Regulatory Requirements on Earth Retaining and Stabilising Structures & Tunnelling Works

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ABSTRACT: The collapse of the Nicoll Highway in 2004 brought about the beginning of regulatory requirements on ERSS and tunnelling works in Singapore. This paper traces the development of the regulatory requirements on ERSS and tunnelling since it began, highlighting the incidents that preceded these regulatory requirements and explains the reason why some of these regulations are currently in place. Through this paper, the authors hope to remind the construction industry on the importance and relevance of these regulatory requirements, and more importantly, remind personal parties of the important roles they play in keeping our built environment safe.

1 INTRODUCTION

Singapore's dense urban environment makes excavation and tunnelling in close proximity to buildings inevitable. The collapse of Nicoll Highway in 2004 served as a wake-up call to the industry on the catastrophic consequences such an incident could bring, and brought about the beginning of the regulatory framework on Earth Retaining and Stabilising Structures (ERSS)[1] and tunnelling works in Singapore. Regulatory requirements on tunnelling works were further tightened after the Cornwall Garden sinkhole which occurred in 2008, following several other sinkhole incidents. Most recently, in response to the sinkhole incidents which occurred during the construction of tunnels from the proposed Steven Station to the proposed Napier Station in the Thomson-East Coast Line (TEL), a circular detailing a list of safety requirements on bored tunnelling based on a risk approach was issued on 15 Sep 2017.

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[1]Earth Retaining and Stabilising Structures (ERSS) was previously known as Temporary Earth Retaining Structures (TERS).

This paper traces the development of the regulatory requirements on ERSS and tunnelling through the years. While the incidents that preceded the implementation of these regulatory requirements were unfortunate and unforgettable, the authors hope to remind the construction industry on the importance and relevance of these regulatory requirements, and more importantly, remind all parties of the important roles they play in keeping our built environment safe.

1.1 ERSS and tunnelling works before Nicoll Highway

The Nicoll Highway Collapse occurred at 3.30pm, 20 April 2004. A photograph taken of the site after the collapse is shown in Figure 1. The incident had occurred due to the failure of the temporary earth retaining wall system constructed for a 34m deep cut-and-cover tunnel excavation adjacent to Nicoll Highway. During that time, design and construction of temporary earth retaining structures (TERS) were not regulated under the Building Control Act and Regulations and hence there were no requirements for plan submission. For private projects, TERS were regulated through conditions stipulated under the Permit to carry out structural works issued by the Commissioner of Building Control (CBC). For public projects administered by agencies such as LTA, HDB and JTC, the TERS plans were submitted to the respective Building Control Unit (BCU) for review. Wall installation was normally allowed to proceed upon submission of the TERS plans. In some cases, Professional Engineers may need to enhance the TERS design if there were adverse comments from the respective BCU.

Figure 1. Nicoll Highway site after the collapse

1.2 Recommendation by the Committee of Inquiry (COI) following Nicoll Highway Collapse

The COI was appointed on 22 April 2004 to look into the events leading up to the collapse of the Nicoll Highway and provide recommendations to prevent recurrence of similar incidents. The COI was led by Richard Magnus, Dr Teh Cee Ing and Er. Lau Joo Ming, and it involved 173 witnesses of facts and 20 local and international experts.

Separately, a Joint MND-MOM Review Committee (JRC) on Construction Safety was convened to raise safety standards in the construction industry. The committee was tasked to review the regulatory framework and consider commendations from the COI. The JRC was also assisted by a panel of resource persons (comprising of experts and experienced practitioners in construction works) appointed to provide their independent views on the construction safety issues and recommendations. The JRC actively consulted the industry on issues related to construction safety.

The JRC's recommendations had addressed gaps observed in the regulatory framework then as well as the safety systems along the construction value chain from design, to procurement and construction stage. At the end of the joint review, the JRC had put up several recommendations to strengthen the building control framework as follows:

- A) Changes to regulatory framework
  - i) Greater accountability for all parties; Workplace Safety and Health Act to be tightened to include personal accountability of all stakeholders;
  - ii) Centralisation of building control units; On 1 October 2005, BCA took over the processing and approval for all plan submissions for HDB, JTC and LTA projects from the respective BCUs; such move would help to restore public confidence in the regulatory framework.
  - iii) Streamlining the responsibilities of BCA and MOM; BCA to act as the single authority to regulate temporary earth-retaining structures related to excavation works.
- B) Improving safety at the design stage
  - i) Tightening of regulations on TERS for excavation works;
    - a. Excavation not deeper than 4m or one level basement; TERS design and supervision to be carried out by a Professional Engineer (PE) and checked by an Accredited Checker (AC).
    - b. Excavation deeper than 4m or one level basement; TERS design and supervision to be carried out by a PE and a PE(Geo), and checked by an AC and an AC(Geo). JRC further recommended that the requirements for PE(Geo) and AC(Geo) to be extended

to slopes, tunnelling works of more than 2m in diameter and foundation of buildings of 30-storey or more using caissons, bored piles or raft.

- ii) Development of design guidelines and specifications for deep excavation works
- iii) Imposition of statutory duties on professional engineers carrying out the design of other temporary structures
- iv) Requirement on continuous training for professional engineers
- v) Upholding the professionalism of supervising qualified person, QP(S) to be independent from builder and developer.

C) Improving safety at the procurement stage

- i) Incorporation of non-price attributes in government's tender evaluation framework
- ii) Licensing of contractors and specialist sub-contractors to raise the competency and professionalism of builders in the construction industry; two types of licences, General Builder and Specialist Builder for six specialist work areas in piling, ground support and stabilisation, site investigation, structural steel, precast concrete and post-tensioning work were introduced. In addition, the developer is required to directly appoint the specialist instrumentation contractor for all complex excavation works, so that the instrumentation contractor will be independent of the main contractor, in order to achieve better control and processing of instrumentation data.

D) Improving safety at the construction stage

- i) Requirement on safety training for all site supervisors
- ii) Requirement on supervision as well as endorsement and certification for temporary structures
- iii) Introduction of site supervisor teams for supervision of structural works; the QP is to appoint a supervision team instead of one qualified site supervisor to assist in the supervision of the construction of structural works especially in larger work sites
- iv) Enhancement of site safety co-ordination and implementation of permit-to-work system

2 REGULATORY REQUIREMENTS OF ERSS FROM 1 OCT 2008

2.1 Design and supervision of ERSS

During the consultation phase of the amendment to Building Control (BC) Act and Regulations, the professional societies had provided strong recommendation to adopt

6m to be the depth for one level basement as many one level basements were 6m deep. After much deliberation, BCA accepted the industry's recommendation to adopt 6m depth as the benchmark level for one level basement. Modifications were made to the proposed changes to BC Act and Regulations to require ERSS of up to 4m deep to be submitted by a PE; ERSS of between 4 and 6m deep to be submitted by a PE and checked by an AC; ERSS of more than 6m deep to be submitted by a PE and a PE(Geo) and checked by an AC and an AC(Geo).

