# Controlling the risk of sinkholes over EPB driven tunnels – a client perspective

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ABSTRACT: The occurrence of occasional sinkholes or very large settlements over EPB driven tunnels has been documented on a number of projects. Primary responsibility for avoiding sinkholes must lie with the tunnelling contractor, and the shield manufacturer. Almost all of the documented cases can be ascribed directly to failures in the planning, procedures, operation and maintenance of the machine, or to the design of the machine. However, the client has a major stake in controlling this risk. Sinkholes in urban areas are likely to lead to damage to roads and utilities, may damage buildings, and pose a risk to the public. It is current experience that simply appointing an experienced tunnelling contractor and requiring experienced operators are inadequate to control the risk of sinkholes occurring. A client can help to control the risk by providing sufficient site investigation, developing specifications that set minimum standards, and appointing experienced site supervision teams.

## 1 INTRODUCTION

The development of very large settlement (>150 mm) in a localized area, or sinkholes, over EPB driven tunnels is much more common than is generally recognized. Shirlaw and Boone (2005) record 57 cases in 77 km of urban tunnelling in Canada and Singapore. The overall frequency was greater than one per 1.4 km of EPB driven tunnel. Cases in many other countries are recorded in other published papers (Shirlaw et al 2003) although, generally, the records are not in sufficient detail to allow the frequency of the incidents to be assessed. It is also unlikely that all of such incidents have been recorded in the public domain, as many owners and contractors are concerned about the adverse publicity involved.

The potential for localised, large, settlements and sinkholes poses a particular problem for the client. Traditionally, tunnelling contracts have been let on a performance basis. The specialist tunnelling contractor assesses the ground conditions, specifies and sources the appropriate tunnelling machinery and develops the tunnelling procedures. Financially, the contractor is rewarded for tunnelling rapidly with the lowest cost machinery that can achieve the required production. With traditional, open face shields the effect of a major ground loss on the contractor was severe, with the shield buried and/or flooded, requiring a major and costly effort to recover the tunnel and resume tunnelling. In contrast, overexcavation during EPB tunnelling often has little adverse effect on tunnelling progress. The direct impact on the contractor is therefore generally minimal. However, for the client, the adverse effects of large settlements or sinkholes are potentially very serious. Much urban tunnelling takes place below roads and, increasingly, beneath buildings. Any major loss of ground therefore poses an unacceptable risk to the general public. Even incidents that do not endanger life or property may cause major concern among the general public, and could result in major delays to the project.

The client's interests are such that it is essential that active measures are taken to ensure that the contractor minimises the risk of large settlements or sinkholes developing over the tunnel. The past cases of large settlements and sinkholes can be used to decide where the client's efforts can best be directed.

## 2 RECORDED CASES

The basic cause of sinkholes is the use of inadequate face pressure and consequent overexcavation. Shirlaw and Boone (2005) have shown that almost all of the 57 cases of large settlements and sinkholes on 7 major projects fall into six basic categories, as shown in table 1. These risk areas are where inadequate face pressure is most likely to be applied.

In table 1 a distinction is made between interfaces involving stable and unstable soils, and those involving rock and soil. Problems at interfaces between stable and unstable soils usually involve poor planning of face pressures, such that the face pressure is not adjusted upwards in advance of the interface. The problems can also arise due to inadequate site investigation or probing, such that the interface is not identified in time to allow the necessary adjustments to be made. The problems at the interfaces between rock or hard till and soil (particularly granular soils) are kept separate because it is often very difficult to maintain EPB pressure in these conditions. It is very difficult to form an effective EPB plug using a combination of rock cuttings and granular soil. Without an effective EPB plug, water pressures in the ground cannot be effectively resisted. The attempt to form a plug in a mixture of soil and rock often results in extreme wear on the shield machine. This increases the number of head interventions for maintenance, another area of risk, and the risk of mechanical problems, yet another area of risk.

