Feedback from a database created for reporting accidents in tunnels and galleries

J. Idris, M. Al Heib & T. Verdel
LAEGO - INERIS – Ecole Nationale Supérieure des Mines de Nancy, Institut National Polytechnique de Lorraine, France

Abstract

Underground construction instability has been a major cause of undesirable accidents, especially in those which are related to transportation. Experience feedback is one of the useful methods available to improve the design of construction. The main first part of this paper is to present a database, which has been developed to record instabilities of affected tunnels and other underground constructions around the world, at both phases of construction or exploitation. The second part aims to analyse all the parameters responsible for instability phenomena and to assess their impact on the affected construction itself as well as on neighbouring constructions and the environment where they reflect effects on human safety and activities.

Our future aim is to develop a risk analysis methodology to help engineers for taking safety issues better into account in the design of underground infrastructures.

Keywords: database, risk, instability, tunnels, and underground infrastructures.

1 Introduction

Transport and communication structures play an important role in the development of societies and human activities in all fields. With the help of huge nets of transportation infrastructures (motorways, roads, railroads, etc), the communication is much improved between people, regions and countries. Underground infrastructures in particular have solved many communication problems as far as topographic difficulties and urban space limitations are concerned. Like as a tax of this development, the underground transport history is full of tragic accidents where man was the first victim [1,2]. Sometimes,
infrastructures instability was a major cause of accidents. At another side, underground infrastructures instability can be a direct or indirect consequence of many other accidents that may happen during realization and using phases. These accidents may induce economical loses and social impacts that cannot be neglected [3]. The search of main instabilities accidents causes is an essential step for risk management improvement.

In the following text, we present our first efforts concerning the analysis of collected data. After a brief chapter about the characteristics of underground transport infrastructures we focus on instability problems affecting underground infrastructures at the construction stage or at the exploitation stage. Then we describe the contents of the proposed database and present some global statistics about instability phenomena and their consequences as obtained from the database.

2 Underground transport infrastructures

Underground transport infrastructures cover different types of constructions, which include subways galleries and their attached constructions (subway stations), motorway tunnels, road tunnels, railway tunnels, tunnels of navigation, water transport tunnels, underground stations and parks etc. Underground urban infrastructures have specific characters following the purposes of their construction and the urban zones topography. Tunnels generally are located at shallow depth, nearby several other civil constructions above them as buildings and surface transport infrastructures or other neighbouring underground constructions and services nets. Normally there is an interaction between them; underground urban infrastructures are sensible to neighbouring human activities (new constructions) and natural, environmental phenomena [4].

3 Underground infrastructure instabilities

3.1 Underground constructions instabilities at construction stage

Apart the high cost of underground transport constructions, they are relatively difficult to realise because of the complexity of construction medium (rocks, soils). Their stability depends firstly on the underground geotechnical, geomechanical and hydrological conditions, then it depends on the construction method and finally on the geometrical characters of the concerned construction itself.

Table 1: Gothard tunnels accidents during the construction phase.

<table>
<thead>
<tr>
<th>Project period</th>
<th>Workmen</th>
<th>Wounded persons</th>
<th>Fatal accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway tunnel 1872 - 81</td>
<td>2500 - 4000</td>
<td>260</td>
<td>177</td>
</tr>
<tr>
<td>Road tunnel 1969 - 80</td>
<td>Until 700</td>
<td>25</td>
<td>12</td>
</tr>
</tbody>
</table>

Therefore it is very necessary to insure the construction stability during the successive stages of the construction to avoid undesirable accidents which are
generally accompanied with serious human losses that leave their undesirable shade on all society, as well as with high economical losses and delays of construction period. For example, accidents reported on Table 1 have caused serious human losses during the construction of two Saint Gotthard tunnels [5].

3.2 Underground constructions instabilities at exploitation stage

Underground transport construction stability is an important element of transport safety, efficiency and traffic security.

Underground constructions have a long service age compared with other civil constructions. For this reason, some of observed instability phenomena are due to their age (ageing), where several instability phenomena develop under one or several factors combination (degradation of construction materials, pollution...etc). At this phase, the underground stability depends on the construction function and on the development of underground geotechnical or hydrological condition as well as on natural catastrophes.

Consequences of such instabilities can be dramatic with a possibility of a high human loss level among the users and consequently with high social and economical impact. For instance, the Vierzy railway tunnel accident (110 years old tunnel, 800m length) which happened in France in 1972, where some parts of the roof lining felt downwards on the line and blocked the two ways had the following consequences: derailment of two trains, collision, 108 died people and 240 wounded people, enormous economic and social losses [6].

