MINE CLOSURE AND POST-MINING MANAGEMENT
INTERNATIONAL STATE-OF-THE-ART

INTERNATIONAL COMMISSION ON MINE CLOSURE
INTERNATIONAL SOCIETY FOR ROCK MECHANICS

June 2008

ISRM

INERIS
BON-TERRA Mining (Pty) Ltd
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TOKAI UNIVERSITY
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Preliminary remark

The elaboration of the present report by the ISRM mine closure commission has necessitated a significant work. In addition to the technical work, photos, figures and references have been collected from different countries and sources.

Despite the effort made, some of the included illustrations or references may appear to be unclear, wrong or uncompleted. In case of such a detection, the authors previously thank all readers to let them be aware of any improvement and suggestion, especially with respect to copyright issues. The document will be improved as soon as possible by taking into account corrections and suggestions.

Morever, the present document concludes the first step of the commission work that can be completed and ameliorated. Any further contribution will thus be welcome (e.g. complementary references, technical modifications). They will be considered by the commission in a further edition of the document.

The authors warmly thank the readers for sending them their opinion expression and advice that would be essential in improving the quality of the commission work.

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Taking part in the mine closure commission has been a wonderful experience.

I would like to warmly thank each member for his generous and precious involvement in the commission process, from a technical but also and probably above all, from a human point of view.

It has been a real pleasure to work together during the last two years, to learn from each other and to contribute to a common work.

The friendship initiated between the members will, certainly, survive beyond the commission mandate. So will our desire to continue and consolidate our technical exchanges.

Together with others members of this commission, I sincerely hope that the present report will be helpful and of interest for the community involved in mining, post-mining and connected areas.

Christophe DIDIER

President of the Mine Closure Commission

CONTENTS

1 INTRODUCTION AND OBJECTIVES

1.1 COMMISSION CONSTITUTION

During the 10th Congress of the International Society of Rock Mechanics (ISRM), held in Johannesburg, South Africa, in September 2003, a technical symposium was organised concerning the potential effects that inactive mines may have on people and property located in the area of influence of mine workings. The interest and the role of rock mechanics on this complex subject were discussed. As a conclusion to the discussion, the international participants in the symposium agreed on the creation of an International Commission concerning this subject within the ISRM.

The international commission on mine closure was thus been initiated in 2004, at the initiative of Prof. Nielen Van der Merwe, President of the International Society of Rock Mechanics. The objective of the commission was to facilitate the constitution of an international network of experts involved in the topics of mine closure and post-mining management. Considering the experience of France for this particular subject (some major problems have affected several parts of French territory during the last decade), the French Group for Rock Mechanics (CFMR) has been proposed to lead of the commission. The Group suggested Christophe Didier to represent CFMR in assuring the presidence of the commission.

The first objective of this Commission was to facilitate contacts between experts in rock mechanics from different countries concerned with post mining management in order to create opportunities to exchange experiences, back-analyse case studies, scientific data, etc. Specialised international literature on documented back-analyses on geotechnical accidents or problems developing above abandoned mines is not easily available. The other aim of the commission was thus to elaborate technical guidelines, synthesising the international “state-of-the-art” for existing techniques and methods enabling the identification, characterisation and management of geotechnical hazards related to mine closure processes.

In order to reach this ambitious aim, an expert panel has been progressively constituted with the help of National Groups for Rock Mechanics and taking benefit of meetings during ISRM scientific symposia. All the members that accepted to join the commission got involved on a strictly voluntary basis. The members that gave considerably of their time and expertise to the benefit of the commission work are listed below:

- Prof. Nielen Van der MERWE, University of Pretoria, South-Africa, President of the ISRM.
- Dr. Ömer AYDAN, Tokaï University, Department of Marine Civil Engineering, Shizuoka, Japan.
- Dr. Marc BÉTOURNAY, CANMET, Mining and Mineral Sciences Laboratories, Natural Resources Canada, Ottawa, Ontario, Canada.
- Christophe DIDIER, INERIS, Ground and Underground Division, Verneuil-en-Halatte, France.
- Jean-Pierre JOSIEN, GEODERIS, Metz, France.
- Dr. Andrej KOTYRBA, Central Mining Institute, Katowice, Poland.
- Dr.-Ing. Mark MAINZ, IHS (Ingenieurbüro Heitfeld-Schetelig, Consulting Geologists and Engineers), Aachen, Germany.
- Dr. Won-Kyong SONG, Korea Institution of Geoscience and Mineral Resources, Daejeon, Korea.

Special thanks are also addressed to Dr. Robert FOWELL from the University of Leeds, England, and Prof. Dr. Christian Wolkersdorfer, General Secretary of International Mine Water Association, who made a detailed and careful reading of the document draft and propose suggestions and corrections.

1.2 ORGANISATION OF THE COMMISSION'S WORK

The mine closure commission intended to initiate and facilitate contacts between international experts. As much as possible, commission meetings have been organised, taking advantage of the ISRM-Sponsored Regional Symposia. Commission meetings were held in:

- Kyoto (Japan) on 29th November 2004, during the 3rd Asian Rock Mechanics Symposium;
- Brno (Czech Republic) on 17th May 2005, during EUROCK 2005;
- Lisbon (Portugal) on 12th July 2007, during 11th ISRM Congress, a dedicated specialised session was scheduled.

Other meetings were also organised, taking benefit of each opportunity to gather commission members. In addition to small-scale meetings (Liege in May 2006 during EUROCK 2006, Paris in January 2007), the entire commission met during a week, in November 2005 during the “GISOS Post Mining 2005 Symposium” in Nancy, France.

Technical visits and meetings were also organised. The post mining contexts of the represented countries were presented and each member had the opportunity to present to the commission his field of expertise. At the end of the seminar, the table of contents had been defined and contributions to the several sections have been distributed to each member.

The commission members have then agreed to provide parts of the document. Frequent internet exchanges were used to facilitate re-reading, comments and validation of individual contributions.

The report, in its present state, should thus be considered as a first version of the final document. It shall be improved and completed in the coming months.

1.3 REPORT OUTLINE

The closure of mining operations does not lead to the complete and permanent elimination of risks and harmful effects likely to affect the surface within the geographical limits of the old mine workings. Therefore, during the period following extraction, traditionally known as the "post-mining" period, several kinds of problems may develop, sometimes just after the closure process but also, possibly much later. These phenomena may have major consequences for people, ground, water, atmosphere (gas) and infrastructures. They are also likely to have a major influence on regional development in mining areas.

Therefore, it is of primary importance to assist mining operators and authorities in the definition of adapted mine closure processes from a geomechanical point of view. The elaboration of evaluation methods able to identify and evaluate the residual risks that may affect people and properties after closure is also of great interest.

Having been developed within an ISRM commission, the present guidelines will mainly focus on potential problems related to rock mechanics. Surface movements will thus represent a large part of the document but other kinds of potential consequences will also be very briefly discussed (water, gas).

The result of the mine closure commission work is expressed in the form of a single document comprising 7 sections and 3 appendices. Section 1 presents the commission objectives as well as its constitution and its organisation. The structure and plan of the final document in its present state is also shortly introduced. A brief presentation of the mine closure context on an international scale, as well as an overview on national policies and typical hazards, are given in section 2. The description takes, in particular, examples of some countries represented by members of the commission. The aim of section 3 is to give an introduction to mining methods in order to ease the understanding of the document.

Section 4 describes, as precisely as possible, the several forms of hazards that may be present, both in the short and long term for the environment of the abandoned mine. In addition to consequence description and potential effects on people and surface structures, explanation of the basic mechanisms that may initiate the problems will be proposed.

Descriptions of the most frequently adopted hazard assessment methods will be given in section 5. The most sensitive factors able to influence the hazard level are described as well as the main assessment process stages required to identify and analyse the residual hazard as accurately as possible. As a technical expert group, we decided to limit the work of the commission to the hazard evaluation stage. The risk evaluation stage, which is the ultimate stage of the analysis, requires integration of notions like "identification of people and property that may be affected by post-mining problems", "financial considerations", "regulatory and socio-political contexts" that concern authorities more than scientific and technical experts. Risk assessment methods have thus not been considered within the commission mission.

Section 6 describes some major hazard management methods available. Those methods gather techniques of hazard treatment, of geotechnical and geophysical monitoring and of surface land occupation plans. Specific references are included at the end of each sector. Recommended additional literature is presented in section 7. Three appendices complete the document.

2 BRIEF OVERVIEW OF THE INTERNATIONAL POST MINING CONTEXT

2.1 INTERNATIONAL MINING EVOLUTION

2.1.1 Very old mining activities

Mining activity and metal production are two techniques that are closely connected and which have usually progressed together. It is however usually considered that mining activity started before the first steps of metal production. Stone and raw materials used for the first tools and weapons have thus been extracted from mines since ancient times.

Different kinds of minerals were already extracted from open pit mines in Turkey during the Mesolithic era (around 8000 years BC) and some “flint mines” might have developed throughout Europe at that time. The earliest evidence of mining in Canada dates back to about the 7th millenium BC, when aboriginal peoples worked a quartzite quarry on Manitoulin Island (Lake Huron, Ontario).

Native and ductile metals were obviously the first metal substances used by mankind. Concerning the metal industry, the Mesopotamian area (e.g. Turkey, Egypt, Iran) has, for a long time, been the most developed region of the world. Copper was worked since the 8th millenium BC, soon followed by gold (probably around the 5th millenium BC).

Asia Minor was also among the first to gain the bronze production technology (the very beginning of 3rd mill. BC.). The invention of bronze led to the development of new skills in processing and refining gold, silver and other metals. Discoveries such as the Kestel tin mine (3rd mill. BC) and the miner’s village, Göltepe, in the central Taurus Mountains demonstrate the importance of metal technology in the Anadolu society. The underground mining system in Kestel is assumed to measure more than three kilometres. Tools such as hammers and cutting instruments made from copper, flint, and other types of hard stone have been discovered (Yener, 2004).

From the 3rd millennium BC flint stone mining became an important industry, in Eastern Europe notably. In Poland, well-preserved underground mines of flint stones were discovered in the village of Krzemionki Opatowskie. It is assumed that mining in this area began during 4th mill. BC. In the period from the 3rd to 2nd mill. BC, about 4,000 mines probably existed in this area extracting flint stone as a raw material. From this material were manufactured axes and other tools. The mines consisted of shallow galleries at depth ranging from 2 to 9 m.

According to history, coal was the first commodity to be mined in South Africa dating back to the Iron Age. There is in fact some coal evidence on the debris of ancient iron works. Tribesmen used coal for iron production in the KwaZulu Natal area.

In Europe, other mining activity and metal working developed even before the Roman occupation (1st mill. BC). The Celts and then the Gauls as well as other Central European tribes regularly exploited gold, and tin and, of lesser importance, silver and iron (Olkusz and Tarnowskie Góry in Poland).

During the Gallo-Roman period, mining activity really develops with the beginning of silver, lead, copper and iron extraction. The mining activity then took the form of a multitude of local small-scale mining sites, distributed throughout the whole empire (1st and 2nd centuries). Many of those very old mining sites can be encountered in archaeological pits and ancient burial places (the most important mines were mainly located in Spain). After the fall of the Roman Empire, mining exploration and extraction strongly decreased and remained very low for several centuries.

In central Europe, in particular Germany, an intensive open cast and underground mining activity re-started during the early Middle Ages (11th-13th centuries). Coal began to be mined throughout Europe (Ruhr, Saarbrücken and Aachen areas in Germany, Provence and Herault in France) as well as salt, lead and silver (Krakow area in Poland, North-East of France). According to historical records, the exploitation of minerals in Japan started around the 7th century. The earliest known mining activity by Europeans in Canada was around 1000 when the Vikings mined iron ore at l'Anse aux Meadows, Newfoundland.

Most of those ancient activities were systematically small-scale mining. The mining works were usually shallow (above the water table: usually not more than a few tens of meters) and generated very small voids. Ore deposits were mainly mined by small-scale open cast mines or underground man-sized galleries. Located near the outcrops, due to their old age, those mining works have mostly been covered over. Some small-scale voids may sometimes remain open and generate low to moderate magnitude desorder phenomena.

Post mining hazards that are related to those very old works are thus usually limited in extent and magnitude.

2.1.2 Industrial development period and present situation

The industrial revolution (second half of 18th century) initiated the decisive impulse in the development of the mining activity and the beginning of the "golden era" of this activity which was going to rule the economy for about two to three centuries. Technological progress contributed to transform an activity, which up to that period was mainly small-scale, into an industrial production activity. Major mining fields were established focussing on single commodities: e.g. hard coal and lignite, iron, salt, bauxite, zinc, lead.

The beginning of the 19th century also was characterised by an important diversification of exploited materials (e.g. oil, manganese, fluorite, copper, sulphur). Mainly under the impact of the two World Wars, the national mining activities continued to develop during the first half of the 20th century. Then, the progressive exhaustion of some mineral resources fields and the relatively low value of the raw materials led to a progressive decline of a large part of the international mining activity.

As it is described below, some countries have seen their national mining industry almost disappear. For some others a severe decline has affected the mining activity. Finally, other ones have seen their mining activity developed, sometimes very strongly, during those last decades. But, for all those mining countries, even the last ones, the progressive changes and evolutions have contributed to the abandonment of old mining sites (sometimes replaced by new ones, sometimes not). It can thus be considered that the mine closure process as well as the management of post-mining hazards concern every country that is, or at least has been, involved in mining activity.

Countries whose mining industry is nowadays almost dormant

In some countries, the decrease in mining activity has led to the almost disappearance of active mining industries. Japan, for example, developed its mining industry to lead industrial modernisation. The country once was an important producer of copper and silver (figure 2.1). Since the end of the 1960s and the closure of the lignite mines, many mines in Japan have been forced to stop their operations, mostly because of the yen's sharp revaluation. The last coal mine closed down in 1997 and, except Kushikino and Hishikari gold mines, most metallic and non-metallic mines were abandoned. Mining activity presently is in a dormant state in Japan, where some 6,000 inactive or abandoned mines are located all over the country.

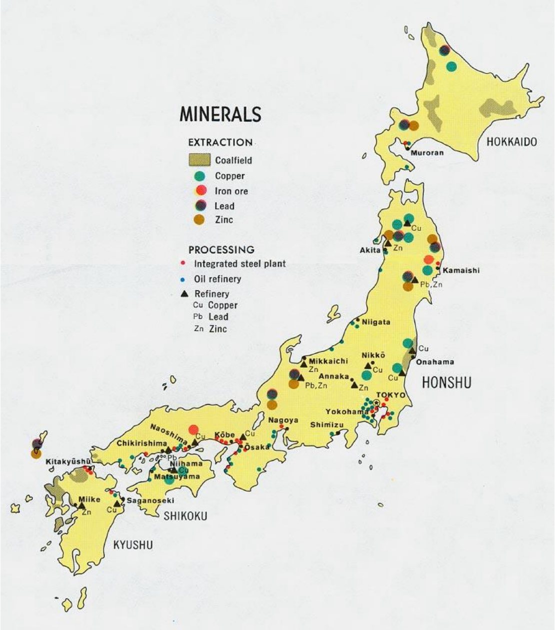

Figure 2.1. Abandoned and active mines in Japan.

Initiated, at the beginning of the sixties for coal and iron and at the beginning of the eighties for the exploitation of the other minerals, the decline of French mining activity accelerated since the beginning of the 1990s. The closure of the last iron mine occurred in 1995 and the last exploitation of uranium ended in 2001. The exploitation of potash stopped in 2003 and the last underground extraction of a coal panel closed down in 2004. From that time, the only active mining industry in Metropolitan France results from the extraction of salt, by underground or by solution mining. Today, about 4,000 abandoned mining sites are located over the French territory (figure 2.2).

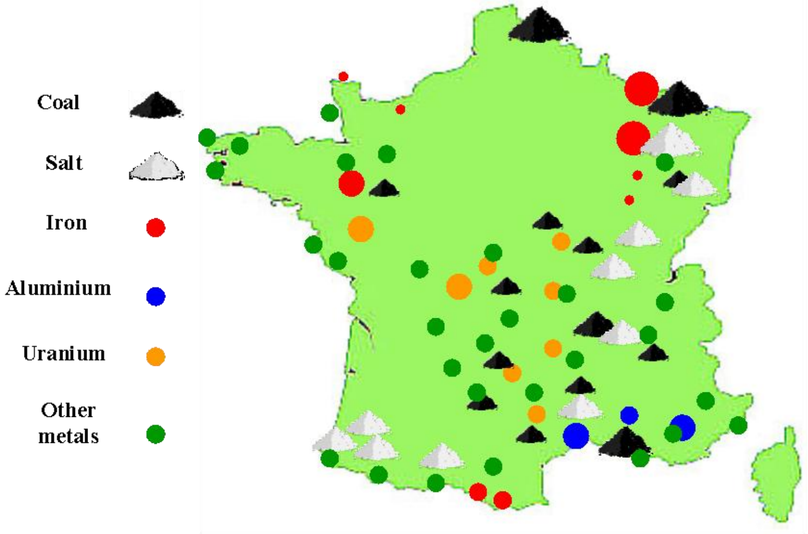

Figure 2.2. Major former mining fields in France.

Countries whose mining industry has been affected by recent decline

In several other countries, even if the mining decline has contributed to reduce the importance of this industrial sector, some important mining activity remains.

In Poland for example, the restructuring process in the mining industry began in 1990. Since this date, about one third of the collieries, most of the zinc, lead and salt mines and all sulphur mines have been closed. Mining activity however remains an important branch of industry, especially regarding coal, copper and chemical minerals. Even if it is very difficult to assess the total number of abandoned mining sites in Poland, it can be estimated that there are about 1,000 to 1,500 post-mining sites located in Poland, mainly in its southern portion (figure 2.3).

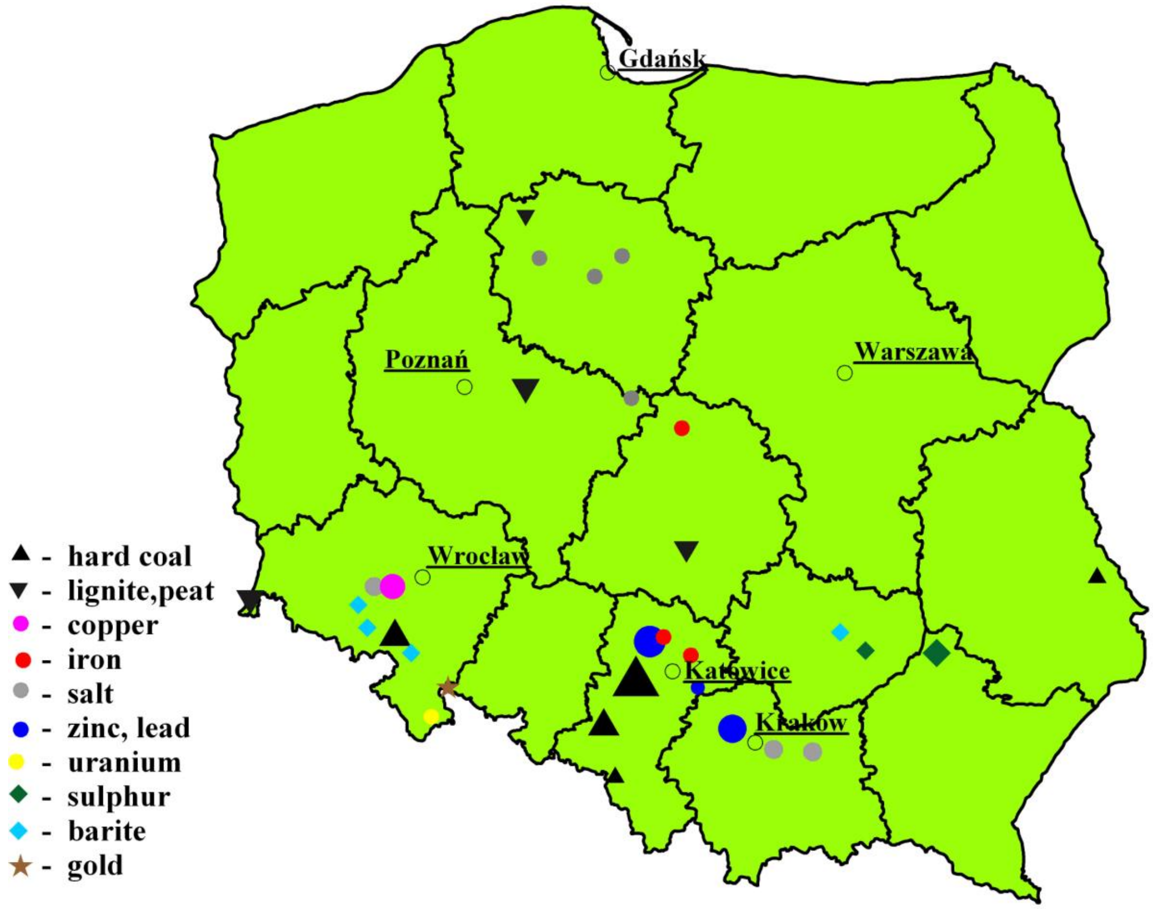

Figure 2.3. Major mining fields in Poland.

