Lessons from Accidents during Tunnel Construction

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Abstract:

The number and complexity of tunnel systems will surely increase with ever increasing population and urbanization. Although most tunnel construction projects have been completed safely, there have been several incidents that have resulted in delays, cost overruns, and sometimes more significant consequences such as injury and loss of life. In this paper we present a database of tunnel accidents that occurred during construction containing 206 cases that were collected from a combination of literature review, newspapers, and correspondence with tunneling experts around the world. This paper describes the data collection and the results of the data analysis. The study of the accidents in the database made it possible to identify and categorize accidents into different types, typical causes, and consequences, as well as identify the scenarios in which these events (accidents) are more likely to occur. The analysis of the database shows that unexpected ground conditions are often the main reason for tunneling accidents during construction. Despite recent efforts made to improve existing tunneling technologies, forecasting ground conditions in tunneling remains the most challenging task in tunneling because of significant uncertainties related to the subsurface. The study of the different cases of the database made it possible to identify different scenarios, in which these events are most likely to occur. As a result of the analysis, influence diagrams were constructed for each type of accident containing the main factors, and the interactions between them. To emphasize: The objectives of the paper are: 1. To provide information on tunnel accidents and the related data collection process and 2. Present a process with which the information can be systematically evaluated.

1. Introduction

Construction of tunnels has been increasing worldwide. Most tunnels have been completed safely. However, there are a number of events that happened all around the world that have raised concerns regarding the risk of tunneling. There are often not enough and reliable data regarding the risks that tunnels face during construction. Efforts have been made by some institutions and researchers to collect data on problems occurring during construction as will be briefly discussed later. However, there is no centralized world-wide database on tunnel failures. This was the motivation for the authors to collect data from different sources. Equally important is the development of a systematic data collection and analysis process that can be used by others with other data. This paper describes this process of data collection and analysis of accidents that occurred during tunnel construction worldwide, work done between 2007 and 2009 at MIT (Sousa, 2010), which has never been published before. While only including a couple of hundred cases the data are representative and the data collection and analysis processes are generally applicable.

In 1994, following the collapse of three tunnels of the Heathrow Express in the United Kingdom, HSE (Health and Safety Executive) collected cases of failures during the construction of NATM tunnels (39 cases) (HSE, 1996). In 2001, Vlasov et al. (2001) published a book regarding accidents in transportation and subway tunnels, during construction and operation. The book contains data on several cases in Russia and around the world occurring during construction and operation. It also presents preliminary recommendations on accident forecast and prevention based on the analyzed data. In 2006, HSE issued another research report entitled "the risk to third parties from bored tunneling in soft ground" that contains a list of NATM events (66 cases) and a list of non-NATM Emergency events (42 cases) during construction and operation. The list does not provide many details regarding the actual events (apart from the type of event, reported causes and references). Stallman (2005) contains a collection of 33 cases of failures during construction with details on the geological and hydrological conditions of the accident, the causes, consequences and type of collapse. Seidenfuss (2006) compiled 110 cases of problems that occurred during construction and operation, categorizing them, describing their causes and mechanisms. In addition to the above listed reports and theses, 71 incidents have been reported in 65 tunnels constructed in Japan between 1978 and 1991 at unspecified locations. These ground collapses ranged from the "quite small" through volumes of between 50 – 500 m^3 of ground (15 Incidents.) to volumes of over 1,000 m^3 of ground (3 incidents) (Inokuma, 1994).

More recent work by Peixoto (2010) compiled a database of 62 rockburst cases, in various tunnels particularly related to the Jinping II hydroelectric scheme in China, in order to better understand the factors and conditions that trigger rockburst. He et al. (2015) compiled and analyzed large number of rockburst tests performed at the Laboratory for Geomechanics and Deep Underground Engineering (SKL-GDUE) in Beijing. In their work 139 of these tests were gathered in a database and data mining techniques were applied in order to develop predictive models for rockburst parameters and a risk index.

2. MIT Data collection process

The data on accidents were collected from the technical literature, newspapers and correspondence with experts in the tunneling domain. The data were stored in a database, analyzed, and the accidents were then classified into different categories, and their causes and their consequences were evaluated (Sousa, 2010). Figure 1 shows the methodology used in creating the database.

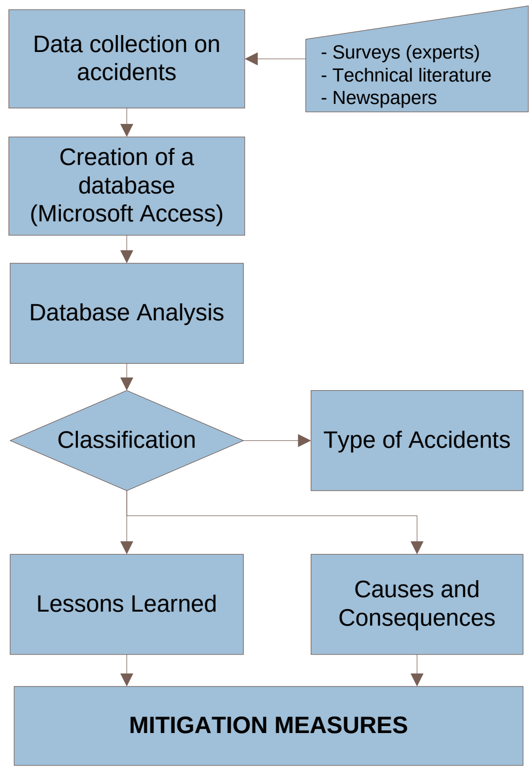


Figure 1. Methodology followed during the creation and analysis of the database on accidents

A formal survey was created to facilitate the interaction with the experts. The survey consisted of two sections: Project Information and Accident Information.

The **Project Information** section asks for information related to the project, where the accident occurred and comprises five subsections: General information; Tunnel dimensions; Geological and geotechnical information; Construction method; Other relevant information / Comments. The **Accident Information** section is most important and collects information that is specific to the accident itself. It comprises two subsections: *General Information* containing information regarding the date of occurrence, as well as the geomechanical characterization and construction sequence of the collapsed zone; and *Description of the occurrence*. This is the most relevant sub-section. Here the accident is described as well as the details, such as the type of occurrence, the location of the occurrence (e.g. heading, lining, etc), the time of occurrence, consequences and possible causes. An example of the *General Information* section is presented in Figure 2. Table 1 shows the list of variables of each case of the database.

A total of 113 questionnaires with the formal survey were sent out to tunneling experts in the field. Each record in the database is based on the interpretation of both the filled in questionnaires, private correspondence with experts and technical and newspaper articles. The combination of these sources resulted in total of 206 cases which were recorded in the database.

3. Database Structure

The collected data were assembled in the database, which is a collection of information from accidents/major problems that have occurred in different areas of the world and covers almost all types of tunnels: railway, road, subway, hydraulic and sewerage. The database was created with Microsoft Access and consists of records of the different cases. Each record contains general information about the project. Linked to each project record there are one or more accident records, which contain detailed information on the accident/problem(s) that occurred during construction. The most important information recorded is presented in Table 1.

1. PROJECT INFORMATION

1.1 General information

Project Name:	Lausanne Metro M2
Client:	Metro Lausanne-Ouchy SA
Designer :	Several Designers (table attached)
Contractor:	Several contractors (table attached)
Location:	Lausanne / Switzerland
Start of construction:	Spring 2004
End of construction:	Fall 2008
Type of environment [(1)] :	Urban
Type of tunnel	Metro tunnel

Maps, Figures:

Saint-Laurent tunnel's passage under the 19th Century masonry bridge

Layout of the Lausanne M2 Metro Line

Line M2 in construction on the stretch of the former Metro-Ouchy

Figure 2 Extract of the questionnaire – General Information section (Lausanne M2 metro line) (Sousa, 2010)

Table 1. List of variables for each record

Number	***Variables***
1	Title
2	Location
3	Type of tunnel
4	Length
5	Number of accidents registered
6	Type of environment (1)
7	Cross section shape
8	Cross section dimensions
9	Ground Mass Type
10	Construction Method
11	Type of occurrence
12	Year of occurrence
13	Local of occurrence (2)
14	Time of occurrence (3)
15	Description of occurrence
16	Overburden
17	Geomechanical characterization of the collapsed zone
18	Errors / Possible Causes
19	Consequences
20	Mitigation Measures (4)
21	Source of information
22	Photos

(1) Type of environment in which the tunnel was constructed: urban, mountainous, rural or other
(2) Location of the occurrence: heading, bench, lining, shaft, portal or other
(3) Time of occurrence: when in the constructive process did the failure occur?: During excavation of the section heading? During the excavation of section invert? After excavation?
(4) What measures were taken after the occurrence in order to ensure the successful completion of the construction? Were they effective?

In addition to these variables other information was also registered, such as the client, designer, contractor, date of start and end of construction, average, maximum and minimum overburden along the tunnel, general geological and groundwater conditions. Figure 3 shows an extract of section 2.2 of the questionnaire (Lausanne M2 metro line), which is the *Description of the occurrence* section. Figures 4 and 5 show the geographical distribution of the tunnel cases in the database and the distribution of the type of use of the tunnels in the database, respectively.

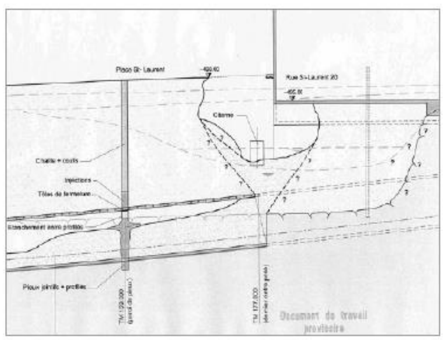
2.2 Description of the occurrence

Type of the occurrence :	Daylight collapse			
Location of the occurrence :	Heading	■	Invert	☐
	Lining	☐	Other:	
Time of occurrence (5) :	The cave-in occurred on Tuesday at six o'clock in the evening. At the time of the incident investigation works were said to be underway following an earlier inrush.			
Description of the occurrence:	A tunnel collapse on Lot 1200 consisting of the 306 m-long Saint-Laurent tunnel between Flon and Riponne stations and the 272 m-long Viret tunnel between Riponne and Bessières stations displaced a huge amount of material – soil + water (1400m3) into the tunnel and caused extensive damage as it cratered towards the surface in the busy St. Laurent's commercial district.			

Possible mechanisms (sketches or figures):

Collapsed area at the surface

Aspect of the front after collapse
(ingress of soil and water)



Drawing of the collapse

Figure 3. Extract of section 2.2 of the questionnaire: Lausanne M2 metro line (Sousa, 2010)

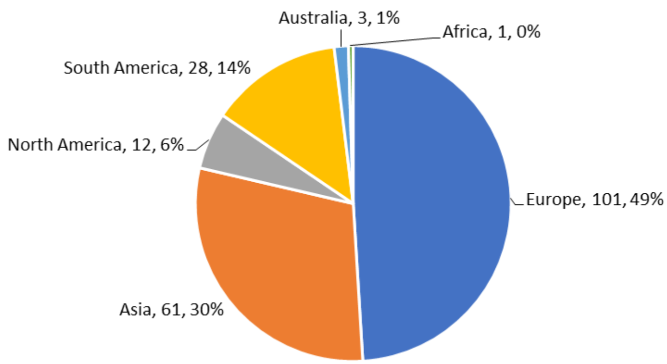


Figure 4 Geographical distribution of the tunnel cases

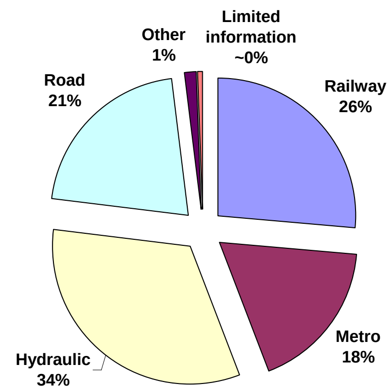


Figure 5 Distribution of the type of use of the tunnels in the database

4. Type of Accidents

Figure 6 shows the distribution of undesirable events (accidents) in the database. Most of the events reported are *Collapses* and *Daylight Collapses* (41% and 28%). This does not mean that these are the majority of events that occur during tunnelling construction. We belive that they are the most frequently reported in the literature and by the experts because most likely they are the ones with more severe consequences on the construction process, the safety of the workers and people and structures on the surface. Thus, they may not be the “actual” most frequent accidents during tunnel construction. Fire and Explosions —included in the “other” category in Figure 6—are probably the most common type of accidents during the operation of tunnels. They can also occur during construction but are less frequent. They can cause loss of live, equipment damage and damage to the tunnel structure that may lead to a collapse. However, since they do not occur frequently in tunnels under construction, and although one case was collected, this type of incindent was not considered in detail.

A complete list of all cases in the database can be found in Appendix A.

4.1 Rock Fall

A rock fall consists of a block that detaches by sliding or falling. The different mechanisms involved in block slide are wedge or planar failure while pure rockfalls involve detachment from the roof (crown) due to gravity without sliding. Although the database shows no pure rockfall case, they are in fact not that uncommon and responsible for fatalities during tunnel construction due to the unexpected nature of this type event. Unfavorable geology is the principal cause for the mechanisms of rock fall. This includes discontinuities within the rock mass and weathered and weak zones in the rock. An example of a large rock fall (a block of about 2,000m^3) is the accident that occurred during the construction of one of the surge chambers part of the Cahora-Bassa hydroelectric system in Angola (project ID 50). The rock fall was caused by a wedge failure that took place along the intersection line of the two inclined discontinuity planes belonging to the family of discontinuities at this location and bounded on top by a lamprophiric dyke (Figures 7 and 8) (Ribeiro e Sousa, 2006 and private correspondence). Another example of wedge failure is the case of the extension of the Harsprånget hydroelectric power plant in Norway (Project ID 51) constructed during the period 1974-

1982 where while excavating the upper bench a new unlined tailrace tunnel, a rockslide occurred along 60 m of the tunnel (Hansen, 1993). An example of a planar failure is what happened during the construction of Holjebro hydroelectric power plant in Sweden (Project ID 52), where a planar failure occurred on the sidewall along 35m length of the tunnel. The area where the failure occurred had been pre-supported, but the support proved not to be sufficient (Hansen, 1993).

Block falls and slides are normally also caused by *discontinuities* such as fractures and faults. The orientation (between the discontinuities and the tunnel and between discontinuities themselves), the spacing, the persistence, as well as the thickness of the discontinuity and the filling material, and shear strength of the discontinuities are extremely important factors in the determination of potential unstable wedges or blocks. A combination of factors which include the discontinuity characteristics and conditions (described above), the presence of water, the support system and the construction method used will determine whether or not the rock fall will occur, as well as its volume, which can range from 0.5-1m^3 like the Cross City tunnel (project ID 5) and M5 East Motorway (project ID 6), both in Australia (Muller et all, 2005; Peglas and Scott, 2005; Bertuzzi and Pells, 2002 and private correspondence) to 2000m^3 in a very extreme case such as the Cahora Bassa power scheme in Mozambique (project ID 50) mentioned previously.