The requirements for PE(Geo) and AC(Geo) were also extended to cover other major permanent geotechnical engineering works given that these works would be as critical as ERSS in deep excavation, in terms of their complexity and their potential impact on the surrounding buildings. Such works would include the protection of slopes with a vertical height of more than 6 metres, independent retaining walls with a vertical exposed height of more than 6 metres, tunnelling works of more than 2 metres in diameter and foundation of buildings of 30 storey or more using caissons, piles or raft. Amendment to BC Act was passed in the parliament in 2007 while the amendment to BC Regulation was gazetted in 2008 and implemented since 1 Oct 2008.

2.2 Advisory Note 1/05 on deep excavation

SPRING Singapore was then tasked to develop the Technical Reference for Deep Excavation TR26:2010, which was only published in 2010. Prior to its publication, BCA (2005B) had issued "Advisory Note 1/05 on Deep Excavation" to serve as an interim design guideline and specifications for deep excavation works. The Advisory Note, which was to be complied with by the Professional Engineers for TERS (PE(TERS)), QPs and builders, covered the following four main sections:

<u>Section A: Site investigation</u>

The Advisory Note highlighted that proper site investigation shall be carried out for the design and construction of ERSS so as to give a thorough understanding and determination of the type and characteristics of the ground conditions and ground water conditions. Key aspects covered under this section include the Codes and Standards, the extent of investigation, the establishment of ground water conditions and the need for pre-construction surveys to establish the pre-construction condition of adjacent properties.

Section B: Design

Key aspects covered under this section include a summary of design considerations for a robust TERS design as shown in Table 1, adoption of an adequate safety factor that is not less than that of permanent works, and the need to incorporate a sufficient redundancy in TERS design including consideration of accidental loads and one-strut failure, to avoid catastrophic collapse. Other aspects covered under this section include selection of representative strength values, use of the most onerous water pressure regime, use of numerical modelling, the need to carry out sensitivity analyses and the use of jet grout piles (JGP) to be restricted to ground strengthening or soil improvement works only and not as compressive strutting systems.

Table 1. Key design considerations on ERSS (BCA, 2005B).

S/N	**Key Design Considerations**
1	Adequate site investigation
2	Proper selection of the soil parameters for design
3	Effects due to onerous water pressures and seepage forces
4	Effects under both drained and undrained conditions of the soils, as well as the effect of time on soil drainage conditions
5	Effects of surcharge loads, including incidental loads, construction loads, adjacent slope, adjacent structures etc.
6	Varying load conditions during stages of the construction
7	Design robustness and redundancy considerations which shall include one-strut failure, accidental loads etc.
8	Adequacy of wall embedment
9	Overall wall stability and basal heave
10	Structural adequacy of supporting system e.g. walers, struts, anchors etc. including provision of adequate stiffeners
11	Provisions of restraints in structural members' connections, ties and bracings
12	Sensitivity analyses and impact on the performance of ERSS
13	Effects due to ground water lowering
14	Effects of ground deformation on neighbouring properties
S/N	**Specific Controls on Design**
1	Surcharge load of at least 10kN/m^2, construction loadings, and loads from adjacent existing structures and usage etc.
2	Non allowance for any material overstress
3	One-strut failure and accidental loads
4	Full or onerous groundwater level conditions and seepage pressures acting on both sides of the wall
5	Factor of safety for design of ERSS shall not be less than that for permanent works
6	Mobilisation factors of not less than 1.2 and 1.5 for effective stress and total stress parameters respectively for limit equilibrium calculations
7	Unplanned excavation

Section C: Construction

The Advisory Note highlighted the need for a multi-tier level monitoring, in which the pre-determined levels shall be set for each strutting level, in addition to the critical levels based on the final values. The performance of ERSS shall also be monitored. When the soil movement has exceeded work suspension level or any structural element of ERSS has exceeded the design level or where there is a structural distress, works shall be stopped and made safe pending the outcome of a design review. The Advisory Note also emphasised the need for the design of the ERSS, which was carried out by PE(TERS), to be checked and reviewed independently by the QP, as listed in Table 2. The Advisory Note put in place two forms – Annex C and Annex D, for the builder to obtain appropriate approvals from the PE(TERS) and QP to proceed with excavation or strut removal to the next level, and for the QP to assess the monitoring data of ground movement respectively, to ensure that site inspection and construction control are put in place.

Table 2. Main Tasks for Checks to be performed on ERSS by QP (BCA, 2005B).

S/N	Main Tasks
1	Independently review and check the design and construction of ERSS to satisfy that the ERSS is structurally safe and adequate, and is in accordance to the building codes and regulations. As a minimum, it shall take into account the following: - Appropriate standards and codes of practice for ERSS; - Adequate site investigation and tests; - Appropriate soil parameters e.g. strength and stiffness; undrained and drained conditions of soils, effect of time on drainage conditions, effective stress parameters, and in-situ stresses; - Surcharge load and loads from the adjacent existing structures and usage; - Construction, incidental and abnormal loads etc.; - Varying load conditions during stages of the construction; - Onerous water conditions and seepage pressures acting on both sides of the wall; - Robustness and redundancy considerations e.g. accidental strut removal and on-strut failure; - No allowance for any material overstress; - Factor of safety for the design of ERSS shall not be less than that for permanent works; - Appropriate mobilization factors for effective stress and total stress analyses for limit equilibrium calculations; - Impact on ERSS due to soil drainage conditions with time; - Basal heave, overall wall stability and adequate wall embedment; - Structural adequacy of supporting system e.g. walers, struts, anchors etc.; - Adequacy in structural members' connections, ties and bracings; - Effects due to ground water lowering; and - Effects of ground deformation on neighbouring properties.
2	Before the commencement of ERSS, review and check that the instrumentation and monitoring plan, measures to prevent damages to neighbouring structures, and the critical limits set for the works are acceptable and adequate.

3	At critical stages, inspect the site and review the actual site conditions and monitoring data to assess and evaluate the performance of the structural supporting system to ensure that the structural adequacy of ERSS shall be maintained.
4	Carry out independent review and check on any amendment on ERSS which have or would have structural or stability implications.