Table 1 is based on the seven tunnelling projects in Singapore and Canada. A significant proportion of the tunnelling, and the great majority of the large settlements and sinkholes, took place in weathered rocks incised with buried valleys of soft deposits (Singapore) or glacial soils (Canada). These ground conditions are heterogeneous and often high abrasive, and may be considered particularly onerous for EPB tunnelling. It is probable that the frequency of large settlements and sinkholes on these projects was affected by the ground conditions, and that there is less risk where the ground conditions are more consistent and less abrasive. However, the cases quoted in Shirlaw et al (2003) give enough examples of problems on other projects, in other countries, to show that the risk areas given in table 1 are not specific to the conditions in Singapore and Canada. Particular examples of problems during launching occurred on the Taipei Rapid Transit (Moh et al.); these tunnels also experienced a number of problems during breaking into the recovery shaft. Interfaces between stable and unstable strata were a problem for the Changi line tunnels, Singapore (Raju et al) and the Lille metro (Leblais et al). Large ground losses in mixed grades of weathered granite were experienced in Shenzen (Wallis, 2002) and Oporto (Anon, 2002), and in mixed sand and clay tills at the Anacostia River (Clough and Leca), the Storebaelt tunnels (Doran and Athenoux) and the Sheppard Subway (Boone et al). Maintenance stoppages resulted in loss of ground on the Storebaelt tunnels (Biggart and Sternath) and the Sheppard Subway. It can be seen that these basic areas of risk of loss of ground are common to many projects.

The number of cases of large loss of ground over EPB tunnels that have been reported worldwide, and the repetitious nature of the basic causes, shows that it is necessary for the client to put in place measures to control this risk. Such measures can include improved site investigation, definition of anticipated ground conditions, more detailed requirements for the tunnelling machines, and ensuring detailed planning for the operation of the shield. These are discussed below.

Table 1. High risk areas for large settlements and sinkholes due to EPB tunnelling.

| Risk area | Number |
|---|---|
| Launching the shield | 10 |
| Breaking into recovery shaft | 4 |
| Interfaces between stable and unstable soils | 6 |
| Mixed faces of rock or hard till and soil | 15 |
| Head access for maintenance | 13 |
| Mechanical failures | 5 |
| Others | 4 |
| Total | 57 |

## 3 SITE INVESTIGATION

Most of the main risk areas for large ground losses can be related to particular ground conditions. Detailed knowledge of the ground conditions is therefore an essential precondition to knowing what measures to take to control the risks. In terms of the main risk areas, the critical information that is required is outlined in table 2.

In Singapore the interfaces between stable and unstable soils are generally major stratigraphic

Table 2. Risk area.

| | |
|---|---|
| Launching the shield<br>Breaking into recovery shaft | Granular soils, below the water table, at the tunnel horizon |
| Interfaces, stable/unstable soils<br>Mixed faces of rock and soil | Location of interfaces, soil behaviour |
| Head access for maintenance | Abrasiveness of ground |
| Mechanical failure | Abrasiveness of ground, likelihood of obstructions |

boundaries, between geological formations. The likelihood of such boundaries being encountered at, or just above, tunnel level can generally be established with a standard borehole spacing of 25 m to 40 m along the tunnel route. Additional boreholes are needed to give more precise information on the location of the interface. Also in Singapore, mixed faces of rock and soil are generally, although not always, a result of tropical weathering. The number of such interfaces that will be encountered cannot be determined from even a very detailed investigation, due to the complexity of weathered profiles. However, a combination of a detailed site investigation and a thorough geological assessment should give a reasonable basis for assessing the likely conditions. This assessment can then be supplemented by probing during tunnelling.

The level of investigative effort required for EPB shield drives, at least in complex conditions such as those in Singapore, should be at least as high as that for open face shields. In certain respects, such as assessing abrasiveness and the potential for encountering rock, the level of effort needs to be even higher than for open face shields. This level of investigation is needed to define both the requirements for the shield and for the planning of the tunnelling procedures. The bulk of investigation therefore needs to be carried out prior to awarding the tunnelling contract, so that the tenderers can reasonably price the work.

