1  INTRODUCTION

The outcome of most projects is determined by the competence and experience of the people involved, the thoroughness of the pre-planning and the degree of attention given to details and potential risks. A major challenge encountered in many underground construction projects is the paucity of information available at the various stages of the project regarding potential hazards. With the progressive increase in the numbers and length of tunnels constructed in Singapore, there is now a much greater awareness and understanding of the ground conditions, tunnelling processes and the risks associated with constructing major underground works in a densely populated city with a highly complex and challenging geology.

2  SAFETY AND HEALTH LEGISLATION

2.1  General

The Workplace Safety and Health Act (WSHA) that came into effect on 1 March 2006 forms part of a new Occupational Safety and Health (OSH) framework introduced in 2005 to cultivate good safety practices at workplaces. The OSH framework is based on three principles which are: a) reducing risks at source by requiring all stakeholders to eliminate or minimise the risks they create; b) instilling greater ownership of safety and health outcomes in the industry participants; and c) preventing accidents through higher penalties for poor safety management.

Under the WSHA every person must take reasonably practicable steps to ensure the safety and health of every workplace and worker. The scope of WSHA is wider than the now superseded Factories Act with respect to allocating liabilities to persons at the workplaces. Its focus is more on workplace safety, health goals and systems than setting prescriptive rules.

WSH (Risk Management) Regulations which is a subsidiary legislation under the WSHA has had a dramatic impact on the safety of tunnelling and underground construction sites. This new legislation places greater responsibilities on clients, designers and contractors to adopt proper risk management techniques on projects for the effective identification and control of all major safety and health risks that could occur during construction. The use of Risk Registers to indentify and track risks during the design and construction phases is proving to be a very useful and effective risk management tool.

In addition to the new legislative requirements, the major tunnelling clients in Singapore such as the Land Transport Authority (LTA) and the Public Utilities Board (PUB) have their own extensive safety specifications and requirements specific to controlling health and safety in their tunnelling and underground works. These specifications are updated and improved continually based on ‘lessons learnt’ from completed projects.
2.2 Client's Role under WSHA

The client's role is very important in the safe and successful delivery of a project. The client is able to influence several key decisions in a project including engaging of designers and contractors, the type of construction as well as the materials used. The client is in a position to identify and mitigate the risks during conceptual and early planning phase of a project. The client’s role is also to ensure that adequate resources (time and money) are provided for the design and construction in a safe manner. Clients cannot assume that with the award of the construction contract all risks are transferred to the contractor. A contractor’s failure to complete the works safely and within programme can ultimately become a risk to the client.

2.3 Designer's Role under WSHA

In specifying the design of a structure, the designer should possess a clear understanding with respect to the processes involved during the construction, maintenance and demolition phases of the works. The designer has a duty to consider the risks to those carrying out the construction works and to those affected by it, including the public and end users.

A cardinal principle of WSHA is that the person who creates the risk must be responsible to control it. This is applicable to the designers, who should ensure that the safety and health risks created as a result of their design, be reviewed through a systematic process of risk identification, classification of likelihood and severity, and finally mitigation and management. Where hazards cannot be completely eliminated, designers should assess the resultant risks by considering the severity and probability of occurrence. The resultant risks should be reduced by proposing alternative solutions and providing the safety coordinator, contractors and end users with adequate information so as to prevent hazards from occurring. The residual risks should then be highlighted to the contractor to manage during the construction phase.

The Eighth Schedule, Part 1 of the Building Control (Amendment No. 2) Regulations 2008 which came into effect on 1 October 2008 stipulates the specific duties of Qualified Persons (QPs) appointed to prepare the plans of geotechnical aspects of underground building works.