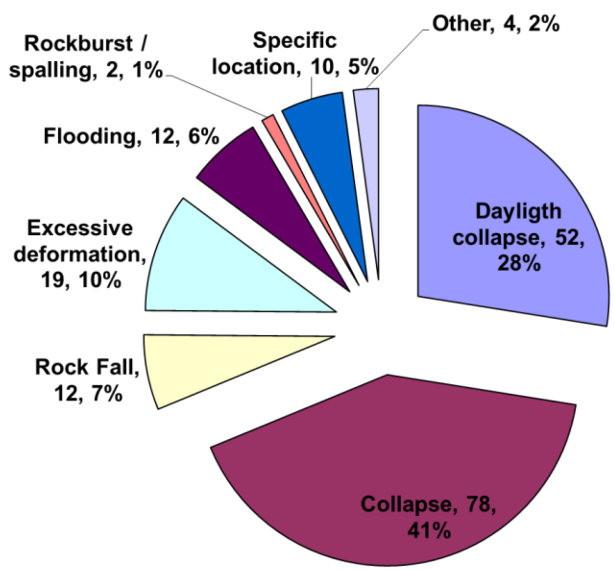
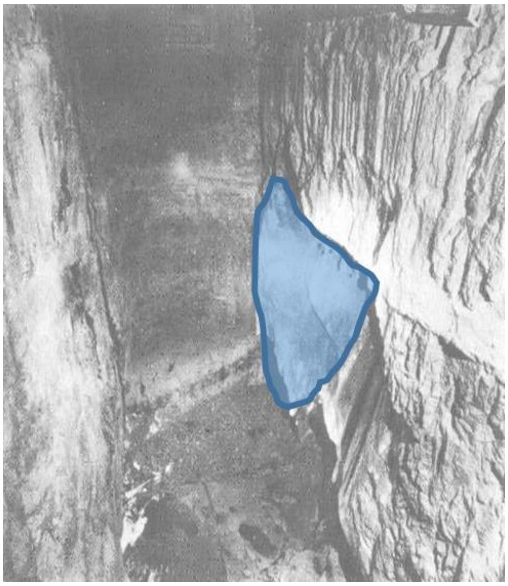


Figure 6 accident type distribution in the database



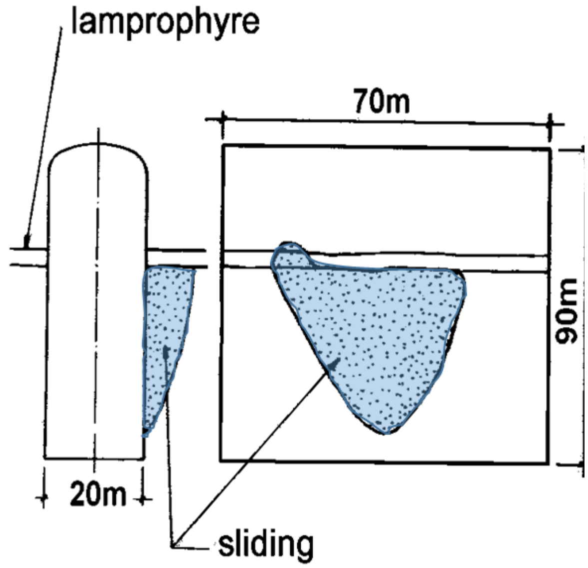


Figure 7 Photo of the collapsed area (adapted from Rocha, 1977)

Figure 8. Accident schematic (adapted from Sousa, 2006)

Figure 9 shows the influence diagram containing the factors that affect the likelihood of a rockfall as well as its consequences. The influence diagram is a summary of the most important factors that appear to be common to most of the cases of rockfall in the database. The dashed arrows in Figure 9 show how the factors related to the rock structure (discontinuities), stress state, water flow and construction method relate to each other. The presence of the discontinuities influences the local stress field around the tunnel. The discontinuities affect the water flow, since they will dictate the permeability during construction. Also, the presence of water / water flow will affect the effective stress state. Finally, the support system used is extremely important. The existence of an adequate support system will prevent an unstable wedge to slide and cause damage to the tunnel and machinery, as well as injuries to the workers. If the construction method is drill and blasting, it will affect the stress and fracturing around the excavation.

4.2 Collapse

These are collapses which occur in tunnels under construction but do not reach the surface. The majority occurs in the heading (face and/or crown) area of the tunnel. Others occur behind the face. A collapse can be partial like the one that occurred on 11 April 2002 in the Fadio zone, of the Gotthard Base tunnel (Project ID 97) in Switzerland, leaving a cavity of about 8m height. In this case the accident was caused by squeezing ground that led to excessive deformation that ultimately led to the partial collapse of the lining. This is a good example that shows that an accident is normally a result of a chain of events and has at its origin in more than one cause or error (Einstein, 2007).

4.3 Daylight Collapse

These are collapses that reach the surface creating a crater. They are the most sensational types of events and frequently the ones that cause the most serious consequences, specifically if they occur in urban areas. The propagation of the collapse to the surface can be quick and without warning as happened in the Munich Metro in 1994 (Project ID 121) where a bus passing by was trapped in the sinkhole (Friedrichsen G., 1998) or in the Pinheiros Station in Rio Paulo, in 2007 (Project ID 93), where the collapse of the shaft of the station dragged pedestrians and a passing minibus into the crater, causing seven deaths (Barton, 2008). In rural areas the consequences of daylight collapses are far less catastrophic. An example of a daylight collapse in a rural area is case Project ID 101, the collapse of a highway tunnel in Switzerland in a rural area (Kovari, and Descoeudres, 2001). A special case of daylight collapse can occur in Karst terrains where natural caverns can collapse because of tunneling activities.

As mentioned before, most events occur in the heading (face and or crown) area of the tunnel, but some behind the face. This was the case in the Porto Metro accident (Project ID 9). On January 12, 2001 the foundation underneath a building collapsed suddenly in just a few minutes, resulting in the death of one person inside the building and causing a crater at the surface with a net volume of around 250 m^3 (Figure 10). The TBM had passed under building between December 16 and 18, it was stopped 50 m ahead since December 28, 2000. The stoppage was due to excessive settlements at the surface and the need to fill a cavity of around 15 m^3 due to over-excavation (accident 2 in Figure 10). The above-mentioned major accident is accident 3 in Figure10.

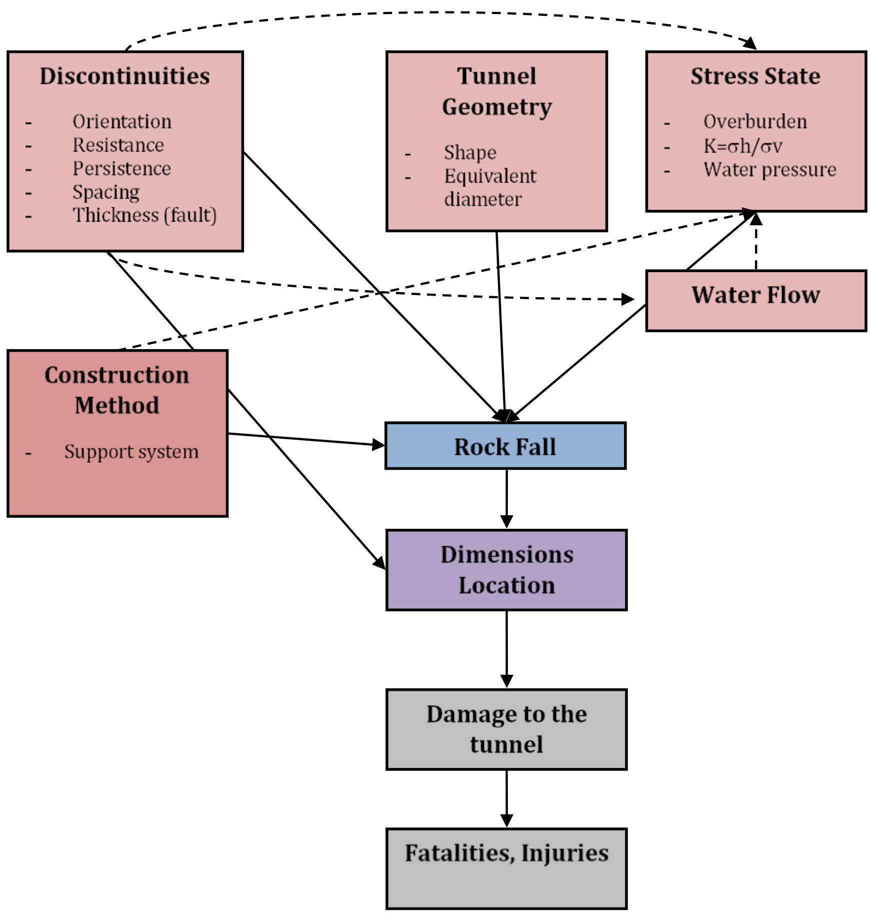


Figure 9 Rock Fall influence diagram

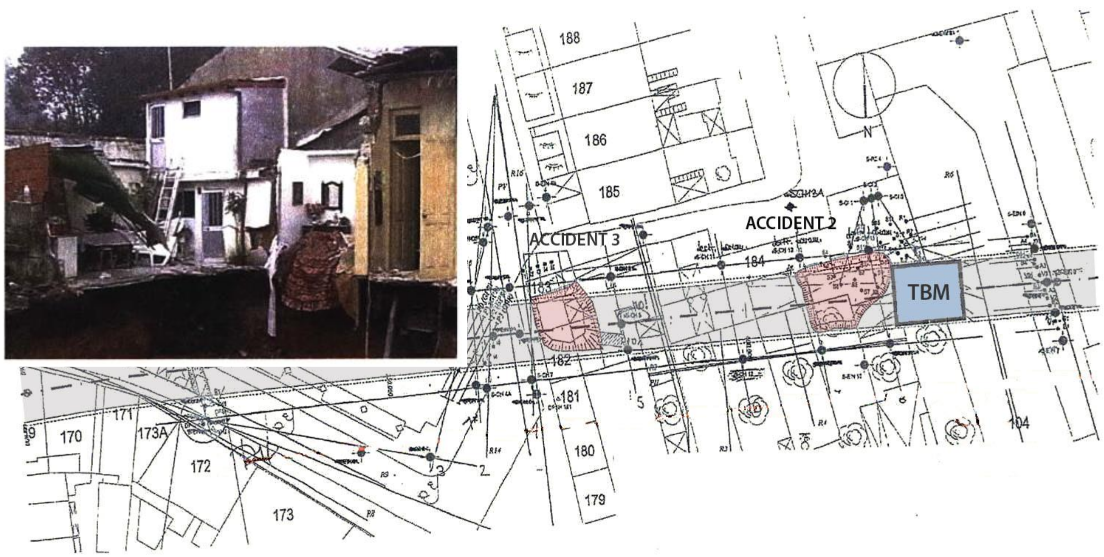


Figure 10 Collapse of Porto Metro line C in January 2001 (adapted from Forrest, 2006 and private correspondence)

The main "reported" cause of collapses and daylight collapses is unpredicted geology, i.e. *geology* that has not been predicted during the design phase. In most of the cases this corresponded to weak zones and fault zones, or karstic features. Examples are the collapses that occurred in Kurtkullagi irrigation tunnel in Turkey (project ID 12), where four collapses (two of them reaching the surface) occurred when the tunnel crossed an oversaturated clayey fault zone. Other examples are the Pinglin tunnels (project ID 30), the Evino-Morno tunnel in Greece (project ID 49) where a collapse occurred when the TBM ran into a very disturbed Flysch zone or the Shisanling pumped storage power station in China (project ID 54) where three large scale collapses occurred when the penstock tunnel was crossing a fault zones. Collapses can also be a consequence of *excessive deformation* and *excessive water inflow* (project ID 7) where excessive deformation among other causes led to a total or partial collapse of the tunnel lining. Excessive deformation of the lining can reach certain values that will result in the failure of the lining and eventually led to a partial or total collapse.

The construction method used is of great importance. Different construction methods lead to different consequences. According to the results of the database collapses/ daylight collapses in tunnels excavated by conventional means tend to involve on average greater volumes than the ones driven by shield or TBM. Certainly, there are also other factors that will determine the volume of ground involved in collapses, as well as the shape of the crater at the surface in daylight collapses, such as the type of ground, the overburden, the shape and dimensions of the tunnel cross section (although there are not enough data in the database to confirm this).

Overburden is another very important parameter. The smaller the overburden the more likely is that the collapse reaches the surface. This is extremely important especially when driving in an urban environment, where the consequences of a daylight collapse can be extremely severe.

The presence of other man-made structures is another important factor. It is crucial to have them charted as best as possible, to avoid running into them and possible destabilizing the excavation, causing a collapse. This is what happened in the first collapse that occurred in the Porto metro (project ID 9) construction when the TBM hit an old well causing a collapse. Another collapse caused by man-made structures is the Istanbul metro (project ID 14), which involved an uncharted well. (1.5m diameter to about 12 m deep), located almost exactly above the place where the liquefied mud had flowed into the tunnel. It can be assumed that there was only about 1.5-2.0m between the well bottom and the tunnel crown and that the saturated clay and well water flowed into the tunnel, causing the well walls and surrounding clay to collapse. This allowed a fine-grained sand layer to drain into the resulting cavity. For other structures already built in the ground, it is necessary to consider their effect on the excavation of the new structure and vice versa. In the case of the Olivais station of the Lisbon metro (project ID 10), Portugal, a daylight collapse occurred in December 1996; one of the errors during construction that ultimately contributed to the daylight collapse was that a preexisting large utility tunnel located near the metro tunnel was not considered.

Figure 11 shows the influence diagram for Collapse and Daylight collapse.