4 Databases description

In underground construction, it is difficult to expect some underground responses to excavation actions due to the complexity and the heterogeneity of the surrounding medium. So feedback is one of the useful sources in underground construction works (at construction stages) for engineers, which may help them to take decisions to avoiding undesirable accidents to happen not only at constructions stages but also at exploitation period. In this paper, we are concerned with tunnels and other underground constructions accidents, where construction instability was a direct or indirect cause of human or economical losses and we hold a special attention to construction durability at exploitation phase.

Table 2: Database contents.

<table>
<thead>
<tr>
<th>Type of underground structures</th>
<th>No of accident cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel or car park</td>
<td>90</td>
</tr>
<tr>
<td>Railway tunnel and station</td>
<td>73</td>
</tr>
<tr>
<td>Water transport tunnel</td>
<td>23</td>
</tr>
<tr>
<td>Unknown</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td>210</td>
</tr>
</tbody>
</table>
Powerful feedback requires huge available data of previous analysed accidents. For this purpose, we started to establish a database for underground construction instabilities in March 2002. At present, it contains about 210 underground constructions instabilities cases obtained from different resources. Most of them concern transportation infrastructures. Table 1 shows the distribution of cases according to the function of the construction.

### 4.1 Available data

The database contains 212 cases. For each case, we collected quantitative and qualitative information. 21 variables have been defined. Certain of them concern the tunnel and others concern the accident (causes and consequences). Table 3 gives the list of used variables. But it was impossible to have all data, from the references, for all cases.

<table>
<thead>
<tr>
<th>Number</th>
<th>Data</th>
<th>Number</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Construction name</td>
<td>12</td>
<td>Construction method</td>
</tr>
<tr>
<td>2</td>
<td>Localisation</td>
<td>13</td>
<td>Depth</td>
</tr>
<tr>
<td>3</td>
<td>Age of construction</td>
<td>14</td>
<td>Construction length</td>
</tr>
<tr>
<td>4</td>
<td>Usage</td>
<td>15</td>
<td>Diameter</td>
</tr>
<tr>
<td>5</td>
<td>Accident date</td>
<td>16</td>
<td>Section form</td>
</tr>
<tr>
<td>6</td>
<td>Instability phenomena</td>
<td>17</td>
<td>Human losses</td>
</tr>
<tr>
<td>7</td>
<td>Causes</td>
<td>18</td>
<td>Material losses</td>
</tr>
<tr>
<td>8</td>
<td>Origin of the cause</td>
<td>19</td>
<td>Social impacts</td>
</tr>
<tr>
<td>9</td>
<td>Supporting mode</td>
<td>20</td>
<td>Bibliographic reference</td>
</tr>
<tr>
<td>10</td>
<td>Ground</td>
<td>21</td>
<td>Photographic reference</td>
</tr>
<tr>
<td>11</td>
<td>Topography</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To start the classification and basic analysis and to have a homogenous database, we have used a numeric and alphanumeric coding system. We separated the cases into two families: instabilities during construction phase and others during the service phase. Some variables have many classes like depth, instability phenomena. The following paragraphs give the definition of each one.

### 4.2 Instability phenomena classification

We proposed the principal following instability phenomena classification for the two phases (construction and exploitation phases): Collapses (partial and total collapses); disorders (blocks fall, cracking, support deformation); floods (infiltration of much water into the construction); convergence during construction phase only; total and differential settlement.
4.3 Soil and rock classification

The underground of every construction was classified according to one of four underground categories according to the DIN 18196 international soil classification (this norm is one of many used for soil and rock classification, it’s the more complete than others), which divide the underground into four grand categories: hard rock, soft rock, soft soil without cohesion and soft soil with cohesion [7].

4.4 Infrastructure depth classification

For this purpose, we have adopted two classifications [8, 9]. Then our infrastructures were classified according three depth levels: Shallow tunnels or underground constructions, \( P \leq 100 \) m, median depth tunnels: \( 100 \) m \( \leq P \leq 300 \) m and deep tunnels: where \( P > 300 \). Where \( P \) is tunnel depth.

5 First data analyses

We have realised an elementary analysis of instability phenomena and theirs corresponding causes and consequences. This analysis has a special importance because the large number of analysed accidents makes us able to identify all real sources of underground constructions instability, hazards and accidents. This analyse was carried out for each of the two main stages: construction stage and exploitation stage.

