FORENSIC ENGINEERING FOR UNDERGROUND CONSTRUCTION

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In the context of underground construction, forensic engineering is taken to be the application of engineering principles and methodologies to determine the cause of a performance deficiency, often a collapse, in an excavation, and the reporting of the findings, usually in the form of an expert opinion within the legal system. The procedures that may be used in forensic geotechnical investigations and the interface of the engineer with the legal system are discussed. The application of the principles and methodologies outlined are illustrated through a brief account of the investigation of the collapse of a small part of an excavation in the Lane Cove Tunnel Project, Sydney, Australia, on 2 November, 2005.

Keywords: Accident investigation; failure; forensic engineering; mining; risk; tunnelling; underground construction.

1. Introduction

In common with other areas of geotechnical engineering practice, underground construction involves a number of uncertainties and risks, many of them associated with the inherent variability and unknown properties of the geological materials involved. These and other factors may lead to deficiencies in excavation performance, to the collapse of an excavation and, on occasion, to the loss of life.

It is inevitable that, when an underground failure or collapse has occurred, either in civil engineering construction or in mining, an investigation will be carried out into the causes of the failure. Depending on the nature and severity of the failure, this investigation will be carried out, at least in part, by suitably experienced specialist engineers. In many cases, some form of legal proceedings will follow, either to determine the causes of damage, loss of income or, in some cases, the loss of life, and/or to resolve contractual and responsibility issues and allocate costs. This process will also involve specialist engineers, usually as expert witnesses. The professional engineering work carried out in these cases has come to be described as forensic engineering.

This paper discusses the general nature of forensic engineering and the special issues and difficulties confronting forensic geotechnical engineers, particularly in the investigation of failures or collapses in underground construction and underground mining. The investigation methods used are outlined and the important interface with legal systems is discussed. In the author's experience of forensic investigations in underground civil construction and mining, this legal aspect of the forensic engineer's role is becoming increasingly important and demanding, given the increasing proclivity of some authorities to prosecute engineers and their employers in the courts. Finally, a brief account is given of the author's investigation of the collapse of a small section of an excavation in the Lane Cove Tunnel Project in Sydney, New South Wales, Australia, on 2 November 2005.

2. The General Nature of Forensic Engineering

Technological innovation and advances in engineering have always been attended by failure of one type or another, including the quite spectacular collapse of structures such as bridges and

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dams (e.g. Lewis, 2004; Petroski, 1985, 1994). More recently, as financial losses and the loss of reputation have increased, personal injury and the loss of life have come to be regraded more seriously than they sometimes were in the past, and society has become generally more litigious, an area of engineering practice known as **forensic engineering** has developed. Forensic engineering now has its own specialist societies, consulting firms, conferences, literature and university courses, and has attracted popular attention through television programs and books (e.g. Lewis, 2004; Wearne, 1999).

A number of definitions of forensic engineering are available in the literature. For example, Specter (1987) defines forensic engineering as "*the art and science of professional practice of those qualified to serve as engineering experts in matters before courts of law or in arbitration proceedings*". Similarly, Noon (2001) defines forensic engineering as "*the application of engineering principles, knowledge, skills, and methodologies to answer questions of fact that may have legal ramifications*". Carper (2000) says that "*the forensic engineer is a professional engineer who deals with the engineering aspects of legal problems. Activities associated with forensic engineering include determination of the physical or technical causes of accidents or failures, preparation of reports, and presentation of testimony or advisory opinions that assist in resolution of related disputes. The forensic engineer may also be asked to render an opinion regarding responsibility for the accident or failure*".

Following Lewis (2003) and Noon (2001), in the context of underground construction, forensic engineering will be taken here to be the application of engineering principles and methodologies to determine the cause of a performance deficiency, usually a collapse, in an excavation, and the reporting of the findings, usually in the form of an expert opinion within the legal system. Some uses of the term forensic engineering do not reflect this involvement with the legal system. However, this legal element is central to the definition, recognition and practice of forensic engineering in some countries (e.g. Australia, USA), and will form an essential part of the discussion presented here.

Forensic engineering as defined above is concerned typically with investigations of failures of constructed facilities; rock falls, excavation collapses and other accidents in mines; fires and explosions; air and rail crashes; aspects of traffic accidents; and failures of consumer products. The more serious events of these types can lead to significant injury and to fatalities as well as to financial loss.

Forensic engineering investigations involve a number of steps. In general, the forensic engineer collects evidence of several types and then carries out analyses, again of various types, to determine the "who, what, where, when, why and how" of the deficient performance or failure of engineered facilities, systems and products, including accidents. A range of formal and less formal procedures may be used to guide the investigations (e.g. Greenspan *et al.*, 1989; Lewis, 2003; Noon, 2001). Figure 1 shows the steps typically used in forensic engineering investigations within a civil engineering context. The legal terminology used is that applying in the USA.