2.4 Safety Regulations

WSHA is supported by several subsidiary legislations, some of which are based on the now superseded Factories Act. Among these, WSH (Risk Management) Regulations and the WSH (Incident Reporting) Regulations were introduced in 2006 as a priority, together with the WSHA. The WSH (Incident Reporting) Regulations require all workplaces to report work-related accidents, dangerous occurrences and occupational diseases, thereby facilitating the identification and monitoring of WSH trends. The following is a comprehensive list of new subsidiary legislation related to WSH:

- WSH (Workplace Safety and Health Officers) Regulations 2007;
- WSH (General Provisions) Regulations 2006;
- WSH (Construction) Regulations 2007;
- WSH (First Aid) Regulations 2006;
- WSH (Incident Reporting) Regulations 2006;
- WSH (Risk Management) Regulations 2006;
- WSH (Composition of Offences) Regulations 2006;
- WSH (Transitional Provision) Regulations 2006;
- WSH (Offences and Penalties) Regulations 2006;
- WSH (Registration of Factories) Regulations 2008;
- WSH (Workplace Safety and Health Committees) Regulations 2008;
- WSH (Abrasive Blasting) Regulations 2008;
Even though the Factories Act had been repealed, under Section 66(14) of the WSHA, the following Factories subsidiary legislations are still in force but will be reviewed and promulgated in the near future as new WSH subsidiary legislation:

- Factories (Asbestos) Regulations;
- Factories (Certificate of Competency - Examinations) Regulations;
- Factories (Medical Examinations) Regulations;
- Factories (Noise) Regulations;
- Factories (Operations of Cranes) Regulations;
- Factories (Persons-In-Charge) Regulations;
- Factories (Registration and Other Services - Fees and Forms) Regulations;
- Factories (Safety Training Courses) Order;
- Factories (Scaffolds) Regulations 2004.

2.5 **Occupational Health**

Under the WSH (Medical Examinations) Regulations, workers exposed to compressed air working must undergo specific medical examinations. The medical examinations are not "general checkups", but are specific to the type of hazard involved and must be conducted by Designated Factory Doctors, registered with the Ministry of Manpower. The types and frequency of examinations are specified in the Regulations. For most hazards, the medical examinations are to be carried out once a year. In some cases, the frequency may be at six monthly intervals or less. The results of health surveillance should be evaluated and measures taken to safeguard the health of employees. For LTA projects it is also a specified requirement for contractors to follow the UK Health and Safety Executive (HSE) 'Work in Compressed Air Regulations 1996', together with the accompanying guidance notes.

Under the WSH (General Provisions) Regulations, regular monitoring is required in workplaces where toxic substances are used or emitted. Regular noise monitoring is required for workplaces with excessive noise. Monitoring of atmosphere in confined spaces, measurement of dust particles and heat are essential for tunnelling sites. Monitoring of the hazards must be done by a competent person. Workplace monitoring aids in the assessment of possible health risks that may result. It also helps to gauge the need for and/or effectiveness of hazard control measures. The top management's support is essential to the successful implementation of a surveillance programme. The results of workplace monitoring should be evaluated and the necessary measures taken to safeguard worker health. Employees must be also informed of the results, which should be recorded.

3 **RISK MANAGEMENT**

The WSH (Risk Management) Regulations require construction sites to carry out proper risk assessments and implement control measures to eliminate or minimise the identified safety and health risks. The introduction of the Risk Registers is a very useful risk management tool during the construction phase as it enables the project team to properly identify and track all major risks through the construction phase to ensure that risks are sufficiently mitigated or closed out before they can impact the project. The Risk Register should identify suitable project team members as 'owners' of each risk and make them responsible to ensure close-out by a certain date which is linked to the construction programme. Holding regular Risk Register Review meetings allows the project team to manage the project risks in a more systematic and controlled manner.

4 **SAFETY PRACTICES**

The safety practices required by the subsidiary legislation on construction sites related to tunnelling and underground construction include the setting up of a Workplace Safety and Health
Committees which employ over 50 workers. Approved Safety officers have to be employed on sites where the contract value exceeds S$10 million or the number of workers exceeds 100.

The general provisions with respect to safety and health on construction sites are covered by the WSH (Construction) Regulations 2007. Work sites have to be inspected by the Safety Committee at least once a month. Contractors will be issued with demerit points for breaches under the WSH Act and Regulations. A contractor that has received more than 18 demerit points within a 12-month period will receive a formal written warning from the Ministry of Manpower (MOM). Any further demerit points will lead to limits or rejection on applications from the company for new and renewal of all types of work passes for foreign employees.