Section D: Instrumentation and monitoring

The Advisory Note stated that as a minimum, monitoring of wall and ground movements / deformation, strut loads and piezometric pressures shall be carried out within and outside the excavation to provide data for design review on the performance. Control sections of the ERSS shall also be identified and adequately instrumented. The validation between the design and predicted values must be verified as early as possible during the construction stage.

2.3 Advisory Note 1/09 on Deep Excavation

After the Nicoll Highway incident, BCA has adopted an internal guideline on setting allowable wall deflection of 0.5% of the depth of excavation, H, as an interim measure to safeguard all deep excavation works. For excavation in close proximity to structures, an additional cap of 100mm on allowable wall deflection was imposed to prevent damage to adjacent building. The practice of imposing the 100mm cap on deflection limit was eventually dropped after an observation which showed that a proper impact assessment would have limited the wall deflection below 100mm in order to prevent damage to buildings in close proximity to the deep excavations. With that, BCA continued to practise the requirement of allowable wall deflection of 0.5%H after the implementation of plan submission requirements for ERSS and Geotechnical building works (GBW) on 1 Oct 2008.

During the construction of Marina Coastal Expressway (MCE) in 2008, the project parties provided strong feedback to BCA that the adoption of 0.5%H in greenfield sites such as MCE would be too onerous. BCA therefore conducted a review in 2009 on the requirements of design and construction of ERSS, and convened an independent Technical Expert Panel (TEP) to review the technical issues pertaining to regulatory controls on the design and construction of deep excavations in Singapore as well as to advise on the setting of allowable wall deflection as a criterion for control.

The outcome of the TEP review resulted in BCA issuing the Advisory Note 1/09 on 2 April 2009. The main changes captured in Advisory Note 1/09 include: a) Allowable wall deflection limits; b) Ground improvement; c) Control strategies; and d) Instrumentation and monitoring.

Allowable wall deflection limits

The TEP recommended that the 0.5%H criterion should be retained where buildings are in close proximity to the deep excavation works. However, for areas where buildings are further away from the excavation sites and when deep excavation works are carried out in greenfield sites, the wall deflection design limits could be relaxed according to the distance of buildings from the excavation sites as well as soil types, to allow greater flexibility in design. A more relaxed allowable wall deflection limit would be allowed for greenfield sites subjected to additional inspection, monitoring and checking procedures. The allowable wall deflection limits are shown in Table 3.

Table 3. Allowable maximum ERSS wall deflection limits (BCA 2009).

Wall deflection limits / Zones where x = distance from excavation face; H = excavation depth δ_w = wall deflection	**Locations of buildings, structures and critical utilities**			
	Zone 1 (x/H < 1)	**Zone 2 (1 ≤ x/H ≤ 2)**	**Zone 3 (x/H > 2)**	
			Ground Type A	**Ground Type B**
Allowable maximum ERSS wall deflection limits (δ_w/H)	**0.5%**	**0.7%**	**0.7%**	**1.0%**

Figure 2 shows the comparison of soil characteristics and the Strength Mobilisation Factor, M for soft soils among cities around the world, including Singapore, Mexico City, Bangkok, Oslo, Boston, San Francisco, Chicago, Shanghai, and Taipei (Bolton 2012). The Singapore's soft marine clay falls into the middle range of the data. Based on the Singapore's marine clay and stiff clay data, BCA's TEP had justified that the use of a smaller value of M of up to 1.2 could still satisfy the requirements stipulated in BS8002 and fulfil COI's recommendations. With this, BCA's TEP proceeded to derive limit values for the wall deflection for stiff soils and soft soils in Singapore.

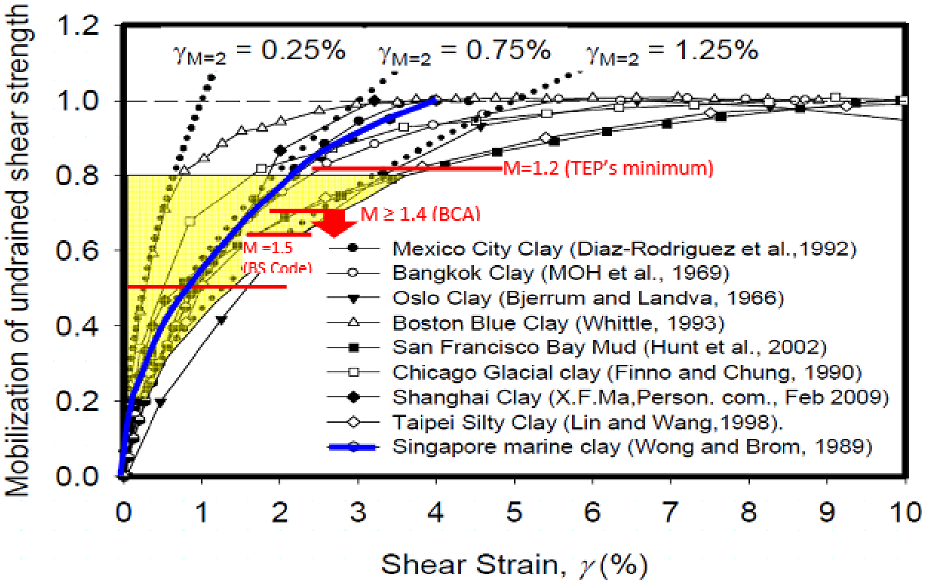

Figure 2. Validation of strength mobilisation of soft soils beneath nine cities (Bolton 2012).

<u>Preventing damage to buildings</u>

BCA (2009) highlighted that in any case, the allowable wall deflection limits shall also be checked and confirmed taking into consideration the prevention of structural damage to neighbouring buildings or structures arising from ground deformations. For ERSS in close proximity to buildings, the allowable wall deflection is often governed by the need to prevent damage to adjacent buildings. For example, for LTA's rail projects, LTA's consultants had imposed an absolute allowable lateral wall deflection value of below 0.5%H in the contract drawings to prevent damage to the adjacent structures. An example of such practice is shown in Figure 3.

PERFORMANCE CRITERIA (TEMPORARY WORKS)		
STRUCTURE	PATTERN	MAXIMUM ALLOWABLE LATERAL DEFLECTION
DT12 ROCHOR DWALL 1	[vertical lines]	70 mm
DT12 ROCHOR DWALL 3	[cross-hatch]	100 mm
DT12 ROCHOR DWALL 4	[dense grid]	40 mm
DT12 ROCHOR DWALL 5	[circles]	80 mm

Figure 3. Example of absolute allowable wall deflection specified for DT12 Rochor Station.