Communicating the results is a vitally important stage of the investigation. This communication may be required, not only to facility owners, contractors and other professional engineers, but also in reports to lawyers and statutory bodies, in expert witness statements in legal proceedings, and in statements to the press and the public. In many cases, the expert's report may be confidential or protected by legal professional privilege. It is probable that only a low percentage of cases for which forensic engineering investigations are undertaken and expert witness reports are prepared, actually reach the courts (e.g. Brookes, 2006). However, the information contained in the reports may be protected by legal privilege and remain confidential so

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that the results cannot be published and the potentially valuable information that the reports contain never reach the engineering profession.

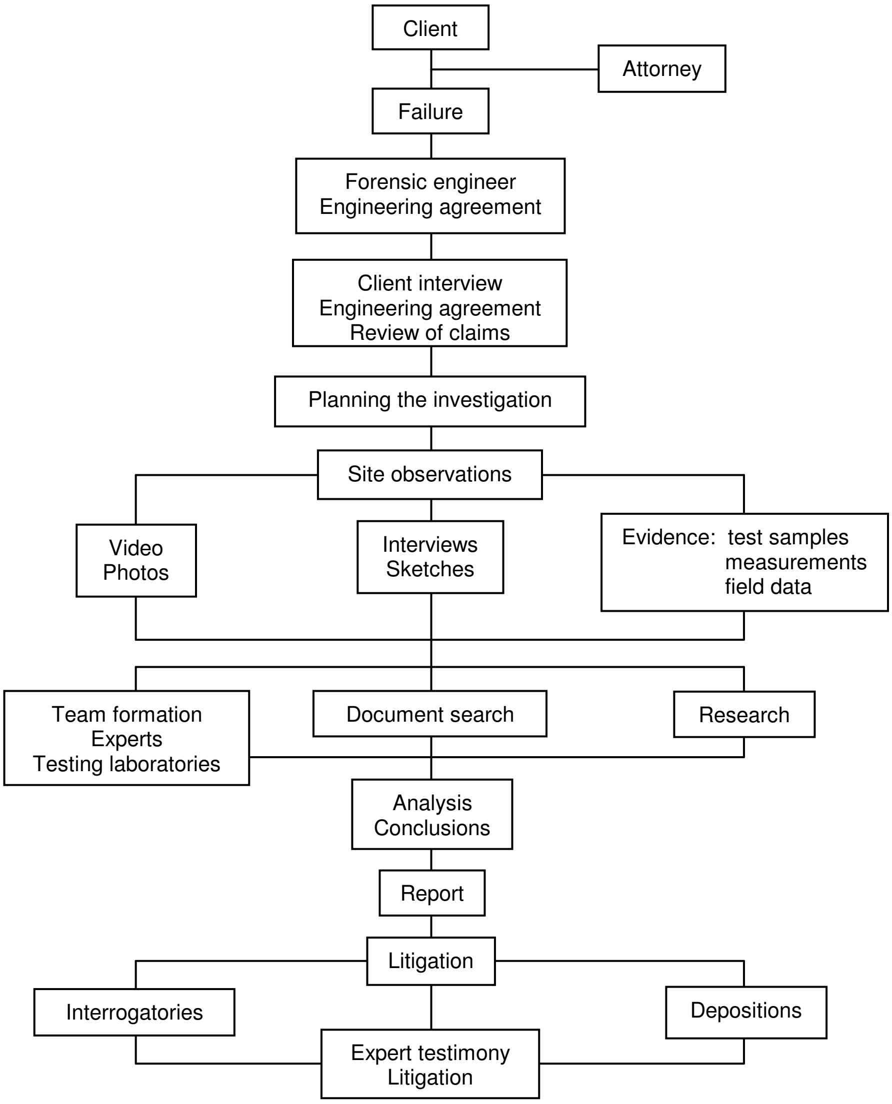

Fig. 1. Flow chart of a typical forensic engineering investigation (after Greenspan *et al*., 1989).

The important question of what qualifies an engineer to be recognised as an "expert" is discussed in some detail by a number of authorities including Carper (2001), Greenspan *et al.* (1989) and Lewis (2003) who concludes that the key attributes of an expert engineer are "*education, training, experience, skill and knowledge*" and that the engineer must be able to "*perform his or her work accurately, objectively and in a professional manner*". Forensic engineers or engineers serving as expert witnesses have to be especially aware of the ethical practice issues to be discussed in Section 5 below.

