projects and their safety performance track record. A more structured safety dimension will be added for future tender evaluation in line with the proposed Price. Quality Method (PQM)." However, in practice, prequalification does not give good contractors any margin on bidding, and at the end price still plays a dominating role in tender evaluation and unhealthy competition still continues. It is therefore suggested that preferential status be given to contractors with better safety records and a certain margin be allowed on their bidding prices. This also complies with the FIDIC's recommendation of "Selection on Quality". Selection of designers is even more critical than selection of contractors and shall be based on quality rather than price because design fees are only a few percents of construction costs while a poor design, either over-design or under-design, might lead to economic losses which could be many times the design fees.

Mode of tendering is another factor to be considered in evaluation of potential of risks. It has become more and more popular for projects to be tendered on a turnkey basis. Turnkey projects (design-and-construct), in contrast to Engineer's-design projects, do have the benefits of speediness and cost-saving, but often at the expenses of quality of works. To avoid any deficiency in quality, stringent specifications and tight supervision are necessary. This may or may not work because specifications sometimes are difficult to enforce at sites. Engineer's-design projects, on the other hand, have the drawback that there is a discontinuity in concept between the designer and the contractor and, as a result, some of the safety measures adopted in the design may not be appreciated by the contractor. This situation becomes more serious if the designer is not playing a major role in supervision during construction. As pointed out by COI that "problems in the inter- and intra-party chain of command and communication between the project owner, contractor and sub-contractors; and lack of clarity in the reporting structure for decision-making among the different parties involved in the project" were partly responsible for the collapse of Nicoll Highway. For a MRT line, there are several designers and many more contractors and all of them have different design concepts and diverse approaches. Miscommunication and breakdown of chain of command are often the causes of failures. It will thus be useful to have someone with the specific duty of performing system-wide risk assessment and standardizing safety-related operation procedures.

Responsibility Shall Be Clearly Defined

It is also important for everyone involved in a project to realize the responsibility he is taking and the legal consequences he will face if he fails to perform his duties. In the case of Nicoll Highway, COI attributed "Lack of safety culture" to be a primary factor responsible for the collapse, and recommended criminal charges against 4 persons, 3 from the contractor and 1 from LTA. Engineers are now more alert and cautious about safety and the safety culture will certainly be improved. However, on the other hand, over-caution has the side effect that engineers either look for ways to disclaim their responsibility or become reluctant to give their approvals making it difficult to proceed with the construction. It is therefore important to clearly define everyone's duties and the associated responsibilities and avoid ambiguities in job descriptions. It is also essential to ensure that senior positions, where responsibility needs to be taken, are filled with people who have enough relevant experience to take their decisions with confidence.

Information Shall Be Shared Promptly

Information sharing is a vital element in project management and a hybrid computer system incorporating MIS (management information system) and GIS (geographical information system) functions will enable engineers to visualize what is going on at sites and, at the same time, to obtain all the information they need at their finger tips. The system shall have the capability of checking instrument readings for accuracy and reliability. Information, such as borehole logs, buildings and structures, instrument locations and readings, utilities, etc., can be linked to warnings as soon as abnormal instrument readings are detected. This will enable all the parties to be in a position to take necessary actions promptly.

Insurers Shall Participate In the Works

Insurance is an important element in risk management, as a lifeboat whenever disastrous events occur. However, because of the frequent occurrence of failures, insurers suffered great losses and have become reluctant to cover underground construction. Insurance premiums have increased drastically in the past 10 years and indirectly jacked up construction costs. Many projects even face the difficulty of obtaining insurance coverage.

In most projects, insurers are not involved in the works till after a failure has occurred. Once a failure occurs, the insurer is in a disadvantaged position because of lack of information. It will be more effective for an insurer to alert the contractor or the project owner to pay attention to signs of dangers and to take necessary actions because insurer may refuse to pay for damages due to negligence or nonperformance. Therefore, it is recommended that insurers have their representatives at sites and obtain safety related information, for example, progress of excavation and instrument readings. It is to everyone's benefits to reduce the occurrence of failures so insurance premiums can be reduced. However, insurers and their representatives shall not be empowered to interfere with the works.

PROTECTING OTHERS AND BEING PROTECTED

It is usually mandatory for contractors to protect adjacent buildings and properties during construction of rapid transit systems and procedures have been more or less standardized. Firstly, designers have to identify buildings and properties which are likely to be affected by the construction and determine their tolerances to ground movements. Contractors have to propose measures to protect those buildings and properties which are likely to suffer damage due to construction. During construction, the response of these buildings and properties are constantly monitored to see if it will be safe to continue the construction. Mitigation measures are taken to safeguard endangered buildings and properties if necessary.