In Germany, most legacies of hard coal mining at shallow depths are found in the southern Ruhr-area (e.g. around Essen), in the area around Saarbrücken and north of Aachen. Numerous abandoned mines exist in the Harz and Erzgebirge as well as in the Rhenish Massive and the Black Forest (figure 2.4). Shallow iron ore mines are spread all over Germany. Open cast lignite mines exist in the area west of Cologne, around Leipzig and the Lausitz (between Berlin and Dresden).

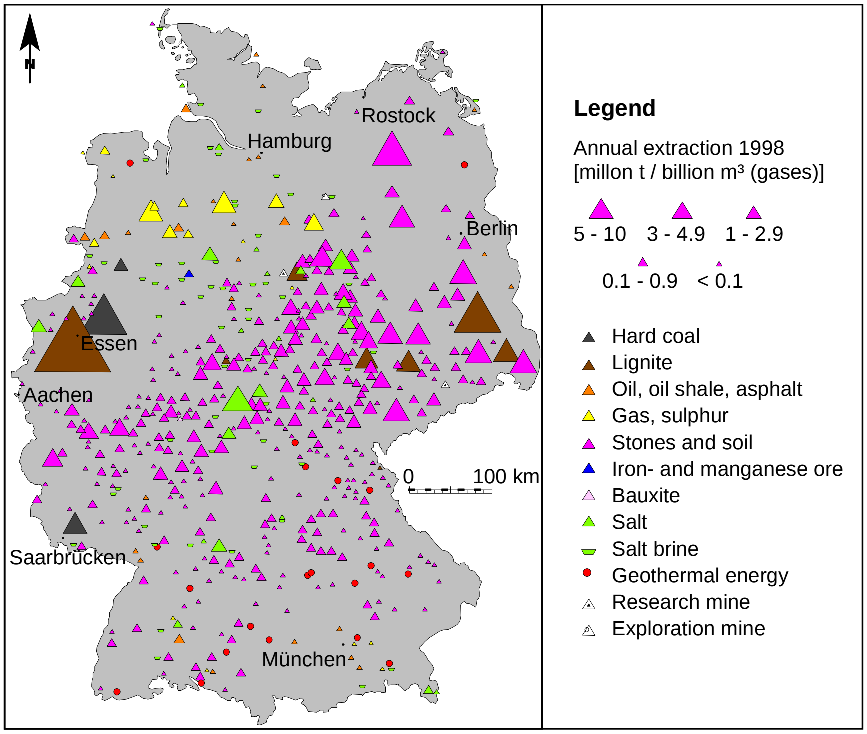

Fig. 2.4 : Mining activity in Germany
(Modified after Bundesanstalt für Geowissenschaften und Rohstoffe, 1999)

In Turkey, some mercury mines were closed down due to world-wide environmental concerns. However, coal, lignite, boron, iron, chromite, bauxite, copper-zinc gold mines are still actively operated throughout the country (figure 2.5). Turkey is, in particular, one of the major chromite and chromite concentrate producing and exporting countries. There are about 710 known chromite deposits and occurrences in Turkey. The country also has the largest borate reserves in the world.

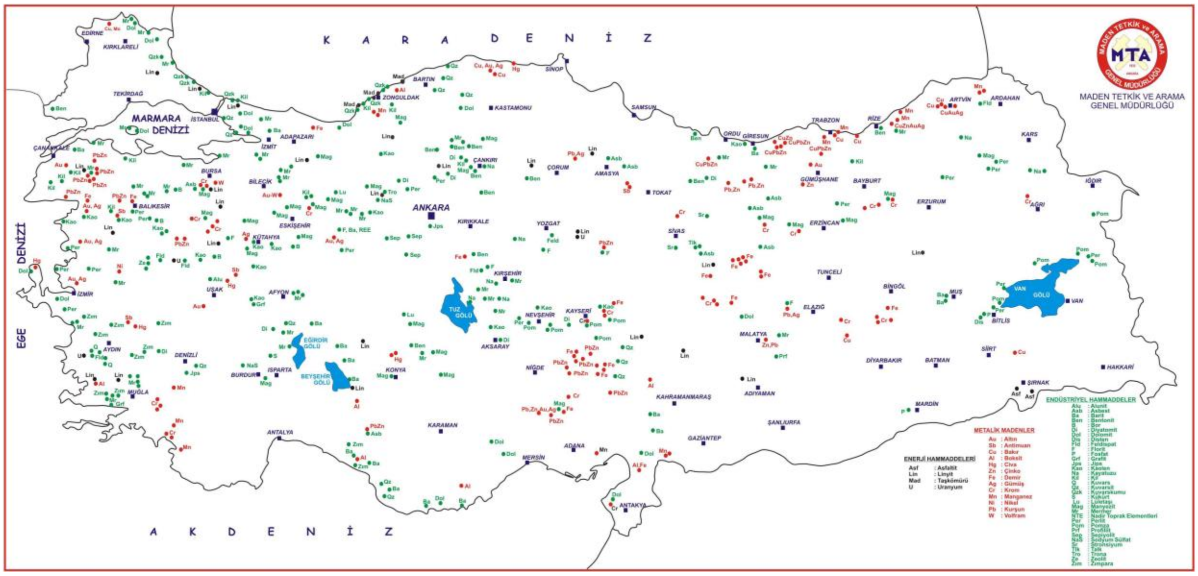

Figure 2.5. Abandoned and active mines in Turkey (source MTA).

The principal mineral resources in Korea are coal (mainly anthracite) and limestone. Korea annually produced a maximum of 27 million tons of anthracite from approximately 400 underground coal mines in 1986. The production decreased abruptly thereafter, and at present, only 8 major companies are working, producing about 2 million tons.

Metallic and non-metallic active mines are spread over the country, but have been developed on a small scale. Their total number was 553 in 2002, however, only 18 of them achieve sales of more than 5 million US dollars per year. Resources of note are limestone and silica, and other minerals are being produced on a smaller scale.

According to a detailed investigation of the closed or abandoned metal mines in 2005, 1,082 mines are found distributed all over the territory (figure 2.6). Some of these mines cause problems related to subsidence, water contamination and environmental pollution. THE MRC (Mine Reclamation Corporation) has been carrying out reclamation projects for these regions since 1989, to prevent mine hazards.

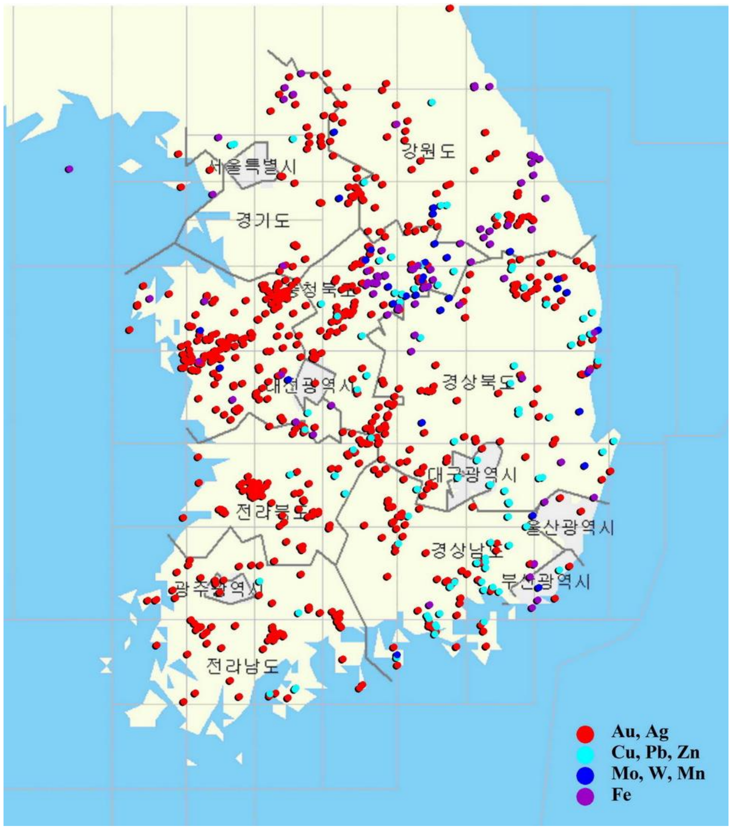

Figure 2.6. *Closed or abandoned metal mines in Korea (Jung, 2006).*

As an example, a hazard prevention program for closed coal mines (forest rehabilitation, water treatment, prevention of subsidence, etc.) has been operated by the CIPB (Coal Industry Promotion Board) since 1987. 182 million US dollars have been expended for rehabilitation and environmental improvement of coal mine hazard regions from 1995 to 2005.

Countries that remain with a strong mining industry

In South Africa, from earliest modern times, coal exploitation probably took place in Natal, around 1840. Then came the discovery of alluvial diamonds along the Vaal River in 1867. A kimberlite igneous pipe was then identified as the source of these alluvial diamonds. Mining started on the pipe and more diamonds were produced. The town of Kimberly quickly developed into the economic heart of the country. This was until gold was discovered in Johannesburg in 1887. The city quickly became the industrial and economic hub of sub Saharan Africa, the position still holds to date.

The economy of South Africa is nowadays supported by mining and agriculture. The mining industry in SA is the major employer, accounting for employment of more than 450,000 people in 2004 (DME, Mining and Minerals Ministry). For over a century mining in South Africa was largely supported by gold, diamond, coal and platinum production. South Africa is also a leading world supplier of a range of minerals and mineral products of consistently high quality. In 2004, some 59 different minerals were produced.

The mining industry continues to grow in the country. In the late 1990s and early 2000s, the gold sector was declining, due to the strength of the currency and gold price depreciation. Fortunately, the impact of this decline came at a time when the platinum industry grew dramatically. In the mid 2000s the gold price grew stronger and the mining industry was stabilised.

Figure 2.7 indicates the position of mines in South Africa. For the areas indicated, there are 337 mines that are producing. This is out of the total number of around 1,000 recorded mines in the DME list, meaning that there are more than 650 mines closed or dormant. To those, one must added the unlisted mines located all around the country.

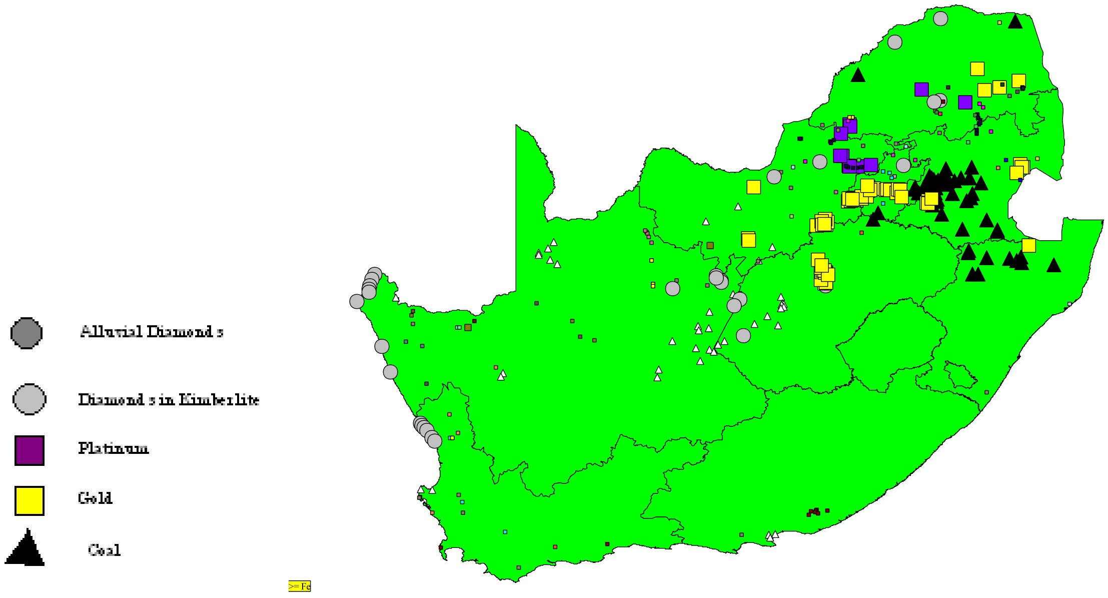

Figure 2.7. Abandoned and active mines in South-Africa (source Department of Minerals and Energy).

Canadian mining activity remains also a very powerful industry (Geological Survey of Canada, 1997). It is so large and diverse that it is difficult to highlight any particular area or commodity. Among the main mineral resources that have been (and for most of them continue to be) extracted, one may quote: gold (e.g. British Columbia, Ontario, Northwestern Québec), copper-nickel (Sudbury Basin, Manitoba), copper-zinc (Manitoba), silver (Ontario), iron (Québec-Labrador); potash (Saskatchewan), tar sands (Alberta) coal (Nova Scotia, Western Canada), uranium (Ontario, Northern Saskatchewan), diamonds (Northwest Territories). Not less than 229 locations have been listed as principal producing areas (figure 2.8).

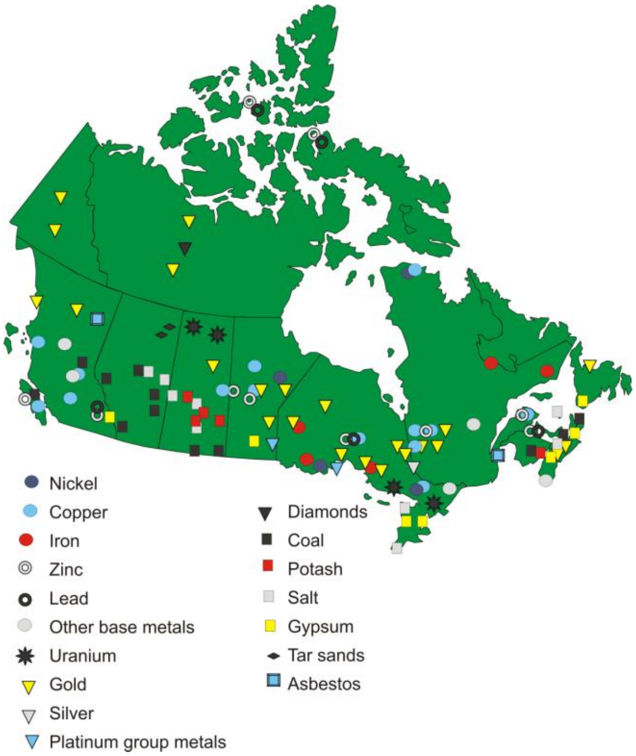

Figure 2.8. *Major historical mining areas and related extracted commodities in Canada.*

Thus, many sites of former mining operations exist throughout Canada. Those exploitations vary from small one-person operations to the very large open pits and underground mines that were developed from the 20th Century onwards. Probably most of them date from the 19th and 20th Centuries (technical improvement, accessibility to prospectors).

At present, there are only estimates of how many abandoned mine sites existing in Canada. While some organisations, such as the Sierra Club and Mining Watch have estimated that there may be over 10,000 such sites in the country (Mackasey, 2000), there are probably many more than that. As a matter of fact, a recent regional survey of the nation's capital alone listed about 4,000 small to medium-sized deposits and occurrences (Udd, 2005). Nonetheless, there are many similar mineral-rich areas in other parts of Canada, leading to the supposition that there must be much more than 10,000 abandoned workings in the country, that number representing known larger scale mines only.

2.2 POTENTIAL HAZARDS AND HARMFUL EFFECTS DURING POST-MINING PERIOD

Several kinds of risks and/or harmful effects may persist in the long term, after mine closure. Even when no longer exploited, the abandoned mine sites may indeed generate consequences that may affect people and goods located under the influence of mining works and disturb occupation or economic development on surface within the vicinity of the mine.

Impacts induced by abandoned mines are of several kinds and appear to be quite similar from one country to another. They can result in potentially harmful surface or underground water flow modifications as well as surface instability developments capable of affecting sometimes dangerously people or infrastructure. Closures can also result in potentially dangerous or toxic gas emissions or produce discharges of potentially dangerous chemical substances into the environment. Polluted mine drainage is therefore the biggest single waste stream in the world (Wolkersdorfer, 2006).

2.2.1 Flooding or disturbance of river flows

With mine closure, the dewatering system designed for mineral extraction usually stops. This induces the flooding of abandoned mine workings and raising of the water table level. At the end of the mine water recovery period, natural drainage of old mine workings is established, generally from the topographically lowest adits emerging on surface (figure 2.9). Abandoned workings, even when they have been backfilled, generally constitute a much more permeable medium than the surrounding rock mass. They thus form a local hydraulic perturbation inducing, in the surroundings of the abandoned mine, a water table that never completely reaches its initial position (before mining extraction).

Figure 2.9. Discharge through an adit (left)
and (right) development of a wet zone close to an other adit (Didier & Leloup, 2006)

The main harmful phenomena related to mine flooding classically encountered are very briefly described below (Younger et al., 2004):

- Modification of the outlet flow (increasing discharge of springs in sensitive areas, appearance of new artificial or natural springs or reactivation of old ones).
- Appearance of humid zones or marshes.
- Flooding of basements (e.g. equilibrium of the water table level close to the surface, possible impact on underground structures like car parks or cellars).
- Modification of the river flows (risks of floods, impact on rivers quality during low water periods).
- Sudden and violent floods (e.g. sudden emission of water flows through adits, mudflow resulting from retention dam failures).

2.2.2 Surface instabilities

Mining exploitation usually consisted in extracting a great amount of rock material. The artificial excavations, dug underground or in an open pit, modified the rock mass equilibrium in an irreversible way.

Concerning open pit mines, the main instabilities vary from localised rockfalls to major landslides that can affect huge volumes of rock. Concerning underground mining works, the mining method used mainly depends on the geological context and technologies available at the period of extraction. After abandonment, surface instabilities that may affect mines that have been exploited by total extraction methods are generally restricted thanks to a low level of smooth subsidence. For the exploitations allowing the persistence of important residual voids, the surface may also, depending on the context, be affected by discontinuous subsidence features (sinkholes, massive collapses). Other kind of surface instabilities may also affect waste dumps that have not been properly designed. The main disorders will be described and discussed in detail in section 4 of the report.

2.2.3 Mine gas emission on surface

The extraction of large quantities of rock in gas-rich rock masses contributes to form an underground mining tank filled with mine gas. This gas consists of a mixture of several components with variable compositions. Under the effect of various mechanisms (watertable rising, pressure differential) mine gas may flow out (figure 2.10) through natural openings (faults, cracks) or artificial ones (shafts, adits).

Figure 2.10. Gas emission on surface through an adit. Fumes are used to show gas flow (source INERIS).

If the mining atmosphere presents dangerous gas mixtures, safety on surface can be affected when mine gas is trapped in non-ventilated voids (e.g. cellars). The major hazards are: ignition or explosion (methane), intoxication (e.g. CO, CO_2, H_2S), suffocation (lack of oxygen) or irradiation (radon).

Appendix A presents the main phenomena and mechanisms involved in mine gas emission after mine closure.

2.2.4 Ground and water pollution, emission of ionising radiation

Modifications and disturbances induced by mine workings may result, in a more or less significant way, deterioration of parameters governing the environmental quality within the mine surroundings (figure 2.11). This degradation mainly affects underground or surface water as well as soil. They can also affect the atmosphere, particularly in case of ionising radiation or toxic particle emission.

Figure 2.11. Examples of water pollution due to mining activity in Japan and Turkey.

2.3 NATIONAL POST-MINING MANAGEMENT POLICIES

In most country concerned with post-mining issues, mining operators, when they still exist, are considered to be the first, if not the only body responsible with regard to the compensation for the damages resulting from exploitation mining as well as costs generated by abandoned mining site rehabilitation (Petit, 2004).

However, due to the progressive closure or insolvency of site owners, the national or regional authorities are progressively required to be involved in financing and management of the post-mining period (Drebenstedt, 2006). For example, some 60 million CDN$ have been spent over by provincial governments in Canada for mine site remediation projects during the last 5 years. During the same period, about 110 million € have been spent by French authorities for post-mining prevention and remediation. Germany spent about 10 billion € for the only uranium mine restoration (Lersow & Schmidt, 2006). Some countries (e.g. England, France, Australia, United States, Germany) have created national institutions specifically dedicated to the operational treatment of post-mining damages. Nevertheless, quite often, these are the property owners that have to deal with the problems.

Funding of public costs related to the mine closure management is often guaranteed, in countries where active mining industry is still going on, by taxation indexed on the ore production. Anglo-Saxon countries (United-States, England) also use public or private insurance contracts that are made compulsory within old mining area identified as potential risk zones.

In many countries (e.g. France, Belgium, England, Australia, Canada), an important effort is being made to perform an inventory of abandoned mining sites that may affect public safety (identification, location, data base constitution, etc.) in order to optimise the prevention policy (Strickland & Ormsby, 2006).

In almost every country, the authorities' first objective is to give notice of the identified or suspected risk for people, in order to prevent them from building in areas that may be affected by post-mining damages at long term.

In Belgium, for example, *non-aedificandi* areas are prescribed around mine shafts and above shallow mining works (galleries). People who want to settle in previous mining areas need to contact the local administration with regard to the mining context before buying a piece of land.

In England, the Coal Authority each year prepares numerous *Mining Reports*. Solicitors constitute the most frequent users of this service, considering the necessity for them to provide those data to the purchasers in case of bargain of property liable to damage from mining activity.