BCA (2013) completed a benchmarking project on regulatory control of deep excavation on wall deflection, to benchmark BCA's deflection limits of retaining wall for deep excavations against practices in other established jurisdictions. The benchmarking project was carried out against several cities or countries including South Korea, Shanghai, Tokyo, Hong Kong, New York, Washington, Boston Toronto, Germany and the Netherlands. Based on the findings of the study, the wall deflection limits practised in areas in close proximity to buildings were either comparable to or more stringent than BCA's current limits on wall deflections of 0.5%H.

As such, BCA conducted further study on local practices of design allowable wall deflection limits adopted for deep excavations located in close proximity to buildings. Figure 4 shows the design allowable wall deflection adopted by design engineers for more than five hundred design sections of deep excavations located in Zone 1 where the maximum wall deflection limit has been limited to 0.5%H. About 10% of these design sections had adopted allowable wall deflection of between 0.4%H and 0.5%H. Majority of the design sections had adopted an allowable wall deflection of between 0.1%H and 0.3%H. The data shows that for deep excavations located within close proximity to buildings (Zone 1), the designers would adopt a more stringent allowable wall deflection limit than the 0.5%H limit, to prevent damage to buildings.

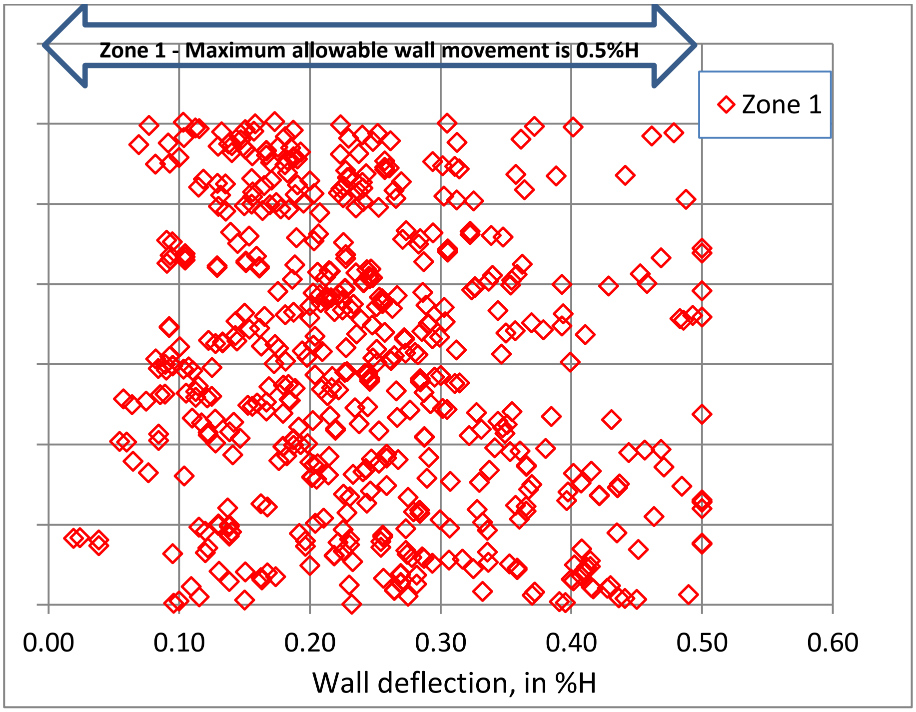

Figure 4. Allowable design wall deflection adopted by local designers for deep excavation in close proximity to buildings.

Ground improvement

In addition to JGP, deep soil or cement mixing (DSM or DCM) are also included as types of ground improvement, the use of which shall be restricted to the purpose of ground strengthening or soil improvement works. The Advisory Note 1/09 highlighted the need for continuous monitoring particularly when the ground improvement layer is used as a base shear plug below the formation level, used to control basal heave, or where the design of ERSS has placed a lot of reliance on the interface shear resistance between the improved ground mass and the piles anchoring the ground improvement layer, for stability. One recent example which showed the importance of continuous monitoring is the launch shaft for Thomson Line Contract T227 where the poor quality control of the ground improvement layer had resulted in excessive deflection.

Control strategies

The guide for control strategies on ERSS is specified in Advisory Note 1/09, as shown in Table 4. The performance of ERSS shall be monitored and checked throughout the construction period against the check, alert and work suspension levels.

Instrumentation and monitoring

Advisory Note 1/09 added that the movement of adjacent ground shall be monitored with appropriate allowable limits to safeguard against any adverse construction effects to neighbouring properties during the installation or construction of JGP, DCM or DSM and trenching of the ground, e.g. to form diaphragm walls.

Table 4. Control strategies guide for ERSS (BCA 2009)

<table>
<tr><td rowspan="3">Zone 1</td><td colspan="3">Allowable limits</td></tr>
<tr><td>Alert level</td><td colspan="2">Work suspension level</td></tr>
<tr><td>70% WSL</td><td colspan="2">Allowable wall deflection limit</td></tr>
<tr><td rowspan="3">Zones 2 and 3</td><td colspan="3">Allowable limits</td></tr>
<tr><td>Check level</td><td>Alert level</td><td>Work suspension level</td></tr>
<tr><td>50% WSL</td><td>70%WSL</td><td>Allowable wall deflection limit</td></tr>
</table>

2.4 Guidelines on pre-construction survey prior to carrying out construction works

In September 2012, about 40 houses were reported damaged due to groundwater lowering during the excavation for DTL2 Tan Kah Kee Station. These houses were located about 100 to 150m away from the excavation site, well beyond the normal zone of influence of three times the excavation depth commonly adopted by the industry. Investigation had revealed that such large extent of zone of influence was attributed to the presence of highly permeable F1 sand layer and soil-rock interface of Bukit Timah Granite Formation. A similar case of large extent of damage was also observed during the construction of DTL2 Stevens Station. In the latter case, ineffective grouting at the soil and rock interface of the Bukit Timah Granite Formation had caused excessive lowering of ground water level and the effect had extended to a large area. These two incidents highlighted the inadequacy on the extent of pre-construction survey to be carried out for deep excavations in highly permeable F1 sand layer and soil-rock interface of the Bukit Timah Granite Formation.

BCA (2015) issued a guideline for the minimum extent of pre-construction survey to be carried out by the builder before carrying out any excavation work. For excavation works carried out for landed developments, pre-construction survey shall be carried out covering a zone of not less than 15 metres from the project site boundary.