The provision of baseline geotechnical reports with the contract documents, as is now being required by the insurance industry in some jurisdictions, should act as a spur to the client to carry out as comprehensive an investigation as possible.

## 4 SPECIFICATION OF THE SHIELD

It is essential to procure a correctly specified machine to minimise the risk of problem developing during tunnelling. The items needed to control the risk of sinkholes can add significantly to the cost of a machine. In a competitive tender there is a real risk that some, or all, of these items will be omitted by tenderers, if there is no common basis for them to work from. Reilly (1997) provides an assessment of the risks of leaving the selection of the machine entirely to the contractor. Although specification and procurement of tunnelling machines had traditionally been left to the contractor, these activities have been undertaken by the client on a number of projects. This has usually been done to make machine and contractor procurement parallel activities, thus reducing overall project duration. An additional advantage has been that the client procured machines have generally been of a high specification, although, as described by Reilly , there are also potential risks in this approach.

Intermediate between client and contractor specification is for the client to provide specifications that give minimum standards, but allow the contractor to develop from these minimum standards. Key issues in such a specification relate to choice of machine, the cutterhead, muck removal and measurement, pressure measurement, the man lock, the tail seals and tail void grouting system. The client may wish to provide specifications for other aspects of the machine and back-up for safety or other reasons, but the items listed above are the key ones with respect to controlling the risk of sinkhole development. These items are discussed further below.

### 4.1 *Choice of machine*

The choice of the type of machine is a fundamental issue. The basic cost of EPB and slurry machines is typically similar, but the costs for slurry, slurry treatment and spoil disposal are a significant additional cost for slurry shield tunnelling. However, EPB shields have a poor record in mixed conditions of rock and granular soil, and in glacial soils. Problems with surface sinkholes in these conditions often accompany poor progress rates and excessive wear, with associated costs for maintenance. Where sinkholes or excessive settlements are unacceptable, and the geological conditions are not favourable for EPB tunnelling, the owner may choose to specify the use of slurry, or the convertible slurry/EPB machines that are now becoming available.

### 4.2 *The cutterhead*

The design of the cutterhead is important for all TBMs, but is particularly critical where the machine is to operate in mixed faces of rock and soil. The owner may choose to specify minimum requirements for:

- Cutterhead power
- Size of disc cutters
- Spacing between adjacent discs
- Number of injection ports
- Hardness of discs, and of abrasion resisting materials on the cutterhead and throat or openings of buckets or scoops.

In addition to ensuring sufficient hardness, other measures to help reduce wear are to ensure that all disc cutters form a single concentric track, that adjacent discs do not share common bearings, and that cutter housings are designed to prevent muck from getting trapped and compacted around the disc. An example of an assembly designed to avoid trapping muck around the disc, by use of a shroud, is given in Figure 1. Figure 2 shows how material tends to be drawn into the narrow neck around an unshrouded disc.

Although it is important to minimise wear, it is also necessary to accept that maintenance will safely be necessary. It is therefore important to build in the means to maintain the cutting head and cutting tools

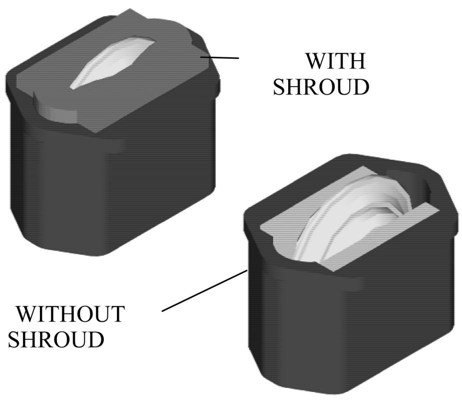


Figure 1. Addition of a shroud to the disc cutter assembly to avoid material being trapped around the disc.