4.4 Flooding / Large Water Inflow

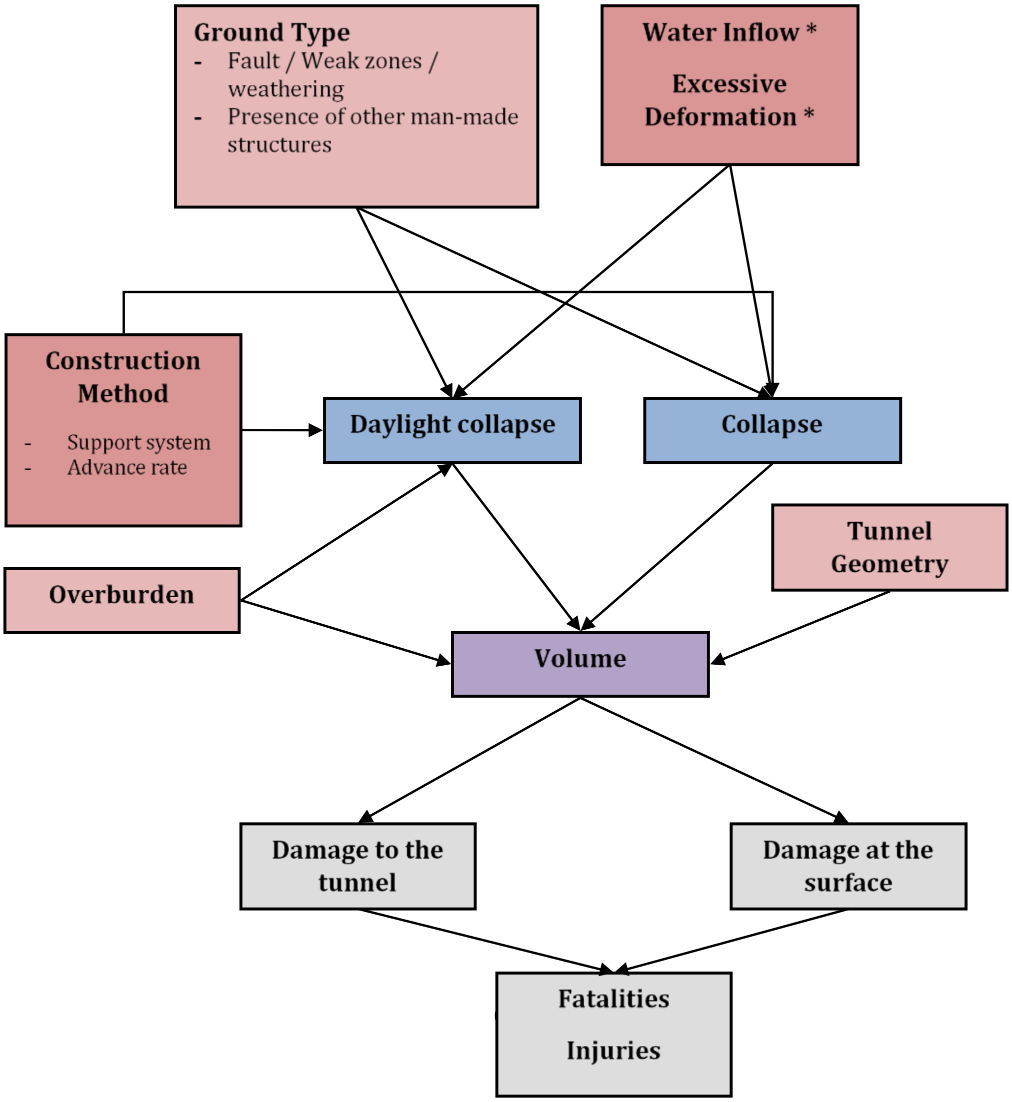
These are cases where the tunnel was invaded by large quantities of underground water, causing flooding. It is during the construction of underwater tunnels that the largest scale flooding has occurred. The ground under rivers, channels and bays is often weak and under high water pressure and therefore extreme safety measures and efficient protection against water inflow are usually required.

A well know example of an underwater tunnel where flooding events have occurred is the Seikan tunnel, a 53.85 km long railway tunnel in Japan with 23.3 km long underwater tunnel portion, underneath the Tsugaru strait, with an overburden of 100 m and 240 m below the water surface. Much of the tunnel crosses heavily fissured rock. The sea and underground water penetrate these zones, and the maximum water pressure is about 25 MPa. To minimize the risk of water inflows and rock failures cement - and chemical grouting was carried out along the main tunnel. Despite these measures four large flooding accidents (Project ID 88) occurred between 1969 and 1976, with severe consequences on tunnel construction and resulting in 34 casualties. The fourth accident, which took place in May 1979 while driving the service tunnel, was the most severe. The water inflow was of 70 m^3/min under a maximum pressure of 2.8 MPa, causing the flooding of 3015 m of service tunnel and 1493 m of the main tunnel with 120 000 m^3 of water, in the first three days.

Many collapses (or daylight collapses) occur in conjunction with water inflow or may lead to flooding. An example of a daylight collapse with water inflow is the one that occurred in Switzerland in the Lausanne metro construction (Project ID 2) which was due to the sudden inrush of groundwater from a pocket in the glacial moraine the tunnel was being driven through. A huge amount of soil and water (1400m^3) displaced into the tunnel and caused extensive damage as it cratered towards the surface in the busy St. Laurent's commercial district (Stallmann, 2005 and private correspondence)

A special case of water inflow is water burst which consists of water inflow under pressure in the tunnel. Figure 12 shows water bursts that occurred in a tunnel in China.

The impact of ground water on tunnel construction can be considerable. Gradual inflow of water is detrimental to the construction process, while the sudden inrush of water is a source of great danger, and many accidents have been caused by it. The sources of a sudden water inflow into the tunnels are faults, water bearing strata, caverns in karst formations. Therefore, the *hydrology* and *geology* along the tunnel alignment, such as the presence of faults or water bearing strata, as well as the knowledge of the permeability (soil) and fracture conductivity (rock) are extremely important when studying the problem of water inflow, in order to design and choose construction and mitigation measures that are adequate for the encountered conditions.



* These events are shown here as possible causes for Collapse/ Daylight collapse. For more details see their own influence diagrams, which are not shown in this figure for reasons of space.

Figure 11 Influence Diagram for Collapse and Daylight collapse

Figure 12 Water burst resulting in flooding, China (private correspondence)

Water inflow and presence of water during construction can lead to *flooding* of the tunnel, can cause instability and eventually *collapse or daylight collapse* of the tunnel and / or have adverse effects on the *environment*, due to lowering of the water table. An example where collapses occurred with flooding of the tunnel is the case of the Pinglin tunnels, in Taiwan (project ID 30). Several incidents occurred due to a combination of fractured shear zones and highly pressurized water inflow. The collapses were large~~r~~ because the water washed the fine-grained material into the excavation, burying the TBM. The 10th stoppage was the worst incident of the pilot tunnel and caused the TBM to be totally buried requiring the construction of a bypass tunnel.

Water inflow is difficult to predict based on monitoring instrumentation results. However, exploration ahead of the face can be of great use in the identification of faults and water bearing strata. The most common mitigation measure for the problem of water inflow is to pre-treat the ground with grouting or/ and drainage. There were some cases where ground freezing was also used.

Figure 13 shows the influence diagram for water inflow/flooding.

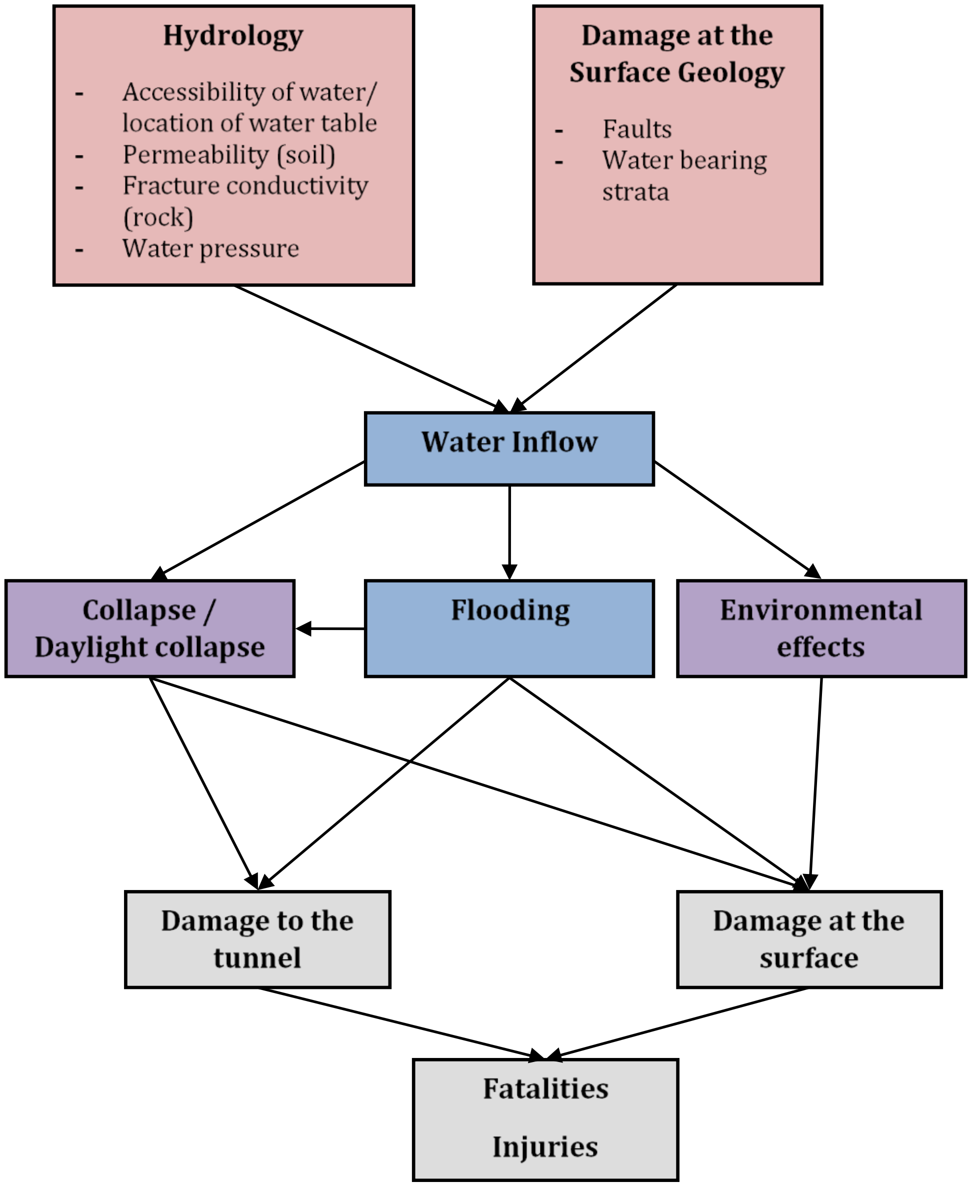


Figure 13 Influence Diagram for Excessive water inflow / Flooding

4.5 Rockburst/ Spalling

This type of event is caused by the overstressing of massive or intact brittle rock, i.e. the stresses developed in the ground exceed the local strength of the material. It can cause spalling or in the worst case sudden and violent failure of the rock mass. There are several types of rockburst and different rockburst damage mechanisms. In this work, we narrowly define rockbursts as violent and sudden ruptures of rock that can cause serious, and often fatal, injuries. They are mainly dependent on the stress exerted on the rock, which increases with depth.

The main source mechanisms of rockbursts are according to Ortlepp and Stacey, 1994: strain bursting, buckling, face crushing, virgin shear in the rock mass and reactivated shear on existing faults and/or shear rupture on existing discontinuities. For the first three mechanisms, the source and damage locations are normally coincident i.e., where the source occurs is normally where the damage occurs as well. These mechanisms, strain bursting, buckling and face crushing, are strongly influenced by stress concentration / stress state and by the shape of the excavation. The last two mechanisms, virgin shear in the rock mass and reactivated shear on existing faults and/or shear rupture on existing discontinuities, correspond to shear failure on a plane and can extend for several meters. They normally can occur in large scale mining operations. The most typical type of rockburst in tunnels is due to strain bursting (Ortlepp, 2001), resulting fragments of rock consist usually of thin plates with sharp edges, that are violently ejected locally from the rock surface. For more details on the different types rockbursts and damage mechanisms please refer to Kaiser et al., 1996; Martin, 1997; Kaiser et al., 2000; Kaiser & Cai, 2013; Ortlepp & Stacey, 1994; Diederichs, 2003; Brady & Brown, 2004; Peixoto et al, 2012, Ribeiro e Sousa et al., 2012, Ribeiro e Sousa et al., 2017.

The location where the rockburst occurs usually depends on the *in-situ stress* and the *geometry* of the tunnel. An example is the Laerdal tunnel in Norway (Project ID 61), where the vertical stress was high due to an overburden reaching a maximum of 1450 m, but where the horizontal stress was also high, caused by the tectonics of the area. The rockburst can occur at the face of the tunnel or behind the face (i.e., once the face has passed) on the side walls and roof. A case of rockbursts occurring at the roof of the tunnel was a water tunnel in Korea, project ID 123 (Figure 14). Another parameter that seems to influence the time delay of the occurrence is the *advance rate* of the construction.

The *construction method* seems to also have an influence on the susceptibility of an excavation to rockburst. Not only the existence of a support system that stops the violent ejection of fragments of rock is essential to guarantee the safety, but also the type of construction process seems to influence the severity of the rockburst. According to experience, for the same type of conditions, for the same rock, strain bursting is more likely to occur in a machine-excavated tunnel than in a drill-and-blast tunnel (Stacey and Thompson 1991), because in the latter situation, the induced fracturing in the rock around the tunnel caused by blasting, destresses the rock mass and creates conditions that are less prone to rockburst by strain bursting.

The *type of rock* is another important factor which affects rockburst and its severity. Rockburst occurs more likely and with greater severity in brittle rocks.

Rockbursts are not easy to predict. Investigations using acoustic emission monitoring are sometimes recommended. Acoustic emissions allow one to monitor the accumulation of cracking and evaluate the tendency for the rock to suffer rockburst.

Figure 15 shows the influence diagram for rockburst.

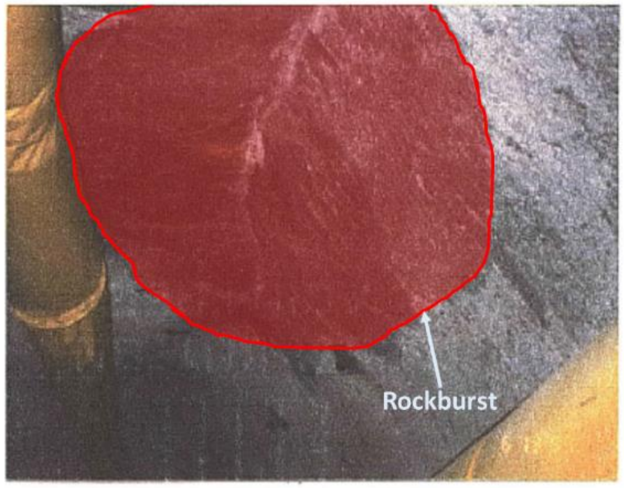


Figure 14 Rockburst at the crown in a in a waterway tunnel in Korea (adapted from Lee et al., 2004)

4.6 Excessive Deformation

These are cases where excessive deformations occur inside the tunnel or at the surface, but an actual total collapse does not happen. This can occur for example due to deficient design, construction defects and/or in a particular type of terrain, such as swelling and squeezing ground.

Swelling is described as a time dependent volume increase of the ground, leading to inward movement of the tunnel perimeter. Three types of mechanisms have been identified: 'mechanic', 'osmotic' and 'intra crystalline' (for more details see Einstein, 1996). Common to all three mechanisms is the important role of *pore pressure* in the phenomenon of swelling. To predict the behavior of a tunnel in swelling or squeezing ground, it is necessary to know the natural stress state, stress changes, *ground water conditions* and *material properties*. In order to be able to make adequate predictions regarding this type of behavior, the engineer should perform several tests that will allow him/her to identify and quantify the swelling properties of the ground (see Einstein, 1996; Barla, 2008). However, due to the interaction of different mechanisms, it is not always very easy to predict the amount of swelling that may occur. Swelling occurs mostly in the tunnel invert and can develop rapidly depending on the access of water to the excavation. A case of swelling that occurred during tunnel construction is the one of the Chienberg tunnel in Switzerland (project ID 71), where during the time that the tunnel construction was stopped due to a previous collapse, the invert was left open. After 4 weeks a heave of 1.5m was observed in the invert near (behind) the zone of the collapse. Another example of excessive deformation due to swelling is what occurred in a tunnel from Rotarelle to San Vittore, part of the Naples Aqueduct, in Italy (Project ID 22). After *650m* of excavation, enormous ground pressures caused cracking of the shotcrete, buckling of the steel arches after a few hours, and deformations of 200 mm in 24h and 400 mm after 12 days. The deformations were caused by swelling clay filling of the rock. Einstein (2000) presents several case studies of tunnels excavated through Opalinus Clayshale and gypsum (Keuper) in the Swiss Jura Mountains, which show how problematic swelling can be during construction and also during operation, if the invert is not strong enough and if water flows into the rock.