All workers on a construction site have to complete Construction Safety Orientation Course. In addition those who carry out work in a manhole or confined space have to complete Safety Orientation Course (Manhole) while their supervisors must complete a Safety Instruction Course (Manhole). Any Project Manager appointed to be in charge of a construction site of a contract sum over S$10 million must complete a Construction Safety Course for Project Managers.

The purpose of the training is to identify the responsibilities under the WSH Act, follow hazard identification and risk control procedures; and contribute to the management of WSH through consultation and participation. In addition, managers must be able to establish and maintain the framework for the WSH system, participate and communicate for the management of WSH, establish and maintain the organisation’s risk management procedures, and evaluate the organisation’s WSH system, policies, procedures and programmes.

5 SAFETY AND HEALTH RECORDS

As part of the preparation of this paper safety and health records collected and published by the MOM were reviewed to study the trends in the construction industry in general and the tunnelling and underground construction sector in particular. The published data does not separately distinguish between underground and above ground construction. For the purposes of our study we have assumed that the trends may be similar. However we note here that since most of the underground construction projects executed during the last five years are large and these include the 33 km long Circle Line Railway, 12 km long Kallang-Paya Lebar Expressway, 25 km long Deep Tunnel Sewage System and 7 km long cable tunnels. These projects have been followed closely by MOM and therefore their performance with respect to safety and health is expected to be better than that for the rest of the construction industry.

The fluctuations in the construction activities in Singapore over the last 10 years can be seen in Figure 1. which clearly shows a remarkable increasing trend in the construction activity from a dip in 2004.

The number of accidents recorded at construction sites over the period 1994 to 2008 can be seen in Figure 2. Upto year 2005, the number of site accidents were recorded as a measure of the number of incidents. Since 2006 this has been changed as a measure of the number of victims. This change accounts for the sudden jump in the numbers between 2005 and 2006. Notwithstanding this an increase over the period 2006 to 2008 can be seen which is a reflection of both the increased activity in the construction sector as well as the introduction of the WSH (Incidents Reporting) Regulations in 2006.

The total number of fatalities in the construction industry, Figure 3, shows a stagnating trend since 2003 though it had been falling sharply from a peak in 1997. When measured against the increased activity in the construction industry over the period 2004 to 2008 (Figure 1) the fatality numbers are in fact showing a decreasing trend. The fatality rate in 2008 of 6.9 in the construction industry is still well above the national objective of achieving a rate of 2.5 by the year 2015.
The accident frequency rate, which uses number of man hours worked as a common base indicates a sudden increase in 2006, when WSHA came into effect, followed by a declining trend. It is not clear whether the change in the definition of accidents (incidents to victims) has had an influence. Nevertheless the current figure of approximately 3 accidents in the construction industry per 1 million man hours worked is well above the national average of 1.9.

The severity of accidents has been declining since 1997 and a significant drop can be seen from 2005 in Figure 5. This is encouraging in that even though there is little change in the accident frequency the severity rate is showing a declining trend. The accident severity rate of 221 in the construction industry during 2008 is however double the national average of 112.

The incidence of both barotrauma and compressed air illness can be almost wholly related to tunnelling and underground construction. Figure 6, shows a disturbing picture in that these two health issues are still proving to be significant.

Of the ten cases reported in 2005 one was a freelance diver laying pipes as part of the Deep Tunnel Sewage System. Other nine were involved with the construction of a cable tunnel working at pressures of up to 2.3 bar to change cutter tools of a TBM. In the latter case a sudden loss of pressure in the decompression chamber occurred as a result of damage to the rubber gasket providing an air tight seal to the high pressure door which was caused by a grit particle.