The current German approach consists of requiring permission procedures delivered by local building permission authorities and/or mining authorities for new building projects (existing buildings are not pertained by any legal constraint due to mining hazards). Those procedures are based on hazard or risk assessments performed by specialists and may lead to treatment measure regulations.

To face the post-mining problems, the French Mining Administration decided to apply a systematic prevention policy, in order to identify potential harmful effects before they occur. The objective is to prevent future accidents and social crisis. This policy represents a kind of "bet", assuming that the large amount of money invested in the prevention step will be cost-effective on a long-term basis by reducing drastically victims and damages compensation costs. Several regulatory and technical tools, have thus been developed in order to take risks into account within land-use management (Didier & Leloup, 2006). This includes notably "mining works closure procedures" performed by the mining operator before closing the mine and "Mining Risk Prevention Plans (MRPP)" performed by the State to define surface management approaches above disused mines. MRPP identifies zones, which are directly or indirectly exposed, and issues instructions based on town planning and construction regulations that have to be applied to each building project, concerning new installations as well as existing property and activities (Didier, 2007).

In Canada, there is an absence of a national, provincial, or municipal building codes, that would require identification of the presence of active or abandoned mines as well as the assessment of geo-mechanical risk potentials before projects for new or updated infrastructure. Standard site closure remediation to prevent access is normally required from property owners, e.g. shaft capping. Provincial site projects focus on remediating sites known to have an important failure consequence potential. The remediation option of choice is placing a fence around the danger zones when further site use is not critical, and placing a concrete cap over the zone in question when site use is an issue. Due to costs, other options such as backfilling, digging/blasting, structural bridging, are rarely used for abandoned metal mines, unless there are special surface considerations. Broad consultations with populations impacted by inactive mine problems are carried out routinely. This can take the form of advisories, information availability and meetings with citizens and municipal representatives. Specific abandoned mine site use is reviewed by municipalities and requires professional advice. A manual for disused metal mines management has thus been elaborated in order to define a common methodology to understand the site conditions, record the necessary data and apply site solutions for pursuing long-term site stability and evaluate risk and related site use (Bétournay, 2004).

In Japan, due to the fact that the risk of collapse above shallow mines exploited by room and abandoned pillar technique (e.g. lignite, limestone) is increased by frequent serious earthquakes, the backfilling technique is now frequently used to deal with the problem in urbanised areas (Sakamoto et al., 2005). Figure 2.12 shows an example of the principle and actual application of this technique to deal with this problem in the Tokai region.

Figure 2.12. Illustration and application of backfilling technique (source Tobishima Co.).

In South Africa, the government through the Department of Minerals and Energy (DME) has put in place strict measures to control closure of mines. In the past, some mines were just boarded up but now it is the responsibility of the government to ensure that closure of those mines is done properly. All mines that were abandoned before 1956 are the responsibility of the State. Mines belonging to companies that were liquidated before 1976 are also the state's responsibility. Operations that stopped after 1976 are the responsibility of their respective owners.

The Department of Minerals and Energy (DME) is formulating mine closure guidelines defining the way to close properly a mine. Regional closure will focus on closure certificates being awarded at the end of life of the last mine in the region. The implications might be that mines in the same region will carry all the cost of maintaining the shafts until the last mine stops production.

In Korea, the owner of a mine is responsible for the treatment of the mine area for 5 years after closure. The mine safety code prescribes that the government is thereafter endowed with the responsibility for the closed or abandoned mines. The authorities that finance the expenses for the programs of mine hazard prevention are the MOCIE (Ministry of Commerce, Industry and Energy), ME (Ministry of Environment) and provincial governments.

The MOCIE provides a budget for the construction of facilities required to treat mine hazards occurring during development or production of the mines and executes mine hazard prevention projects after closure. The ME executes mine hazard prevention projects for the prevention of contamination of water and ground due to closed mines together with the provincial governments. Finally, provincial governments execute mine hazard prevention projects for the prevention of contamination of water and ground due to closed mines within the province area with a budget funded by itself or by the government.

In addition to surface instabilities, many countries have indeed also to face important environmental issues. Out of 6,000 suspended or abandoned Japanese mines, about 450 abandoned mines are reported to have (or will need) a pollution prevention project being implemented (JOCMEC, 2006). Mine pollution prevention measures are roughly classified into measures against sources of pollution and measures of mine drainage treatment. The measures against sources of pollution include pressure-proof sealing of mine openings, and the reshaping, covering and plantation of dumping sites, and hillside channel works. The measures of mine drainage treatment aim to treat and to control the concentrations of heavy metals in mine wastewater.

In addition to risk management concerning land use development, national policies are also designed to limit the impact of mining works on the environment after closure. More and more, the closure plan must be designed from the very start of mining works. Some examples of success in reclamation works concerning abandoned lignite mines in Turkey confirm that well-projected reclamation program can considerably reduce damages to the environment (figure 2.13).

Figure 2.13. Reclamation and forestation works in abandoned Turkish lignite mines.

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3 MINING METHODS

The nature of the potential post mining disturbances is strongly related to the mining configuration. Therefore, the commission has considered that a very brief description of the main mining methods used world-wide would be helpful for many readers.

The selection of the mining method to be used in a particular exploitation mainly depends on the configuration of the deposit (e.g. size, depth, extent). Table 3.1.1 constitutes a useful rough guide to indicate the most likely mining method used under different circumstances.

Table 3.1. Mining Methods adapted to the deposit configuration

Mining Method	deposit Characteristics						Deposit Configuration							
	Deposit Strength			Waste Strength			Beds		Veins		Massive	deposit Dip		
	Weak	Moderate	Strong	Weak	Moderate	Strong	Thick	Thin	Narrow	Wide		Flat	Moderate	Steep
Room-and-pillar		X	X		X	X	X	X				X	X	
Sub-level stoping		X	X			X			X	X	X			X
Shrinkage		X	X		X	X			X	X			X	X
Cut and fill		X	X	X	X				X	X	X		X	X
Block caving	X	X		X	X					X	X			X
Sub-level caving		X	X	X	X					X	X			X
Longwall	X	X		X								X	X	

In the following sub-chapters, the mining methods will be briefly explained. More details can be found by consulting any of the books listed in the bibliography. For the elaboration of the present document, extensive use was made of the Atlas Copco mining guide.

3.1 VERY OLD MINING METHODS

Very old mines were exploited by hand-made extraction methods. Generally, these methods consisted of galleries of very limited size (usually calibrated to allow human circulation). Some of those galleries crossed each other, designing pillars with normally quite low extraction ratios.

Because of the lack of industrial ventilation and dewatering processes, those old mining sites were generally very limited concerning lateral extension (up to few hundreds of metres) and depth (usually no more than a few tens of metres to remain above the water table and thus avoid mining works flooding during wet seasons).

Due to the limited size of the mining works and their age, the very old mining works that remain open are mostly limited to small residual voids. The potential problems that may develop on the surface above those ancient mining sites are thus usually limited to instabilities of low magnitude (e.g. small amount of continuous subsidence, small-size isolated sinkholes). The main danger may be related to mine shafts that have not been properly closed.

3.2 ROOM-AND-PILLAR MINING

In the room and pillar method, the deposit is excavated as completely as possible, leaving parts of the ore as pillars to support the hanging wall. The dimensions of the stopes (rooms or bords) and the pillars depend on factors such as the ore grade, the stability of the hanging wall, stability of the deposit, the thickness of the deposit and the rock pressure (depth below surface). Generally, the objective is to extract the deposit as completely as possible without jeopardising working conditions or personnel safety. In recent mining, the pillars are arranged in a regular pattern, and they can be circular, square or longitudinal walls that separate stopes (figure 3.1). Older workings can typically have irregularly shaped and placed pillars. Although some of the ore left in pillars can be extracted by “robbing” (pillar extraction) as a final operation in the mine, the deposits in the pillars usually are regarded as non-recoverable.

In modern mining sectors, pillar dimensions are calculated to be conform to a suitable safety factor, which is a function of the depth below surface, percent extraction and mining height. Consequently, the greater the depth below surface, the larger the pillars have to be to maintain an acceptable safety factor at a given mining height and room width.

Pillar size is also influenced by their intended function and life-span. Some pillars are intended to be extracted later, and are consequently larger than they would have been had they not been intended for later extraction. The main cause of post-mining problems in room-and-pillar mining is subsidence, usually occurring long time after the mine has closed. The main reason for this is that pillars may deteriorate and weaken over time.

Room and pillar mining methods appear to be well adapted to deposits with a horizontal or flat dip not exceeding about 30 degrees while the hanging wall and the deposit must be relatively competent. To increase the stability of the hanging wall, one may utilise roof bolting. Room-and-pillar mining is the only feasible method of mining flat deposits of limited thickness such as manganese, chrome and coal. Minimum development is required prior to mining. Roadways are however, required for transporting broken material and for access between working areas. Often, the required development can be combined with the actual mining operation, especially if it is on the deposit level, and some mined-out stopes can be utilised as transport routes. The method lends itself to trackless mechanisation particularly if the seam height exceeds 1.5 m.

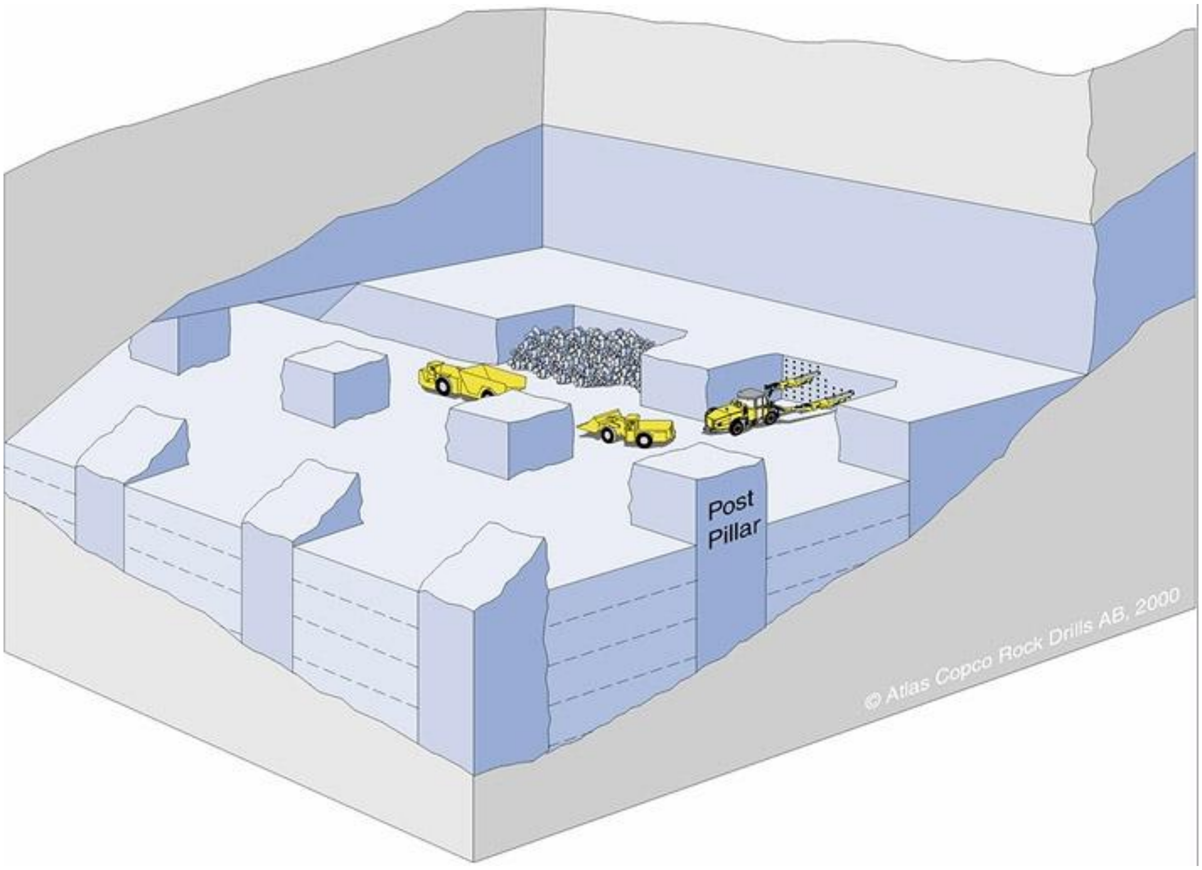

Figure 3.1. Room-and-pillar mining of a flat deposit (source www.atlascopco.com).

Pillar extraction or stooping refers to the method of mining, whereby pillars that were left in the course of room-and-pillar mining, are extracted on a retreat basis. The back area is left unsupported and is allowed to collapse. Methods that allow caving of the roof generally tend to give higher extraction rates than methods that rely on part of the ore reserve as means of support. Where pillar extraction is practised, the norm is to leave large pillars (safety factor in excess of 1.8) during the primary development phase while advancing. Once the panel development has been completed, the pillars are extracted during the secondary phase of mining on the retreat.

3.3 SUB-LEVEL STOPING OR BLASTHOLE STOPING

The sub-level stoping method only applies to vertical or steeply dipping ore bodies. Sub-level stoping is a mining method in which ore is extracted using ring drilling as a primary means of breaking the ore, and the stope can be left empty. The stope is often very large, with the largest dimension being in the vertical direction. To prevent the stope walls from collapsing, large ore bodies normally are divided into two or more separate stopes. Between the stopes, part of the ore is not mined, instead it is left in place to serve as the support for the hanging wall. These pillars can be both vertical and horizontal (crown pillars). In some cases the pillars can be recovered during the final stages of the mining operation.

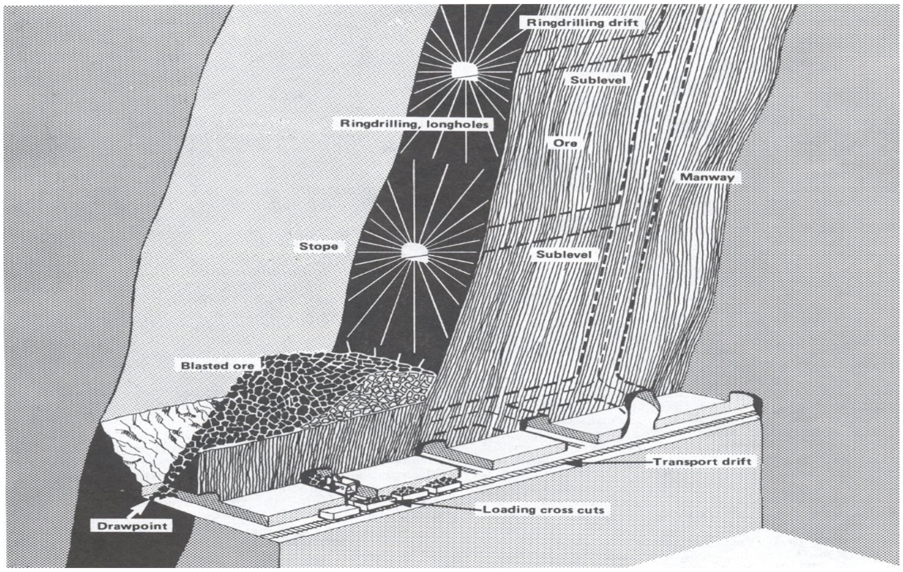

Figure 3.2. Sub level stoping with ring drilling (Atlas Copco, 1997).

3.4 SHRINKAGE STOPING

In this method, the ore is excavated in horizontal slices, starting at the bottom of the stope and advancing upward. Part of the broken ore is left in the mined-out stope, serving as a working platform, while mining the ore above and supporting the stope walls.

The blasted ore increases its occupied volume by about 70%, hence 30% to 40% of the ore must be drawn off continuously to keep a suitable working distance between the back and the top of the broken ore. When the stoping has advanced eventually to the upper limit of the planned stope, drilling and blasting are discontinued and the remaining 60% to 70% of the broken ore can be recovered. Small ore bodies are usually mined as a complete shrinkage stope, but large ore bodies usually are divided into separate stopes with intermediate pillars to stabilise the hanging wall. Generally the pillars are recovered when the regular mining operations have been completed.

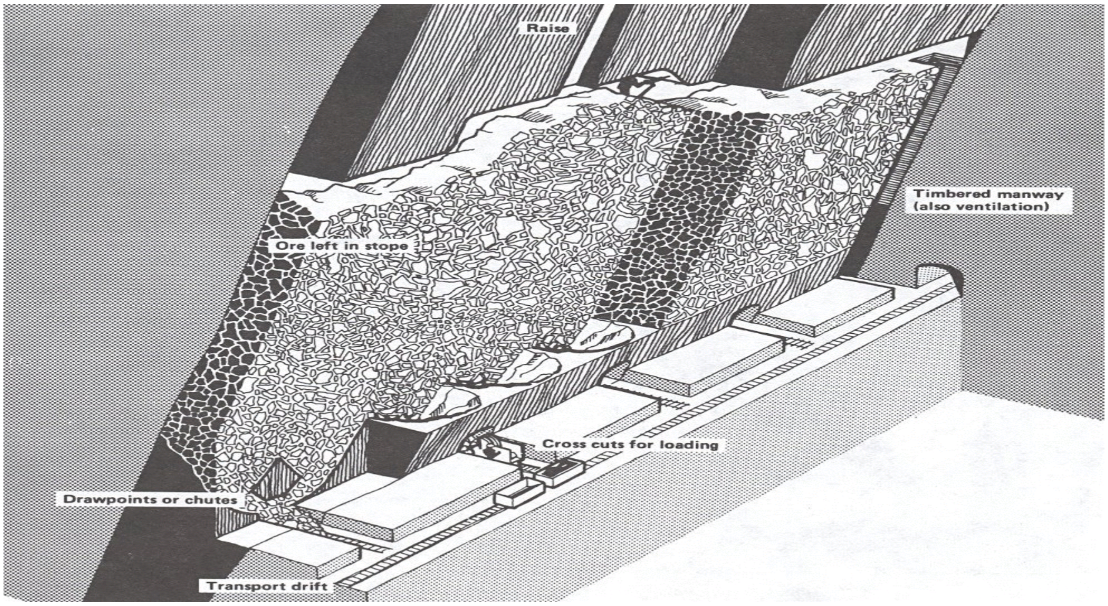

Figure 3.3. Shrinkage stoping in a large vertical body (Atlas Copco, 1997).

3.5 CUT-AND-FILL MINING

The cut-and-fill mining method excavates the ore in horizontal slices starting at the bottom of the stope and advancing upward (figure 3.1.4.1). The broken ore is loaded and completely removed from the stope. When a full slice has been excavated, the vacated volume is filled with waste material that supports the wall and provides a working platform prior to the mining of the next slice. The fill, mainly consisting of waste material can be distributed mechanically over the stoped-out area. In modern cut-and-fill operations however, the fill is distributed by hydraulic means. Normally the filling material consists of fine-grained tailings from the mill, mixed with water and piped into the mine. When the water is drained off, a competent fill with a smooth surface is produced. Cement is sometimes mixed in to provide harder and more durable support characteristics.

Cut-and-fill mining can be applied in steeply dipping ore bodies in reasonably strong ore. Compared with sub-level stoping and shrinkage used in similar ore bodies, the cut-and-fill system offers the advantage of selectivity. The system can also be adapted to irregular and discontinuous ore bodies extracting the high-grade ore and leaving the low grade and/or intercalated waste in the fill.

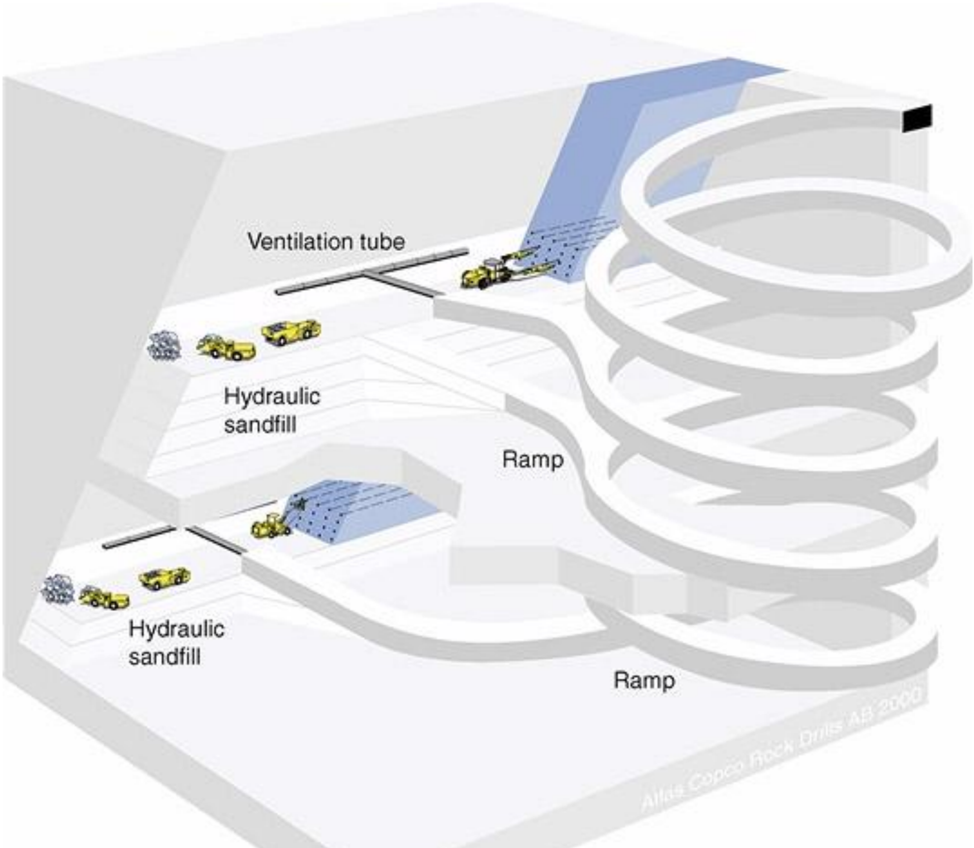

Figure 3.4. Cut-and-fill mining (Source www.atlascopco.com).