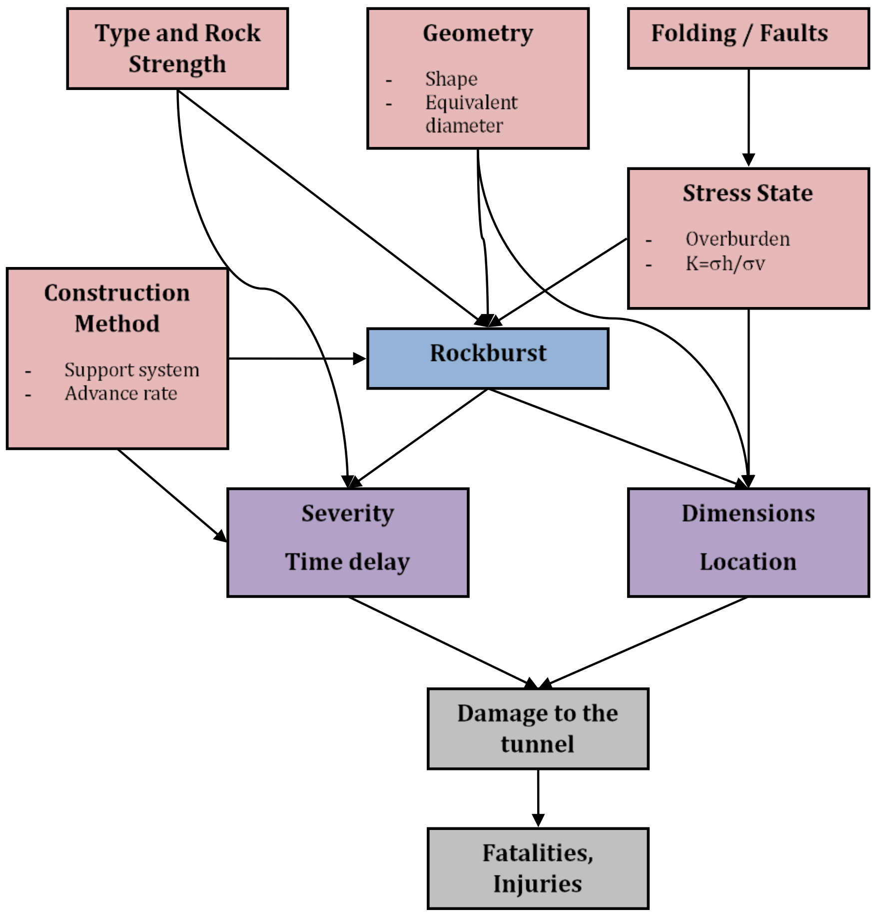


Figure 15 Influence diagram for Rockburst

Squeezing is characterized by large time-dependent convergence during and after tunnel excavation. Many authors refer to squeezing ground behavior whenever large convergence occurs, whether it happens during construction or with a time delay. This occurrence of large pressure may lead to failure of the lining and / or result in great difficulties for completing underground works, with major delays in construction schedules and cost overruns (Barla and Pelizza, 2000; Kovari, K. and Staus, J. 1996). An extreme consequence of excessive deformation in tunnels is the partial or total collapse of a tunnel, which was the case in the Gotthard base tunnel (Project ID 97) in Switzerland, where a partial collapse occurred due to squeezing.

The support options for tunnel in squeezing and swelling ground can either follow the yielding principle allowing a controlled amount of deformation or the resisting principle designed to resist squeezing or swelling. In the case Naples Aqueduct tunnel in Italy (Project ID 22), a non-shie lded TBM with expanded precast segmental concrete lining was used to deal with the swelling properties of the ground.

During construction one strategy that can be utilized is probing ahead of the face. If for example a fault (composed of squeezing ground) is anticipated and an adequate strategy is developed, normally the squeezing problems can usually be overcome (Hoek, 2001). Figure 16 shows the influence diagram for excessive deformation.

4.7 Collapses in specific locations

These are collapses that occur in particular locations of a tunnel, where there is a lower resistance of the ground and/ or concentration of stresses, such as portals and connections to shafts. A tunnel collapse and flooding of a shaft during construction occurred in Munich Metro in Germany (Project ID 121). The competent rock cover just outside the shaft had been predicted to be 1.5m, however the actual value of the competent rock was half of the initially predicted value. As a consequence, a full collapse involving 450 m^3 of ground occurred (Weber, 1987).

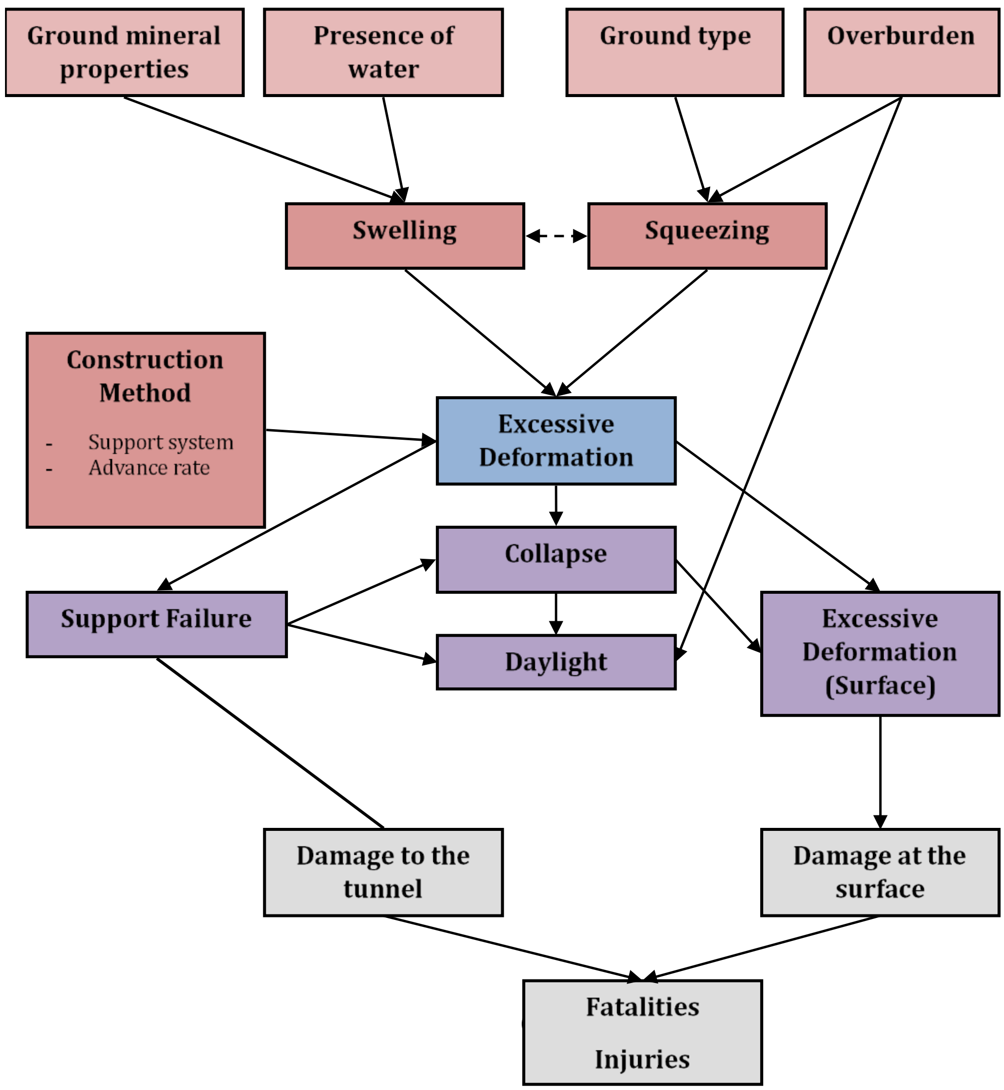


Figure 16 Influence Diagram for Excessive Deformation (inside tunnel)

5. Data Analysis

The analysis of the tunnel accident data (Fig 17) shows that more than half (56%) of the accidents occur near the face, while a smaller percentage occurred behind the face i.e., in the excavated tunnel,

The database associates construction methods with the cases. Since there is no generally accepted classification, we used the classification reported in the source of information. This led to the following main distinction: TBM (mechanical) versus Conventional. We further subdivided Conventional method into: NATM or Drill and Blast to reflect what is reported in the literature.

Figure 18 shows what we consider to be the face in this paper for TBM and NATM (for drilling and blasting the face is usually analogous to what is shown for the NATM). The criticality of the face is expected because the largest perturbation to the ground usually occurs there. In the Conventional Method (NATM/Sequential Excavation Method or Drill and Blast) the events at the face correspond to events that occurred in the area of the tunnel heading between the excavated face and the first completed ring of support (definition used by HSE, 1994). In the shield / TBM construction correspond to events that occurred at the cutterhead. Behind the face corresponds to events that occur in the area of the tunnel with the completed primary lining (for the conventional excavation methods). In TBM driven tunnels, Behind the face corresponds to events that occur behind the cutterhead, either immediately behind it in the shield area or in the primary lining.

Figures 19a and 19b show the distribution of the different types of events, considering the influence of the construction method, divided into conventional and mechanized methods. It is interesting to compare the two methods and it is possible to observe that the number of daylight collapse cases, often associated with larger volumes and larger consequences, is larger (reported) for the conventional type of construction (NATM/Drill and Blast), than for Shield/ TBM~~.~~ For excessive deformations and rock falls the rate of occurrence is similar in the conventional type of construction (NATM / Drill and Blast) and mechanized methods (shield/TBM), constituting 20% and 18% of the cases, respectively. Flooding and water inflow have occurred more in mechanized methods, which can be explained by the fact that more catastrophic floodings have occurred in long underwater tunnels or long mountain tunnels with high overburden and water pressures that are normally driven with TBMs. For the other events (specific location and rockburst) the construction method is not so relevant.

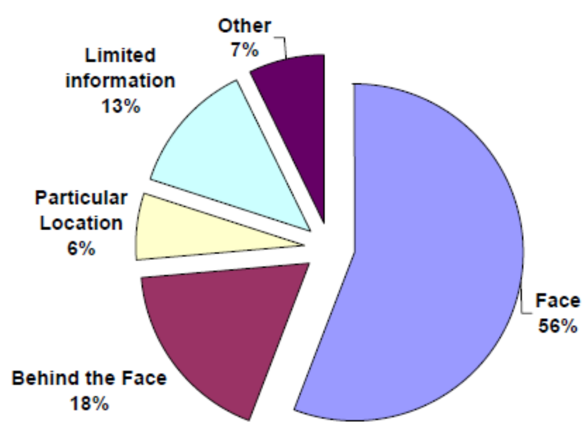
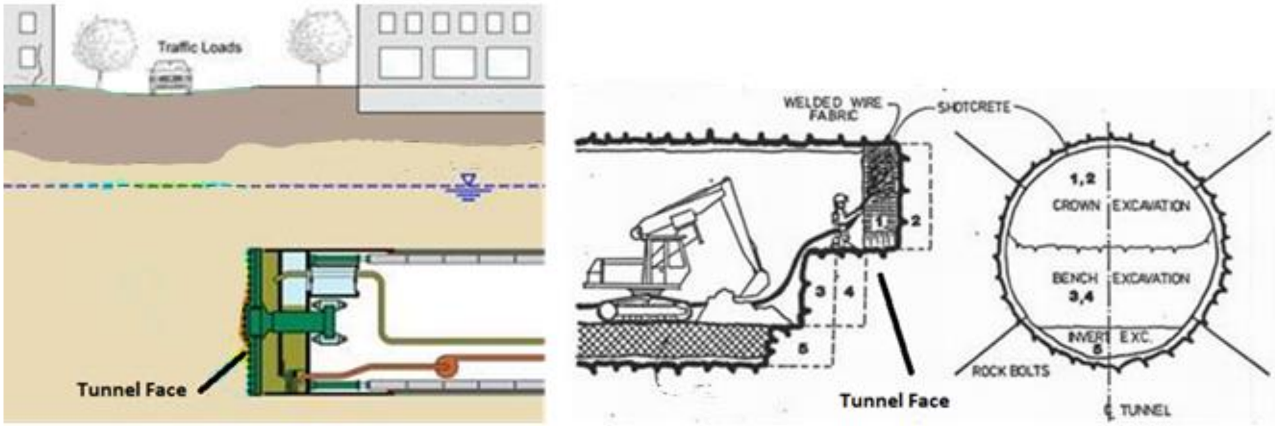