3. Forensic Geotechnical Engineering

3.1. *Failures in Geotechnical Engineering*

Engineering in the natural materials found on and under the surface of the Earth has long been fraught with difficulty. Perhaps even more so than in other areas of engineering, there have always been performance deficiencies and failures of geotechnical engineering projects. The most extreme cases, generally arising from dam failures or major landslides, can cause significant damage to property and infrastructure, and the loss of life (e.g. Wearne, 1999). Particular difficulties arise from the inherent spatial variability of soil deposits and rock masses. Errors or omissions having significant engineering consequences can be made in geological interpretations, there can be variations in geotechnical properties over a project site, and apparently minor geological features can have major influences on the performance of engineered structures (e.g. Terzaghi, 1929). Attempts have been made over the last two or three decades to account for some of these factors through probability-based reliability and risk analyses which have now become part of the corpus of geotechnical engineering (e.g. Bea 2006; Christian, 2004; Einstein, 1996; Eskesen *et al*., 2004). The concept of reliability as "*the likelihood that a system will perform in an acceptable manner*" (Bea, 2006) is important in forensic geotechnical engineering.

It is not surprising, therefore, that studies and analyses of the failures of foundations, slopes, dams and tunnels, for example, have been important in the development of geotechnical engineering research, knowledge and practice. Following Leonards (1982), failure will be taken here to be an "*unacceptable difference between expected and observed performance*". Many failures involve sometimes catastrophic instability which arises when some form of sudden rupture develops. The geotechnical engineering literature is replete with detailed examples and broader studies of the causes of geotechnical failures (e.g. Bea, 2006; Day, 1998; Leonards, 1982; Londe, 1987; Müller, 1968; Osterberg, 1989; Sowers, 1993). Several of these studies include considerations of the influence of human factors on geotechnical engineering failures. For example, Sowers' (1993) study of more than 500 well-documented foundation failures showed that the majority of the failures were due to "*human shortcomings*". Only 12% of the failures studied were attributed to the absence of relevant technical knowledge or solutions.

Generally, forensic geotechnical investigations follow the broad pattern illustrated by Figure 1 (Day, 1998). In many cases, careful and detailed re-investigation of the site is required with detailed geological mapping, drilling, sampling and testing (e.g. Alonso and Gens, 2006a; Skempton and Vaughan, 1993). In order to resolve some cases, similarly careful and detailed analyses of the data, and back-analyses of the problem, are required (e.g. Alonso and Gens, 2006b; Gens and Alonso, 2006; Potts *et al*., 1990). Although not always falling within the purview of forensic engineering as defined here, similar forensic investigations may also be associated with the repair and/or restitution of historic structures (as in the famous case of the Leaning Tower of Pisa), with geoenvironmental problems, or in the aftermath of natural disasters such as earthquakes. If the results of such investigations can be brought to the attention of the profession through conference presentations or publication, they can make significant contributions to the advancement of geotechnical engineering knowledge (e.g. Londe, 1987).

3.2. *Underground Construction*

Underground construction in soils and rocks can suffer from the same types of errors and uncertainties as those outlined for geotechnical engineering more generally. Although fatalities can

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occur and severe financial losses may result, the failures or collapses occurring in underground construction do not often have the spectacular or disastrous effects of the major dam failures or landslides referred to above. Tunnelling or the excavation of caverns may be slowed or halted by frequent small or large falls of ground (e.g. Feld and Carper, 1997), squeezing ground conditions (e.g. Hoek, 2001), groundwater problems (Hoek, 2001) including inundation, the sudden development of very large settlements or sinkholes above tunnels or other underground excavations (Shirlaw and Boone, 2005), or the unanticipated and continuing development of excavation deformations (e.g. Stabel and Samani, 2003). Occurrences of the penultimate type have occurred in a large number of projects, including railway tunnels in Singapore (Shirlaw *et al.*, 2003). Such occurrences can have damaging effects on buildings and on surface and near-surface infrastructure, as in the case to be discussed in Section 6 below.

Underground mining in hard or soft rock can suffer from similar problems to those outlined for underground construction. Although the purposes of many of the excavations made and of the operations carried out in underground mining, specifically those associated with the stopes from which the ore is extracted, differ from those in underground construction, modern large-scale underground mining does have associated with it, large numbers of underground infrastructure and transportation excavations which have elements in common with civil engineering excavations. Unfortunately, fatalities arising from broadly geotechnical causes have been all too common in the international mining industry, bringing with them legal proceedings of one type or another and the need for forensic engineering investigations of the general type being discussed here. Rock bursting, which is not unknown in civil construction, has been a particular cause of damage and fatalities in deep, hard rock mining, most notably in the deep level gold mines of South Africa. In addition to collapses underground, underground mining can cause subsidence and disruption to the surface, damaging buildings and infrastructure. As in underground construction, throughout mining history, there have been several major cases of the inundation of mine workings by water or tailings leading to loss of life and of production.

The forensic investigations carried out in these various cases use the general principles and methods discussed elsewhere in this paper. They also require knowledge of the principles of rock mechanics and of the engineering behaviour of rocks and rock masses. De Ambrosis and Kotze (2004) provide an excellent example of the detailed investigation of two large stress-induced roof collapses that occurred in the roof strata of an underground LPG storage facility in Sydney, New South Wales, Australia. The author has had experience of investigations of several of the types of failure identified in this sub-section.