5.1 Instability phenomena at construction phase

Five instability types concern the construction phase of underground structures. Table 4 shows the number of cases for each type of instability.

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>No of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse</td>
<td>71</td>
</tr>
<tr>
<td>Disorder (blocks falls, cracking, falls of parts of lining)</td>
<td>27</td>
</tr>
<tr>
<td>Flood</td>
<td>4</td>
</tr>
<tr>
<td>Convergence</td>
<td>19</td>
</tr>
<tr>
<td>Settlement</td>
<td>1</td>
</tr>
</tbody>
</table>

5.1.1 Collapse phenomenon

Collapse phenomenon takes place after serious, grand deformation in the tunnel section. At shallow underground tunnels (urban tunnels and service stations…) this phenomenon sometimes develops until the ground surface, were a subsidence or a sinkhole can be formed. Collapses leave to a combination of several impacts. Firstly, from a social point of view, this type of accidents threatens workmen life and sometimes causes victims in neighbouring civil constructions, secondly and from an economical point of view, the cost of
material losses due to the collapses are very high. *Istanbul Metro tunnels collapse (2001)* [10], *Heathrow airport tunnel collapse (1994)* [11] are some examples.

From the 71 analysed cases, we observed that the principal causes are geotechnical ones, with about 62% of accidents. Poor quality grounds (loose grounds and non-cohesive soils) are responsible of 32% of analysed accidents. Sudden collapses of unexpected poor quality grounds represent 15% of these accidents causes, the swelling behaviour of some grounds is responsible for partial structural collapses of temporary supporting (13% of causes), and finally the rest (1.5%) of collapses causes concern excavations under a slope.

On the other hand, about 18% of collapse cases are due to special hydrological conditions, essentially the presence of an underground high water pressure. However, it is very rare that the heavy rains induced directly the collapse of a tunnel. Technological errors represent 16% of total or partial collapses at construction stage (design and operation errors). Naturals catastrophes (earthquakes, landslides) are responsible of about 3% only of these accidents. Other rare causes as natural gas explosion, and meeting of unknown old underground constructions do not exceed 2% of total causes.

### 5.1.2 Disorder phenomenon

Disorder includes several forms of local instabilities as blocks fall, cracking, sub-soil water infiltration. These instabilities phenomena have considerable economical and material losses. 27 cases were analysed, about 81% of them are due to geotechnical causes: 33% correspond to poor ground quality (loose grounds and non-cohesive soils), 19% of causes concern squeezing rocks, 15% for swelling soils, nearly 7% correspond to sudden disorder accidents of unexpected poor quality grounds and about 7% for excavation under a slope. Hydrological causes are attached directly to underground water presence with high hydraulic pressure. They represent 11% of total causes. At other side, the technologic errors (operation errors) do not exceed 4% and the rest 4% of disorder accidents causes correspond to fire accidents. Here are some examples: *the Santana Railway tunnel cave-in (1983, Brazil)* [12], *the Tuzla water tunnel cracking and sub-soil water infiltration (Turkey)* [13].

### 5.1.3 Convergence phenomenon

The convergence phenomenon results from the deformation of grounds around the excavated construction, under several factors (swelling, squeezing phenomena, poor ground qualities, high excavation depth). Convergence impacts are always material losses, and re-excavation costs ( economical aspect). Through the 19 found cases, we had the following causes: poor quality grounds situated at high depth (37%); poor quality grounds at shallow depth (looses grounds and non-cohesive soils) (26%); swelling soils (26%); and swelling soils situated at high depth (11%). *Tymfristos road tunnel hard convergence (2m) due to a very poor quality grounds (Greece, 1999)* is an example illustrating the convergence problem [14].
5.1.4 Flood phenomenon
It is a consequence of infiltration of great quantities of underground water into
the construction. This type of accidents is rare. Our database contains 4 cases
only. Their economical consequences are usually heavy such as in the case of
the Seikan immersed tunnel which suffered from three floods which caused
several years of project delay (Japan, before 1988) [6]

5.1.5 Settlement phenomenon
One case only founded; the cause was the presence of poor quality ground under
an immersed tunnel.

5.2 Instability phenomena during exploitation phase
Four types of instabilities have been detected regarding the exploitation phase.
They are presented in Table 5. The main phenomenon is the disorder (68 cases).