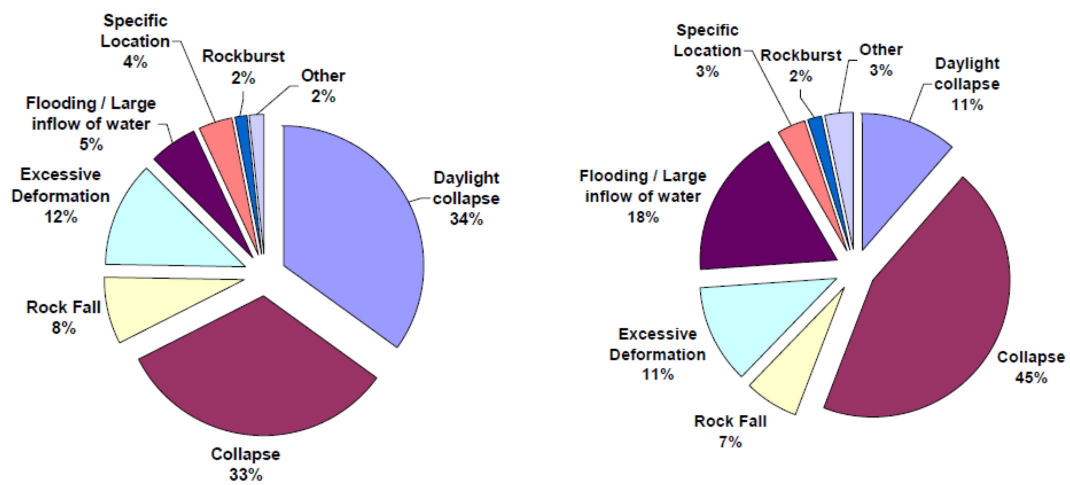
Figure 17 Distribution of the accidents according to their location



a) TBM

b) NATM

Figure 18 Tunnel Face for a) TBM and b) NATM



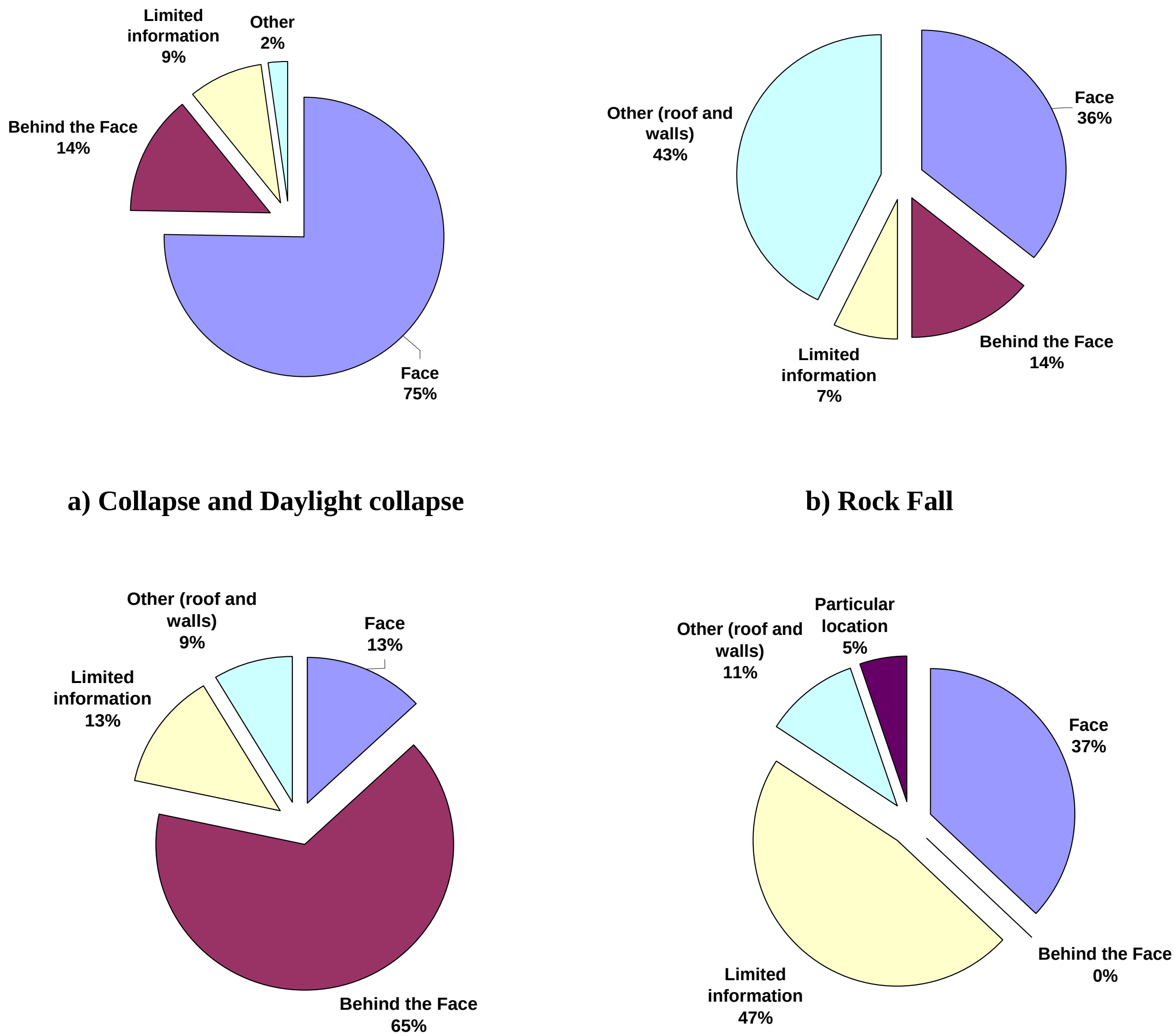
a**) Conventional construction method**

b) Shield machines and TBMs

Figure 19 Distribution of accident type according to the construction method

A separate analysis for each event (collapse/daylight collapse, rock fall, excessive deformation, and flooding/water inflow) is presented in Figure 20. The majority (75%) of collapses and daylight collapses, shown in Figure 20a, occurred at the face. Only 15% occurred behind the face and in almost 9% of the cases there is not enough information regarding the location of the collapse. For rock falls, shown in Figure 20b, the majority of these events occurred at the roof or walls (43%), with no clear indication whether they occurred behind the face or at the face of the excavation, while 36% occurred at the face. In the excessive deformation cases (Figure 20c), 65% of the events occur behind the face, and this at time intervals ranging from days and in some cases reaching up to a year after the face had passed. This is mainly due to swelling or squeezing ground. In 13% of the cases there is not enough information regarding the exact location of the event. In almost half (47%) of the cases of flooding and water inflow (Figure 20d) there is not enough information regarding where the water entered the tunnel. In 35% of the cases the inflow occurred at the face and in 11% of the cases it occurred from both the face and behind the face.

Finally, all rockburst and spalling events (not shown in Figure 20) occurred at different places: roof, walls, and floor, at the face and behind the face.

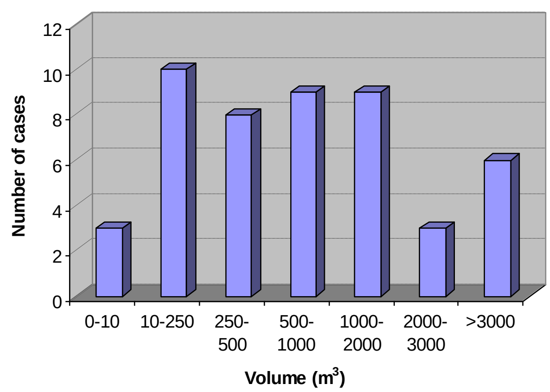


a) Collapse and Daylight collapse **b) Rock Fall**

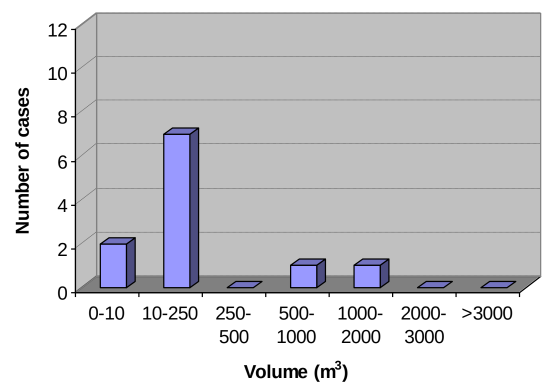
c) Excessive Deformation **d) Flooding / Water inflow**

Figure 20 Distribution of the location for the different types of events

The impact of an event is somewhat related to the volume of ground involved and whether the tunnel is in an urban environment. Figure 21a shows the volume of collapses (daylight or not) or rockfalls associated with conventional type of construction (NATM and Drill and Blast) events, while Figure 21b shows the volumes of collapses associated with TBM. The volumes associated with TBM construction are normally in the range 0-250 m^3, while the volumes associated with NATM and, Drill and Blast collapses tend to be larger in volume and have also a larger range, i.e. from 10 and 2,000 m^3. Some cases involve large volumes, like the Khimti I hydropower project (Project ID 94) with 14,000 m^3 (Note, however, that the number of cases for which there is information regarding the volume of collapsed ground is about 5 times larger for the conventional methods than for the mechanized methods).



a) NATM and Drill and Blast



b) Shield / TBM

Figure 21 Volume involved in events (Collapse, Daylight collapse and Rock fall) for different construction methods

The volume of ground involved can also be categorized in other ways:

- Typical volumes involved in (non-daylight) collapses are mainly in the range of 10-250 m^3, although some very large volumes can occur (Figure 22). The volume can be probably associated with the dimensions of the tunnel.
- The volume involved in daylight collapses is normally associated with a crater that reaches the surface. The volumes are approximately uniformly distributed between 10 and 3000m^3 as can be seen in Figure 23.
- Finally, the volumes involved in rock falls are generally small, in the range of 0-250m^3 (Figure 24) There are however two cases, the Cahora Bassa hydroelectric scheme (Sousa, 2006) and the Laerdal road tunnel (T&TI, October 2003) where a large volumes of rock fell.
- Figure 25 presents the distribution of volumes corresponding to daylight collapses in urban areas. They follow the same pattern as Figure 23.

The next set of figures (Figures 26 to 28) presents the volume of collapse versus H/D, the relation between overburden (H) and equivalent diameter of the tunnel (D). The Figures have been divided by ground type (Figure 26 shows cases in rock, Figure 27 in soil and Figure 28 in mixed conditions). Within each ground type a distinction between the construction methods (NATM, Drill and Blast, TBM) was also made. Daylight collapses occur generally for H/D up to 5 (normally H/D < 3), i.e. for overburden up to 5 times greater than the diameter of the excavation. This is an expected observation since for a collapse to reach the surface the excavation should be relatively close to the surface. Also tunnels in rock present a broader range of H/D. This is also expected since deeper tunnels are normally in rock. Unfortunately, based on the available data it is not possible to observe a clear trend relating the volume of the collapse with H/D. This could be a result of not enough data being available as well as a not enough detailed descriptions of the ground type, again due to lack of information.

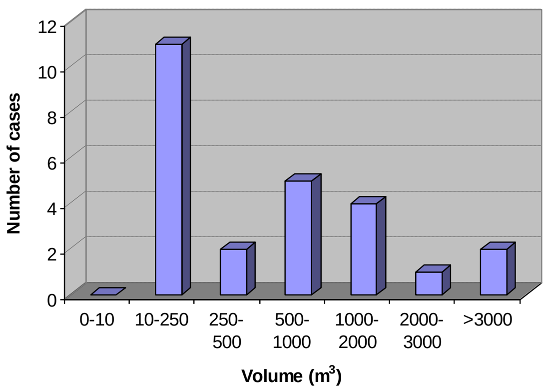


Figure 22 Volume involved in collapses for both conventional and mechanized construction methods

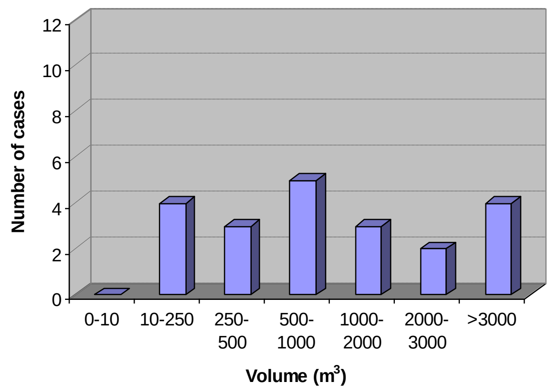


Figure 23 Volume involved in daylight collapse for both conventional and mechanized construction methods

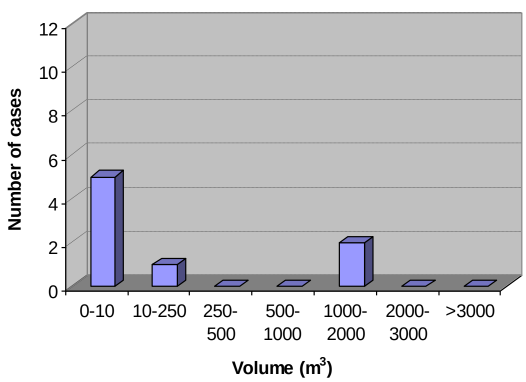


Figure 24 Volume involved in rock falls for both conventional and mechanized construction methods

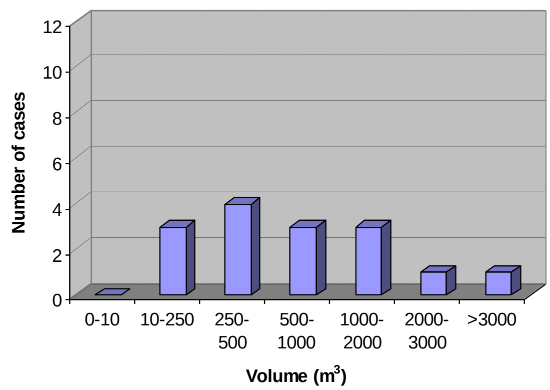
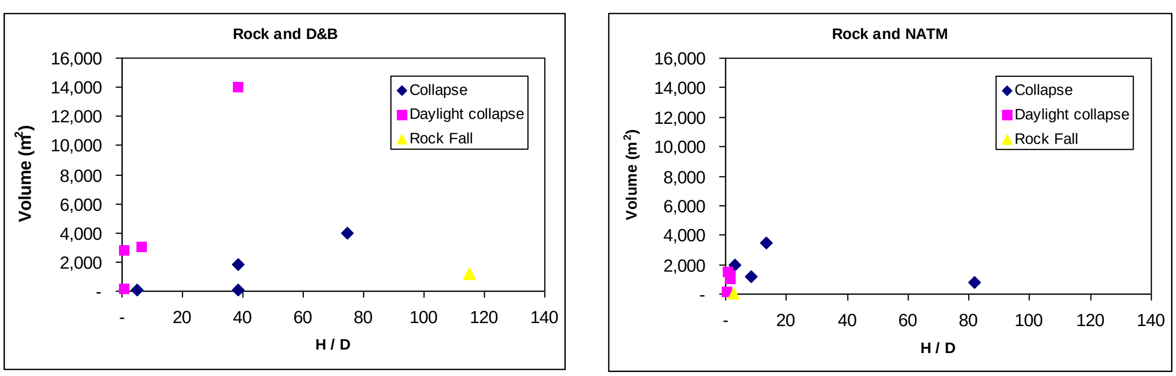


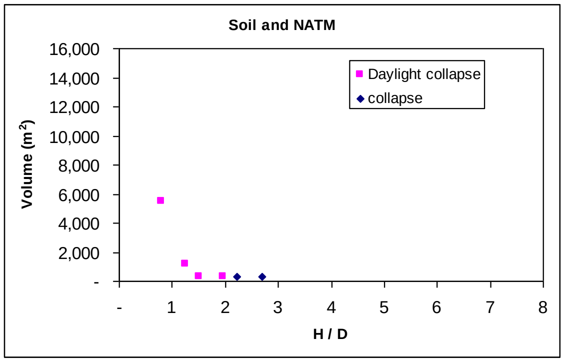
Figure 25 Volume involved in daylight collapses in urban environments for all construction methods

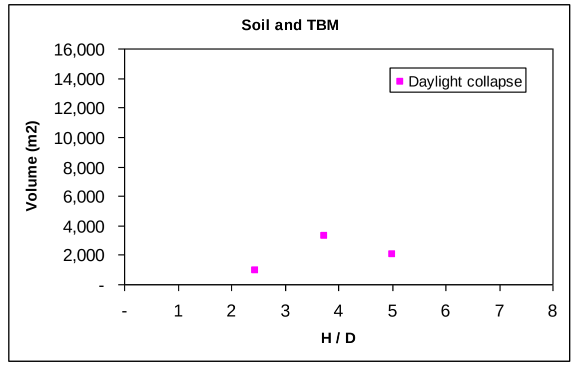


a) Drill and Blast

b) NATM

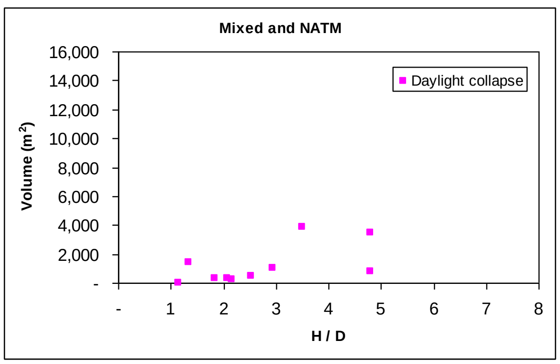
Figure 26 Data available on volume of collapse versus H/D (overburden/ tunnel diameter) for tunnels in rock formations