4. Formal Analysis Tools and Investigation Methods

4.1. *Overview*

A wide range of formal investigation methods and analysis tools and approaches are available for use in forensic engineering investigations. Many of them have their basis in hazard identification, risk assessment and risk management or control. Indeed, it can be argued that in underground construction and rock engineering more generally, it is now possible to identify all of the geotechnical hazards likely to have an impact on a project. The forensic engineering task then becomes one of determining which of those hazards contributed to the incident being investigated (Hudson, 2006).

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The analytical tools available include a range of specific techniques such as causal analysis, energy/barrier analysis, event trees, fault trees, human error analysis, Petri nets and sequentially timed events plotting (STEP) (e.g. Hadipriono, 2002; Joy, 2004; Kontogiannis *et al*., 2000). These specific techniques may be incorporated into more integrated analysis methods such as the Incident Cause Analysis Method (ICAM) (Gibb *et al*., 2004) and overall investigation methods such as the System Safety Accident Investigation (SSAI) approach (Joy, 2004).

These tools and approaches have been developed and applied to accidents and failures of a range of types in a number of industries, including the construction and mining industries. The extent to which they are applied in a given case will depend on the severity or consequences of the incident concerned. Quite often, these tools and approaches may form the basis of the in-house policies and protocols of companies or organizations. In other cases, particularly when major catastrophic events occur, they may be used in accident investigations carried out by external parties. The following outlines of ICAM and SSAI are presented in generic terms rather than in terms that are specific to underground construction.

4.2. *The Incident Cause Analysis Method (ICAM)*

The Incident Cause Analysis Method (ICAM) is an analysis tool that sorts the findings of an investigation into a structured framework. Its fundamental concept is the acceptance of the inevitability of human error. It is based on a conceptual and theoretical approach to the safety of large, complex, socio-technical systems developed by Reason (1997, 2000). This brief account of ICAM is taken directly from that of Gibb *et al*. (2004). The specific objectives of investigations carried out using ICAM are to:

- establish all the relevant and material facts surrounding the event,
- ensure that the investigation is not restricted to the errors and violations of operating personnel,
- identify the underlying or latent causes of the event,
- review the adequacy of existing controls and procedures,
- recommend corrective actions to reduce risk, prevent recurrence and improve operational efficiency,
- detect developing trends that can be analysed to identify specific or recurring problems,
- ensure that it is not the purpose of the investigation to apportion blame or liability, and
- meet relevant statutory requirements for incident investigation and reporting.

Reason (1997) defines ***organisational accidents*** as those in which latent conditions (arising mainly from management decisions, practices or cultural influences) combine adversely with local triggering conditions and with active failures (errors and/or procedural violations) committed by individuals or teams to produce an accident. The Reason Model and ICAM focus on those matters over which management could reasonably have been expected to exercise some control.

The ICAM Model organises incident causal factors into four elements as illustrated in Figure 2. ***Organisational factors*** are the underlying factors which promote the task/environmental conditions that affect performance in the workplace, or allow those conditions to remain unaddressed. They may lie dormant or undetected for some time, and their repercussions may become apparent only when they combine with local conditions and errors to breach the system's defences. ***Task/environmental conditions*** are the task, situational or environmental conditions in existence immediately before, or at the time of, the incident. They are the circumstances under

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which the errors or violations took place. They can be embedded in the demands of the task, the work environment, individual capabilities and/or human factors. ***Individual or team actions*** are errors or violations of a standard or procedure committed in the presence of a potential hazard that is not properly controlled. They are the actions or omissions that led directly to the incident or accident. ***Absent or failed defences*** fail to provide the required protection to the system against technical or human failures. Both proactive and reactive defences are required to prevent incidents or accidents and to minimise adverse effects if they do occur (Gibb *et al.*, 2004).