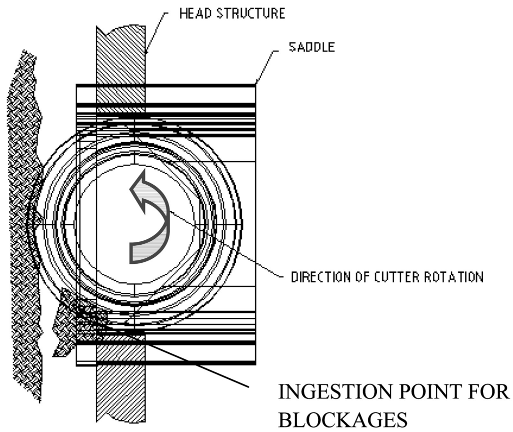


Figure 2. Section showing how cuttings tend to be drawn into the narrow neck around an unshrouded disc.

as quickly and safely as possible. Cutting tools and wear protection should be replaceable without having personnel leave the rear of the cutterhead. Sufficient non-slip foot steps and safety harness attachment points must be provided to allow safe access to all cutter locations. Where the cutter assembly weighs more than 30 kg there needs to be either a mechanical device to support the cutter, or attachment points for lifting devices.

### 4.3 *Muck removal and measurement*

The owner may choose to specify minimum requirements for:

- The hardness of the screw conveyor flights and replaceable wear plates on the screw conveyor casing.
- The length of the screw conveyor.
- The provision of either a belt weighing or belt scanning device, to allow the volume of muck being removed to be measured.
- The number of conditioning points along the screw conveyor.

Provision should be made for the closure of both ends of the screw conveyor casing. At the discharge end, there should be a closing mechanism capable of inducing a back-pressure of at least 25% greater than the maximum head of water anticipated. The mechanism should automatically close if there is a power failure. At the plenum chamber end, the opening through the pressure bulkhead should also be provided with a closing device. This will allow the opening to be sealed in case it is necessary to remove the screw conveyor for maintenance or replacement. Provision should also be made for attachments for lifting devices to aid the removal of the conveyor, and inspection covers to allow monitoring of the condition of the conveyor.

### 4.4 *Pressure measurement*

The owner may choose to specify minimum requirements for the number of pressure transducers. These transducers are placed on the bulkhead, typically close to the crown and invert, and at axis level. Placing two transducers at each location provides a degree of redundancy and avoids having to stop tunnelling each time a transducer is damaged. These pressure transducers are critical to successful tunnelling, and provision should be made to allow accurate calibration during normal tunnel operation.

### 4.5 *The man-lock and auxiliary equipment*

The man-lock must be designed to allow access at the highest anticipated compressed air pressure. Provision should also be made for service penetrations through the pressure bulkhead. These service penetrations would be for electricity, water, high-pressure air, or any other facility that may be required when working in compressed air. However, such penetrations need to be carefully designed, to avoid additional problems. Electrical arcing under an enriched air environment is extremely dangerous. Water jetting from a failed service penetration could cause instability of the face.

### 4.6 *Tail seals*

The minimum number of rows of tail seals can be specified, although the basic specification should still be a performance specification in terms of withstanding the maximum water pressure and excluding the ingress of grout.

### 4.7 *Tail void grouting system*

The use of grout pipes that are laid along the tail skin, to allow grouting simultaneous with tunnel advance, is now widely adopted. It is, however, essential to ensure that sufficient pipes are available for grouting at all times. Blockage of the tail void grouting pipes is common, particularly where accelerated grouts are used. Means should be provided to clear blockages. It must be possible to maintain and, if necessary, replace the grout pipes, from within the shield.

### 4.8 *Probing*

Where probing may be required, it is essential to ensure that the probing can be carried out without major delays. It should be possible to be drilling within 2 hours of requiring probing. Where rock is anticipated, the percussive drilling should be available.

### 4.9 *Preparation of specifications*

The preparation of a specification for a TBM needs to be done by someone with extensive experience in the design and manufacture of such machines. This is true both for a full specification and a 'minimum' requirement specification.