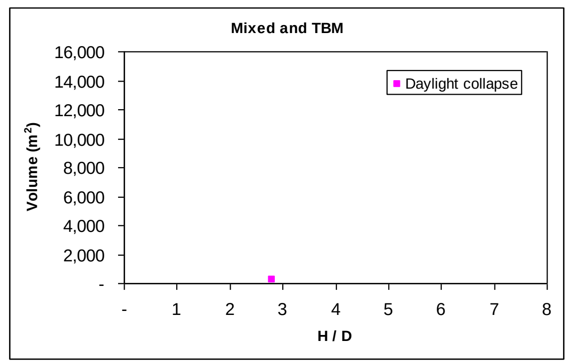




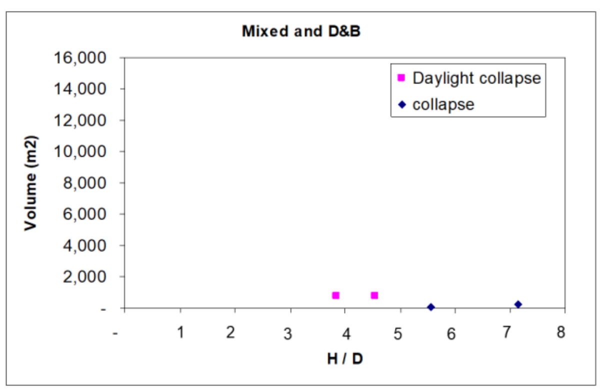
a) NATM **b) TBM**

Figure 27 Data available on volume of collapse versus H/D for tunnels in soil formations





a) NATM **b) TBM**



c) Drill and Blast

Figure 28 Data available on volume of collapse versus H/D for tunnels in mixed conditions

6. Reported causes and consequences

6.1 Most commonly reported causes

The causes for accidents in tunnels under construction do not depend exclusively on the behavior of the ground but also human errors and environmental external factors, such as earthquakes or changes in the water level due intense and persistent precipitation.

6.1.1 External causes

External causes are related to hydrological and geological conditions, as well as earthquakes and fires. The most common external reported causes are listed below.

Unpredicted geology

The main reported cause of failure in tunnels during construction is attributed to unpredicted ground conditions. The most reported unpredicted features in soils are lenses of water bearing sand or gravel that cause the reduction of the resistance of the ground. This was the case of collapse that occurred in the metro of Lausanne (Project ID 2), mentioned previously in section 4. It was assumed in the design that the there was a constant gradient of the molasse layer between boring no. A21 and A22 (50 m apart). Unfortunately, there was no constant gradient between the two boreholes. This can be observed in Figure 29 where the ground conditions assumed by the design are shown and in Figure 30 where the ground actual ground conditions are presented. It is therefore important to continue ground exploration, especially by probing ahead of the face, during the construction of the tunnel.

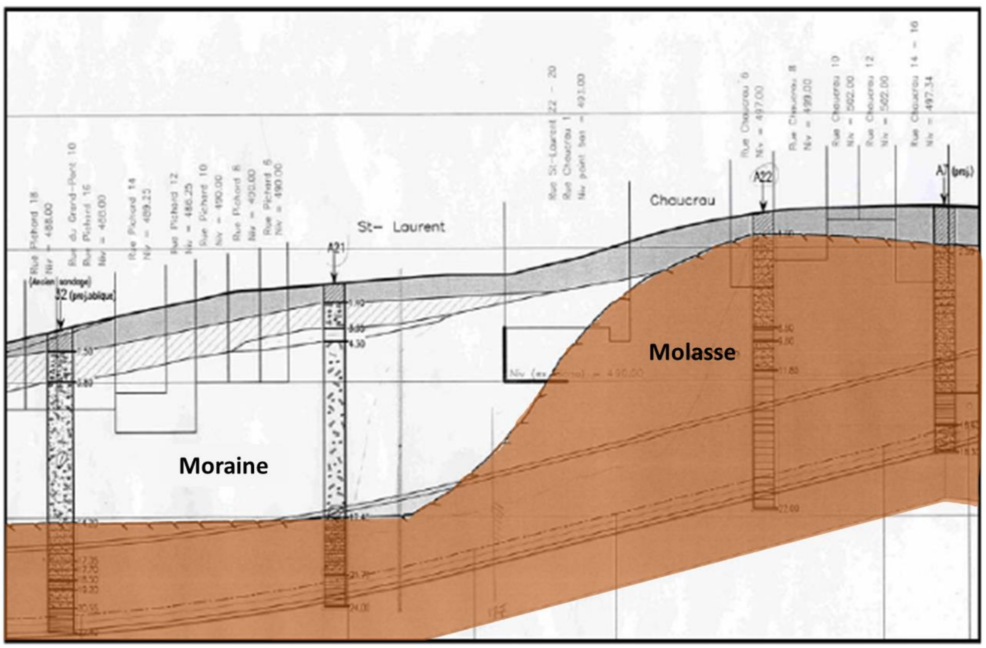


Figure 29 Ground conditions in the final design documents (adapted from Seidenfuss, 2006)

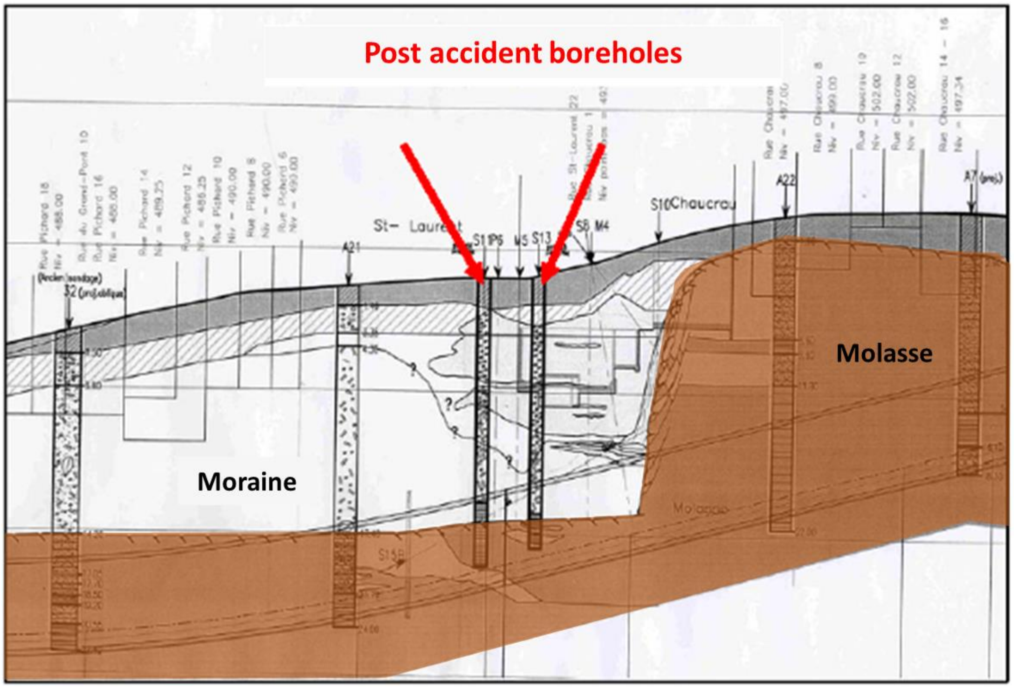


Figure 30 Actual ground conditions after collapse (adapted from Seidenfuss, 2006)

For tunnels in rock one of the most common "unpredicted" features are weak zones, fault zones and/or low strength surfaces. Fault zones are particularly adverse in the cases of tunnels driven by TBMs where a collapse may burry the TBM causing it to get stuck, which may require excavation of bypass tunnels in order to rescue the machine or may even lead to abandoning the TBM, in extremely severe cases (Barton, 2006).

The case of Evinos-Mornos Tunnel (Project ID 49) in Greece (Figure 31) is an example where several (Grandori et al. 1995) problems, ranging from small continuous collapse of the face, squeezing ground and some larger collapses were caused by faults. In some of these situations when the TBM cutterhead is pulled back for ground treatment after the collapse, loosening happens creating a larger collapse dome (Grandori et al., 1995)

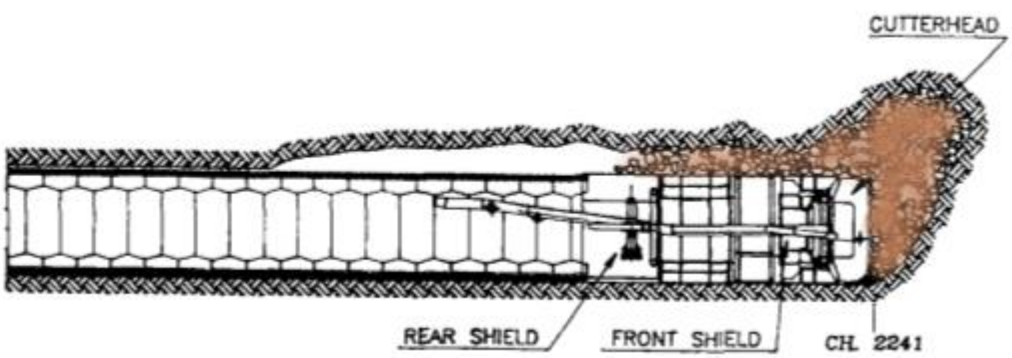


Figure 31 Collapse at the face of the TBM, Evino Mornos, Greece (adapted from Grandori et al., 1995)

Presence of water

The presence of water and especially high-water pressure can be very adverse to tunnel stability during construction and may lead to collapse or / and flooding.

The Pont Ventoux (Project ID 69) continuous collapses presented in Figure 32 is a good example where adverse water pressure was the most important cause with respect to the cutterhead getting stuck in the various fault zones. In this tunnel, the high (non-vertical) major principal stress, and very high-water inflows, were very adverse to the stability in fault zones full of clay, silt, sand and crushed rock.

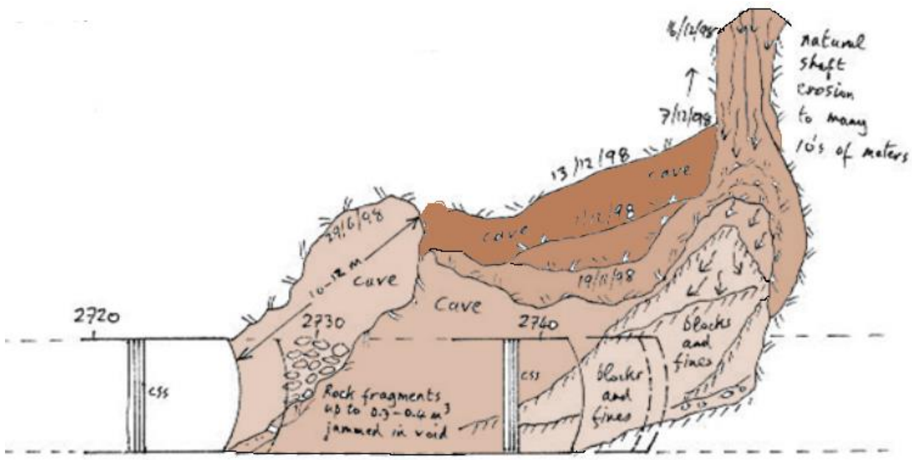


Figure 32 Continuous collapses due to the 'fault shaft', assisted by water and/or water pressure. These sketches are super-imposed on one sheet, from the geologist's daily logs. TBM was stuck for 6 months in this location (adapted from Barton, 2006)

Unpredicted man-made structures

Man-made structures, such as wells, old galleries or old boreholes, can affect the stability of a tunnel while being excavated and may be the cause for a collapse. Some features when in large number can also alter the hydro-geological characteristics of the ground.

This was the case in the Porto Metro (Project ID 9), in Portugal, where many old wells and "minas" (old and small handmade water tunnels) were present in the area and uncharted due to their ancient nature. They modified the hydro-geological characteristics of the ground, such that the groundwater moved not only in the porous medium and fractures, but also along the preferential channels represented by the "minas", which strongly influenced the underground water circulation (Grasso et al., 2003). Figure 33 shows a man-made water mine beneath the city of Porto.

Figure 33 Man-made tunnels ("minas") in Porto, Portugal (from Forrest, 2006)

Earthquakes

Earthquake associated collapses during construction are extremely rare. One of the few cases occurred in Bolu tunnels in Turkey (Project ID 65) in 12 November 1999. An earthquake and the following aftershocks caused the failure of both Bolu tunnels. At the time of the earthquake, a 700 m section had been excavated from the Elmalık Portal, and a 300 m section of reinforced concrete lining had been completed. The collapse took place in the clay gouge material in the unlined section of the tunnel, 300 m from the Elmalık portal. The collapse was progressive. Two sinkholes appeared at the surface. One of them occurred immediately after the major earthquake of 12 November 1999 and the other one occurred 2 months later (Ghasemi, 2000, Dalgıç, 2002).

Fires

The great majority of the fires in tunnels during construction are associated with mines. Nevertheless, in the history of tunneling there several cases of fire during excavation, generally associated with the use of timber for temporary supports, blasting with high explosives, tunnel driving under compressed air with elevated oxygen content among others. The main causes are normally faulting electric equipment or short circuits in power lines.

In June 1994 a TBM fire occurred in the Great Belt (Project ID 125), when oil from the TBM spilled and ignited during construction. The fire that lasted for several hours produced temperatures of about 800º C and damaged up to two-thirds of the concrete lining. The reported costs associated to this accident were of about US$ 33 million (Vlasov, 2001; Khoury, 2003)

The excessive presence of gas in the air during construction may lead to emergency situations. Accidents that occur are normally mainly due to an inadequate ventilation system. The gas can result from several sources, such as construction procedures like blasting and soil freezing, or as a result of the geological composition of the rock being excavated. Although normally associated with tunnels for mines, there have been such cases in the construction of metros in the city of Baku, in 1983 and 1987, Moscow, in 1982 and Nizhny Novgorod, in 1981 (Vlasov, 2001). In all these cases the source of elevated concentrations of saturated hydrocarbons in the air was because of petroleum products that had seeped into the tunnel works from the surrounding ground. In the case of Baku and Moscow the excavation through these rocks was accompanied by flames. Most of the tunnels that were affected by this problem were in places where oil storage and oil pipes were previously situated.