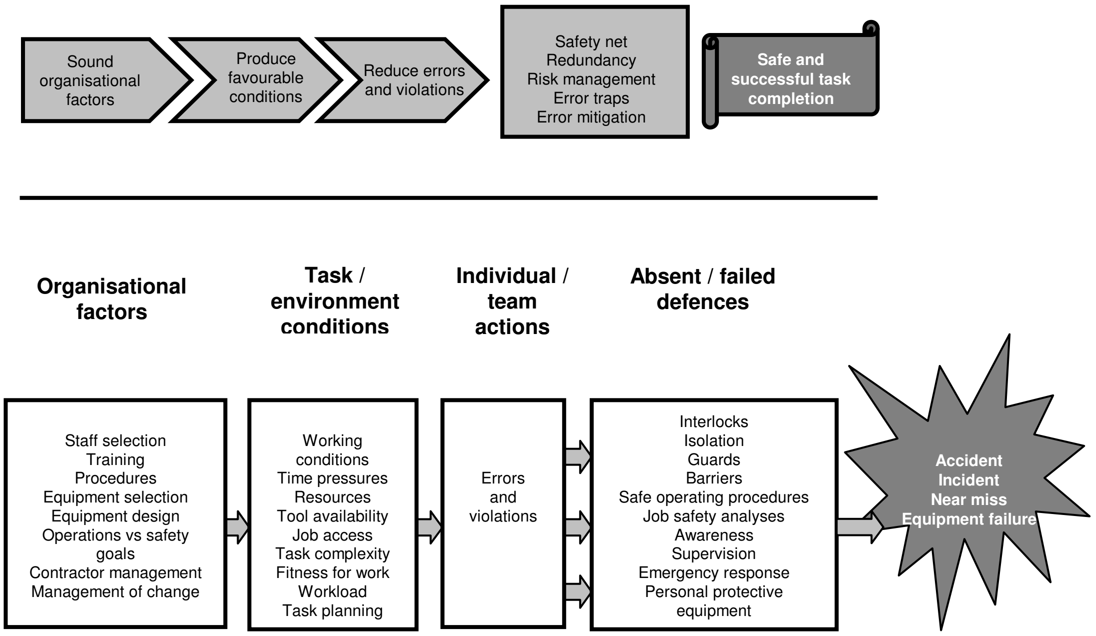

Fig. 2. The ICAM model of accident causation (Gibb *et al.*, 2004).

4.3. *System Safety Accident Investigation (SSAI)*

The System Safety Accident Investigation (SSAI) approach was developed in the 1970s for use in the US nuclear power industry. The techniques have since been modified for use in many high risk industries where fatalities or other catastrophes can occur. This brief account of SSAI is drawn from that given by Joy (2004) who has developed the approach particularly for application to the mining industry.

SSAI provides a systematic and logical process for fact finding in accident investigations and the drawing of conclusions. It imposes an overall discipline on the investigation process, providing a systematic method of identifying what happened and why it happened. SSAI uses several analytical techniques which are usually applied in a specific order:

- ***event and condition charting*** for displaying graphically the events in the accident sequence and the preconditions that affected those events,
- ***fault tree analysis*** for depicting the possible scenarios leading to an event in the accident sequence (where there were no witnesses),

- ***energy/barrier*** analysis to illustrate the unwanted energy flows and barrier inadequacies that contributed to the accident,
- ***human error analysis*** for the systematic examination of any deviations from expected human performance, and
- ***gap analysis*** to provide some insight into why the accident occurred by comparing accident-free conditions with the accident conditions.

Not all of these techniques are necessarily applied in any given accident investigation. They are tools to be used by an accident investigation facilitator. Typically, accidents resulting in or having the potential for loss of life, massive equipment damage, or prolonged system failure, receive a full and extensive investigation. The author has been part of such SSAI investigations in two cases involving fatalities in the Australian mining industry.

5. The Legal Interface

It is axiomatic to the concept and definition of forensic engineering being used here, that the forensic engineer's investigations have a relation to the legal system of the state or country in which the incident took place. The forensic engineer may be required to act as an expert witness in coronial enquiries, in civil or criminal court proceedings, in mediated or arbitrated disputes, or in tribunals. Even in legal cases that may be settled out of court, the forensic engineer will usually be required to prepare an expert witness statement in a prescribed format.

Most court systems issue guidelines for the preparation of expert witness statements, emphasising the need for the expert witness to be objective and impartial in giving opinion evidence (e.g. Department of Constitutional Affairs, UK, 2006; Federal Court of Australia, 2004). In the adversarial court systems in which the author has appeared as an expert witness, cross-examination by barristers can be a challenging, and sometimes harrowing, experience. The Federal Court of Australia's guidelines make provision for the Court to direct the experts retained by the parties to meet in an attempt to reach agreement about matters of expert opinion. Interestingly, the Civil Procedure Rules of the UK now give the Court the power to direct that evidence on a given issue be given by a single joint expert (Department of Constitutional Affairs, UK, 2006).

Professional engineering practice is governed by Codes of Ethics to which engineers subscribe on becoming members of professional engineering organisations. Ethical conduct is especially important in forensic engineering where the stakes can be high and there can be pressure on the forensic engineer to orient his/her investigation, findings and/or expert statement in the interests of one party or another. The *Guidelines for Forensic Engineering Practice* of the American Society of Civil Engineers (Lewis, 2003) define ethical forensic engineering practice as "*the conduct of forensic investigations and providing expert testimony based on sound, comprehensive, and unbiased investigation, and demonstrating exemplary professional conduct and honesty in serving the trier of fact, the public, and clients, as a qualified expert*".