Table 5 summarises minimum zone of pre-construction survey to be carried out for excavation works for non-landed developments with basement or underground space. For good soils, the pre-construction survey shall be carried out for a zone of not less than 30 metres from the project site boundary, or 3 times the maximum excavation depth, whichever is larger. Similarly, for soft soils without fluvial sand / peat / peaty clay, pre-construction survey shall be carried out for a zone of not less than 60 metres from the project site boundary, or 6 times the maximum excavation depth, whichever is larger. And finally, for soft soils with fluvial sand / peat / peaty clay, pre-construction survey shall be carried out for a zone of not less than 90 metres from the project site boundary, or 9 times the maximum excavation depth, whichever is larger.

Table 5. Guideline for minimum zone of pre-construction survey for excavation works for non-landed development with basement or underground space.

Types of Soils	Minimum zone of pre-construction survey^
Good soils♦	30 m or 3H*
Soft soils† (e.g. marine clay) without fluvial sand/peat/peaty clay	60 m or 6H*
Soft soils† with fluvial sand/peat/peaty clay	90 m or 9H*

Note:

1. **Maximum excavation depth include localise pits;**
2. **^For cases with two values, the larger of the two values should be adopted.**
3. **♦Good soils refer to medium dense to very dense sand and gravel, and firm to hard silt and clay.**
4. **†Soft soils refer to very loose to loose sand and gravel, and very soft to soft silt and clay.**
5. *** H is defined as the maximum excavation depth.**

2.5 Recommendation for spacing of Site Investigation boreholes

With the implementation of the structural Eurocodes with effect from 1 April 2015, GeoSS had issued a guide on “Ground Investigation and Geotechnical Characteristic Values to Eurocode 7”. In this guide, it is recommended that for ERSS or retaining wall of less than 6m in height, there should be one site investigation borehole every 15 to 40m. For ERSS or retaining wall of greater than 6m in height, there should be one site investigation borehole every 30m.

3 REGULATORY REQUIREMENT OF BORED TUNNELLING WORKS

3.1 Challenges for Tunnelling in Close Proximity to Buildings

With intensification of the rail network, more bored tunnelling works is expected to be carried out in close proximity to existing buildings. This gives rise to several issues that the tunnelling team will have to deal with for the tunnelling works to be completed without causing any major problems to the neighbouring properties and structures. Tunnelling works, if not operated carefully, may lead to excessive ground deformation above the tunnel crown. This in turn may cause distress to the foundations of surrounding buildings and structures. In serious cases, the foundations, whether shallow or deep, could be damaged, leading to tilting of the building or structure, and possibly structural damage and even collapse.

Another potential problem is related to water or soil ingress at the tunnel face, resulting in excessive ground loss and settlement within the influence zone of the tunnelling works. Severe ground loss can result in formation of sinkholes, causing danger to the neighbouring buildings and structures as the geotechnical bearing capacity of the soil is affected. Again, this can cause damage to buildings and possibly collapse and risks to the public. The problem inversely related to ground loss will be that of blow-outs during the tunnelling process, usually as a result of setting the face pressure at too high a level. Blow-outs of the ground above the tunnel crown can also lead to structural damage to buildings and structures in close proximity to the tunnel alignment.

All these problems are usually exacerbated in mixed ground conditions, in which the tunnelling works have to be operated within a narrower range of tunnelling parameters and monitoring have to be conducted more carefully.

3.2 Tunnelling Works Prior to Cornwall Garden Sinkhole Incident

As detailed in Section 1, prior to the Nicoll Highway collapse, there were no requirements for the Professional Engineers of ERSS and tunnelling works to have the relevant geotechnical experience, neither were there any requirements for the design of ERSS and tunnelling works to be reviewed by an independent AC. Even after the centralisation of the BCU functions on 1 October 2005 to be within BCA, only plan submission of permanent tunnel lining is required.

On 24 May 2008, a 12m (length) by 5m (width) by 3m (depth) sinkhole, occurred at Cornwall Gardens, off Holland Road (Figure 5). The incident happened near an existing house. It did not cause any damage to the house but it has damaged a drain, water pipe, power and telecom cables and the 2-lane road. Fortunately no one was injured in this Cornwall Garden sinkhole (CGS) incident. The subsequent investigations by the project parties suggested that the CGS was caused by the Circle Line (CCL 4) tunnelling works during the construction of the inner tunnel. The cause of CGS is likely due to six reasons, namely faulty equipment, excessive over-excavation, face instability, face pressure not in accordance with SOP, no surface grouting of over-excavated void and inexperienced tunnelling personnel.


Figure 5. Photo of CGS.

There were a total of 10 incidents due to LTA's bored tunnelling works in 2006 prior to the CGS incident, as listed in Table 6.

Table 6. Details and locations of sinkhole incidents prior to CGS.

S/n	Location of Incident	Date
1	Sinkhole at One-North	4 Apr 2006
2	Sinkhole at Nepal Park	27 May 2006
3	Depression at Polo Club	1 Aug 2006
4	Blow-out and sinkhole at Bukit Brown Cemetery	3 Aug 2006
5	Blow-out and sinkhole at North Buona Vista Road	10 Oct 2006
6	Sinkhole at North Buona Vista Road in front of MOE building inner bound tunnel	19 Jan 2007
7	Sinkhole at Pasir Panjang Road	5 May 2007
8	Depression at North Buona Vista Road after existing MRT viaduct	25 May 2007
9	Sinkhole at Pasir Panjang Road	3 Jun 2007
10	Depression at Telok Blangah Road	18 Aug 2007

3.3 Specific Conditions of Permit for bored tunnelling works

The CGS and the series of sinkhole incidents before it, reinforced the need for a control framework for bored tunnelling works to be put in place to reduce the risks associated with tunnelling works. Since 2008, alongside the general Conditions of Permit (COP) imposed on all projects, specific COP were introduced for bored tunnelling works stipulating a list of control measures targeting on most, if not all, of the six aspects identified as a result of the CGS incident. The key points of the specific COP that are relevant to bored tunnelling in close proximity to or beneath existing buildings are summarised in Table 7.