## 5 PLANNING FOR TUNNELLING

Specifying and obtaining an appropriate TBM are only the first steps in minimising the risk of sinkholes and excessive settlements. The next steps are to plan and carry out the tunnelling. The planning of the tunnelling will be discussed in the context of each of the main risk areas identified in table 1.

### 5.1 *Launching the shield*

A seal for launching should be a basic minimum requirement for all TBM launches. However, for launches where the risk of a major loss of ground is totally unacceptable, additional measures need to be considered. These measures could include ground treatment. Particularly where granular soils below the water table are present in or very close to the tunnel horizon, the zone of ground treatment needs to be at least the length of the TBM plus one ring. This length allows for one ring to be grouted in before the head of the machine penetrates beyond the treated ground.

### 5.2 *Breaking into the recovery shaft*

Breaking into the recovery shaft is basically the obverse of launching, and the same measures need to be taken.

### 5.3 *Tunnelling – general*

In all ground conditions, the requisite face pressure needs to be applied, careful checks have to be made of the volume of excavated material, and the tail void grouting has to be effective.

The planned face pressures can be established using previous tunnelling experience in similar ground conditions and by calculation. Anagnostou and Kovari 1996 have provided simple, limit equilibrium methods for calculating the necessary face pressure. However, this method does not consider settlement, and higher pressures may be necessary to control settlement. For clays, published data on centrifuge model tests can be used to assess the relationship between face pressure and settlement. Sakai and Sugden (2001) also discuss the face pressure necessary to control settlements.

It is necessary to establish planned face pressures for the whole tunnel before starting tunnelling, based on calculation and experience. This should be done for every ring of advance. However, it must also be recognised that the tunnelling staff must respond to the information that is obtained during tunnelling. This information includes the machine operating parameters, muck volume measurement, probing, face inspections and geotechnical monitoring. The organisation chart should show levels of authority with respect to changing the face pressure from that planned. Planned face pressures should be established for both normal tunnel operation and during head intervention. It is not possible to forecast where head intervention will be necessary, so the planned face pressure in the event of an intervention should be established for every ring of advance.

Volume control is just as important as pressure control, in order to avoid major ground loss. For EPB tunnelling it is recommended that two, independent methods of measuring muck volume be used. Typically, this would involve skip counting plus either belt weighing or belt scanning. The two latter methods can be set up to feed data directly to the on-board computer, so that the operator has continuous information on the volume excavated. It has been the experience in Singapore that the ratio of excavated to theoretical volume needs to be checked at least every 200 mm to 300 mm of advance, in order to provide meaningful warning of overexcavation.

It is essential to ensure that tail void grouting is carried out to both a limiting pressure and a volume, to ensure an even distribution of pressure around the lining.

### 5.4 *Interfaces between stable and unstable soils*

Interfaces between stable and unstable soils need particular care, as demonstrated by the problems experienced during the construction of the Lille Metro. Shirlaw et al (2003) show that it is not adequate to raise the face pressure to control the unstable soil only on encountering that soil. The face pressure must be raised while there is still sufficient cover of stable soil to form an arch over the tunnel.

### 5.5 *Mixed faces of soil and rock*

The risk involved in mixed faces of soil and rock depends on the nature of the soil and the rock. If the ground is basically stable without face pressure, or if the cutting can be turned into a suitable EPB plug, then careful EPB operation is possible through these interfaces. If, however, pressure is needed but face pressure is required for stability and the cuttings cannot readily be turned into an EPB plug, then successful EPB tunnelling is unlikely to be achieved.

### 5.6 *Head access*

As discussed above, the face pressure and procedures for head access need to be planned in advance of tunnelling. As it is not always possible to forecast exactly where or when head access will be required, the planning has to be done before starting tunnelling.

### 5.7 *Mechanical failure*

In addition to using an appropriate machine for the ground conditions, regular maintenance needs to be carried out to reduce the risk of mechanical failure.