3.6 LONGWALL MINING

Hard rock

Longwall mining is typically practised by the deep level gold and platinum group metal mines in South Africa (figure 3.5). Longwall mining is applicable only to tabular thin-bedded deposits as a seam of large horizontal extent at great depth, usually in excess of 1,000 m.

Hard rock longwalling removes the ore in slices along a straight working face. The excavated area close to the face is supported to provide space for drilling and ore removal. At some distance from the face, the roof may be allowed to cave relieving pressure on the face and immediate working area.

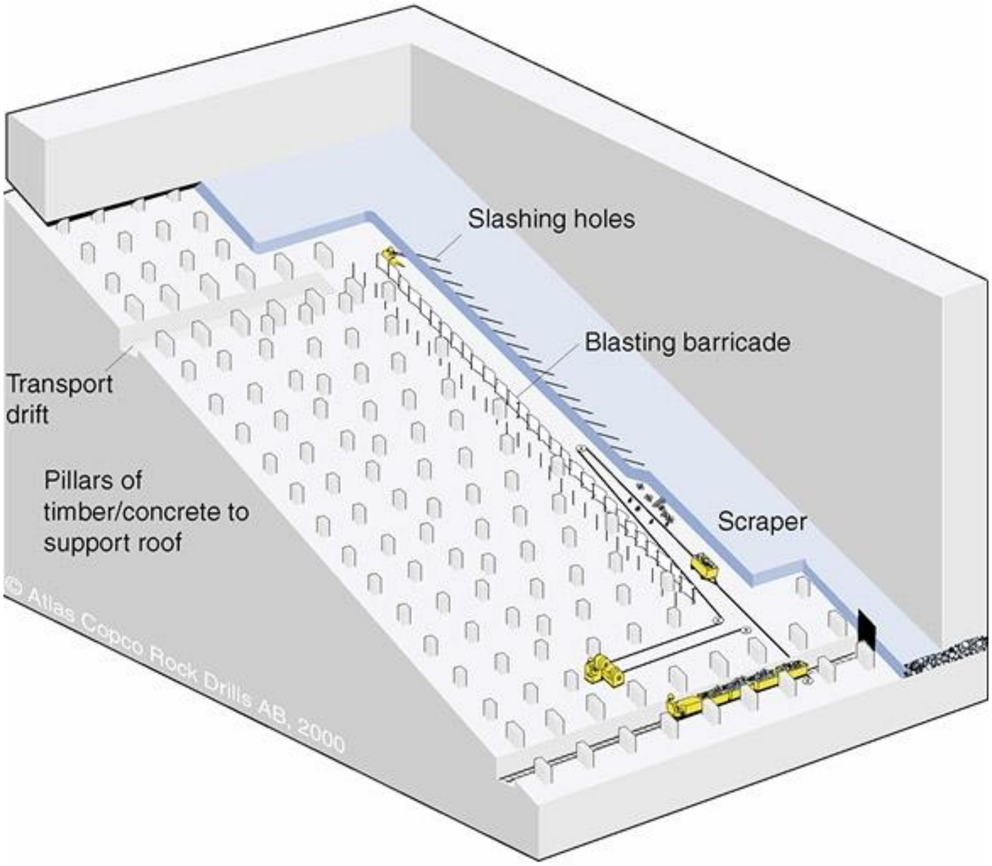

Figure 3.5. Longwall mining in a hard rock environment (Source www.atlascopco.com)

Coal

With the so-called longwall methods, the principle is to extract all of the coal over the width of the panel face in successive slices or cuts, with the roof being allowed to cave or goaf behind the supports (figure 3.6). There are two basic methods, namely longwalling and shortwalling. The difference between longwall and shortwall mining lies in the length of the face. Longwall faces are usually of the order of 150 m to 300 m long, while shortwall faces are in the range of 50 m to 100 m.

Wall mining can be practised as an advancing or a retreating system. It usually makes use of some type of shearer in conjunction with an armoured face conveyor as illustrated in figure 3.7. Face support is provided by self advancing hydraulic-powered supports.

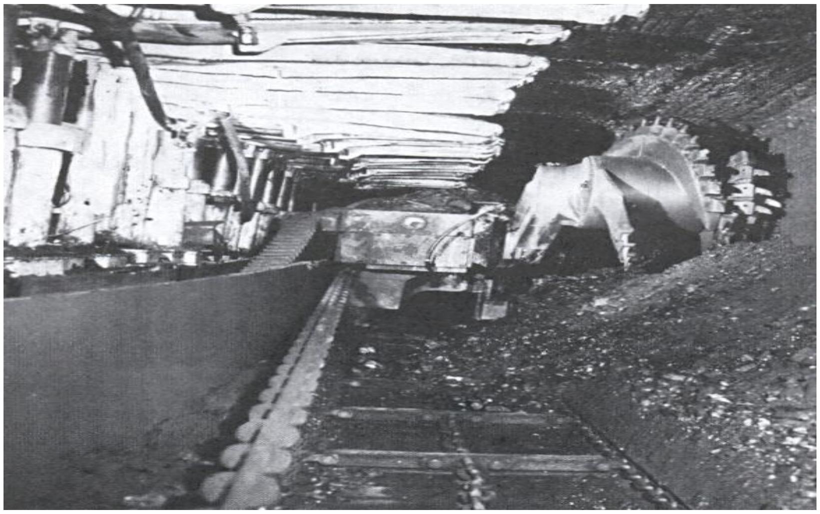

Figure 3.6. Typical longwall face equipped with a shearer loader, armoured face conveyor and shield supports.

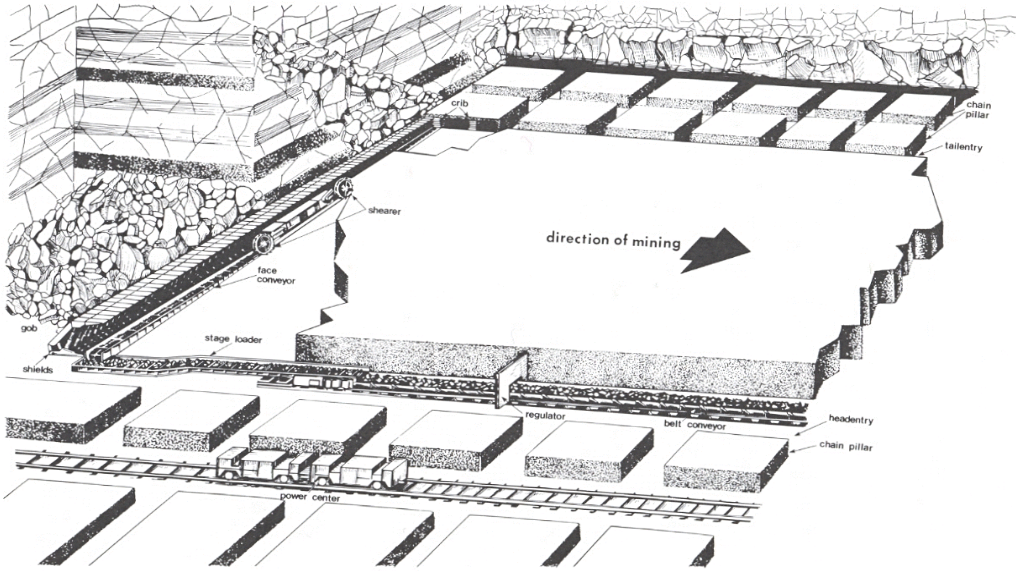

Figure 3.7. Typical longwall retreat lay-out (Atlas Copco, 1997).

3.6.1 Sub-level caving

Normally the orebody is divided into sub-levels with fairly close vertical spacing, 8 to 15 m apart. Each sub-level is developed with a regular network of drifts that penetrate the complete ore section as illustrated in figure 3.8. In wide ore bodies, the drifts are laid out as crosscuts from a footwall drift while in narrow deposits the drifts are parallel along the strike.

Sub-level caving is used in steeply dipping ore bodies and other deposits having large vertical dimensions. A primary requirement is that the ore is stable enough for the sub-level drifts to be largely self supporting, requiring only occasional reinforcement by roofbolts or similar support methods. The hanging wall must follow the ore extraction in a continuous cave, and surface conditions must allow for subsidence.

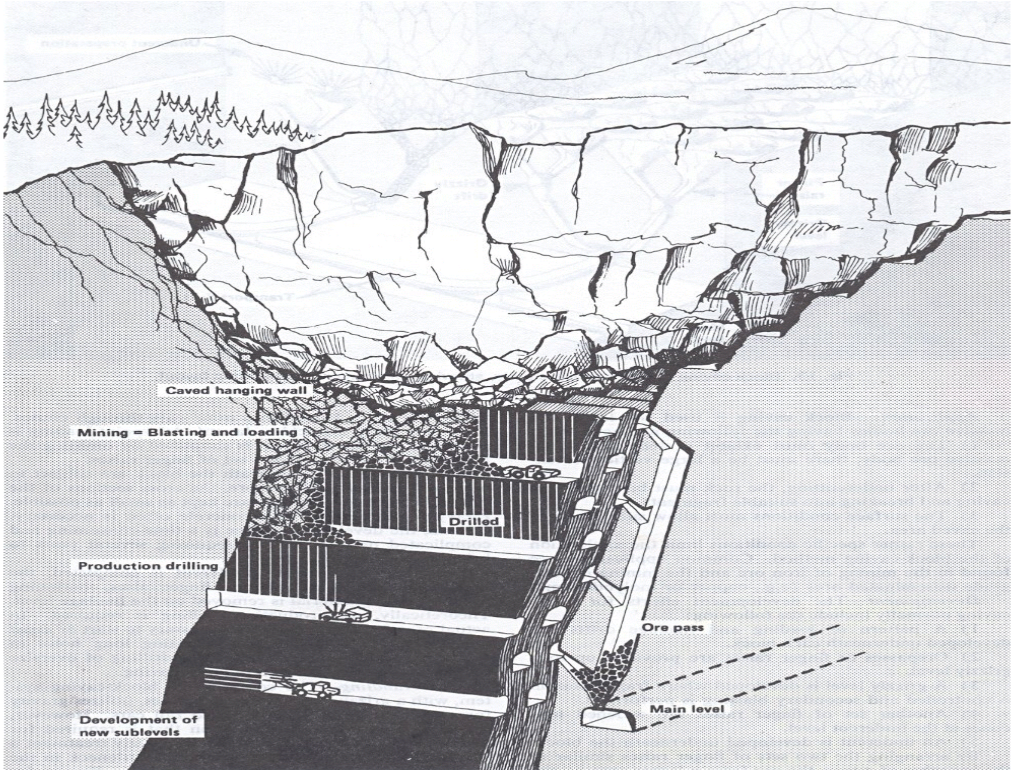

Figure 3.8. Sub level caving (Atlas Copco, 1997).

3.7 BLOCK CAVING

Block caving is a mining system that depends on the ore fracturing and breaking by itself as a result of internal stresses and forces. Virtually no drilling and blasting is needed in the production operation. If some drilling and blasting is required, it is kept to a minimum and is normally for secondary blasting to break up large oversized boulders causing blockages or "hangups" in draw points.

The mining plan is made up of large blocks, usually with a square horizontal cross section area of more than 1,000 m^2. Each block is undercut completely by a horizontal slot excavated in the lower part of the block as illustrated in figure 3.9. Gravity forces act on the rock mass and successive fracturing occurs, affecting the entire block. As the rock pressure increases at the bottom of the block, the ore is crushed to a fragmentation that allows removal at draw points.

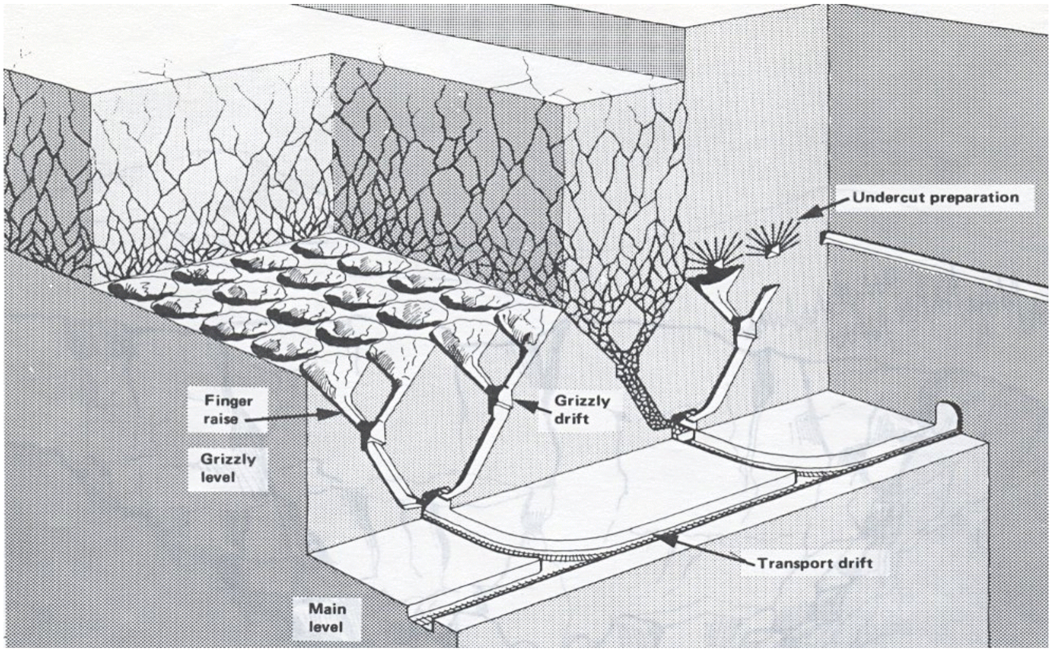

Figure 3.9. Block caving in a massive orebody (Atlas Copco, 1997).

Common applications are found in the mining of kimberlite pipes (diamonds), iron ore and low grade disseminated ores such as a porphyry copper or molybdenum.

3.8 REFERENCES

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4 NATURE OF GEOMECHANICAL HAZARDS

4.1 GROUND MOVEMENTS ABOVE UNDERGROUND MINES

4.1.1 Continuous movements

Subsidence or heave

Description and effects

Subsidence is characterised by a usually slow, smooth and flexible readjustment of surface. This well-known phenomenon induces topographical depressions without major failure that leads to a "dish-shaped" feature on surface (figure 4.1). In most cases, the maximum amplitudes observed in the centre of the depression, during or after operations, are on a decimetric to metric scale (Kratzsch, 1983; Peng, 1996).

Figure 4.1. Example of subsidence effect on a motorway.

Generally, it is not so much vertical displacements which affect surface buildings and infrastructures, but ground deformation (e.g. differential horizontal displacement, flexion, development of slopes; NCB, 1975). Depending on its position in the subsidence depression (figure 4.2), differential horizontal displacement may take the form of shortening (compressed zone toward the inside of the depression) or extension (tensile zones towards the outside of the depression).

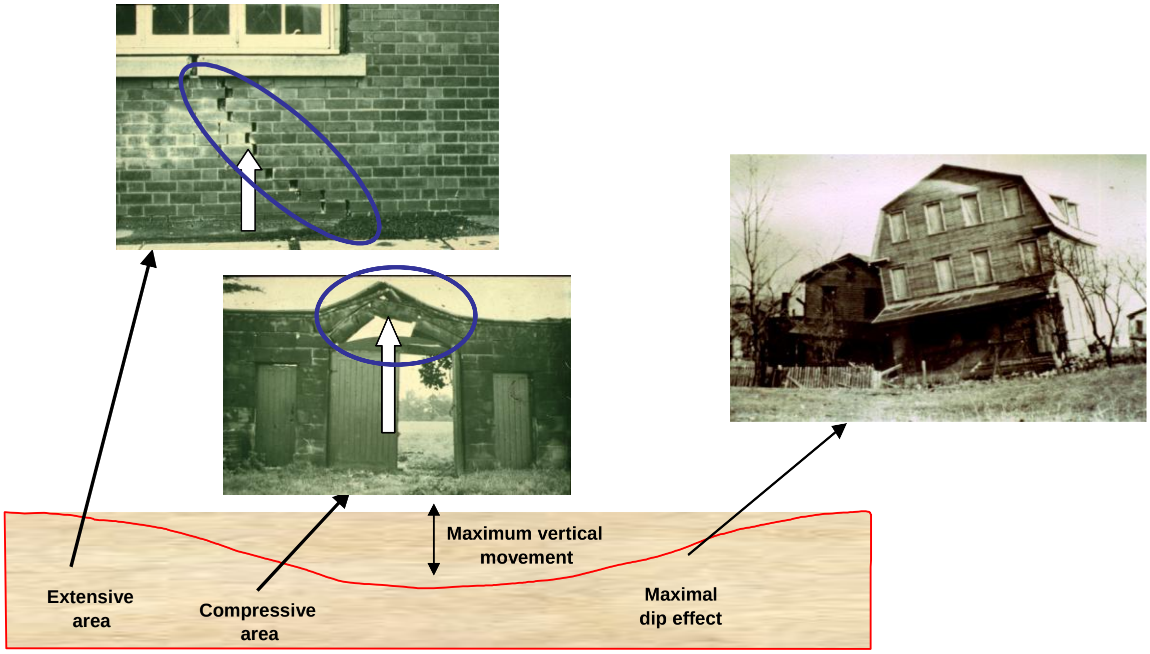

Figure 4.2. Effects of subsidence on surface structures.

In most cases, subsidence results from the collapse of underground cavities due to the extraction or “disappearance” (dissolution, combustion) of deposits. Deformations and slopes are then proportional to the maximum subsidence in the centre of the subsidence trough (itself proportional to the volume of residual voids underground) and inversely proportional to the depth of mining works. Therefore, for a single thickness exploited, the deeper the operations, the lower the size of the effect (Whittaker & Reddish, 1989).

Like most other instability events, mining subsidence is not strictly limited to the contours of the underground workings. The angle between the vertical and the straight line joining the underground perimeter of the workings and the outer limit of the surface subsidence depression is called the "angle of influence". Depending on the nature and thickness of the overburden, the angle of influence usually varies between ten and forty degrees. The existence of dip also has a direct influence on the angle of influence, as does the occurrence of major geological faults.

In some specific contexts however, subsidence may also be induced by recompaction of loose rock (spoil heaps made up of granular material) or strata affected by underground work (overburden located over sectors exploited by caving long time ago). Under the impact of outside disturbance (e.g. overloaded surface, flooding, vibratory stresses) or of their own weight, highly porous land may settle, causing slight surface movements (no more than decimetres, apart from exceptions). The feared consequences are mainly due to the fact that the surface can be affected by differential settlement which is likely to affect sensitive buildings and infrastructures.

Quite similar to this phenomenon, ground heave is sometimes observed above an abandoned working after flooding of the mine if there are no more active mining operations around. This is caused by unloading due to uplift by rising mine water, possibly supported by additional physical effects related to capillary strains and/or swelling processes in the rock and soil containing certain kind of clays. Except in very exceptional contexts, the impacts of ground heave on buildings and infrastructure is negligible due to the large extent of the phenomenon.

Initiating mechanisms or scenarios

Total extraction in stratified formations

Any total extraction method, at any depth, generates caving-in of the layers forming the roof of the underground workings (Van der Merwe & Madden, 2002). This failure generates the formation of blocks of variable shapes and sizes, which, piling up on top of each other, leave residual voids. This "bulking effect" can considerably increase the volume occupied by the broken rock compared to that occupied by the original intact rock.

The bulking effect makes it possible for the caved rock formed to fill the mining cavity and the volume originally occupied by solid rock. This thus stops the collapse process, enabling the overlying formations resting on the pile of broken rock. This broken rock remains, however, highly compressible. Thus, the overlying layers split by natural discontinuities, gradually bend and induce a progressive development of a surface depression. The amplitude of subsidence is directly proportional to the cavity cumulative opening. It is thus not rare to observe surface subsidence of several metres to, more exceptionally, more than ten metres during active operations.

The available feedback on various mining areas shows that almost all subsidence occurs during extraction and the period of residual subsidence is limited to just a few years. Later on, the risk of postponed subsidence (or uplift), resulting from major variations in environmental conditions (flooding or drainage of the workings, application of overload on the surface) and mainly concerns shallow mining works.