Table 7. Key points of specific COP for bored tunnelling works (before 15 Sep 2017)

	Context	Requirements
1	Damage to neighbouring properties/ structures under construction	• Take immediate action to maintain the neighbouring property in a safe condition, with QP(S)'s instructions • Suspend the tunnelling works and implement all necessary remedial/protective measures if the tunnelling works are likely to cause or cause excessive movements, sinkhole or blowout or likely to cause or cause damage to adjacent buildings/structures • Notify CBC on damage/accident immediately
2	Proactive measures when tunnelling in close proximity to existing buildings	• Carry out adequate site investigation • Evaluate the need for temporarily vacating occupants, appropriate proactive measures (e.g. ground improvement, strengthening of foundation) to be implemented for each building that the route under-crosses/is in close proximity to, to ensure tunnelling can safely pass through • Provide sufficient instrumentation and monitoring system including sufficient deep monitoring instruments that can provide early warning of any underground soil movements and real time monitoring system for key structural elements of these buildings • Provide sufficient recharge wells if the tunnelling work is likely to cause ground water lowering
3	Supervision and monitoring regime and measures to minimise risk during	• Establish, control, monitor and review the key tunnelling operational parameters (includes face pressure and excavation volume) to maintain a safe and stable tunnelling face at all times • Adhere to tunnel control measures, tunnelling procedures/work methods • Establish the monitoring and control of water ingress vis-à-vis maintaining a stable face pressure

	tunnelling operation	• Identify safe locations for planned stoppages and implement pro-active measures at all planned and unplanned stoppages • Cary out probe and grout for any areas of suspected voids • Avoid carrying out cutter head interventions under free air conditions where there is a risk of exposing the tunnelling operation/work to face instability and/or risks of water ingress and excessive ground loss • Identify problematic and high risk areas ahead of tunnelling works and implement safe protective measures • Assess the risk, and probe and grout areas where there are fractured or weak zones or discontinuities e.g. fault or sheared zones, loose or soft soil layers

Impact Assessment

Under the BC Regulations, the QP or builder has to implement protective or preventive measures to ensure that the neighbouring properties/ structures will not be damaged by the tunnelling works. During the plan submission stage, the QP(Design) has to submit an impact assessment report containing recommendations on the measures to be taken so as to prevent any settlement or other movement which may impair the stability of or cause damage to the adjacent buildings. The impact assessment is commonly carried out using the damage categories criteria established by Burland (1997), based on aspects of visual appearance, serviceability and stability, and Boscardin & Cording (1989) based on quantitative damage levels using angular distortion and tensile strain. In general, the damage categories for buildings have to be limited to the 'negligible' or 'very slight' categories, depending on the sensitivity of the structures while angular distortions have to be limited to not steeper than 1:500. For tunnelling in close proximity to buildings, a detailed impact assessment using 2D or 3D numerical methods may be carried out especially for sensitive buildings or buildings with mixed foundations.

Tunnelling in close proximity to buildings

The specific COP also advise that proactive measures can be adopted during the planning and design stages. Some measures that can be explored include a shift in the tunnel horizontal and/or vertical alignment to put more distance between the tunnels and the surrounding existing buildings and their foundations. If this is not feasible, the QPs and ACs involved in the tunnelling works have to assess the impact of the tunnelling works on the existing buildings and determine whether the building occupants have to be vacated temporarily. During this stage, it is useful for the project parties to have a proper communication plan and engage the main stakeholders, in order to understand and address their concerns. In addition, as part of the communication plan, the project teams can inform the residents/occupants of the buildings about the tunnelling plan and the actual implementation work. Contingency plans and provisions for accommodation in case of emergency should also be put in place prior to commencement of the tunnelling works. Other precautionary measures such as additional site investigation can be undertaken to reduce the risks of uncertainty associated with unforeseen ground conditions.

Other proactive measures that can be implemented include the adoption of a more robust design, specifying the need for installation of ground water recharge wells to prevent excessive lowering of ground water and installation of ground improvement in the poor soil layers, such as compensation grouting and deep cement mixing. These measures should be considered during the design stage of the project by integrating adoption of proactive protective measures within problematic and high risk areas identified during the impact assessment and soil investigation studies.

For tunnelling works carried out in close proximity to existing buildings, the operational, monitoring and supervision regimes are very crucial. These are also clearly specified in the specific COP. The tunnel designers should specify key operational parameters (KPIs) for the tunnelling works, such as the safe range of face pressure and allowable excavation volume, which the supervision team and builder have to adhere to. With the establishment of safe and allowable operational KPIs as well as implementation of close monitoring using extensive instrumentation, such as the use of real-time monitoring systems, the tunnelling team and the QP(Supervision)'s team can receive the relevant data promptly for decision-making and response processes. Such close monitoring is expected to provide early warning for the activation of emergency plan and rectification measures, if necessary.

Supervision and Monitoring Regime

Besides acting as an early warning system for tunnelling operation, the operational parameters and monitoring regime provide a feedback system to indicate whether the key TBM equipment are in order and functioning as they should be. This enables the team to verify the design on site by checking whether the ground conditions are as reported in the site investigation reports and whether the design operating parameters can be met. If any of the key equipment is not functioning as they should be, the tunnelling team should not proceed with tunnelling operation as this may endanger the tunnelling works as well as the surrounding buildings.

During the tunnelling works, both the supervision team and the builder have to constantly monitor the parameters closely and if necessary, suspend the tunnelling operation if the tunnelling work is likely to cause excessive movements, sinkhole or blowout or likely to cause damage to adjacent buildings/structures. The suspension will enable the team to have the opportunity to make the tunnelling works safe. During critical tunnelling operation such as planned and unplanned cutter head interventions, close monitoring and feedback of the actual ground conditions have to be carried out to ensure timely revision of procedures, if necessary. Measures such as probing and grouting can be carried out to reduce uncertainty and/or improve the ground conditions and hence, minimise the associated risks. Face instability, ground loss and/or water ingress have to be monitored and feedback on any instability and movement must be given immediately in order to minimise risks of damage to buildings in close proximity to or above the tunnelling works.

3.4 Effectiveness of Specific COP in Mitigating Risk to Tunnelling Works

The specific COP framework thus aims to set the minimum standards that tunnelling project teams have to adhere to in Singapore in order to mitigate the risks and problems associated with bored tunnelling works carried out in close proximity to existing buildings. Since the implementation of the specific COP, it is observed that the frequency of reported tunnelling incidents has been reduced significantly. For the construction of the CCL tunnels, which was prior to the implementation of the specific COP, there was an average of more than one incident per kilometre of tunnel. However, for the construction of the DTL 2 tunnels which was after the implementation of the tunnelling specific COP framework, the average number of tunnelling incidents was reduced to about 0.25 incident per kilometre of tunnel. It should also be noted that the DTL 2 tunnels were predominantly constructed in mixed ground conditions. The introduction of specific COP for bored tunnelling works had indeed seen a reduction in the severity and occurrence of sinkhole incidents over the past eight years.

However, the occurrence of three consecutive large sinkholes over the course of four months under a same project team of the TEL bored tunnelling contracts identified the gaps in the specific COP for bored tunnelling works framework detailed in Section 3.3.