### 5.8 *Preparation of specifications*

For successful tunnelling, the contractor and operator must respond quickly to changes in machine parameters, ground behaviour and geotechnical monitoring. The specification should not be such as to constrain the contractor from making the necessary adjustments, based on observation. It is also essential that the degree of specification should not conflict with the allocation of responsibility for risk between the client and the contractor. The specifications therefore need to be developed in a way that helps to control the risk of damage to third parties, a major client concern, without shifting the allocation of risk between the client and the contractor.

## 6 CLIENT SUPERVISION TEAM

Where the client has provided minimum standards for the machine and the planning for the tunnel, then the client also needs to ensure that the contractor is following those standards. A supervision team that is experienced in EPB tunnelling is necessary to ensure that the contractor's implementation of the requirements is appropriate.

## 7 CONCLUSIONS

Sinkholes and large local settlements are recorded quite frequently over EPB driven tunnels. These incidents may be of more concern to the client than the contractor. The client can help to reduce the risk of such occurrences by carrying out a detailed pre-tender site investigation, providing minimum standards for the machine and for the planning for tunnelling, and appointing an experienced site supervision team.

## REFERENCES

Anagnostou, G. and Kovari, K. 1996. Face stability in slurry and EPB shield tunnelling. *Proc. Geotechnical Aspects of Underground Construction in Soft Ground*, London, April 1996.

Anon 2002. Oporto Metro breakthrough. Tunnels and Tunnelling International, November 2002, 7.

Biggart, A.R. and Sternath, R. 1996. Storebaelt eastern railway tunnel: construction. *Proc. Instn. Civ. Engrs Civ. Engng*. 20–39

Boone, S.J., McGaghran, S., Bouwer, G. and Leinala, T. 2002. Monitoring the performance of earth pressure balance tunneling in Toronto. *Proc. North American Tunnelling*, in press.

Clough, G.W. and Leca, E. 1993. EPB Shield Tunnelling in Mixed Face Conditions. *Journal of Geot. Engineering, ASCE*. Vol 119, 10. 1640–1656.

Doran, S.R. and Athenoux, Storebaelt Eastern railway Tunnel – Denmark. Geotechnical Aspects of TBM Selection and Operation.

Leblais, Y., Leca, E. and Mauroy, F. 1996. Deplacements verticaux lies au creusement au bouclier a pression de terre (EPBM); cas du Metro de Lille – Ligne 2: lots 1 et 2. Proceedings International AFTES, Underground Works: Techniques and Men, Chambery, 21–24 October 1996, pp 483–487.

Moh, Z.C., Chang, J.L. and Hwang, R.N. 1999. Soft ground tunnelling in Taipei – problems and solutions. *Proc. Dr Tan Swan Beng Memorial Symposium*, Singapore. 87–97.

Raju, G.V.R., Ng, C.C. and Kumar, B.S. 2001. Damage assessment of adjacent structures due to bored tunnelling for Changi Airport Line. *Proc. Underground Singapore 2001*, 65–75.

Reilly, J.J. 1997. Owner responsibility in the selection of tunnel boring machines, with reference to contractual requirements and construction conditions. ITA, Vienna, April.

Sakai, K. and Sugden, N.B. Control of ground movements due to tunnelling with an earth pressure balance TBM. RETC, 2001.

Shirlaw, J.N., Ong, J.C.W., Rosser, H.B., Tan, C.G, Osborne, N.H. and Heslop, P.J.E. 2003. Local settlements and sinkholes due to EPB tunnelling. *Proc. ICE, Geotechnical Engineering I 56*, October Issue GE4, pp 193–211.

Shirlaw, J.N. and Boone, S. 2005. The risk of very large settlements due to EPB tunnelling. Australian Tunnelling Conference *in press*.

Wallis, S. 2002. Shenzen Metro. *World Tunnelling*, April, pp 130–134.