Partial extraction in stratified formations

For partial extraction methods, caving-in within underground workings results from the failure of structures providing general stability (pillars, middling, roof, foot-wall). This may develop several years, decades or even centuries after the mine has closed down (Madden et al., 1998). The "ageing" or "weathering" effects on rock strength can have an important role in the failure process. When the mining works cave-in over a sufficiently large area, expansion and flexion of overlying beds are quite similar to that occurring over a sector extracted by total extraction methods.

The amplitude of the subsidence is proportional to the volume of the cavities in underground workings. It is therefore not rare thay the vertical movement observed exceeds one metre. The movement amplitude is proportional to the extraction ratio. Indeed, the larger the pillars, the more space they occupy and thus they limit the displacement.

Subsidence in the area of partial operations can therefore be divided down into three separate phases. The first "installation" phase may be very long (several years to several hundred years). It is attributed to the gradual weakening of pillars under the cumulative effect of time, pressure from overlying formations and environmental parameters of the mine (water, temperature, etc.). The second "subsidence" phase occurs when the pillars start to fail, usually under the effect of a triggering factor (change in stresses or environmental parameters for example). It usually develops over a period varying from a few days to several months, during which most of the subsidence takes place on the surface. This is the most critical phase during which it may be necessary to monitor surface structures carefully. The last phase includes residual subsidence.Tthis phase can extend over fairly long periods (several years), residual movement is usually very limited, and in most cases, not detectable on the surface.

It must be noticed that the subsidence effect may develop up to the surface only if the extent of the underground mining works affected by failure is large enough as regard to mining depth. Otherwise the failure zone is restricted to an underground volume that does not affect surface stability.

Vein mining operations

Vein mining operations can also give rise to surface subsidence. When mining operations are very deep, because of the small volume of residual cavities (often small seams), surface damage usually takes the form of a wide extension of the surface depression of very low amplitude with regard to differential vertical and horizontal subsidence. Vein mining operations have given rise to several different operating methods. Therefore several mechanisms may generate development of surface subsidence troughs.

For backfilled rooms and pillars, the residual cavities and/or compressibility of the backfill may cause convergence of vein walls. This convergence results from the formation of a decompression dome around the mining works. If the pillars separating adjacent extracted sectors have failed and the mining works are sufficiently extensive, this decompression dome may reach the surface and generate subsidence (figure 4.3). The risk of slippage of fine backfill initiating the generation and then closure of deep cavities likely to generate surface subsidence, should also be noticed.

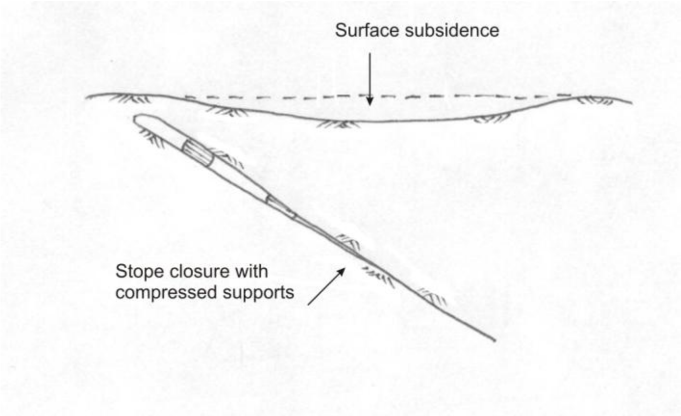

Figure 4.3. South African gold mine hangingwall subsidence (Stacey, 1981).

Operations using "abandoned pillar" or "caved sublevel" methods, can generate failed hanging-walls in chambers left empty or pillar failure, as for partial operations in stratified formations. When mining operations are deep, the repercussion of damage on the surface usually takes the form of a surface depression.

Salt solution mining

Surface lowering due to subsidence developing in areas of salt extraction may result from different mechanisms depending on the geological and operational contexts of the abandoned mine works.

During the operational phase, the extraction of large quantities of brine from the top of the salt layers results in preferential dissolution by leading surface freshwater down towards the salt, to replace the extracted brine. If large quantities of brine are extracted, the resulting subsidence may be significant and cause surface deformation, which may damage buildings or infrastructure.

Concerning the post-mining phase, hydrogeological modifications caused by salt extraction may lead to long (or even permanent) periods of unsaturated water flow on the surface of the salt layers. If these changes are slight and affect very large sectors, the effect on the surface is very limited and often undetectable. In some specific contexts however (significant thickness of salt, variation in dip of the layers), dissolution may remove enough salt to give rise to small but evident subsidence (Bérest, 2007).

Cavities created by salt dissolution tend to close because of the Specific Creep behaviour of salt. For shallow cavities (up to a few hundred metres), the closure is slow. This is not the case for deep cavities however (more than 1,000m) which close much rapidly. The result is surface subsidence, often slight because the closure "attracts" salt, which may come from far away. Subsidence therefore develops over a much wider area than the area of influence defined on the periphery of mines extracting other types of mineral. Finally, the slow, gradual intrusion of water into old evaporite mine workings exploited by total extraction methods, may lead to dissolution, also slow and gradual and likely to induce surface subsidence (Thoms & Gehle, 1994; Bérest & Côme, 1993).

Burning structures

Accidental or spontaneous heating of organic material remaining in old underground workings can initiate combustion in solid fuel mines (e.g. coal, lignite, bituminous shale). This combustion causes the "disappearance" of material and therefore the possible development of surface subsidence (figure 4.4). The slowness of this mechanism and the generally limited volumes of space created explain the fact that the surface effect is usually very limited subsidence.

Figure 4.4. Subsidence above underground fire in Pennsylvania (USA)
(Source http://www.offroaders.com/album/centralia/Jonathan_Gatarz/FL00026.jpg).

This phenomenon may also be observed on the surface of burning stockpiles or slag heaps in the area of old mine workings subject to spontaneous combustion. Apart from ground movement, other types of risks or harmful effects, which are much more critical, can affect people and property in the surroundings (fires, accumulation of toxic gases) or be the source of secondary accidents (e.g. proximity of gas feeders, presence of old munitions).

Ground located above old cave-in extraction methods zones

Even though most of the ground located above cave-in methods (longwalls, pillar extraction) are subject to subsidence during the residual movement phase, the most significant effects develop above shallow sectors (a few tens of metres below the surface). As a matter of fact, in these conditions, the overburden weight is not sufficient to guarantee complete re-compaction of the overburden affected during the years following mining operations. This results in the persistence of high artificial porosity close to the surface that may be re-compacted in time under the influence of external factors.

In very old locations that have been exploited by non-mechanised pillar extraction (stoping) or by short wall mining, it is common that some residual pillars or support piles remain unfailed within "goaf area". If those residual support structures fail eventually, long time after closure, some subsidence effects may develop on the surface even if the underlying mining areas have been exploited by total extraction methods. For recent mechanised sectors, this hazard may be neglected.

Subsidence over spoil heaps or backfilled open-cast or underground mines

Mining waste, dry deposited in the form of mine dump or used for filling in old open-cast mines, have often been simply dumped with no guarantee of satisfying compaction. In this case, the mining waste may, sometimes, develop large compaction, which may result in surface subsidence.

Usually, the magnitude of surface movements, proportional to waste thickness, is limited, except in the case of huge deposits.

Secondary compaction of loose land

Although it is very exceptional, a fairly similar mechanism can be observed when the hydrogeological regime is altered by mining operations closing down and groundwater levels changing in land sensitive to secondary compaction (peat-lands for instance). If a significant load is applied on the surface (buildings or infrastructures), secondary compaction can lead to significant settling even if the sector concerned is not directly affected by the old mining works.

Ground heave

During deep mining operations, dewatering pumping dries out the overburden. In certain specific contexts, resaturation of the rock mass during flooding can lead to slow ground heave, spreading throughout the previously drained zone (Pöttgens, 1998). The amplitude of vertical displacement can reach several decimetres. This phenomenon involves remobilisation of land affected by old mining operations after work has closed down.

With respect to available feedback, except for some very specific contexts (Heitfeld et al., 2006), movements of this type are widespread in area (small slope) and do not cause any visible effects on traditional buildings.

4.1.2 Discontinuous movements

Sinkholes

Description and effects

A sinkhole is characterised by a sudden appearance of a collapse crater at surface (Piggott & Eynon, 1978). The horizontal extension of this kind of instability varies usually from a few metres (figure 4.5) to several tens of metres in diameter (figure 4.6). The depth of the crater mainly depends on the depth and dimensions of the underground workings.

Although, in most cases, this depth is only a few metres. In some specific contexts, it can reach more than ten metres (shaft collapse for example).

Figure 4.5. Small sinkhole over disused shallow coal mining works (Katowice - the Upper Silesia Region – Poland).

Figure 4.6: Large sinkhole above a gypsum mine (Source INERIS).

Depending on the mechanism initiating the damage and the type of subsurface rock, the walls of the crater may be sub-vertical or inclined, thus giving rise to a characteristic funnel shape (figure 4.7).

Figure 4.7. Sinkhole crater

The dimensions of the crater and suddenness of its development on surface make sinkholes potentially dangerous events, particularly when they develop in or close to urban sectors or infrastructures (figures 4.8 and 4.9).

*Figure 4.8. Sinkhole crater in Korea (*photo by Song*).*

Figure 4.9. Sinkhole within urban area (Neuville-sur-Authou –Normandie – France, source CETE/MEEDAT).

<u>Initiating mechanisms or scenarios</u>

<u>Strata failure affecting the roof of a cavity</u>

When the dome initiated by the failure of the hanging-wall is not mechanically stabilised because of the presence of massive beds in the overburden, it gradually propagates towards the surface. Then, if there is enough space in the mining works for the bulking material to accumulate without preventing "self-backfilling", the dome may reach the surface (Wardell & Eynon, 1968). Although the development of an expansion dome is very slow and may take several years or decades. The appearance of a sinkhole on the surface is very sudden, which makes it potentially dangerous to people and property in the vicinity.

The occurrence of this kind of instability only is related to shallow workings. Evidence from several mining areas has shown that, within flat sedimentary deposits, old mine cavities can cause this type of surface event if they are less than forty to fifty metres deep (Taylor & Fowell, 2007). There may, nevertheless, be some exceptions in case of major geological or mining specificity (thick layer of sand in the overburden, very large cavity underground),

Chimneying Disintegration

Depending on the characteristics of overburden, several failure mechanisms may be lead to sinkhole development on surface. When the overburden failure is not mainly conditioned by joint orientation, one speaks of chimneying disintegration (Dyne, 1998). This mechanism includes horizontal to semi-horizontal strata failure (figure 4.10) as well as progressive failure of week rock mass. It leads to the creation of near vertically-sided cavities that cut across overburden and form narrow openings (<5 m). In the case of a weak, steep-dipping material bounded by competent hangingwall rock, the development of disintegration follows the contact (Bétournay, 1994).

Low-cohesion homogeneous material is the signature for potential chimneying disintegration, but the mechanism requires a shearing path of no resistance (figures 4.10 and 4.11). It occurs in weak rock (e.g. severely altered rock, sericitic or chlorite schists, graphitic slate) with very low cohesion (<0.2 MPa).

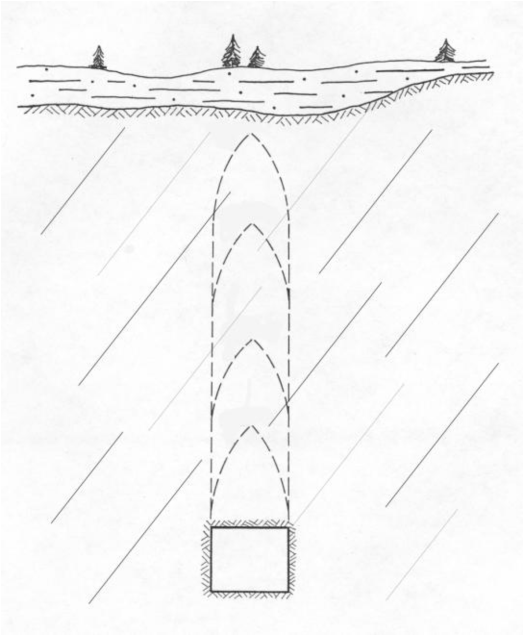

Figure 4.10. Chimneying disintegration in weak rock (Bétournay, 1994)

Figure 4.11. Examples of chimneying development in underground mining works

Ravelling

Gradual failure from an unsupported periphery of unfavourably oriented but well-developed rock blocks is common place when lateral confinement is low. Ravelling is the peripheral block-by-block rock mass failure when no self-support cavity form SERVED TO DEVELOP (figures 4.12 and 4.13). This can occur in the hangingwall, footwall, or the surface crown pillar. In unfavourable contexts, ravelling can reach the surface or cause destabilisation of a surface crown pillar.

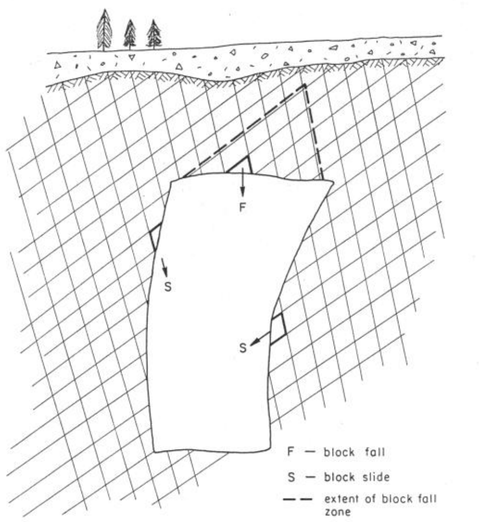

Figure 4.12. Generic ravelling (Bétournay, 2004)

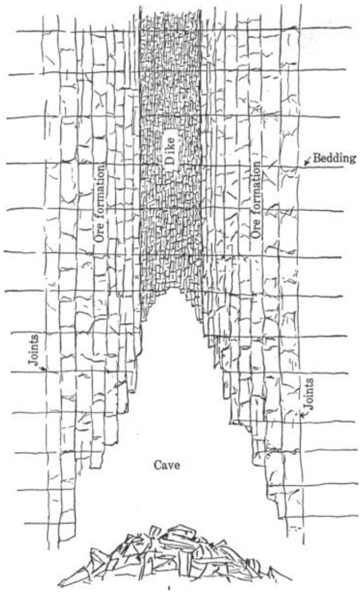

Figure 4.13. Progressive block ravelling block falls and slides with unfavourable joint orientations (Crane, 1929).

Isolated pillar failure

In abandoned room and pillar workings, the failure of one (or few) pillars can generate a sinkhole on the surface, if the mining voids are shallow enough and the overburden behaviour is sensitive to this kind of mechanism (Bruhn et al., 1981).

The size of the zone affected on the surface is much smaller than that of a general cave-in described later on. Like roof failure, isolated pillar failures are purely local events, which do not depend on the overall geometry of the workings, but simply unfavourable local rock mass conditions.

Figure 4.15. View of a degraded pillar in Provence – France (Source INERIS).

These unfavourable conditions may result from the working method having led to over-intensive local extraction in some sectors, leaving pillars which are too small, weakened or incorrectly superposed (figure 4.15). They may also result from geological heterogeneities (e.g. fractured or faulted zone, water inflow). Like roof failures, the occurrence of this type of surface damage only is related to shallow workings.

<u>Shaft failure</u>

An old mine shaft which has not been properly filled, may be affected by sudden backfill run-out. This is notably the case during the flooding period, if underground galleries are connected to the shaft. Backfill material may then flow within the available underground voids, with the resulting formation of a crater on surface (Didier, 1997; HMSO, 1994; NCB, 1982).

The backfill material remobilisation may, in some cases (very common in case of very old shaft), lead to failure of the shaft lining. In this case, the collapse of surrounding non-competent rock leads to formation of a crater, whose diameter is larger (diameter over ten metres) than that of the shaft (generally few meters).

Surface collapse can also result from the failure of an existing structure localised at the top of the shaft column (e.g. wooden cap, surface slab, incorrectly sized plug). In this case, the collapse may be confined to the shaft diameter if the lining remain stable. In case of shaft lining failure resulting from the disappearance of backfill material, a large crater may develop on surface all around the pre-existing shaft location (figure 4.16).

Figure 4.16. Sinkhole resulting of a shaft failure (Source BZR Arnsberg).

Plug failure

When a seam has been mined out close to the surface or when an open-cast mine has contributed to reduce the thickness of a pre-existing barrier pillar left on top of an underground mined seam, the risk of crown pillar failure must be assessed (figure 4.17).

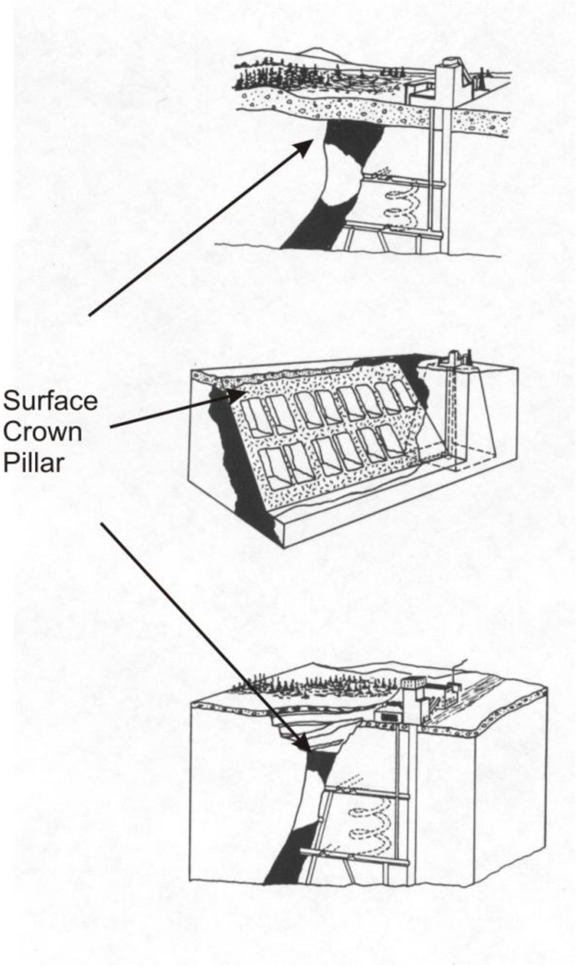

Figure 4.17. Examples of surface crown pillars of metal mines (Bétournay, 2004)

A plug failure is the sudden fall of the surface crown pillar as an integral block, delineated by well-defined boundary plane discontinuities, into the shallow stope (figure 4.18). Case studies have shown that failures occur under well-defined, continuous or near-continuous peripheral discontinuity conditions (Bétournay, 2004). In very unfavourable context, plug heights can be as great as several hundreds of metres. They also show that bounding surface frictional properties need to be low and lateral confinement insufficient to mobilise sufficient shear strength (e.g. areas of high lateral underground extraction or low tectonic stress). There is a significant reduction in failure potential when the bounding planes are not continuous and the dip of the planes decreases from vertical.

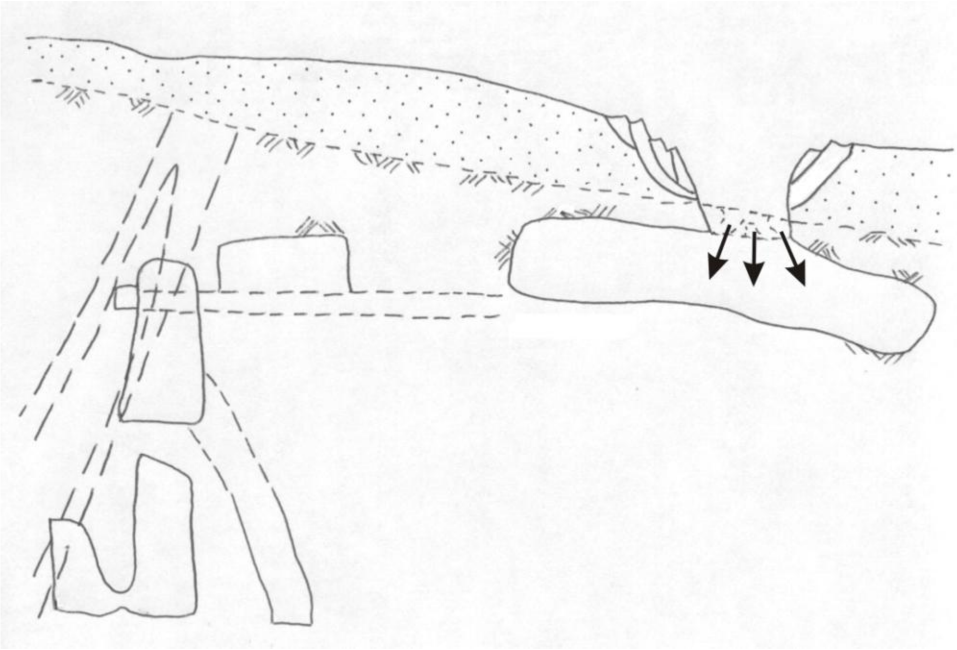

Figure 4.18. McAdam gold mine, Quebec, surface crown pillar rupture (Golder Associates, 1990).

These failures can crush underlying stope pillars when they are insufficient to support the load of the plug (figure 4.19).