What is less clear is the protection of MRT structures and facilities if someone is carrying out construction nearby. Because a large number of lives are at stake, it is just as important to protect MRT structures against adjacent construction as to protect adjacent buildings and properties against MRT construction. Even without fatalities, disruption of services will cause inconvenience to numerous commuters and serious traffic congestion. Severe damage to MRT structures and facilities may result in long closure of the system and such an event may even lead to political chaos.

Many cities already have in place laws regulating construction activities near MRT structures but in many other cities such legislation is long overdue. A recent failure (21 July 2005) in Guangzhou, which took 3 lives and resulted in serious damage to several adjacent buildings, of which one had to be demolished, is worth mentioning. Since the excavation is very close to No. 2 Line of the Guangzhou Metro, as a precaution, a section of the route (4 stations) was closed for an hour and 18 minutes for inspection. Fortunately MRT structures and facilities appeared to be undamaged and services were soon resumed. What is astonishing is the fact that the 20m excavation had been carried out for more than 2 years and was carried out not only without supervision but also without being approved by the building control authority. It is to the authors' knowledge that there are laws governing construction activities near the Metro lines in Guangzhou, however, they were obviously disregarded. Fourteen government officials were punished for not performing their duties and seven persons who were in charge of the project have been prosecuted.

After the completion of a section of tunnels in the Banqiao Line of TRTS in November 1995, excavation was commenced in August 1996 to construct a highrise building with a 5-level basement in a close proximity to MRT tunnels (Chang et al., 2001). Cracks in segments were observed in the up-track tunnel in July 1998 while excavation had reached its final depth of 21.1m two months earlier. Inclinometer readings indicated that the tunnel had moved horizontally 44mm by then, and the movement reached 54mm in November. Configuration survey indicated that the tunnel lining was shortened by 45mm in the vertical direction and elongated by 26mm in the horizontal direction due to squashing as a result of relaxation of geo-stress as the diaphragm wall moved toward the excavation and away from the tunnel. In the end, steel segments had to be installed as secondary lining to support the 51 rings of concrete segments which were damaged. Fortunately the line was not in service; otherwise, the repair work would have been difficult to carry out. Although the excavation was approved by the Department of Rapid Transit Systems (DORTS) and sufficient instruments were available to monitor the response of the ground and the tunnel, instrument readings were not available to DORTS till damages to the tunnel were observed. The quality of the readings was so poor that considerable effort had to be spent to make sense out of them. It was later realized that there were already signs of distress in the lining in February 1998 when excavation was at a depth of 14m and damage to the lining could have been prevented if mitigation measures were carried out soon enough.

Approval from the MRT authority is necessary for the adjacent construction to proceed on the condition that it will be carried out with care and with necessary precautionary measures. It does not relieve the developer the responsibility of ensuring the safety of MRT structures. On an earlier occasion during the construction of the Tuen Mun LRT in Hong Kong, a structural engineer for a private high rise development with deep basement adjacent to the line was convinced that his excavation would not disturb the rail line because he had a sheet pile and strutting drawing approved under the Buildings Ordinance. This is obviously a misconception.

These cases demonstrate the fact that not only are laws required to protect MRT structures and facilities, they have to be understood and enforced. It is also important for MRT authorities to monitor construction activities carried out near their routes and to pay great attention to what happens to their property.

SPECIAL GEOTECHNICAL SERVICES

It is beyond any doubt that geotechnical engineering plays a very dominant role in underground constructions and geotechnical engineers shall be engaged in all stages of construction. It is important to identify potential risks beforehand and constantly monitor the performance of temporary and permanent works during the course of construction. As construction goes deeper and deeper, failures have occurred more and more frequently. Many failures were disastrous and took many lives. It is therefore advisable for owners of large projects to engage independent geotechnical teams to safeguard their interests. This is particularly true for construction of underground rapid transit systems in urban areas which involve construction of numerous deep excavations and long tunnels in poor ground. The scale of projects and length of construction periods make it justifiable to engage a team of specialists. On behalf of the owner, an independent geotechnical team shall participate in, or sometimes lead, the following tasks:

(1) Interpreting and characterizing ground conditions
(2) Preparing design manuals, specifications and tender documents
(3) Reviewing designs of temporary works and instrumentation programs
(4) Identifying potential risks and reviewing of contractors' contingency plans
(5) Assuring the quality of instrument installation works and monitoring
(6) Inspecting sites and monitoring site activities
(7) Examining instrument readings and managing databases
(8) Issuing warnings if signs of dangers are detected
(9) Reviewing contractors' mitigation plans if adverse conditions are encountered
(10) Ensuring that building protection measures are carried out effectively
(11) Evaluating contractors' claims on adverse ground conditions

Characterization of ground conditions is fundamental for underground works. Ground conditions are easily misinterpreted if investigation is not carried out properly. The same can be said for instrumentation works. Instruments can easily be misread and experience is the key to avoid such problems. Furthermore, it is becoming impractical to deal with the large quantities of instruments installed and the instrument readings collected, and powerful software packages are necessary for data management and identification of potential risks based on these readings.