A particular area of litigation often arising in underground construction concerns the consequences of what may be described variously as unforeseen, changed, differing or latent ground conditions. These are ground conditions encountered during construction that it is argued could not reasonably have been foreseen at the time of tendering. Modern risk management techniques and contractual practices (e.g. Eskesen *et al*., 2004) seek to avoid or minimise litigation arising from this cause. However, the area remains one in which forensic geotechnical engineers often become seriously involved. Gould (1995) notes that, in the USA, progress in dispute resolution has brought with it the increasing involvement of geotechnical engineers in changed-

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condition claims. Gould (1995) further notes that "*in the present highly competitive heavy-construction market, bidders commonly accept hazards without contingency in their proposal, expecting that "claimsmanship" will turn a marginal job into a profitable one*".

In some jurisdictions, proceedings in underground construction and mining cases may be taken by government agencies under occupational or work place health and safety legislation. In some states of Australia there appears to be an increasing trend to institute such proceedings against individual professional engineers and against operating companies, contractors and suppliers, for exposing employees to risk in the work place, both in the civil construction and mining industries. Despite the significant advances that have been made in the last decade or more in reducing geotechnically-related lost time injury and fatality rates in Australia's underground mines, Galvin (2005, 2006) has found that seemingly automatic prosecution policies (and some court decisions) are now impacting negatively on the objective of reaching the goal of zero harm because:

- "*Lessons from serious incidents are not being disseminated until some years after because of privilege and other considerations associated with pending charges.*
- *Some organizations and employers are reluctant to encourage near-miss reporting because of concerns that it could be used against them in prosecutions.*
- *It is a major disincentive for young people to seek a management career in the minerals industry*."

6. The Lane Cove Tunnel Project

6.1. *Background*

The Lane Cove Tunnel Project (LCTP) in Sydney, New South Wales, Australia, involves the construction of twin, 3.6 km long, two- and three-lane tunnels together with 3.5 km of bridge and road upgrades to link the M2 motorway at North Ryde with the Gore Hill Freeway, as well as a number of other elements. The twin east-bound and west-bound tunnels run beneath and slightly to the north of Epping Road. Figure 3 shows a schematic diagram of the tunnels in the project.

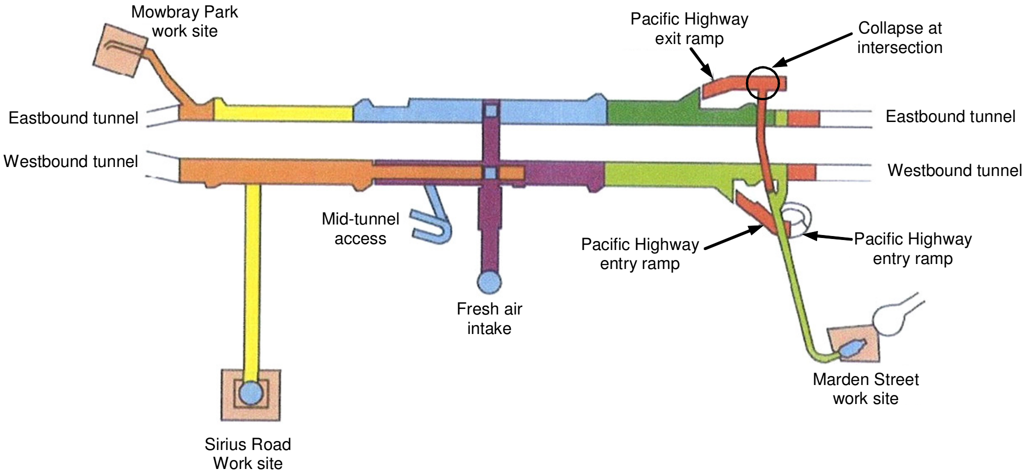

Fig. 3. Tunnel schematic, Lane Cove Tunnel Project (Rozek, 2005).

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The New South Wales Roads and Traffic Authority (RTA) engaged the Lane Cove Tunnel Company (LCTC) to design, construct, maintain and operate the tunnel for a period of 33 years. LCTC, in turn, appointed the Thiess John Holland Joint Venture (TJH) to design and construct the project. TJH's contract commenced in December 2003 and tunnel construction in July 2004. The tunnel works are divided into three parts – a western or Mowbray Park section, a central section, and an eastern or Marden Street section. The contract completion date is May 2007.

The majority of the LCTP tunnelling is in the Hawkesbury Sandstone whose properties and engineering behaviour have been the subject of detailed study. Those sections of the tunnelling to be discussed here are excavated in the overlying and generally horizontally-bedded Ashfield Shale, described by Badelow *et al.* (2005) as a sequence of "*mudrocks including siltstone, mudstone or laminate and lesser shale and claystone*". In the process of the investigation, design and construction of a range of excavations and foundations in the Triassic rocks of the Sydney region, local classifications of the sandstones and shales have been developed and applied (e.g. Bertuzzi and Pells, 2002b; Pells *et al.*, 1998). Specific design methods for the excavations in the Sydney rocks and for their support and reinforcement have also been developed and applied with notable success (e.g. Bertuzzi, 2005; Bertuzzi and Pells, 2002a; Pells, 2002; Pells *et al.*, 1991). Advantage was taken of these methods and this experience in the design of the LCTP tunnels (Badelow *et al.*, 2005; Maconochie *et al.*, 2005; Rosek, 2005).