On 26 December 2016, a sinkhole of 5m in diameter and 2m in depth was observed in an empty plot of land beside one of the landed houses on Dalvey Road. This sinkhole resulted in localised cracks at the corner of the landed house and its boundary wall. Three months later, another sinkhole measuring 5m (length) by 4m (width) by 2m (depth) occurred on 2 March 2017 on a green field slope within Whitley Detention Centre. Two days later, a third sinkhole, measuring 3m (length) by 2m (width) by 1m (depth), formed within the Old Chinese Cemetery. All three sinkholes incidents involved excessive over-excavation in mixed face conditions comprising of GIII rock and GIV soils.

These three sinkhole incidents highlighted the risk of employing new builders who are unfamiliar with the local complex geological conditions to carry out tunnelling projects. The subsequent investigation revealed that the three TBMs that were utilised were not suitable for the local mixed ground conditions. The investigation also revealed that the TBM operator had adopted risky operational procedures such as continued tunnelling even after excessive over-excavation was detected.

3.5 Enhanced risk-base tunnelling control framework

The occurrence of the sinkholes in the TEL contract indicated that there is a need for a more comprehensive control framework for bored tunnelling works, based on the specific risk level for each project. Targeted mitigation measures for the various risk categories are required, to implement increasing control measures for increasing levels of risk. These control measures have to be targeted at the root causes of such tunnelling incidents, namely over-excavation and instability associated with cutter head interventions. With more tunnelling works in close proximity to buildings, the need for better control of these risks to ensure building and public safety has become increasingly critical. Such control of risks are implemented in the form of additional measures when tunnelling in close proximity to buildings, such as more detailed impact assessment, preparation of emergency preparedness and communication plan as well as standby contingency plan.

A circular on the "Requirements on Bored Tunnelling Works" was thus issued on 15 September 2017 (BCA 2017). The circular informs the industry of a more comprehensive risk-base control framework of safety requirements for bored tunnelling works. The framework aims to mitigate risks associated with bored tunnelling works in order to ensure structural stability of buildings and structures, and public safety. The requirements are applicable to projects involving tunnelling works carried out using TBMs under the category of GBW.

<u>Risk Matrix and Mitigation Measures</u>

The control framework includes a risk matrix for tunnelling works. The risk matrix categorises the risks of bored tunnelling works based on proximity to buildings and ground conditions. The risk categories are to be determined by QP(Design) and shown in the approved plans. For each risk category, the required mitigation measures, as listed in Annex 3 of the circular, shall be implemented during bored tunnelling works.

Two case studies are presented to highlight the importance of implementing appropriate risk mitigation measures to minimise such risks.

Case Study 1: Assessing Suitability of TBM

For each tunnelling project, one of the risk mitigation measures is assessment of suitability of the TBM for its anticipated ground conditions. The TBM adopted for the site should be assessed for suitability, based on the ground condition to be encountered. Modifications should be made where necessary, such as adjusting the operating ratio of the TBM cutter head, changing the type of cutting tools, installing or removing grizzly bar prior to the launching of the TBM and during tunnelling operations.

This case study involved three TBMs namely TBM1, TBM2 and TBM3 for a tunnel contract in TEL where there were five sinkhole incidents occurred consecutively within a period of 7 months. Among the root causes of these incidents was that the TBMs were not suited for the mixed soil and rock interface of Bukit Timah Formation. The TBM was newly introduced and had not been tested in Singapore's mixed ground conditions. One of the sinkholes occurred in close proximity to a residential house (TBM3), causing damage to the house which is supported by pile foundation. The project parties had to implement unplanned decanting of the occupants to ensure safety and to facilitate the repair to the house.

In addition, the builder need to carry out ground improvement block to enable major modifications to TBM3 to be carried out in order to handle the mixed soil and rock conditions. The following modifications were made to TBM3.

a) The slurry grid was modified to have a bigger opening.
b) The slurry jet in the excavation chamber was diverted to prevent clogging at the bubble gate.
c) Mixing arms were added to prevent blockage in bubble gate area.
d) The cutter head opening ratio was reduced from 26% to 19% to prevent choking in the chamber.
e) Protective measures were installed to prevent tools from falling off in mixed ground.

This incident had caused damage to the house and major disruption to its occupants as well as significant delay to the TBM drive (delay of 170 days due to the sinkhole and the subsequent TBM modifications). Such incidents on TBM1, TBM2 and TBM3 could have been avoided if the project parties had carried out proper assessment to ensure that these TBMs were suited for the anticipated ground conditions.

Case Study 2: CHI in Full Face Rock

In this case study, CHI was conducted under free air in full face GII/GIII rock following a gradual pressure step-down procedure. The ground conditions consisted of a thin layer of Kallang Formation, moderate thickness of residual soils and underlain by slight to moderately weathered rock of Bukit Timah Granite. The TBM was located in full face rock with adequate rock cover above it. The CHI was carried out beneath an existing road, more than 10m away from any building. The CHI lasted for 20 hours. A relatively large water ingress rate of 26 litres/min was observed, resulting in a 4.2m drop in piezometric level. This had led to excessive ground settlement over a large area (60m by 150m). It had also caused a building founded on footing located about 30m away from the CHI to settle by about 12mm.

It can been seen from this incident that for CHI in full face rock in the presence of Kallang Formation and sensitive structures, the CHI should be carried out under compressed air if water ingress exceeds the allowable limit. An effective recharge well system should also be adopted to prevent excessive drop in the piezometric level.

Use of Advanced Technology to Mitigate Risk of Larger TBMs

The use of a single larger TBM with a diameter of 10m or more to replace twin smaller conventional TBMs for railway projects offers attractive benefits especially from the angle of productivity. Some upcoming rail tunnelling projects will likely adopt single bored larger TBMs.

However, larger TBMs will involve higher risk due to much larger volume of excavation per tunnel ring. A large number of tunnelling incidents are associated with face instability during CHIs. Advanced technology can be used to reduce the need for CHI, hence mitigating the risk of using large diameter TBMs. One such technology is the adoption of accessible cutter wheel, which allows change in cutter discs within the TBM chamber under free air condition, avoiding the need to carry out cutter disc change in front of the TBM.

Another useful innovative technology is the use of camera to inspect the working chamber, which allows visual inspection of the TBM chamber, enabling the operator to determine if CHI is required. A third innovative technology is the use of a disc cutter rotation monitoring system which can help the operator to determine when the disc cutters are required to be changed. This will greatly optimise the use of the tools and hence avoiding damage to the TBM face which will require extensive and risky CHI to be carried out.

Adoption of innovative technology like a double stone crusher can help to ensure smoother TBM excavation in rock or mixed soil and rock conditions. It can also help to prolong the life span of the pumps. Altogether, it can result in more cost-effective and safer tunnelling operation.