Taipei Experience

Because the Initial Network of TRTS is the first rapid transit system constructed in Taiwan, the Taipei City Government foresaw the difficult situations to be encountered and engaged a Geotechnical Engineering Specialty Consultant (GESC), even before the inauguration of the Department of Rapid Transit Systems (DORTS). A team of specialists was formed to serve the Department in system planning, design review and construction supervision. This has been proved very fruitful as the design was optimized and many potential problems avoided.

At the peak of construction, a total of 18 field stations were setup and managed by the GESC to assist the field staff of the DORTS in solving on-site geotechnical problems. This also enabled high-quality instrument readings to be obtained to facilitate back-analysis for verifying the designs and the design assumptions (Moh and Hwang, 1996). A Data Center was established at the headquarters of GESC to process the tremendous amount of field data in a systematic manner. The database has become a major resource of numerous research studies and has contributed tremendously to the advancement of technology. More than 200 technical papers have been published on various research subjects and engineering applications based on the data obtained and provided valuable references to the subsequent constructions.

Singapore Experience

Subsequent to the collapse of Nicoll Highway, LTA engaged teams of engineers to provide geotechnical services to new construction contracts, for example, Contracts C854, C855 and C856 of the Circle Line. It is now a requirement that designs of underground works have to be checked by independent licensed geotechnical engineers. In addition, construction supervision which was previously conducted by LTA is now tendered out to private consulting firms and the Qualified Person (QP) who are in charge of the supervision will be appointed by the firms awarded. Furthermore, to make up the deficiency in technical capability, LTA has engaged consulting firms to supply qualified geotechnical engineers to be seconded to LTA. It is also a LTA's policy for safety-related instrumentation works to be tendered out to independent specialist subcontractors by LTA directly. It is a clear direction of Building Control Authority of Ministry of National Development to accredit specialist subcontractors for soil investigation and steel works, but the plan is still under study.

Kaohsiung Experience

Although specialist geotechnical engineers, per se, were not engaged, all the designs were checked by Independent Check Engineer (ICE). Learning from the many incidents, the Kaohsiung Rapid Transit Corporation, the Concessionaire of the BOT (build-operate-transfer) project, engaged a team of geotechnical specialists in December 2005 to be stationed at the site to provide geotechnical services to excavations at O1 and another team at O5/R10 Stations to safeguard her interests.

CONCLUDING REMARKS

Based on information available, there were 43 events of geotechnical nature associated with MRT constructions in this region since year 2001. The economic losses are estimated to exceed quarter a billion US dollars. The death toll of 14 is rather alarming in consideration of the fact that non-geotechnical events are not accounted for and also the fact that many failures were not reported.

Many failures could have been avoided if risk management programs were implemented. As most of the existing MRT systems are either extending the existing lines or expanding their networks by adding new lines and, furthermore, constructions of many new systems are to be commenced in the near future, risk management for underground works deserves urgent attention and extensive studies.

As an attempt to establish risk management procedures for underground works; this paper classifies these 43 events, basically, based on the Guidelines proposed by ITA. The appropriateness of the classification system adopted is subjected to further studies as more information becomes available. The database is to be enriched and cases compiled are to be systematically analyzed with the aim of identifying potential risks involved in underground construction and quantifying their occurrence and consequences.

Although it has been known for long, groundwater is the major cause of failures and is the cause of major failures discussed herein. Ground treatment has been adopted in all the 5 disastrous events (jet grouting in 4 and ground freezing in one) discussed herein to deal with problem but it obviously did not achieve its purpose. The design codes currently adopted in this region do not address to situations involving steep hydraulic gradients and, therefore, have to be carefully examined and revised based on local experience and local practice. Furthermore, the quality control of ground treatment works is vital and efforts are needed to enhance codes of practice and specifications for field works.

Risk management requires the collaboration of the project owner, designer, site supervisor and contractor. For large project, it is advisable for the project owner to engage specialist geotechnical service to provide independent checking of the designs and to assist in supervision of field works. It is also advisable for the insurer to engage specialist geotechnical engineers to safeguard his interest.

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