In the early hours of Wednesday, 2 November 2005, subsidence developed above the Pacific Highway Exit Ramp tunnel on design control line MCAA at its junction with the Marden Street ventilation tunnel on design control line MC5B. The road-header and loader working at the location were buried by collapsed material. The subsidence propagated to surface near 11-13 Longueville Road, Lane Cove, and an exit ramp from Longueville Road at the point marked in Figure 3. The subsidence under-mined the front of a building (producing a spectacular effect) and a bored pile retaining wall on the north side of Longueville Road shown in Figure 4. Within a few hours of the collapse, it was decided to fill the cavity with concrete as illustrated in Figure 4 in order to arrest the under-mining and underpin the retaining wall. The incident attracted considerable media attention in Sydney and more widely in Australia.

6.2. *The Investigation*

Two days after the incident, the author was engaged, through Golder Associates Pty Ltd, as an independent expert to investigate and report on the cause(s) of the subsidence. The author visited Sydney in the period 7-11 November 2006 when he carried out the following main activities:

- discussions and interviews with representatives of the contractor, the designer, the geotechnical consultant, and the crew and supervisors working at the collapse site at the time of the incident,
- a surface site visit,
- an underground visit to the site of the collapse and to inspect other tunnels in the Marden Street section of the project,
- study of a wide range of design documents, drawings, construction reports and other documents, and
- giving preliminary consideration to the possible causes of the incident and the preparation of an outline of the report.

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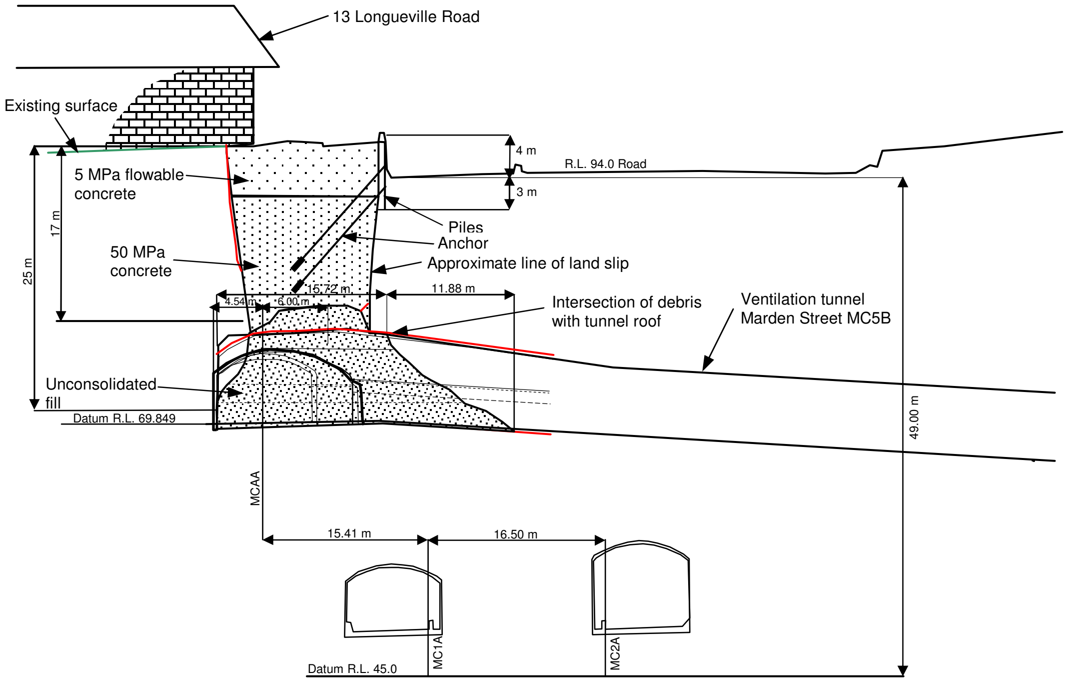

Fig. 4. Vertical section through the Lane Cove Tunnel incident site following the concrete pours.

Following this preliminary analysis of the available information, the following possible contributory factors to the collapse were identified:

- water,
- the weak shale in which the intersection was excavated,
- a low strength, steeply-dipping dolerite dyke crossing the intersection,
- jointing associated with the dyke,
- faulting present at the site,
- the large effective span of the intersection excavation,
- the low depth and nature of the cover,
- the levels of support provided, and
- the proximity of the Longueville Road retaining wall and ground anchors to the roof of the intersection excavation (see Figure 2).

The author then returned to Brisbane to continue his analysis of the information collected during the initial site visit and to prepare his report. During this period, several further documents and items of information were requested and supplied by the contractor and the geotechnical consultant. In the analysis of the incident, formal investigation techniques of the types outlined in Section 4 above were not utilised. However, the issues considered in the SSAI approach were addressed in the investigation, although not in a formal manner. A sequence of events was compiled in tabular rather than diagrammatic format.