Control measures for over-excavation

One common observation from the past incidents is occurrence of excessive over-excavation volume prior to the formation of sinkhole. For example, the CGS recorded a large volume of over-excavation of 105m^3 for three tunnel rings before the occurrence of incidents. Similar large volume of over-excavation (TBM3 - 69m^3 at Ring 106, 3 rings before the sinkhole location; TBM1 - 71m^3 for two rings at the sinkhole location) have also been observed for other sinkhole incidents in TEL T216.

One of the key features of the tunnel control framework is a flowchart stipulating the immediate actions required to be taken by QP(S) and builder when excessive over-excavation is suspected or detected for each tunnel ring, as shown in Figure 6. This control measure requires the QP(S) and builder to immediately suspend the TBM excavation and advancement, so that the builder can carry out necessary grouting to fill up the over-excavated voids. This control measure aims to prevent accumulation of larger over-excavation volume over one ring and hence minimising the likelihood of formation of a sinkhole.

Three forms on Site Inspection and Approval Records for Tunnelling Works, namely Annex C-1, C-2 and C-3 have also been put in place to facilitate the implementation of the tunnel control framework.

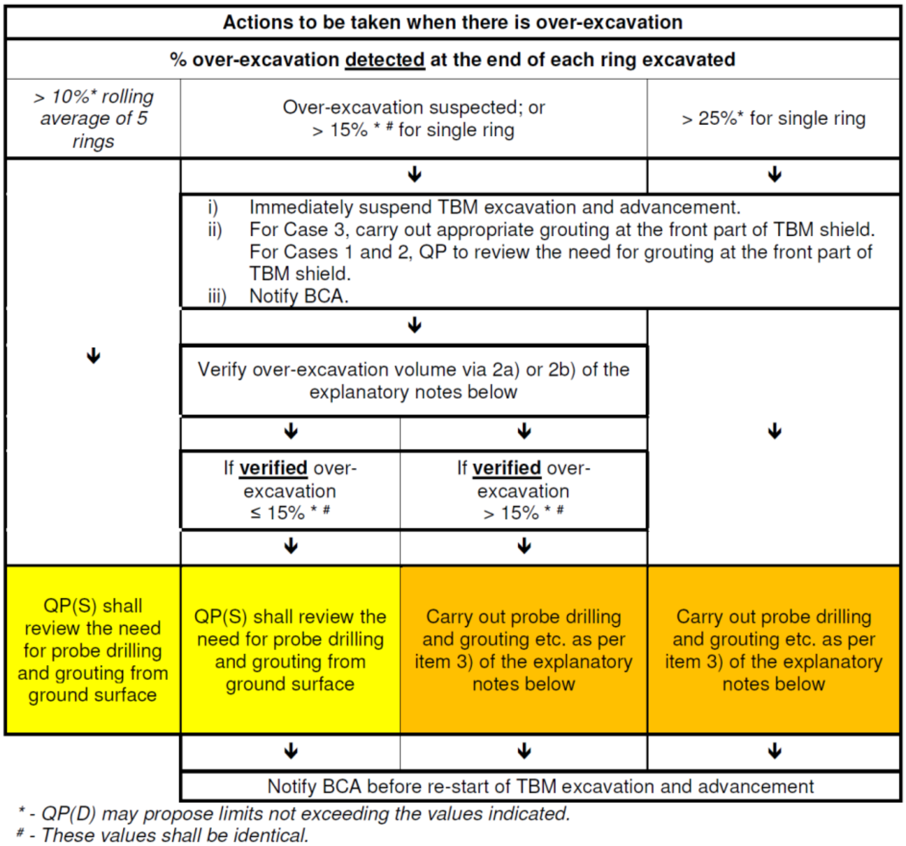

Figure 6. Control measure for over-excavation.

<u>Specific Conditions of Permit for Bored Tunnelling Works (after 15 Sep 2017)</u>

The specific COP have been revised to ensure an effective implementation of the new tunnelling control framework. The revised specific COP stipulate actions that must be carried out by QP(S) and Builder during tunnelling works. The key points of the Specific Conditions of Permit for Bored Tunnelling Works are summarised in Table 8.

Table 8. Key points of specific COP for bored tunnelling works (after 15 Sep 2017).

	Context	Requirements
1	Supervision and monitoring regime and measures to	• QP(S) and Builder shall continuously monitor and review the key tunnelling operational parameters including face pressure and excavation volume • When over-excavation is suspected or when the readings indicate an over-excavation volume exceeding 15% at

	minimise risk during tunnelling operation	the completion of each ring excavated, the Builder and QPs shall immediately suspend TBM excavation and advancement and notify BCA immediately • QPs shall notify BCA before allowing the tunnelling works to resume when QPs are satisfied that all the voids formed from the over-excavation have been filled up • Flushing refers to an operational technique in slurry TBMs to remove obstructions in cutter head chamber in order to move the TBM. For tunnelling in medium and high risk categories*, no flushing is allowed. For tunnelling in low risk category*, builder shall seek written consent from OP(S) before flushing can be carried out. • The Builder shall carry out cutter head interventions (CHI) under compressed air as specified by QP(D) for all planned and unplanned stoppages. CHI shall not be carried out under free air conditions unless assessed and approved by QP(S) under the following conditions: i) in full face rock with face pressure stepped down gradually; or ii) within ground improvement block with face pressure stepped down gradually. • QP(S) and Builder shall notify BCA immediately of any cutter head interventions carried out under free air or when there is an unplanned stoppage for a cutter head intervention • QP(S) and Builder shall suspend TBM excavation and advancement and notify BCA immediately whenever there is excessive movements (immediate settlement exceeding 150 mm for incident reporting purposes), sinkhole or blowout.
2	Proactive measures when tunnelling in close proximity to existing buildings	• When tunnelling within control zone, QP(S) shall submit to CBC daily his certification of structural integrity of the building and assessment of any safety concern in the course of the tunnelling works • The developer, Builder and QP(S) must take all reasonable steps and exercise due diligence to put in place an emergency preparedness plan on decanting occupants of buildings undermined by tunnelling works.

**Risk categories are defined in Annex 1 of BCA (2017)*

4 CONCLUSION

With the rapid urbanisation of cities and increasing densification of underground structures, ERSS constructed and tunnelling works carried out in close proximity to existing buildings pose many challenges in many countries, not just in Singapore. However, recognising the need to minimise the risks associated with underground construction works, BCA has put in place regulations, control framework and guidelines to set the minimum standards for ERSS and tunnelling construction in Singapore. The construction industry should continue to keep in mind the importance and relevance of these regulatory requirements. More importantly, everyone has an important role to play in keeping our built environment safe.

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