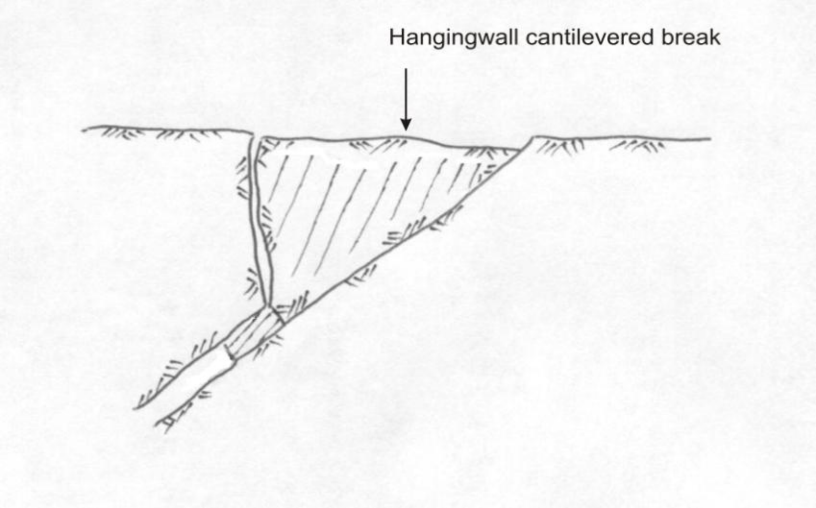

Figure 4.19. South African gold mine hangingwall break (Stacey, 1981).

In some cases, the top portion of the hangingwall of dipping tabular orebodies can drop when it is bounded by extensive discontinuities such as faults or intrusive contacts (Figure 4.20).

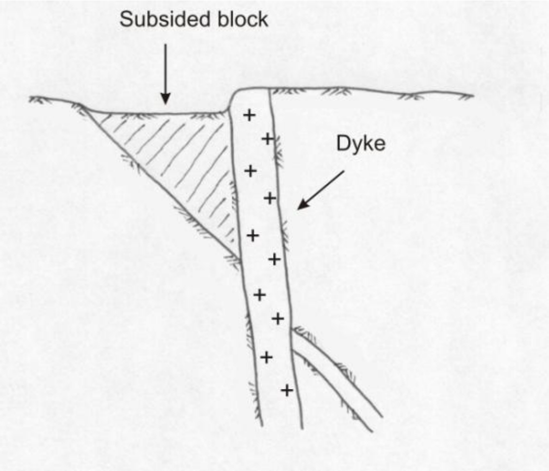

Figure 4.20. South African gold mine hangingwall drop (Stacey, 1981).

Fill run-out

This mechanism, likely to affect strongly inclined layers, is quite similar to that of shaft backfill material remobilisation. In certain cases where the overburden cover is thin, extraction of shallow stopes to surface has been performed and loose fill placed in the stope. Most of the time such filling has not been contained by bulkheads or proper barriers placed to prevent fill-run out.

Two failure modes may occur under such circumstances. The fill may run out progressively leaving behind a “rat hole” chimneying with sloughing of sides, or, on the other hand, lead to a sudden collapse of the top portion of the fill (figure 4.21).

Figure 4.21. Consequence of sudden stope fill collapse, Moneta gold mine, Ontario (Hunt, 1989).

Underground combustion

In some very specific configurations, the combustion of carbonaceous materials in underground mining works or abandoned mining waste dumps, can generate the formation of small cavities close to the surface which are likely to collapse. In this type of scenario, the incandescent temperature of fumes (up to several hundred degrees) may aggravate the potential consequences for victims (figure 4.22).

Figure 4.22. Sinkhole above underground fire in Pennsylvania (USA)
(Source http://www.offroaders.com/album/centralia/Jonathan_Gatarz/FL00026.jpg)

Discontinuous subsidence

Description and effects

Some general discontinuous subsidence events are caused by dynamic failure of all or part of the mining works, which may affect surface stability over several hectares. The height of the maximum subsidence at the central part of the trough can reach several metres. In some very specific contexts (thick salt layer dissolution for example), the vertical displacement can reach up to ten metres. On the opposite of continuous subsidence, in a discontinuous event, the central trough is edged with open, sub-vertical cracks, marking out "steps" (figures 4.23 and 4.24), which can generate severe damage to people and property.

Figure 4.23. Major discontinuous subsidence associated with vertical cracks
(Crouzilles – Pays de Loire – France, source INERIS).

Figure 4.24. Crater above Waihi gold mine - New-Zealand (Richards et al., 2002).

Those kinds of events denote a general instability of the mining works, usually due to over-intensive extraction combined with the presence and a stiff horizon (ore pillars or within the overburden). Fortunately, these events are very rare but the consequences are potentially serious because they release a considerable amount of energy. They may be accompanied by earth tremors, sometimes detectable up to several hundred kilometres from the sector concerned. Note also the blast effect, which is likely to project materials over long distances through the drifts and open shafts, endangering people and installations nearby ("air blast" phenomenon).

Contrary to local cave-in (sinkholes), general discontinuous subsidence effects generally concern relatively deep mines. Their occurrence also requires adequate horizontal extension relative to their depth.

Initiating mechanisms or scenarios

Concomitant failure of overburden and abandoned pillars

General discontinuous subsidence events require an unfavourable combination of criteria that may result in failure initiation. They develop in case of simultaneous failure of both pillars and overburden (Didier & Josien, 2003). Two conditions usually are required (figure 4.25).

Such events require a mining works configuration that may be qualified as "brittle” in the meaning of sensitive to massive and sudden failure. In this sense, a high extraction ratio, large cavity volumes and weak mining works configurations (small pillars, low width/heignt ratio, multilevel operations with poor superimposition of pillars) constitute parameters, which may promote global mine collapse.

Furthermore, one generally considers that pillar failure must be linked with concomitant failure of the overburden. Thus, these events develop preferably under overburden with one or more rigid horizons, capable of supporting all or a part of the weight of the surface layers, transferring it into unexploited borders. This mechanism temporarily relieves the pillars and indirectly allows excessive extraction to take place (small to very small pillars).

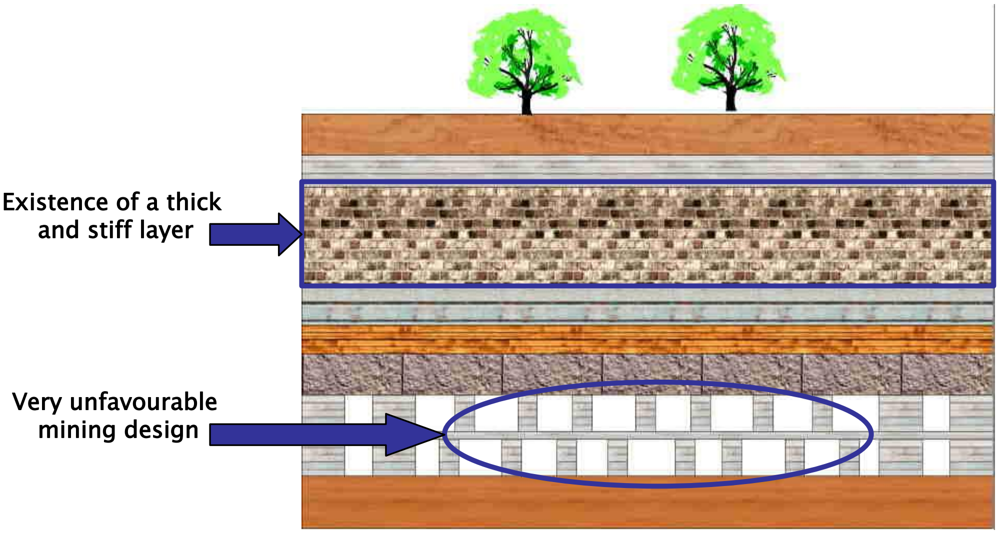

Figure 4.25. Favourable conditions to sudden collapse development.

If the rigid layers in the overburden reach their limit of elasticity, they may suddenly fail. This failure, by deflection or shear along the rigid edges, leads to an overload on the pillars, which are suddenly required to take the full weight of the overburden. The very brittle pillars may then fail simultaneously. The already affected overburden subsequently collapses very quickly (in several seconds), which explains the suddenness and potential dangerousness of the surface movements.

Pillars failure by "domino effect"

Unstability of a large number of pillars does not always lead to sudden collapse provoking a major earth tremor. The discontinuous subsidence may also be gradual and due to a progressive failure of adjacent pillars due to a "domino effect".

However this type of occurrence seems to be fairly rare. Pillars must be constituted of a brittle ore deposit and present a low width/height ration. Moreover, most pillars should have reached a "post-failure" state. Modification or development of a triggering factor may then initiate failure in some pillars. By failing, these transfer the load onto neighbouring pillars, which fail in turn. The overburden then deflates, following the front of the underground cave-in. It is not as violent as the mechanism described above, but the subsidence kinetics makes it potentially dangerous to people and property in the vicinity if major surface movement is involved.

Cave-in of saline dissolution cavities

This problem results from delayed roof failure of isolated saline cavities, the size of which, has exceeded the limit of stability of the structure. The evolution of cavities of the sizes, even long time after the end of brine extraction, is explained by connections between neighbouring cavities, allowing unsaturated water to circulate. The result of this fresh water circulation is the dissolution of salt, preferably at the top of the cavities.

In most cases, these collapses develop over several hours or several tens of hours, the movement kinetics depending on the evacuation of the brine (figure 4.26).

Figure 4.26. Collapse above an old salt dissolution mine in France (By courtesy of Bernard Feuga).

If this brine is replaced by air, which is a rare occurrence, movement may be sudden (figure 4.27).

Figure 4.27. Collapse of the salt cavern of Ocnele Mari – Romania (By courtesy of Bernard Feuga).

Serious damage can be caused by unsealed boreholes crossing salt layers and charged water levels below these formations. Rising water can also produce dissolution and create large cavities within evaporites.

Rock Mass Caving

Rock mass caving is the break-up and gravity mobilisation of blocks (flow) towards and into an opening leading to a progressive failure front moving towards surface (figure 4.27). It is a larger-scope process that may begin, as shown by case studies, with ravelling or chimney disintegration. Few cases of this type of failure have been reported (Bétournay, 2004)

The following conditions may lead to the inception and continuation of mass caving:

- persistent discontinuities
- small block size, of similar shapes
- low block surface friction and low intact rock compressive strength
- low horizontal stresses
- high underground opening spans
- low-dip angle discontinuities

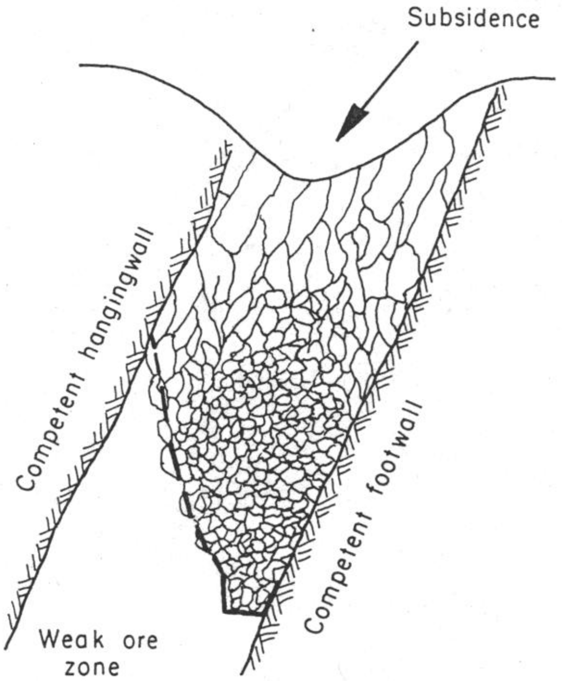

Figure 4.27. Rock mass caving development (Bétournay, 2004)

4.1.3 Induced seismicity

Mining induced seismicity can range in magnitude from less than 1.0 on Richter Scale to more than 5.0. Only a few events with a magnitude higher than 5 have taken place. These events usually occur in areas mined out at great depth, more than 1 000 m below surface. In South Africa, this often occurs in gold mining districts like Johannesburg, Carletonville, Klerksdorp and the Free State gold fields. It has also occurred with various magnitudes in deep coal mining districts in Europe, in several coal basins of France, Poland and Czech Republic.

The mechanism(s) have not yet been sufficently explaindeed, but it is generally accepted that the larger events are associated with major geological discontinuities such as faults : forces acting parallel to them, mau resultd in a displacement of one plane relative to the other. These forces are countered by those acting perpendicular to the fault, clamping the two planes together.

Under certain conditions, mining may cause an increase of the parallel forces or a decrease of the perpendicular forces or both, resulting in a displacement of one plane relative to the other. This in turn gives rise to a seismic shock. The released energy is due to potential energy of the rock compressed at great depth and the energy disturbance caused by mining. In general, mining is often the only trigger that may great release a energy leading to a seismic event.

Seismic events release large amounts of energy, which are dissipated in the rock mass in the form of vibrations. The magnitude of the vibrations and the shock period depend on the amount of energy period released. Mining indirectly causes other energy transfers in the earth's crust, which already contains staggering amounts of energy accumulated mainly in the form of deformation energy, caused by the rock mass weight.

This stored energy does not always generate movement at an equilibrium state : if the forces are in balance with one another, like two people trying to push a car from opposite sides, rockmass will not move even in presence of the acting forces.

Two important consequences of mining are that, firstly, by removing a certain amount of rock, it also removes one of the balancing forces and secondly, it creates space for the unmined rock to move into. This has the potential to release substantial amounts of energy through the movement of the unmined rock above (and also below) the mining void.

A part of this energy is released by lowering the rock mass above the void and heaving of the rock below the excavation. Another part is also spent in fracturing the rock mass around the excavations and finally a part is available for a further deformation of the rock. The latter is stored in the form of deformation (or strain) energy and can later be released either by further fracturing of the rock or by causing large volumes of the rock to move, especially at the positions of pre-existing fractures in the rock, or faults. This is one of the causes of seismicity indirectly caused by mining.

Induced seismicity is usually associated with active mines. The aim of the mining operator is to protect workers underground when a seismic event occurs, generally in trying to predict them so that working places can be evacuated on time.

Induced seismicity does not necessarily disappear after mine closure. Once mining has ceased, even if deformations of the rock mass do not occur at the same rate as during mining, some residual compression can still be active at a diminishing rate. The main concern however, is the potential change in the environment, especially water level rising and, consequently, increase of the hydraulic pressure. This may lubricate pre-existing fault planes, reducing the resistance to displacement and thereby inducing seismic events.

The impact of seismicity in closed mines is not restricted to damage on buildings located on surface. Especially in the case of old mining districts with several closed mines, large seismic events can damage or destroy water plugs placed between mines, disrupting the post closure water management systems.

4.2 SLOPE INSTABILITIES

4.2.1 Rock falls

Definition and effects

A rock fall is a sudden slope movement during which more or less voluminous masses of rock detach from a usually steep rock face and fall down. This essentially concerns open-pit mines excavated in hard rock formations, with steep slopes (Franklin & Dusseault, 1991). Depending on the volume of rock falling, this is referred to stones (< 0.1 m^3), blocks (0.1 m^3 to 10 m^3), rock falls (10 m^3 to 10^4 m^3), or major rock falls (> 10^4 m^3). Whatever the fallen volume, the fall of loose rocks is dangerous to human life within the area of influence. For volumes over 1 m^3, this type of event may also cause irreversible damage to property.

It is therefore essential to identify the extent of the cone of influence, even approximately (Evans & Hungr, 1993). This firstly depends on the type and slope of the land at the foot of the cliff. A slope toe consisting of rock oriented steeply downstream would favour the propagation of blocks over large distances. Extension of the area of influence also depends on the volume of unstable material. All things being equal, because of the mass effect, the distance of propagation is usually greater for mass rock fall than for isolated blocks. The more fractured the mass of rocks which falls, the more it is likely to break into smaller blocks while falling, which favours propagation downhill. Finally, the dimensions of the area of influence also depend on the type and kinetics of movement initiated the rock fall (e.g. toppling, slipping).

For major rock falls, analysis of the effect of the retreating of the rock face may need particular attention if the top edges are close to urban areas.

Initiating mechanisms or scenarios

There are a large number of mechanisms likely to initiate rock falls (Hungr & Evans, 1988). It is usually a combination of the discontinuity network affecting the rock mass (e.g. stratification joints, faults, fractures) and pit flank geometry (height, slope angle, presence of overhangs, etc.) which determines the type of mechanism initiating the failure.

We shall list few of them, without describing in detail. More detail can be found in specialist literature, widely available.

- **Failure of rock masses** : Failure occurs when an unstable rock mass suddenly detaches from the rock face and falls to its foot under the effect of gravity with a mainly vertical trajectory. Several types of geometry (figure 4.28) may cause this rock mass failure mechanism (e.g. overhanging fall, monoliths failure).

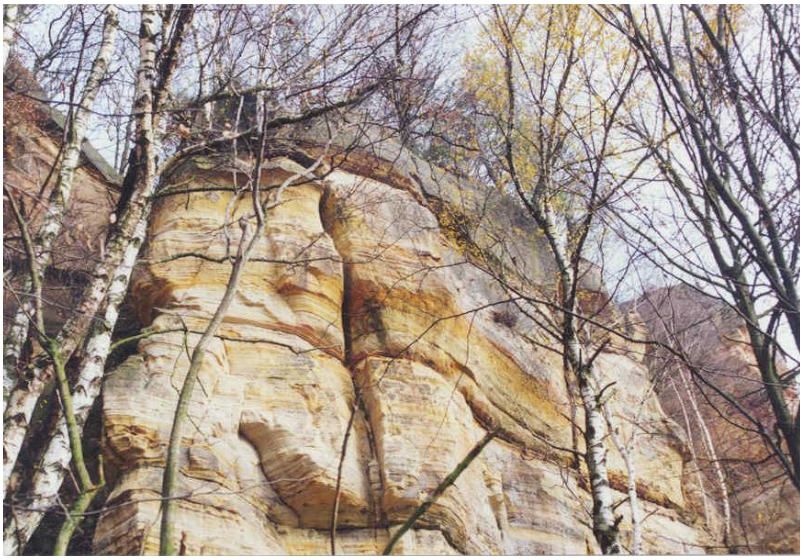

Figure 4.28. Potentially unstable flank of a sandstone open pit mine - North-East France (Source INERIS).

- **Rock slides** : Slides occur when the unstability is propagated along one (or more) tilted heterogeneities which “dailight” on the face. This type of phenomenon occurs when friction between beds is not high enough to contain the forces generated by the weight of the overlying beds. It may be facilitated by the presence of clay stratification joints and/or the natural or artificial weakening of an efficient stop at the foot of the slope (excavation for example). These are called planar slides when the failure takes place along an individual flat weakened surface or corner (or dihedral) slides when two discontinuity planes meet along a line with downwards dip intercepting the side of the pit.
- **Complex ruptures** : Rock falls often result from complex mechanisms or a combination of basic mechanisms. To avoid detail, beyond the scope of this guidelines, we shall simply list undercutting, buckling and creep mechanisms affecting soft layers at the foot of the slope and multi-linear slides.

4.2.2 Slides or slope movement

Definition and effects

Slope movements, whether shallow or deep (slides, erosion), are most commonly observed along the sides of waste heaps or slopes of excavations in loose rock and rock masses of shallow or deep open pit mines.

Shallow rubble movements

These are generally slow and involve small volumes of material (a few tens of m^3). They mainly take the form of superficial erosion, leading to the accumulation of material at the foot. If the debris is not reorganised, this configuration becomes stable again and the instability ceases.

Although this type of event is often a nuisance in the landscape, it is relatively rare to generate risks to people and property, either at the foot or the top of the slope. However, the rubble may affect water flow immediately downstream of the foot of the slope. Furthermore, when eroded gulleys are up to several metres deep with subvertical walls, the risk of someone falling into these "canyons" and the risk of falling rocks or burial in a slide from the walls must be taken into consideration.

The development of shallow instabilities may promote a more serious failure and must therefore be taken into consideration systematically. Particular attention must be paid to the development of this type of damage along the faces of retention dams. Indeed, even limited weakening of structures holding liquid residues must not be neglected under any circumstances.

Deep movements

Deep slipping is due to the movement of a landmass along a failure zone defined by one or several continuous intersecting surfaces or one which will incorporate discontinuities and/or week rock material (HMSO, 1991). These may be circular, flat or of another shape, with a displacement rate in the critical movement phase varying from a few millimetres to a few metres per hour (figure 4.29). This type of phenomenon is likely to affect waste heaps, the ranging walls in soft rock and slopes of shallow to deep open pit mines (Bishop, 1973).

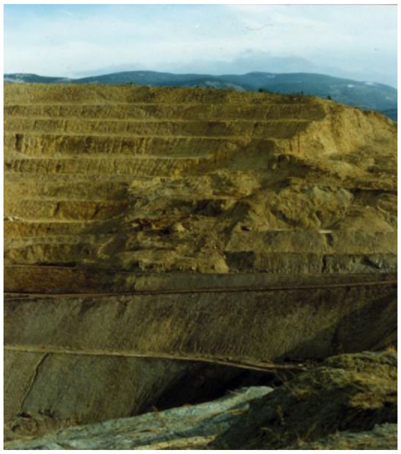

Figure 4.29. Slope failure in a French open pit mine (Source CdF).