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>No of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse</td>
<td>13</td>
</tr>
<tr>
<td>Disorder (blocks falls, cracking, hangs of parts of lining, invert rising)</td>
<td>68</td>
</tr>
<tr>
<td>Flood</td>
<td>2</td>
</tr>
<tr>
<td>Settlement</td>
<td>8</td>
</tr>
</tbody>
</table>

5.2.1 Disorder phenomenon
Disorder phenomena at exploitation phase are all damages, which appear at the
internal underground construction lining and invert, as cracking, deformation,
and water infiltration. Disorder impacts are generally economical or material
ones. For example, the Felbertauerm road tunnel has suffered from instability
lining problems because of ageing (Austria 1989) [15] and the Corchia road
tunnel faced instability lining problems because of underground water seepage
(Italy 1986) [16]

The first and most large detected cause of disorder is the ageing of
constructions (degradation of construction materials under influence of time
factor), these cause represent 46% of disorder causes. We also found that tunnels
fires are the second important source of disorder problems and they represent
24% of total causes. The effect of swelling ground (at long term) occupies the
third position with a ratio of 21%. Design defects are responsible of 7% of our
analysed cases and finally we have found few cases of water infiltration that do
not exceed (1,5%) of total causes, and the rest (1,5%) of disorder causes are of
natural, geological origin (earthquakes, landslides).

5.2.2 Collapse phenomenon
During the exploitation stage, collapse phenomena represent a general structural
rupture of underground construction or a large internal lining or supporting
rupture. This phenomenon is rare but their economical and social impacts are
very serious especially in transport infrastructures. We can give the following examples: Vierzy railway tunnel (France 1972) and Toyama road tunnel collapse (Japan, 1996) after sudden landslide with 22 victims in this accident [17].

13 cases were found; 31% of the causes was a considerable modification of charge situation such as new neighbouring constructions. Ageing is the second source of causes which represent 23% of total collapses causes. 15% of total causes have a geotechnical origin such as swelling ground at long term that increased pressure around tunnel lining. 15% of causes corresponds to earthquakes, 8% to landslides and 8% to water infiltration into underground construction.

5.2.3 Settlement phenomenon
Phenomena of settlement and relative settlement are related to immersed tunnels. The relative settlement represents the difference of settlement value between the successive immersed tunnel elements. These phenomena take place because of the existence of poor qualities soils under the affected tunnels.

5.2.4 Flood phenomenon
Infiltration of grand quantities of water into underground constructions causes considerable damages to the construction and to its equipment. Our database contains two cases only. The flood of (RER – gare de Lyon) station in France after very heavy rains is one of them [6]

![Impacts estimation](image)

**Figure 1:** Impacts estimation.

5.3 Social and economical losses estimation

All instabilities phenomena induce economical losses. To assess all impacts of instabilities found phenomena at construction and exploitation stages, we have proposed the four following criteria for accidents impacts assessment [18]:
- Local level: major consequences of the accident concern the construction itself. No human victims, few material losses and slightly damaged construction
- Regional level: consequences on the construction and neighbouring environment. No human victims, few material losses and slightly damaged construction, social and economical effects on the area where the accident has occurred only
- National level: the accident has caused human victims and seriously damaged construction and it had important social and economical effects. Example: San Fernando tunnel explosion due to methane gas, where 17 workmen died in the tunnel (USA, 1971) [19]
- International level: human losses and seriously damaged infrastructure, which connects between two or more countries. Example: 39 persons dead during Mont Blanc tunnel fire (France – Italy, 1999) [20]

Figure 1, shows the distribution of database tunnels accidents impacts according the previous proposed criteria.

6 Conclusion

In this paper, we have presented an established database concerning underground infrastructure instabilities phenomena and accidents (most of them concerning transport tunnels). A preliminary simple analysis of main causes and consequences level was carried out. We think that we have identified the most instabilities phenomena encountered at both construction and exploitation phases. 210 cases, and 21 variables for each case were collected and analysed from international references. We districted between excavation and using phases. The geotechnical cause (soil and rock quality and behaviour), is the first and can explain the major part of accidents for the two phases. The impact of accidents often is local but 3% of cases have been a regional and international impact.

This work has to be considered as the first step of our future research, which will be devoted to an advanced data analysis of the created database. We will focus on the most relevant variables, and then we plan to propose a risk analysis methodology based on these variables. The experimentation on numerical models will help to identify additional, possible relevant variables that may play an important role in the instability of tunnels.

References

[2] Russian Tunnelling Association, Accidents and emergency situation during the construction of transportation and subway tunnels, Moscow, 1997


[16] Rehabilitation of highway tunnels techniques and procedures, www.golder.com

[17] Toyama Tunnel www.tunnel.org


[20] Fire Accidents in the World’s Road Tunnels, home.no.net