There were 17 cases of barotraumas reported in 2007. Of these 16 workers were from a tunnelling project where compressed air was used to prevent ground water from entering the working chamber and one was a scientific officer. In some cases were the presence of upper respiratory tract infection and the failure to report promptly to the man-lock attendant when they developed symptoms during compression and de-compression. The scientific officer developed aural barotrauma when she continued to dive even though she was unable to clear her ears. In all
cases the victims were given advice and further training which emphasised the importance of reporting if they feel unwell. This can be a common problem since workers may voluntarily take the risk of working in compressed air despite having flu like symptoms in order to earn the additional allowance for compressed air workers.

The other health issues that are relevant but of low level of incidents are noise induced deafness, cement dermatitis and respiratory lung diseases.

6 COMMON ACCIDENTS AND CAUSES IN UNDERGROUND CONSTRUCTION

Common accidents in tunnel construction are related to having to carrying out construction works in a confined space environment, which increases the hazards involved with nearly all normal construction activities. Main tunnel safety hazards include the handling and installation of pre-cast concrete segmental linings, handling heavy components such as cutter discs, slips, trips and falls, being struck by or being caught between objects and machinery, rolling stock accidents and injury by collapses of ground. Some examples of accidents are given below:

Case 1 - A concrete pump operator working in a tunnelling site was cleaning out the pipeline by means of inserting a sponge ball into one end of the pipeline and blowing with compressed air. At the time of the accident he was standing on an intermediate platform located 10m above the bottom of a shaft. The free end of the pipeline was equipped with a rubber hose to discharge the leftover concrete into a container. When the sponge ball was forced out from the rubber hose, the hose swung suddenly and without warning and hit the pump operator. He was flung off the platform, landed on the bottom of the shaft and died on the spot [7].

Case 2 - A carpenter working in a construction site died from heat stroke on the second day of starting work. He was tasked to dismantle a timber formwork at a basement 4m below ground level. At lunchtime, he complained of dizziness but resumed work after lunch at 1pm. By 3.25pm, he was found unconscious was admitted to hospital. He had a body temperature of 43°C (normal = 36.9 °C). Despite aggressive resuscitation, he died from circulatory collapse. Investigations revealed that the average Wet Bulb Globe Temperature (WBGT) where the deceased had worked was 32 °C. This serves as an example to heed in tunnel construction projects where high temperatures are generated by the tunnel boring machine and other ancillary equipment.

Case 3 - During the installation of heavy power cables on an overhead cable rack along a tunnel wall, one worker accidentally dropped one of the cables to the ground which started off a domino effect causing approximately 2 km length of cable to fall off the rack. This accident caused injuries to several workers working in the tunnel at the time. The cause was attributed to the cable being not securely tied to the rack at the time of the accident.
Case 4 - Workers narrowly avoided being struck by a precast concrete lining segment which dropped from the tunnel crown during installation. The TBM rams were inadvertently loosened prior to the full installation of the segment bolts. The segment was prevented from falling onto the erector deck by the partially installed radial bolts. Miscommunication between the ram operator and segment erector crew was the key cause. It should be noted that all the workers spoke the same language.

From the accidents stated above insufficient risk identification, lack of safe work procedures and poor briefing to the workers of potential hazards are key contributing factors. A comprehensive assessment of risks associated with the type of construction being carried out is mandatory. As a minimum, a typical Risk Register for tunnelling works should cover the following aspects:-

<table>
<thead>
<tr>
<th>Fire</th>
<th>Poor ventilation</th>
<th>Access and egress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding</td>
<td>Heat stress</td>
<td>Working at height</td>
</tr>
<tr>
<td>Manual handling</td>
<td>Dust</td>
<td>Working in the cutterhead</td>
</tr>
<tr>
<td>Rolling stock</td>
<td>Noise</td>
<td>Slips, trips and falls</td>
</tr>
<tr>
<td>Lifting gear</td>
<td>Electrocution</td>
<td>Compressed air working</td>
</tr>
<tr>
<td>Ground collapse</td>
<td>Plant and Machinery</td>
<td>Over excavation</td>
</tr>
<tr>
<td>Ground water lowering</td>
<td>Noxious Gases</td>
<td>Explosion</td>
</tr>
<tr>
<td>Ring Building</td>
<td>Shotcreting</td>
<td>Drill &amp; Blast</td>
</tr>
</tbody>
</table>

7 REVIEW OF THE EFFECTIVENESS OF CURRENT WSH PRACTICES

The safety records presented in Section 4 show that there is an improving trend in the fatality and severity of accidents rates. At present the records do not indicate a significant improvement in health especially with respect to carrying out work in compressed air.