The final report (Golder Associates, 2005) was released to the public and attracted some attention in the Sydney media. Other reports of the incident, generally based on the author's report, appeared in the technical press (e.g. Kitching, 2006). A few months later, the WorkCover Authority of New South Wales made public an initial report of its own investigation of the incident

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carried out pursuant to Section 88 of the NSW *Occupational Health and Safety Act 2000* (WorkCover NSW, 2006).

6.3. *Conclusions Drawn*

The report into the causes of the subsidence (Golder Associates, 2005) drew the following conclusions:

(i) Tunnelling and underground construction are always attended by a number of risks and uncertainties, mainly associated with the inherent variability of the geological structure and mechanical properties of the rock masses in which construction takes place.

(ii) During the excavation of the Marden Street ventilation tunnel, a near-vertical dolerite dyke (or pair of dykes), was intersected at a number of locations. Although dykes are known to exist in the sedimentary rocks of the Sydney region, this particular dyke had not been identified in the pre-construction geotechnical investigation. However, the dyke had been intersected previously during construction in ventilation tunnel MC5A and the main lane tunnels MC1A and MC2A.

(iii) Because of the presence of two sets of orthogonal joints associated with the dyke and other jointing and faulting, the shale rock mass at and near the junction of the MC5B ventilation tunnel and the MCAA exit ramp was of poorer quality than had been anticipated in the design stage.

(iv) The collapse started near the north-west corner of the newly extended down drive of the MCAA exit ramp at about 1:38 am on the morning of 2 November 2005, and rapidly extended across the exit ramp face to the dyke in the crown. The fall propagated across the crown of the junction of the MCAA exit ramp and the MC5B ventilation tunnel to the east or south-east and included the dyke. The collapse propagated to surface in Longueville Road in 10-20 minutes.

(v) The collapse initiated with the fall of rock blocks in the north-west corner of the excavation as a result of unravelling under a lack of lateral and normal restraint.

(vi) The ultimate failure mechanism was progressive, probably consisting of several stages (listed in the report).

(vii) The processes and methodology used in the design of the LCTP tunnels was in accord with best practice in Sydney and elsewhere, and the resulting designs were generally suitable for their purposes.

(viii) In the design stage, no special analysis of the MC5B/MCAA junction was carried out. However, because of the inevitable local variations in the geological and geotechnical conditions, it was recognised that it would be necessary to modify or adapt the initial design, particularly the support provisions, to the conditions actually encountered during construction.

(ix) TJH has in place a series of appropriate and best practice processes for the safe and productive execution of the underground construction works on the LCTP. Some of the documents setting out these processes are models of their kind.

(x) Up to the time of the incident of 2 November 2005, the designs and processes in place had been executed in a highly professional and productive manner by a knowledgeable and dedicated workforce and their supervisors.

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(xi) The collapse arose from a combination of factors that were not present together at any other location in the underground works on the project.

(xii) The factors causing the collapse were probably:

- the presence of the dyke providing a persistent, relatively low strength, near vertical discontinuity transecting the roof of the excavation in a strike direction that was closely parallel to the maximum effective span of the junction,
- the presence of orthogonal, closely-spaced jointing associated with the dyke, reducing the already poor mechanical quality of the weathered Ashfield Shale rock mass,
- the presence of faults with orientations such that, in conjunction with the dyke, the joints and the excavations boundaries, they could isolate blocks that were free to fall or slide from the excavation boundaries if not adequately supported,
- a large effective span with relatively low cover to rock head, and
- the level of support existing in the western side of the excavation at the time being inadequate to ensure the excavation's stability given the large effective span, the low rock cover, the presence of persistent vertical discontinuity (the dyke) transecting the excavation, and the poor mechanical properties of the overlying rock mass.

(xiii) Water was not a cause of the collapse.

(xiv) The proximity of the Longueville Road retaining wall and its ground anchors to the crown of the MC5B/MCAA junction excavation may have contributed to the collapse by influencing the loads applied to the rock immediately above the excavation, or by weakening that rock mass, or both.

(xv) The preparation of the best possible longitudinal geological sections and/or progressive geological plans may have been of assistance in projecting conditions ahead of the face as excavation progressed.

7. Concluding Remarks

Forensic investigations of underground construction and mining failures and the associated interactions with the legal system, now represent an important part of the work of many experienced geotechnical engineers. The conduct of these investigations, the drawing of conclusions and the communication of the results impose significant demands on the knowledge and skills of the forensic geotechnical engineer and require the exercise of the highest professional and ethical standards. Forensic geotechnical engineers can play a significant role by explaining publicly and within the legal system, the not widely understood difficulties and risks involved in engineering in the variable natural materials found on and in the crust of the Earth.

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