During the construction of the Los Angeles subway (case ID180) through sandstones and limestones containing hydrocarbons characteristic of the California oil-bearing field, problems related to the presence of gas occurred. Analysis of the data on the gases and soils and the location of active gas bearing horizons were carried out, in order to specify the ventilation requirements as well as technical procedures for the detection of hazardous gas concentrations. Ventilation was the principal means to prevent gas explosions (ENR, June 1989)

6.1.2 Internal Causes

Internal causes are related to the design and planning of the tunnel as well as basic construction and management errors during tunnel construction.

Planning and Design errors

Tunnel collapses have occurred due to errors and mistakes that occurred during planning or design. Among others they include (HSE, 1996; Vlasov, 2001):

- Lack of surveying and geotechnical studies and/or inadequate evaluation of the geotechnical information available.
- Inadequate competent ground cover
- Inadequate excavation process and / or support system for the ground
- Inadequate or faulty ground classification system leading to inappropriate support
- Inadequate construction method
- Inadequate planning for emergency measures
- Inadequate specification for lining repair procedures

An important case related to insufficient geotechnical studies was the collapse that occurred in 2005 in the Barcelona Metro line 5 (Project ID 29). According to the parliamentary investigation conducted after the accident, the lack of geological studies prevented the presence of a fault to be known. The original alignment of the tunnel did not go through the Carmel neighborhood (where the collapse occurred). This decision was made 9 months before the collapse, and the necessary geological studies were not made.

Calculation and numerical errors

Calculation and numerical errors can occur both during the design phase and the construction phase. Most of the calculation and numerical errors that occur during construction are related to the monitoring data, whether it is in their collection or in their processing. In our analysis we considered errors in collection and processing of monitoring data under the umbrella of management and control errors. The most reported causes are:

- The adoption of incorrect geomechanical design parameters.
- Modelling related issues: e.g. use of inappropriate models; no considering the effect of water; no considering the 3D effects such as existing tunnels.

Adoption of incorrect geomechanical design parameters and use of inappropriate models were some of the errors that occurred in the case of Olivais metro (Project ID 10) in Lisbon (Figure 34), where the geomechanical parameters used in the design numerical calculations where overestimated (Appleton, 1998).

Figure 34 Collapse that occurred in Olivais Station, Lisbon, Portugal (adapted from Appleton, 1998)

Construction Errors

Construction errors can also play an important role in tunnel accidents. An example is the Montemor tunnels (Project ID 11) in Portugal. The monitoring data indicates that systematic errors were made when installing the Swellex bolts used in the primary support. The correct sequence of installation of each Swellex bolt is: i) Drill the hole in the rock ; ii) Insert the Swellex bolt in the hole, not expanded; iii) Expand Swellex bolt with the hydraulic pump (reaching 30MPa); iv) Remove the pump, keeping the bolt pressurized. However, the adopted sequence was (at least at several occasions): i) Drill the hole in the rock; ii) Expand the Swellex bolt on the floor of the tunnel; iii) Remove the pump, keeping the bolt pressurized; iv) Insert the Swellex bolt in the hole. This process instead of reinforcing and strengthen the rock mass as was intended by the design ended up probably damaging the ground surrounding the crown of the excavation, due to the wrong installation of the Swellex bolts.

Another famous accident where construction errors played an important role is the Heathrow Express Line tunnels (project ID 24): these included the substandard construction in the initial length of CTA concourse tunnel over a period of some three months and the inadequately executed repairs to a length of tunnel that had been damaged by grout jacking.

Management errors

In many cases, among other causes, management and control errors are reported as one of the causes for the accident:

- Monitoring-related errors:
    1. Errors in the collection of monitoring data
    2. Errors in the processing and not fast enough delivery of monitoring data.
    3. Failure to act on monitoring data and early signs of danger.
- Improper management and inadequate emergency response measures.
- Inexperienced site management
- Poor supervision of construction work
- Allowing the wrong sequence of tunnel construction (especially in multi-tunnel situations)

The Shanghai Metro line 4 collapse (Project ID 33), which occurred in July 2003, was found to be due to improper management and inadequate emergency response measures. The parties involved are accused of failing to take timely emergency measures to deal with danger signs when technical problems were detected in the equipment used in the tunnel construction. When the cooling equipment used to freeze the ground before digging under the river broke down on June 28, two days before the collapse, no one reported the early signs of the impending cave-in to the project's management and engineering supervision officials. The officials were found to have been absent from the site in the days before the accident while reporting everything was "normal" on their daily logs. Instead of halting the excavation and taking effective emergency measures, digging continued and the water pressure built up, resulting in the cave in (T&TI July 2003, Tan et al. 2021).

Failure of Equipment

Failures of TBM machines or some of their components such as the earth pressure control system of an EPBM or the slurry injection system of a slurry machine may also contribute to accidents of tunnels during construction.

6.2 Most commonly reported consequences

The consequences of the undesirable events can be classified according to their location:

- In the tunnel (structure, people and equipment)
- At the surface (structures, people) or other structures (utilities, etc)

Figure 35 lists the most reported consequences (apart from additional costs and delays) in the tunnel and, on the surface and on other structures.

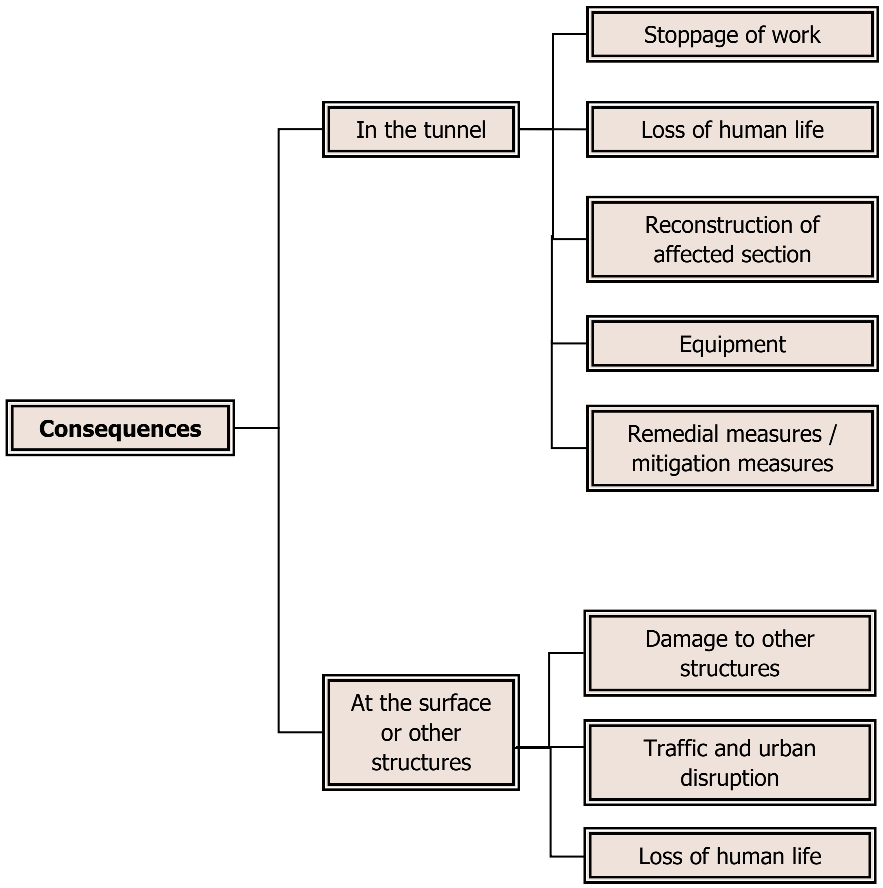


Figure 35 Most commonly reported consequences of undesirable events during tunnel construction.

When an event occurs, depending on its magnitude, the work will have to stop (stoppage of works). Before the work re-starts it is necessary to be sure that all measures are taken to ensure safety. Additional investigation may be required. In some cases, loss of human life and injuries occur. In most cases when an event occurs the affected section of the tunnel needs to be reconstructed ("reconstruction of the affected section" in Fig 35), which is reflected in an additional cost to the project. Equipment can be affected by the incident as well. It can be buried and damaged for example due to face / roof collapse. It can also be damaged due flooding. In the case of a TBM, the cutterhead maybe be damaged due to collapse of blocks or unexpected boulders in the ground, or in the most severe cases, cause the TBM to be stuck in the ground ("equipment"). Remedial and mitigation measures are often needed, the first in order to overcome the accident and the latter in order to ensure the safe completion of the tunnel excavation. When a collapse occurs the first step is normally to prevent the damage to extend to the surface. This is usually accomplished by pouring material into the crater. This mitigation measure is taken before assessing the causes of the accident. After investigation and determining the cause additional remedial methods are normally implemented, which result in delays and additional costs.

Other consequences of collapses in some cases were the change of the alignment (Project ID 80) or abandonment of the tunnel (Project ID 94).

Events also often induce movement at the ground surface ranging from settlements to craters. Consequently, damage to structures on the surface and structures inside the ground can be produced ("damage to other structures"). Daylight collapses when occurring in urban areas usually result in traffic and urban disruption, such as evacuation of residents from their homes, power and water supply cuts and traffic detours, and ultimately, they can cause death of people at surface (loss of human life).

Since the 1990s there have been several great losses involving tunnels in urban areas causing in some cases, repairs costed up to US$ 100m. From the 1990s to the early 2000s CAR (contractors all risks) insurers have suffered losses totaling up to more than 750 million dollars in property damage only (Landrin et al, 2006). Table 2 shows some of the major losses, as well as respective delays, that occurred in tunnel construction since 1994.

Figure 36 shows a histogram of delays, in months, caused by accidents during tunnel construction. This represents the data available in the database (64 cases for which data on delays are available). Most of the delays ranged between 0 and 7 months, with an average of around 6 months.

Table 2 Major losses since 1994

Year	**Project**	**Method**	**Loss ($m)**	**Delay (months)**
1994	Great Belt Link, Denmark	TBM	33	?
1994	Munich Metro, Germany	NATM	4	10
1994	Heathrow Express Link, UK	NATM	141	14
1994	Taipei Metro, Taiwan	TBM	12	12
1995	Los Angeles Metro, USA	TBM	9	15
1995	Taipei Metro, Taiwan	TBM	12	18
1999	Hull Yorkshire, UK	TBM	55	26
1999	Anatolian Motorway (Bolu), Turkey		115	36
2000	Taegu Metro, Korea	Cut and Cover	13	9
2002	Taiwan High Speed Railway	NATM	11	0
2003	Shangai Metro	Freezing	60	47*

Source of data is Landrin et al, 2006 and Munich Re Group, 2004.

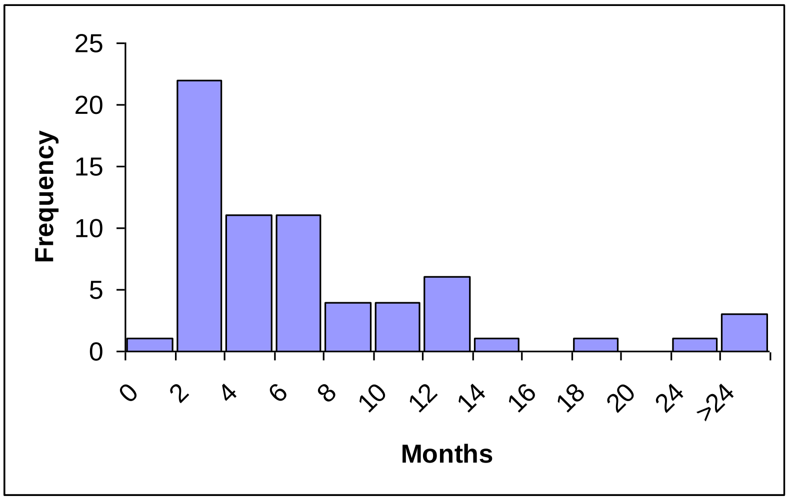


Figure 36 Distribution of the delays (in months) caused by accidents during construction

7. Remedial and Mitigation Measures

The remedial and mitigation measures are often case-specific. There are however some methods that are common in many of these situations. Table 3 lists the most common mitigation measures per event.

Table 3 common mitigation measures per event.

Event	**Mitigation measures**
Collapse	• Fill the tunnel with materials (concrete, rock, sandbags and even water) for immediate stabilization and prevent further propagation of the collapse (used in most of the collapse/ daylight collapse cases) • Collapse hole bulkheaded and backfilled with concrete or / and materials (such as collapsed rock) and then remine. • Stabilization of the tunnel face and crown with shotcrete • Reinforcement of the ground in advance (bolts, forepoling, fiberglass bolts, pre-stressed anchors, etc). Normally applied in combination with preceding measure. • Drainage in advance and / or from the surface (when collapse occurs with or due to water inflow) • Modification of excavation sequence (multiple headings, pilot tunnel) and support • Grouting (in advance or /and from the surface) for consolidation. • Injection of resins • Ground freezing • Bypass tunnel (used also in combination with grouting from inside the bypass tunnel) • Change of alignment • Tunnel abandon

	• Change of construction method (drastic change of construction method, such as change from TBM construction to Drill and Blast) • Modification of TBM (for example: cutterhead and cutterwheel or introduction in an EPBM of an automatic system that pumps bentonite slurry into the excavation chamber whenever the pressure drops below a preset level) • Hand mining of the material accumulated against the cutterhead together with applying a maximum torque + posterior grouting
Daylight collapse	All the above and: • Circular cofferdam isolating the collapse area (for major collapses – e.g. Heathrow case) for posterior excavation from the surface. • Filling in of the cavity at the surface with concrete or other material. • Tieback walls used to isolate collapse and allow open excavation
Rock fall	• Rock bolts • Shotcrete • Fill the cavity with concrete + wire mesh • Reinforcement with concrete buttresses supported at the wall by anchors (for extremely large block fall)
Flooding / Water inflow	• Drainage (in advance and from the surface; use of pumping systems). • Grouting • Bypass tunnel
Rockburst	• Special bolts • Destress blasting
Excessive deformation	• Remine or reprofile the deformed section • Use of yielding elements • Modification of the shape / dimensions of cross section • Modification and reinforcement of the invert lining, such as reinforced invert or a deformable invert (in swelling cases) • Special rock bolt of yielding type
Events in particular locations	• As for collapse / heading collapse • Slope protection and support, e.g. tiebacks (portal areas) • Slope cut back to stable geometry (portal areas)

8. Conclusions

This paper presents a database and the analysis of accidents that occurred during tunnel construction. The database classifies the tunnel accidents and the analysis systematically relates causes to consequences using influence diagrams. Very importantly, this structured approach lends itself to uses beyond the specific data presented in this paper. Moreover, the knowledge gained from the analysis of the database, and the analysis of the data of a particular case (a good amount of data were available), the Porto Metro in Portugal, were then used to develop the risk assessment methodology detailed in Sousa and Einstein, 2012. The specific contributions of this paper can be summarized as follows:

Database: Creation of a database of accidents (description of occurrence, possible causes and mechanisms, consequences and remedial measures) during construction available for designers, contractors, owners and experts in the tunneling domain.
The database will be made available to the tunneling community through the International Tunneling Association (ITA) with the possibility of adding of new cases and complementing the existing ones.