The volumes concerned, which may be significant, spread downhill in the form of a cone and can cause damage to any buildings and structures at the foot of the slope. It may also be necessary to characterise the effects that these mass movements may have on land above the slope (crest retreat effect).

When discontinuities in the rock formation or in the waste heap do not play a dominant role in the behaviour, the instability usually takes the shape of a circle or "arc". On the other hand, when the instability arises in a layer or heterogeneity with poor geomechanical characteristics, it is more likely to be a flat slide.

Any dam failure, even initially slow and gradual, is likely to turn into a slide if the materials stored upstream manage to submerge the failed structure and overflow into the surounding area.

Initiating mechanisms or scenarios

The face of a slope fails when the driving forces (weight and hydraulics forces), become greater than the resistant forces (shear strength) opposing slope deformation and slipping. Usually the development of disturbances results in failure initiation.

Poor water management

The development of slope movement often results from poor groundwater or surface water management. In absence of a control system of drainage and water flow (or when this system is no longer efficient), water runoff down the sides of the slope can start it moving, particularly in areas of heavy rain fall (Mediterranean storms for example). A high groundwater level may affect rock mass discontinuity shear strength if the water level reaches above the toe of the slope and water can flow out from the slope surface.

Failure may also occur if the hydraulic conditions governing a waste dump, for instance, are altered, particularly at the base. In most configurations, the deposit consists of permeable drained material. Nevertheless, certain changes in water flow regime (blockage or failure of a drain, etc.) can contribute to accumulate stagnant water at the interface between deposit and base rock or form swampy zones at the foot of the heap. When the characteristics of the materials forming the base of the slope are sensitive to water, the changes in hydraulic conditions may be a source of failure.

Inappropriate face topography

The development of surface movements is mostly observed on faces with little vegetation, and a large proportion of fine particles (so that some dams may be very sensitive). Where there are large flat surfaces slightly tilted towards the downstream slope or while the downstream slope is too steep, a skin flow or regressive flank erosion are developped (NCB, 1967).

Weakening the base of the slope

Deep failures may develop if the toe of the slope is weakened. This may be due to large quantities of material being removed as a matter of a severe flooding affecting a watercourse following the toe of the slope. Removing material from the toe of the slope for using elsewhere or for developing the land can also contribute to a local unstabilisaty. Finally, if the bottom of the slope is affected by the presence of old potentially unstable underground mine workings, remobilisation of material at the toe of the slope can make the entire heap unstable.

Ground failure

When ground surface failure or creep one water-sensitive (clayey silt for example), it may also be a source of slope instability. The weakening of the mechanical characteristics can generate deformation of the deposit or sides of a pit, under its own weight effect, usually in the direction of the land’s natural slope. A characteristic bulge then forms at the foot of the ground surface.

Other mechanisms

Finally, other aggravating or triggering mechanisms such as dynamic stresses (e.g. earthquakes, vibrations), certain developments (removal of vegetation, uncontrolled development work), some human activities (mountain biking, moto-cross, overloading on the edge of the crest, etc.) or animals (digging ones) are likely to contribute to make the sides of the slope unstable.

On the other hand, some oxidated materials, may have a higher cohesion initially, due to physicochemical transformation. This a factor may help to preserve the overall stability.

4.2.3 Flow slides

Definition and effects

Dynamic flow slides can be placed in between material transport by water and slope failure. Flow slides are the most dangerous disorders likely to affect people and property in the neighbourhood of slopes associated with old waste heaps.

They mainly affect lagoons, which consist of retention ponds of fine materials. This kind of phenomenon may have potential catastrophic environmental consequences (two well known recent examples: Aznalcóllar in Spain [figure 4.30] and Baïa Mare in Romania both occurred during the operating phase). In addition, the propagation of very large quantities of semi-fluid materials at high speed over long distances (similar to an avalanche) can also represent high risks to people and property in the area of the flow.

The flow distance depends on the deposit characteristics (height, volume) and slope geometry (a flow slide is more destructive if the slope is steep). Several hundred metres or more is very common.

Figure 4.30. View of the Aznalcollar dam failure consequences.
(Source http://edafologia.ugr.es/donana/recursos/presa.jpg).

Initiating mechanisms or scenarios

Flow slides affecting old tailings

Weakening and failure of the retention dams built to stabilise tailings usally initiates this type of flow slide. When the dam breaks, fine wet materials without any cohesion may be released.

Dam construction techniques are of major importance. The so-called "upstream" method (the oldest and the least costly in terms of space and materials constituting the flanks) is much more sensitive to major failure than "vertical" or "downstream" methods. This is mainly due to the fact that, in the “upstream” context, the dyke's flank stability is largely dependent on powdered materials, more or less well consolidated, forming the waste itself.

Flow slides due to tailings liquefaction

Flow slides can also be initiated by liquefaction mechanism that may affect tailings materials. When powdered and saturated material inadequately drained, in case of severe vibration (e.g. earthquakes, mine explosion, caving-in of part of the slope), there may be an increase in interstitial pressure within the deposit. When this interstitial pressure exceeds the contact force between grains, the materials even partly consolidated may suddenly liquefy and cause a sudden transmission of stresses onto the dam flanks (Troncosco & Garcès, 2007).

Burning cloud

The mechanisms which can initiate the development of a dynamic flow in semi-fluid materials, consist of the possible flow of hot material leading to the formation of a “burning cloud” (figure 4.31), which may cover large areas at the heap bottom with potentially fatal burning dust (Bishop, 1969).

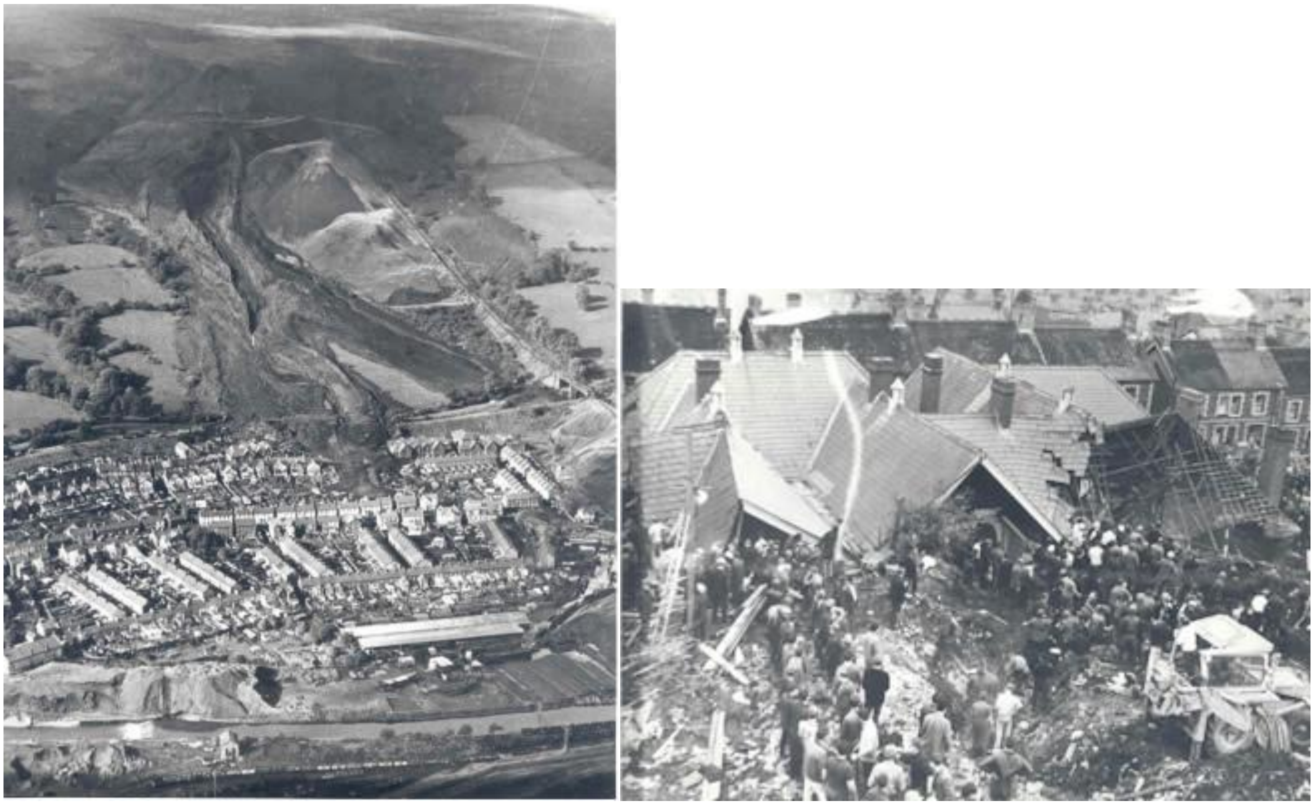

Figure 4.31 : Views of the Aberfan (Wales) Disaster - 21st October 1966 (Source South Wales Police http://www.south-wales.police.uk/fe/master.asp?n1=8&n2=253&n3=492).

Flow slides affecting pit slopes in open-cast mines

These flow slides result from the liquefaction of loose materials (mainly debris on the sides), which are heterogeneous with mainly clay matrix. With the arrival of a large quantity of water (heavy rain, failed drain or conduits, etc.), the water content of these materials may suddenly exceed the critical water content of the matrix. These initially solid elements may then have a semi-fluid material behaviour, flowing down the sides of the pit. The lack of effective drainage to cope with surface flow is a factor in favour of this type of event.

Striking examples include strip mining coal waste pile (>100 m height) failures occurred in Canadian Rockies, running for several kilometres under flow a driven by compressed air and water.

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5 HAZARD ASSESSMENT METHODS

5.1 DEFINITIONS

The majority of rock mechanics experts (and at least those present in the commission) agree on the definition of a hazard. Generically, a hazard corresponds to a condition that has a potential for causing an undesirable consequence (Canadian standards Association 1991).

A specific hazard can be defined by the possibility of its occurrence and on the possibility of a specific magnitude at a specific location.

Hazard = probability of occurrence × possible physical magnitude

Considering surface instabilities, it may for example be characterised by diameter of a crater, horizontal deformations along a subsidence though, volume of unstable rock mass.

Predicting a-priori, the specific magnitude of a hazard, even from well-defined data, may be difficult. However, the types of failure mechanisms and their geometrical occurrences are well defined (see chapter 4). Given a site's discontinuity feature and shallow working geometry and depth, the nature and the magnitude of a particular failure mechanism can be identified. This narrows considerably the range of probability values for specific magnitudes and simplifies the identification of the worst case. In some cases there can be only one failure mechanism (e.g. plug failure). The specific failure mechanism case studies would be helpful for a practical understandinf of the different site behaviours.

The probability of occurrence, reflecting a site's sensitivity to be affected by any of the events analysed, is generally more difficult to quantify than the magnitude. No matter what type of events are feared, the complexity of the mechanisms involved, the heterogeneous environment and the very partial available data denste that it is generally very difficult to assess quantitative probabilities (x% risk of a given event during a defined time period).

Priority may therefore be given to qualitative classification and characterisation of a site's "predisposal" to suffer a particular type of damage or nuisance. Evaluation of this predisposition depends on the combination of different factors, which are favourable or unfavourable to the initiation and development of a given mechanism. The following paragraph describes some of those major factors.

The worst physical magnitude CONCEPT can help in defining the highest level of consequence. The consequence can be quantified for a particular category or a range of features, e.g. specific on-site infrastructure, possible economic impacts (e.g. infrastructure, land value) or an all-encompassing consideration (e.g. public aspects, economic aspects, environmental aspects). Although monetary value is usually the basis for evaluation, a point system can be used when different subjects are jointly considered. Hazard and consequence combine to provide a quantified evaluation of risk.

Risk = hazard × consequence measurement

Qualitative risk assessment will yield a qualitative scale ranging from negligible to high with the number of levels to be decided by the user. Quantification of risk refers to specific numerical values.

For the purposes of risk prevention and regional development, the reference period for identifying risk levels is generally the long term typically human life-time (and not geological), by the date of mine closure.

Considering the mine closure process or post-mining management, the hazard evaluation, characterisation and mapping phase is the main task of the rock mechanics experts. The objective is to identify potential dangerous areas that could affect safety of people and the integrity of infrastructure or property.

The following step (risk assessment phase) concerns local and national authorities rather than technical experts. It would have been difficult to provide an in-depth coverage of abandoned mine risk and related issues regarding the broad range of impacts, interests and jurisdictions particular to the many countries. A common agreement guided to focus the present guideline on the hazard assessment phase and not on the risk evaluation. For further information, the readers may consult Bétournay, 2004.

Nevertheless, some references to the risk concept will be used in the present chapter, notably concerning the selection of the most adapted hazard assessment methods.

5.2 HAZARD ASSESSMENT SPECIFICALLY TO POST MINING

Post-mining hazard assessment studies are performed in specific contexts strongly influence by the general principles defininhazard assessment methods.

First of all, the experts are confronted with very old mining structures, some of them having been abandoned several decades or centuries ago. Most of experts had to face the “collective memory loss” syndrome. Even if a mine has been active during a very long period, very rapidly after its closure (not more than one or two generations), many inhabitants are not aware of the existence of the closed mine, especially if all disused surface structures have disappeared.

This partly results from the progressive mixing of local population (some leaving the area, others settling there) but there is also a kinf of a psychological “repressing process” that consists in forgetting most information that could potentially be inconvenient for the future. However, after appearence of the first problems, it is common that the local memory comes back. People then begin to remember data that they have never mentioned before, even if they have been asked previously. This contributes obviously to the unease in the collection of available data.

Besides old archive management processes (e.g. collecting, referencing) has not always been very well performed. Moreover, due to the very difficult social climate inherent to mine closure, most precious data (e.g. technical notes, maps) have been lost as a result of miners’ anger and demonstrations of despair (e.g. arsons, documents thrown in shafts).

For these different reasons and because it is usually impossible to visit the disused mine workings any longer, post-mining assessment methods need to be adapted to very partial knowledge of the mining context as well as the environment (e.g. geology, hydrogeology).

Mining methods and geological contexts are various. Potential problems may thus vary from almost undetectable subsidence effect to major collapses that may be very dangerous to people and goods. Assessment methods must thus be either very adaptive or previoously selected so as to fit properly the presupposed phenomena or mechanisms.

Surface occupation contexts can, also vary significantly. In many extanded countries, many small-scale disused mines are located in arid and desert areas with no people or property on the surface. Assessment methods, the best adapted to mining sites will generally differ from those dedicated to large mines located in very urban areas. In this case, the hazard identification and location have to be as precise as possible.

It has to be reminded that post-mining hazard assessment studies are generally performed in a delicate socio-economical context. The concerned areas already had to face the closure of the most important local industrial activity (unemployment increase, need for re-industrialisation). In this context, when properties are seriously affected, economical and psychological trauma may be severe.

In the same way, condemning surface occupation in large areas may limit severely the possibility of attracting new organisations in order to develop new industrial activities. This may contribute to the impoverishment of the area and the progressive departure of its inhabitants, especially young population. Risk assessment and management processes have to integrate this delicate issue.

5.3 SELECTION OF BEST ADAPTED HAZARD ASSESSMENT METHODS

5.3.1 Main parameters influencing the selection

A very large variety of methods is available and can contribute to evaluate, characterise and describe post-mining hazards. (See Bétournay, 2004 ; INERIS, 2006 ; Deutsche Gesellschaft für Geotechnik, 2004, for more detail on methodological issues).

Some methods are explicit. The others are implicit. Some methods combine qualitative criteria, others are restricted to quantitative values. Among those methods, one may quote rating, upgrading, multi-criteria hierarchisation, cross-tables, empirical approaches, analytical or numerical modelling.

Some hazard assessment methods require a large amount of precise data and need much time for the analysis. They may then be quite expensive but provide very precise information concerning hazard levels and zoning. Other assessment methods require less data and are much simpler and quick to apply. They are thus much less expensive but generate a much higher level of uncertainty than the first ones. The first step of a hazard assessment process consists generally of the selection of the best adapted method to the local context.

Figure 5.1 illustrates the main stages of a hazard assessment process. Considering the definition of hazard, economic and regulatory considerations are not supposed to influence the assignment of hazard classes. Nevertheless, those socio-economical parameters may strongly influence the selection of the hazard assessment method. As mentioned earlier, the best adapted methods to small-scale isolated sectors are very different compared to those needed for very sensitive areas. Figure 5.1 lists 4 main parameters to be taken into account: economical considerations, regulatory issues, identification of hazards and availability of data.

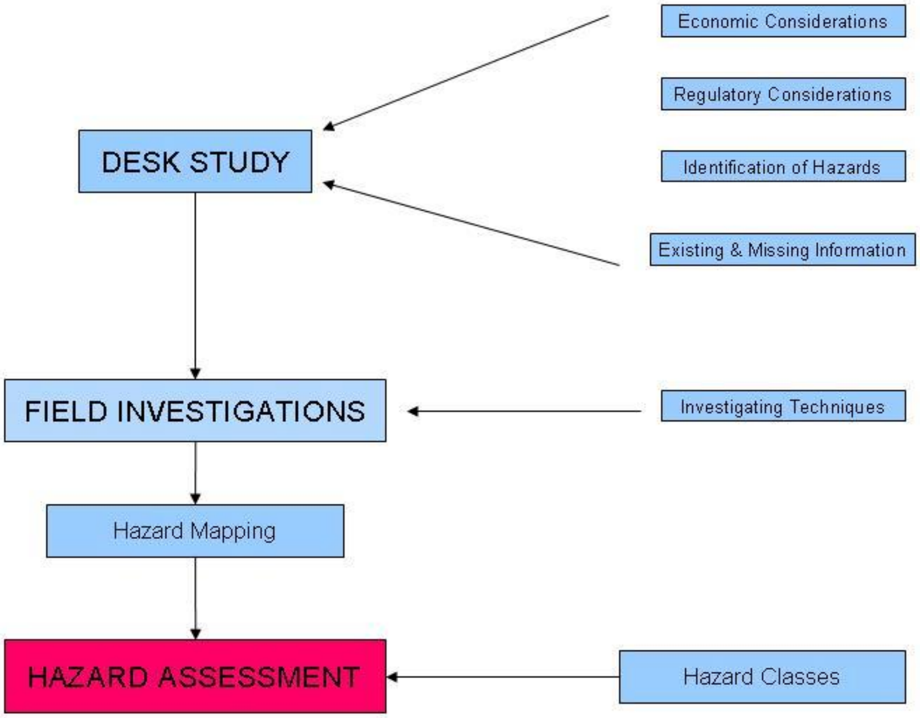


Figure 5.1. Detailed outline of the hazard assessment process stages.

Economic Considerations

The nature of surface occupation and, more precisely, the nature of future surface utilisation are usually the most important parameters in the selection process of the bast adapted hazard assessment method. The objective is to optimise the cost and time period of the assessment process to the sensitivity of a given context (presence of buildings or infrastructure on surface, urbanism development). It is clear that more investment is needed for prevention in the areas with dense surface occupation with respect to the areas, where no people or property are concerned.

Normally, data collection within the process of a full hazard evaluation is significantly more expensive than the cost of assessing the hazard per se. Thus, one will use in the non-sensitive sectors, methods that minimise the exhaustiveness and precision and of requested data, even if the results of the hazard assessment process induces high levels of uncertainty. On the other hand, where important infrastructure is concerned by the supposed hazards, sufficient funding is required to collect large amount of information. Much more detailed and precise hazard assessment methods can thus be selected in order to limit, as far as possible, the uncertainties affecting the location and the characteristics of the feared event.

In some cases, the hazard assessment project may only have a limited objective such as developing a preliminary site evaluation. In this case, representative preliminary, and sometimes empirical evaluations can be carried out using an initial cross-section of data (Bétournay et al., 1994).

Regulatory Considerations

At the initial stages of hazard assessment, it must also be ascertained which jurisdiction, and national, provincial, state or local regulations will guide the process and influence on the selection of the hazard assessment method. Regulatory issues are presented in mining and environmental codes, adopted best practices/national guidelines.

In many countries, there are also legal professional associations of engineers, geophysicists and geologists that require the application of professional obligations. Those obligations may concern due diligence for known hazardous sites, and the application of codes of responsibility in all work, such as the application of best methods and communication of all findings.

Identification of phenomenon

Every assessment method has its specificity. None is adapted to every phenomenon, context and objective that can be encountered in the post mining management process. Thus, it is very important to identify the pre-supposed phenomena that can develop on a given site in order to properly select the hazard assessment method.

As an example, in the case of sinkhole development, simple analytical or empirical approaches appear more adapted than complex and expensive numerical modelling. Most of the analysis will then consist in collecting data on geometry of residual voids (e.g. underground visits, analysis of maps, boreholes visual investigation).

On the contrary, in a complex geomechanical context (e.g. incorrect superimposition of pillars, non-homogeneous stress distribution within the rock mass, presence of major discontinuities such as faults, influence of water or time), advanced and powerful numerical approaches may be developed to enhance the understanding of the triggering mechanisms.