The introduction of mandatory safety and health risk assessment of all construction work activities is proving to be effective in terms of planning pro-actively to eliminate or control safety and health hazards. The increase in penalties as well as holding accountable those individuals who create or manage safety and health risks (which includes not only occupiers and clients, but also designers, workers, manufacturers and suppliers) is making it a stronger deterrent.

The Safety and Health Regulations and individual client Specifications are being updated and improved on the basis of experiences and lessons learnt from the extensive number of tunnelling and underground projects that have been undertaken in Singapore in the recent past.

8 POTENTIAL AREAS FOR IMPROVEMENT

The underground construction industry has a key role to play in ensuring better WSH outcomes in this sector as it is best-placed to identify and develop the appropriate standards and practices to be adopted based on its detailed knowledge and experience of the environment and processes at the workplace. The learned societies such as Institution of Engineers Singapore (IES), Association of Consulting Engineers Singapore (ACES) and Tunnelling and Underground Construction Society Singapore (TUCSS) also have a duty to improve the standards through training and accreditation.

Training helps to instil better safety habits in workers, supervisors and managers alike. In addition to understanding responsibilities under the WSHA it helps to identify hazards and educate workers on safe ways of carrying out their tasks. Factories Act (Chapter 104, Section 27A), Factories (Safety Training Courses) Order does not require any specific training for tunnel workers although there is a requirement for those working in manholes or confined spaces. At present there are 4-hour orientation courses available for construction workers assigned to work in tunnelling or underground construction. These are aimed at the hazards from compressed air work, locomotive operation and tunnelling and underground construction works and the
precautions necessary to avoid accidents. In the authors’ opinion training courses of longer duration imparting more information on the works at a particular site will be more beneficial.

The tunnels workers in Singapore originate from a few countries around the region. Though English is widely used on the sites, this is often a second or third language for many workers. Therefore communication of instructions and information is a continual challenge. This is being addressed to some extent by posting notices and warnings on several languages but constant vigilance is required to ensure that the right message is being conveyed and understood. Clear diagrams and pictures help with safety and health communications and the ITA handbook on Safe Working in Tunnelling has been very useful in this respect.

Particular areas that need improvement are: Compressed air working, health hazards related to silica dust, Radon and heat exhaustion. In more advanced countries oxygen type self rescuers have now replaced the old type which converts carbon monoxide to carbon dioxide. In addition electronic tags are now replacing the traditionally used tallies. Manual shotcrete spray application which is not only hazardous but also harmful to health is also being replaced by the use of robots in many countries. It is believed that these practices will soon be introduced here to help to reduce accidents further and to improve workplace health. Consideration should be given also to removing costs related to safety and health from the competitive bidding process when awarding construction contracts.

9 CONCLUSIONS

The authors have carried out a critical review of the current state of safety and health in the underground construction sector based on information mainly available in the public domain and presented in this paper. The general conclusion is that there is a clear reducing trend in the accident severity rate. The introduction of the WSH (Risk Management) Regulations and keeping of Risk Registers are seen to be making dramatic improvements in the local safety and health practices.

The cyclical and competitive nature of the tunnelling industry and deployment of labour from different countries require both constant vigilance and ensuring that good safety standards are maintained, updated, revised and consistently enforced. Continual briefing of workers and operatives at all levels with regard to the potential hazards related to their tasks and the safe methods to carry out the work will increase awareness and contribute to reducing the number of accidents in the industry. In addition provisions must be made in all contracts to allocate sufficient time and costs for training of workers and for undertaking familiarisation exercises in tunnel rescue and evacuation.

REFERENCES

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[7] WSH Council (2008), Falling from Height Case Studies Construction Industry, MOM Website, Singapore