Events: The majority of events reported in the literature and by experts are collapses and daylight collapses, not necessarily because they are the most likely but because they are the ones with a greater impact on the construction process, the safety of the workers and people and structures at the surface. Daylight collapses with the NATM are the events that involved the largest volume.

Causes: There is not one single probable cause for an accident. They are normally the result of a chain of events and of multiple causes and errors. It was however possible to point out "typical" causes common to all events. They were divided into Internal and External causes. Common to many accidents described in the previous sections was the fact that the main reported causes were unpredicted geological conditions (external cause), whether they consisted of fault zones (and their extent), other weak zones or groundwater presence. Thus, exploration during construction is important and necessary to explore ahead of the face, and sometimes also to the sides. Several techniques are available for probing and advancing exploration. The question is when and where to apply them.

Consequences: Undesirable events have always consequences on the tunneling process, but many times they can also have consequences on the surface (people, traffic) and on other structures (other existing tunnels, utilities). These consequences can be catastrophic, especially in the case of daylight collapses in urban areas and in the most unfortunate cases can result in deaths. In the past two decades there have been a number of great losses involving tunnels in urban areas, which in some cases caused additional costs up to US$ 100m. The delays associated with accidents were in average 6 months. However, in seven cases the delays reported were over 12 months.

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Appendix A List of MIT Database cases

ProjectID	Project Name	Country	Type of Accident	Date of accident
1	Goegglsbuch tunnel	Germany	Daylight collapse	July 1999
2	Lausanne Metro Line M2	Switzerland	Daylight collapse	February 2005
3	Tunnel Schulwald	Germany	Daylight collapse	January 1998
4	NYC Water tunnel - Stage 1	United States of America	Rock Fall	1983
5	Cross City tunnel	Australia	Rock Fall	July 2004
6	M5 East Motorway	Australia	Rock Fall	between 2000 and 2001
7	Wienerwald Railway Tunnel, section LT26/WT2/TF3 - Eastern Section	Austria	Side wall collapse	2005
8	New Nuremberg-Ingolstadt Railway Line (Irlahüll tunnel)	Germany	Daylight collapse Excessive Deformation	2001? December 2001
9	Porto Metro (Line C)	Portugal	Daylight collapse	2000

			Collapse Daylight collapse	2001 January 2001
10	Lisbon Metro Red Line - Olivais Station	Portugal	Daylight collapse	December 1996
11	Montemor road tunnel	Portugal	Daylight collapse Daylight collapse	July 1994 Agust 1994
12	Kurtkulagĭ irrigation tunnel	Turkey	Daylight collapse Collapse Daylight collapse Collapse	1994 1994 1994 1994
13	High Voltage cabe tunnel	Brazil	Daylight collapse	March 1998
14	Istambul Metro - Phase 2	Turkey	Daylight collapse	September 2001
15	Playas Hydroelectric Scheme	Colombia	Collapse Flooding	between March 83 and May 86 between March 83 and May 86
16	Wienerwald Railway Tunnel, section LT26/WT2/TF3 - Western Section	Austria	Rock Fall Collapse Collapse	2005 2005 2005
17	Juktan hydro power plant	Sweden		

			Large inflow of water	Limited information (construction started 1974)
18	Aalensund Fjord tunnels	Norway	Collapse	between 1986-1988
19	Galgenberg tunnel	Austria	Collapse	July 1994
21	Maria Maluf road tunnel	Brazil	Daylight collapse	1993
22	Naples Aqueduct - tunnel from Rotarelle and San Vittore	Itally	Excessive Deformation	between 1983 and 1987 (probably 1985)
24	Heathrow Express Link	United Kingdom	Daylight collapse	October 1994
25	Portsmouth and Havant Wastewater Flow Transfer Tunnel	United Kingdom	Excessive Deformation	2000
26	Hull wastewater flow transfer tunnel	United Kingdom	Daylight collapse	November 1999
27	Liyama tunnel	Japan	Collapse	September 2003
28	Karawanken tunnel	Austria/Slovenia		

			Collapse	1989
29	Barcelona line 5	Spain	Daylight collapse	January 2005
30	Pinglin (Hsuehshan) tunnels	Taiwan	Collapse	between 1993 and 2003
31	Athens Metro (Line 2 - tunnel B)	Greece	Collapse	June 1996
32	Hokou tunnel - THSRL - contract C215	Taiwan	Collapse Collapse	August 2002 between 31 October 2002 and 3 November 2002
33	Shanghai Metro Line 4	China	Daylight collapse	July 2003
34	CTRL (Channel Tunnel Rail Link) - contract 240	United Kingdom	Excessive Deformation Daylight collapse	February 2003 February 2003
35	Tunnel in urban environment (unknown name)	Brazil	Daylight collapse	1999
36	São Paulo Metro Line 2 Jaciporã	Brazil	Daylight collapse	1997
37	Unknown Railway tunnel in Brazil	Brazil	Rock Fall Collapse	1997 1997
38	Unknown roadway tunnel in Brazil	Brazil	Collapse	1994

39	Tribunal de Justica Road Tunnel (Road Tunnel at Avienda Santo Amaro)	Brazil	Daylight collapse	1993
40	Sao Paulo Metro 3 - Cristovao Burgos Shaft	Brazil	Collapse	1991
41	Sao Paulo Metro - Line 2 Cardoso Almeida / Sorocaba	Brazil	Collapse	1989
42	Sao Paulo Metro Line 3 Itaquera tunnel	Brazil	Collapse	October 1989
43	São Paulo Sewer (SANEGRAN)	Brazil	Daylight collapse	1982
44	Frei Caneca Tunnel (or Tunnel Martim de Sa)	Brazil	Excessive Deformation	1974
45	São Paulo Metro Line 1 Extensao Norte Tunnel	Brazil	Collapse Excessive Deformation	1981 1981
46	North East Line	Singapore	Collapse	Limited information (construction started 1997)
47	Kaohsiung Metro	Taiwan	Daylight collapse Daylight collapse	August 2004 December 2005
48	Guangzhou Metro Line 1 and Line 3	China	Daylight collapse Daylight collapse	2004 November 2008
49	Evino Mornos Tunnel	Greece		

			Collapse	Between 1992 and 1995
			Collapse	Between 1992 and 1995
			Collapse	Between 1992 and 1995
50	Cahora -Bassa hydroelectric system (surge chamber)	Mozambique	Rock Fall	Before or in 1977
51	Harspranget hydroeletric power plant (extension works)	Sweden	Rock Fall	Limited information (Between 1974 and 1982)
52	Holjebro hydroelectric	Sweden	Rock Fall	1978
53	Forsmark power station	Sweden	Large inflow of water	Limited Information
54	Shisanling Pumped Storage Power Station	China	Collapse	Limited information (Between 1992 and 1997)
			Collapse	Limited information (Between 1992 and 1997)

			Collapse	Limited information (Between 1992 and 1997)
55	Herzogberg Tunnel second tube	Austria	Rock Fall Collapse	May 2001 2001
56	Lane Cove tunnel	Australia	Daylight collapse	November 2005
57	Tuzla tunnel	Turkey	Collapse	Limited information (Between 1997 and 1998)
58	Bolu tunnel	Turkey	Daylight collapse Excessive Deformation	Limited information (Between 1993 and 2002) November 1999
59	Los Angeles Metro (Red Line)	United States of America	Daylight collapse	June 1995
60	Dranaz tunnel	Turkey	Collapse	Limited information (before 2004)
61	Laerdal tunnel	Norway	Rockburst	1999

			Collapse	June 1999
62	Hai Van Pass tunnel	Vietnam	Daylight collapse	September 2001
63	Jammu - Udhampur Link (tunnel 8)	India	Collapse	Limited information (before 2000)
64	Dul Hasti HEP (head race tunnel)	India	Flooding Large inflow of water Collapse Large inflow of water Large inflow of water	March 1992 May 1992 February 1996 Limited information January 1998
65	Konkan railway	India	Collapse Collapse	1999 ? 1999 ?
66	Fuessen tunnel	Germany / Austria	Large inflow of water	March 1996
67	Calcutta Metropolitan railway	India	Collapse	Limited information (before 2001)
68	Dodoni tunnel	Greece	Daylight collapse Daylight collapse	2000 2000
69	Pont Ventoux Susa Hydropower System	Italy	Large inflow of water Rock Fall	1998 1998

70	SSDS (Strategic Sewage Disposal Scheme) tunnel	Hong Kong, China	Large inflow of water	Limited information (before 2004)
71	Bypass Sissach, N2 Chienbergtunnel	Switzerland	Daylight collapse Excessive Deformation	Between January - February 2001 February 2001
72	Tymfristos	Greece	Collapse Excessive Deformation	Limited information (Between 1992 and 1995) Between 1992-1995
73	Wilson tunnel	USA	Daylight collapse Daylight collapse Daylight collapse	1954 1954 1954
74	Barcelona Metro line 9	Spain	Collapse	July 2003
75	Lilla Tunnel	Spain	Excessive Deformation	Limited information (before 2005)
76	Tauern tunnel	Austria	Excessive Deformation	Limited information (before 1977)
77	Grizzly hydroelectric project	USA		

			Slope slide	Limited information (before 1995)
78	Coyote outlet works	USA	Slope slide	Limited information (before 1995)
79	Forks of the Butte	USA	Slope slide	May 1990
80	Maneri - Uttarkashi	India	Excessive Deformation	1974
			Collapse	1975?
			Collapse	1982?
81	Munich Metro	Germany	Blow out	Limited information (Between 1978-80)
			Daylight collapse	Limited information (Between 1978-80)
			Daylight collapse	Limited information (Between 1978-80)
			Daylight collapse	Limited information (Between 1978-80)
			Daylight collapse	Limited information (Between 1978-80)

			Daylight collapse	Limited information (Between 1978-80)
82	Adler tunnel	Switzerland	Collapse	Limited information (Between 1994-2000)
			Daylight collapse	Limited information (Between 1994-2000)
			Daylight collapse	Limited information (Between 1994-2000)
83	Egnatia Highway (Driskos tunnel)	Greece	Excessive Deformation	Limited Information
			Excessive Deformation	Limited Information
84	Egnatia Highway (Anthochori tunnel)	Greece	Excessive Deformation	Limited Information
85	Galindo El Parque wastewater and effluent tunnel	Spain	Collapse	November/December 1992
			Collapse	August 1993
86	Casecnan Multipurpose Project	Philippines	Difficult ground	Limited information (before 2004)
87	Landrucken tunnel	Germany	Collapse	November 1984
88	Seikan tunnel	Japan	Flooding	1969

			Flooding Flooding Flooding	1974 1974 1976
89	Whabang tunnel	Korea	Collapse	Limited information (before 2000)
90	Seoul metro Line 5	Korea	Daylight collapse Daylight collapse Daylight collapse Daylight collapse Daylight collapse	November 1991 November 1991 November 1992 January 1993 February 1993
91	Buenavista tunnel	Colombia	Collapse	2000
92	Papallacta tunnel	Ecuador	Collapse	1999?
93	Sao Paulo Metro - estação Pinheiros (Pinheiros Station)	Brazil	Daylight collapse	January 2007
94	Khimti I hydropower project	Nepal	Collapse Collapse Collapse Daylight collapse	1997 1998 1998 1999
95	Frasdanello and Antea tunnel	Italy	Collapse	1996
96	Highway A1 between Sasso Marconi and Barberino del Mugello	Italy		

			Rock Fall	Limited information (before 2001)
97	Gotthard Base Tunnel - Faido Multifunction section	Switzerland	Collapse	April 2002
98	Gotthard Base Tunnel - Bodio section	Switzerland	Collapse	February 2003
99	Gotthard BaseTunnel - Piora Zone (pilot tunnel)	Switzerland	Flooding	March 1996
100	Grauholz tunnel	Switzerland	Daylight collapse	Limited information (Between 1990 and 1992)
101	Aescher tunnel	Switzerland	Daylight collapse	Limited information (before 2002)
102	Meteor Metro Line (Line 14)	France	Daylight collapse	February 2003
103	Montelungo tunnel	Italy	Collapse	1997
104	Pacheco Pumping Chamber and Shafts	USA	Excessive Deformation	Limited information (before 1986)
105	Kallidromo tunnel	Greece	Collapse	2002
106	Trojane tunnel	Slovenia	Daylight collapse	2001
107	Guadarrama tunnels	Spain		

			Collapse Collapse	2003 2004
108	Tunnel TO8 (THSRC)	Taiwan	Collapse	September 2003
109	Pitan tunnel	Taiwan Taiwan	Daylight collapse Collapse	Limited information (before or in 1993) Limited information (before or in 1993)
110	Abdalajis Tunnel (tunnel East)	Spain	Collapse	2004
111	Hurtieres tunnel	France	Daylight collapse Daylight collapse	October 1994 March 1995
112	Trasvase Guadiaro Majaceite Project	Spain	Collapse Collapse Flooding	October 1995 1995 1995
113	Inter-Island tunnel (Boston harbor Project)	USA	Collapse Flooding	1993 and 1994 October 1994
114	Lotschberg Base tunnel	Switzerland	Excessive Deformation	Limited information (between 2003-2007)
115	Girokomeion Tunnel Patras by-pass	Greece	Daylight collapse	August 1999

116	German Federal Railway Lines	Germany	Daylight collapse Daylight collapse	1990? 1990?
117	Umiray - Angat Transbasin Project	Philipines	Flooding Excessive Deformation Excessive Deformation Collapse Collapse Excessive Deformation	1999? November 1999 October 1998 December 1998 March 1999 1999
118	St Petersburg metro (red Line)	Russia	Daylight collapse Collapse	April 1974 July 1975
119	Paramithia tunnels, Egnatia Motorway	Greece	Collapse	Limited information
120	Yunnan tunnel	China	Collapse	September 2006
121	Munich Metro (1994)	Germany	Daylight collapse	September 1994
122	Covao Tunnel	Portugal	Rock Fall	2005
123	Waterway tunnel in Korea	Korea	Rockburst	Limited information
124	Ortfjell open pit - exploration tunnel	Norway		

			Rockburst	Limited information (between 1976 and 1977)
125	Great Belt Link	Denmark	Flooding Fire	1994 October 1991
126	Baikal - Amur line - No 2 Mysovy tunnel	Russia	Rock Fall Rock Fall	Limited information Limited information
127	Baikal - Amur line -No1 by - pass route for the Severo-Muysky tunnel	Russia	Slope slide	1986
128	Baikal - Amur line - Kodarsky tunnel	Russia	Collapse Collapse	1984 June 1984
129	Sewage tunnel (Bolshaya Dmitrovka street in Moscow)	Russia	Daylight collapse	May 1998
130	Walgau headrace tunnel	Austria	Collapse Difficult ground Collapse	Limited information (Between 1981 and 1982) Limited information (Between 1981 and 1982) April 1982
131	Iwate tunnel (Ichinoche Contract section)	Japan		

			Excessive Deformation	Limited information (between November 1991 and 1993)
132	Yacambu-Quibor	Venezuela	Excessive Deformation	Limited information (Between 1977 and 1979)
			Excessive Deformation	Limited information (Between 1977 and 1979)
			Collapse	2000