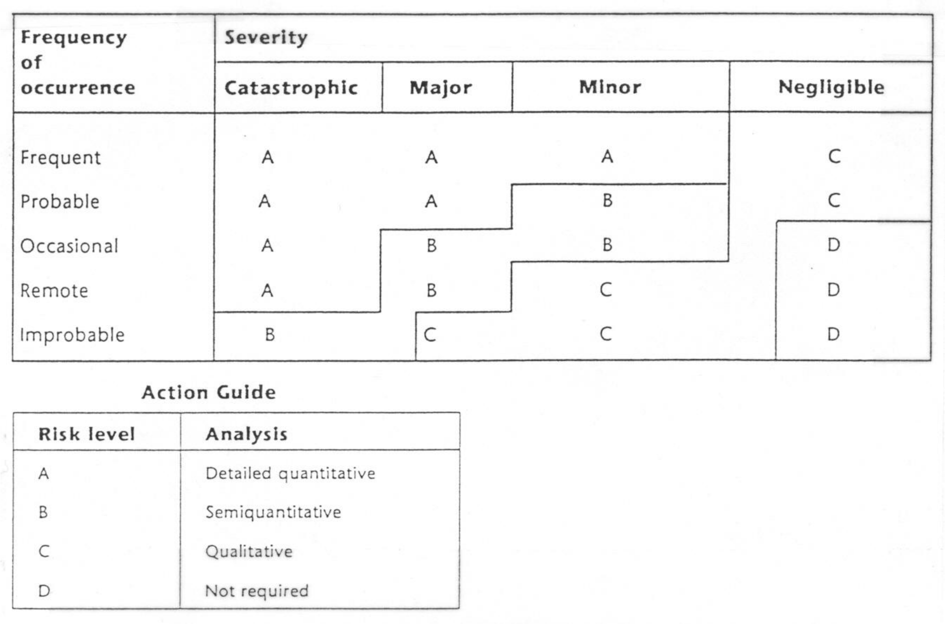
Available data

The extension of the disused mining works and the amount of available data may also influence the selection of the assessment method. When only a few data are available, qualitative methods may be used taking benefit, of the expert judgement.

On the contrary, when large amount of data is available (very large mining field with different mining methods and contexts), one will consider the interest of the decision-making aid methods. Those methods were developed to assist experts in taking benefit of large amounts of data.

By pairing those pre-supposed parameters, it is possible to evaluate the probable consequences of the feared phenomena (in terms of predisposition and severity). Table 5.1 gives an example of a matrix that can be used as a help to define the best-adapted class of hazard assessment methods depending on the “sensitivity” of a given site (from very simplified to precise qualitative approaches).

Table 5.1. Example of a matrix helping to identify hazard assessment method classes (Canadian Standards Association, 1991).



Frequency of occurrence	Severity			
	Catastrophic	Major	Minor	Negligible
Frequent	A	A	A	C
Probable	A	A	B	C
Occasional	A	B	B	D
Remote	A	B	C	D
Improbable	B	C	C	D

Action Guide

Risk level	Analysis
A	Detailed quantitative
B	Semiquantitative
C	Qualitative
D	Not required

It would not have been possible to discuss the main assessment methods within a multi-dimensional matrix integrating every parameter. We thus decided to use the surface occupation parameter (economic consideration) to give a list of the methods presented in the following paragraphs.

5.3.2 Hazard assessment methods adapted to low consequence (non-sensitive) cases

Some abandoned mining sites are located in areas situated far from a significant by developped zone on the surface.

Where the areas are uninhabited and not adopted for future surface occupation development (e.g. arid or marshy zones, mountainous areas), it is generally not necessary to perform specific hazard assessment analyses. One will then identify and localise the mining sites and draw global hazardous envelopes on cartographic documents for surface occupation management. This process ensures memory preservation for future generations.

Such a configuration is principally met in very large geographical territories with a low density of population (e.g. Canada, Australia). For highly populated countries (e.g. France, Germany) or mining areas where towns have grown up over the workings, mining works are rarely encountered in areas whithout surface infrastructure in the surroundings. Such a configuration requires a limited budget for the assessment process

5.3.3 Hazard assessment methods adapted to moderate consequence (semi-sensitive) cases

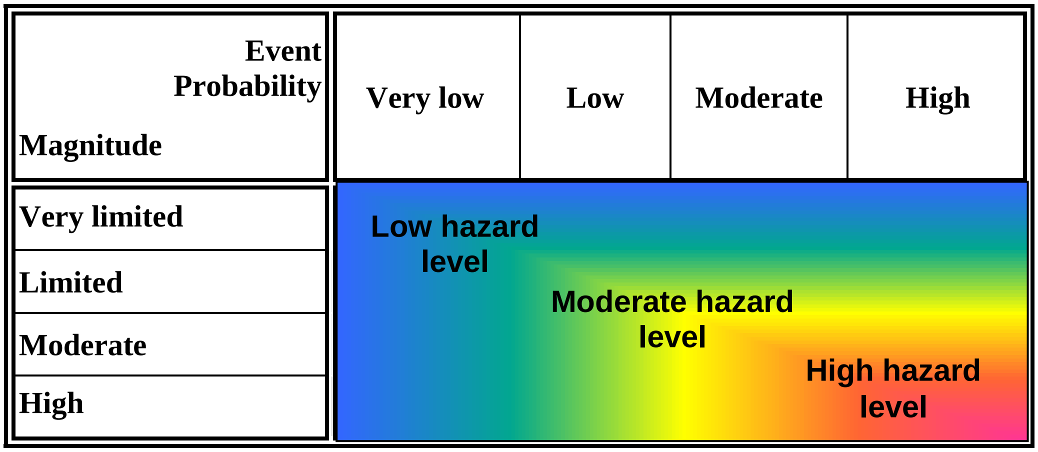
Semi-sensitive case configuration (average hazard class in sectors characterised by moderate surface occupation) is probably the most traditional and widespread situation. Relatively simple, fast and mainly qualitative hazard assessment methods are well adapted to this context.

Qualitative expert analysis

Expert analysis consists in using the knowledge of a rock mechanics expert in order to define the nature of the hazards likely to develop at long term above an old mining site. The analysis is mainly qualitative and attempts to take benefit of the available data (mining maps, past problems, visits of mine workings). Often, the analysis is based on the experience feedback, considering that previously occurred events on the same (or a similar) site constitute a reference index for the prediction of phenomena likely to develop in the future.

Even purely qualitative, the analysis should be as formalised as possible. Several tools can contribute to this. One will quote for example the principle of the matrix given in table 5.2.

Table 5.2. Example of Hazard Class identification



Event Probability Magnitude	Very low	Low	Moderate	High
Very limited	Low hazard level			
Limited				
Moderate			Moderate hazard level	
High				High hazard level

Analytical modelling

Analytical modelling is based on explicit mathematical equations used for the analysis of the mechanical stability. It requires important simplifications of the real problem and provides thus information that has to be interpreted in terms of trends. The simplicity of calculations makes possible to do many simulations and to perform a sensitivity study of the effect of various parameters.

The analytical models used in instability hazard assessment are very numerous. One will quote, for example, the models of beams and plates to simulate the stability of the galleries roofs and the model of tributary area to estimate the vertical stress in a mine pillar.

Empirical approaches

The empirical approaches are based on the experience feedback analyses. They take benefit of previous observations, relatively simple mathematical relationships between parameters characterising the site and a criterion to determine.

One may quote for example empirical laws established to characterise safety factors for mine pillars (e.g. according to the dimension of the pillars, of the nature of material, depth of work). The “10 × H law”, often quoted, constitutes another example. It considers that a sinkhole hazard becomes negligible, in where specific geological configurations, where the overburden thickness is higher than 10 times the height of the opening forming the mine workings (Taylor & Fowell, 2007).

An empirical model for determining the relative stability of surface crown pillars of metal mines has been developed (Golder Associates,1990; Carter & Miller, 1995).

5.3.4 Hazard assessment methods adapted to high consequence (sensitive) cases

The configurations corresponding to very unstable mines or very urbanised areas require precise and detailed hazard assessment methods. Because those methods need quantitative data, detailed field investigations (e.g. core drillings) are often performed depending on the requested information.

Numerical modelling

The context, the failure mechanisms or the constitutive laws are too complicated to make possible analytical modelling, numerical models may be used. There are many codes available. They have been developed based on different methods (e.g. Finite Element Methods, Distinct Element Methods, Finite Difference Method, etc.). Each method has its specificity and requires a high level of expertise (SIMRAC, 1999; Souley et al., 2008).

Numerical modelling does not constitute, by itself, a hazard qualification method. It contributes to a better understanding of the complex instability mechanisms. It thus assist the expert in the validation (or the invalidation) of assumptions.

Decision-making aid methods

Decision-making aid methods applied to post mining issues consist in comparing a great number of mining areas between each other in order to formalise comparison criteria as well as rules that help the expert to identify the most critical areas and the zones of the least risk. Several techniques can contribute to this classification. One will quote the multi-criteria methods by hierarchisation (Merad et al., 2004), the methods by ranking or neural networks. Such methods are mainly justified when the quantity of information is very isignificant and the criteria likely to intervene in classification are numerous.

Probabilistic approaches

Probabilistic approaches in post-mining are not well developed yet. Indeed, a realistic probability quantification requires a goof knowledge of the problem and the application of a quantifying model (analytical, numerical) representing the probability of occurence of the problem (Bétournay, 2004). Semi-quantification of the occurrence probability of a hazardous event can be based on case studies representing stable, limit and unstable cases. This can lead itself to a statistical failure probability (Bétournay et al., 1994).

In practice it is difficult to have sufficiently quantified variables related to the initiation and continuation of the hazard. A simplified qualification of hazards can be achieved if an appropriate scale is used. This is matched to the nature and the extent of the problem understudy (Cauvin et al., 2008).

5.4 PRINCIPAL STAGES OF A HAZARD ASSESSMENT PROCESS

The quality of a hazard assessment is closely related to that of available data. The first (if not the only) stage of the assessment is a desk study. This step aims to gather existing data and applicable knowledge from which pertinent engineering information can be extracted and used in order to identify and evaluate the hazard. Desk study may be complemented by a field study, with the objective to look for supporting information concerning mining works, previous problems and general environmental considerations.

In the case of very old mine workings (serious lack of data) if the surface occupation is very sensitive to potential disorders (urban environment, important infrastructure), complementary information may be necessary. This then leads to a field complementary investigation stage. These three stages are discussed in the following paragraphs.

5.4.1 Desk Study

The purpose a desk study is to locate and review, in detail, potential impacts of the abandoned mine, to identify its possible hazards and to evaluate the possible needs for field studies completing the existing information.

Due to the difficulty in collecting abandoned mining data, practitioners and organisations of record must be aware of the trend of basic loosing and site information with time. Even for contemporary mining companies, very often, only a few mine plans and drawings survive mine closure. Most of them have been lost or have deteriorated over the years. Often, a mine site no longer has surface structures marking its location and the presence of underground mine openings is unknown. Some information may not be reliable or is very approximative.

Hence, there is a need to identify, evaluate, catalogue and store site information as a first step in keeping accurate records and data. This will be necessary for supporting abandoned site management and projects such as hazard assessment and problem mitigation, as well as active mine decommissioning requirements. Furthermore, well-sorted archives facilitate many other applications such as: standardisation of the type of information required by national organisations, 2D and 3D graphical site reconstruction, storage of new site information from subsequent projects, and the development and support of regulatory requirements.

While information currently is easier to handle and transmit in electronic format, the original information must be properly stored in case problems arise from electronic storage, such as future incompatibility of softwares and lost databases.

Analysis of aerial photos taken at various times provides useful information on the evolution over time of the old workings and the environmental conditions.

<u>Review of existing information</u>

There is a wide range of information and sources that a practitioner involved in abandoned mine geotechnical issues should review. It is also at this stage that required but missing information is identified.

Among the most useful information concerning geotechnical issues, one may note :

Source of information

- Town and historical surface maps, testimonials, records
- Local and regional mining literature
- Previous reports (e.g. general mine site information, history, production, mining methods and progression, geomechanical and geotechnical conditions, engineering reports, previous site studies)
- Archives and databases
- Relevant cases studies
- Geophysical surveys
- Media articles on failures and mine fires
- Surface infrastructure and integrity (e.g. waste pile, tailings, buildings, roads, buried services)
- Land use
- Refilling of underground areas
- Geological maps

Type of information

- Site identification by name(s), by location (geographical co-ordinates, local designation), relationship with other mines, location of underground access
- Mine plans and sections; 3D opening or existing hazard reconstruction
- Computational processing of mapped information (mine grid geo-referencing; overlay with modern topographical maps)
- Aerial photographs
- Mine openings on surface
- Geological, geotechnical, subsidence, cave-in, groundwater, and gas emission location maps
- Geology (rock types, formation history, structural trends, contact conditions of ore body)
- Known and suspected underground failures at study and nearby sites (type, dimensions, start location; timeline, monitoring, simulation)
- Surface infrastructure and integrity (e.g. waste pile, tailings, buildings, roads, buried services)
- Land use
- Refilling of underground areas
- Subsurface ground control issues (rock mass quality, existing ground support, fill and bulkheads, recovery of ore to surface)
- Surface remediation and inventory (location, type, date of work, design used, condition)
- Field instrumentation location and data
- Engineering analyses

5.4.2 Field Study

A post-mining hazard assessment process needs to use, as frequently as possible (and necessary), a detailed inspection of the site. Only the knowledge of the site and its history, which is as detailed as possible produces a satisfactory degree of accuracy in the hazard assessment process. This data gathering also provides a strong basis for the expert credibility and his judgement with respect to the local population.

Where the accessibility and the safety conditions allow, visits of the openings help to validate the detail existing maps. They also provide essential information on the operating methods (e.g. back-filled zones, superimposed levels) as well as the mechanisms and instability developing in the old workings (e.g. deteriorated pillars, bowl-shaped depressions in the roof indicating a cave-in).

In principle, the access to underground workings is no longer possible. This restricts the type and range of geomechanical and other information that can be obtained on site. Nevertheless, surface reconnaissance allows detection of damage signs in the past. Attention will be paid to identifying signs of cave-in, collapse craters, wet or flooded zones, taking care of locating them as accurately as possible (using a GPS is particularly recommended) in order to compare them with the geological and mining context.

Apart from listing previous damage, the discovery of access drifts or old mine shafts are available provides indications on the presence of cavities in the areas for which no plans. These items are also very important for completing surface maps of underground workings. Site visits also provide the opportunity to collect information from the local population. These contacts provide the opportunity to collect oral information or even old maps not available elsewhere. The involvement of town management, preparing information meetings and the messages put across are essential to generate an atmosphere propitious to the transmission of information.

5.4.3 Complementary field investigation stage

Complementary field investigation requirements originate from one or several of the following needs:

- Information deficiencies
- Confirmation of the existence of important hazards identified in the desk and field study
- Complementary underground inspection to confirm or complete information, identify newly-developed hazards
- Identify unknown crucial locations of mine openings and their physical conditions
- Qualified or quantified evaluation of parameters that can be used in hazard assessment, remediation strategies and the design of appropriate monitoring means.

Appendix B outlines the benefits. Depending on the direction and level of the investigation campaign, complementary techniques can be used to reach a more complete coverage.

The most challenging application of field investigations corresponds to the case of an abandoned mine is suspected to be present where as no information exists on its location, extent of mining works and potential hazards that may be associated with them. In this case, planning and applying investigation techniques must follow a progressive course of data gathering starting with general site reconnaissance (e.g. outline of openings, variations in rock types and broad rock mass characteristics, location of failures on surface, location of groundwater). This task requires balancing resources and time available with coverage and collection of the information available, this makes judicious the use of the methods available and the combination of information provided by application of several methods.

Geophysics (cf. Appendix C) and exploratory drilling are useful for exploratory investigations. Diamond drilling can also be used for sampling rock mass features and to complete the geophysics survey. Table 5.3 provides an outline of recommended applications and caveats associated with geophysical surveys applied to abandoned mine issues. Recommendations for maximising rock core recovery can be found in Bétournay, 2004.

When general reconnaissance data or information is available from desk study, more specific information can be obtained. Then the focus of specific data gathering is the identification of distinct zones of behaviour, zones of potential hazard impacts and the quantification of parameters including material sampling and analysis, specifying geomechanical conditions around shallow openings and locating ground movements. This should be carried out by understanding the types of hazards such as failure mechanisms rock mass properties, and the soil behaviour.

5.4.4 Main applications of geophysical methods

In post-mining hazard assessment, when an old mine workings is suspected, direct methods of testing for voids have to be applied (geophysical measurements, boreholes). They should investigate the structure of bedrock, e.g. locate the voids and fractures to assess then spatial distribution and dimensions. If the presence of voids in bedrock is confirmed by direct testing, the possible subsidence of the surface can then be studied and predicted in regard to geological conditions and possible dynamic processes. The following groups of parameters have to be characterised by field investigations.

- Spatial extent of mine workings,
- Spatial extent of impacted overburden above mine workings,
- Structure of rock mass altered by mining,
- Physical and mechanical parameters of rock strata,

Geophysical methods can be applied for all the investigations above, although many engineers tend to limit them as “void searching tools”. In unfavourable geological and mining conditions no void can be detected with the use of these methods. In favourable physical conditions of rock strata most voids can be detected if adapted geophysical methods are selected. Several other rock mass parameters,important for hazard assessment process can also be obtained from geophysical data.

Geomechanical and geological analyses confirm that disused mine workings have influenced the rock overburden. They usually induce continuous and discontinuous deformations of overlying strata. There are a wide variety of geophysical methods and techniques, which can supply information on the overburden and bedrock. They use various natural or artificial physical fields and sophisticated numerical methods. The detailed characteristics of each method are outside the scope of this document. Their usefulness for post mining site characterisations depends on the surface conditions (technical availability for survey measurements) and local mining and geological conditions.

There are a few successful applications of geophysical methods for void detection and location in rock strata, all over the world. Those experiences concluded that direct methods for data interpretation based on theoretical assumptions are not useful in practice. The structure of bedrock affected by mining cannot be modelled in a simple way.

This methodology is reasonable both in terms of research and economy. Drilling works are expensive and time-consuming if compared to the geophysical investigations. Attempts were made in the past to investigate the post mining lands only by drilling investigations and cartographic knowledge related to the extent of mining operations. Those experiences confirmed that such a methodology could lead to very high costs, that may be not acceptable in terms of engineering practice and for economic reasons.

From the engineering point of view the main task for geophysical research is to contour zones, where the probability of presence of voids can be considered worrying. This reduces the number of test boreholes and thus costs of hazard assessment.

The costs of geophysical works depend on the method. Very often this is the main constraint factor, which determines the method and the range of measurements. Many investors that plan to develop the surface occupation in post-mining areas intend to choose the cheapest solutions. This constraint can contribute to eliminate sophisticated and up to date methods, which are more expensive.

Table 5.4 presents the main characteristics of classical geophysical methods applied to underground voids location in post-mining areas. They are based on the interpretation of several basic physical parameters such as volumetric density, porosity, specific electrical resistivity/conductivity, dielectric constant, elastic waves velocity and dynamic elastic modules of rock strata. A short description of these basic methods is provided in Appendix C.

Table 5.4. Geophysical methods in post mining applications

Depth of exploitation	Geodynamic process / type of mine openings	Method	Measurement Mode
< 30 m	Sinkholes, subsidence, erosion, leaching, Horizontal, vertical, inclined	Gravimetric	Surface measurements, in rock measurements
		Electro-resistivity	Surface measurements, borehole logging, tomography (ERT), In rock measurements
		GPR	Surface measurements, borehole measurements, In rock measurements, Tomography
		Electromagnetic	Surface measurements, In rock measurements,
		Seismic	Surface measurements, borehole measurements, In rock measurements, Tomography
	Combustion in coal, shafts	Geothermic	Surface measurements, borehole measurements
30 – 80 m	Sinkholes, subsidence, erosion, leaching, washing out/ Horizontal, vertical, inclined	Electro-resistivity	Surface measurements, borehole logging, tomography (ERT), In rock measurements
		Electromagnetic	Surface measurements, In rock measurements
		GPR	Borehole measurements, cross hole tomography
		Seismic	Borehole measurements, cross hole tomography
	Egzogenic processes in coal	Geothermic	Surface measurements, Borehole measurements
> 80 m	Subsidence, erosion, leaching, washing out/ Horizontal, vertical, inclined	Electroresistivity	Cross hole tomography
		Seismic	Surface measurements Cross hole tomography
		GPR	Crosshole tomography

5.5 MAJOR FACTORS INFLUENCING HAZARD PREDISPOSITION

Depending on the rock mass, failure may occur from a general mobilisation of portions overlying extracted areas (e.g. fracturing) or limited to specific portions and mechanisms depending on the weaknesses such as discontinuities and faults.

The rock mass will be affected by several influences.

5.5.1 Influence of time

Active mine stability is generally studied for short-term periods (about ten years). On the contrary, one of the specificities of post-mining is that mechanisms are to be studied at very long time scales, about a few hundred years (the time period for land use development).

Time is thus a fundamental factor, which must be taken into account in the hazard assessment process (Van der Merwe, 1998; Auvray & al., 2004). The phenomena observed today often occur for mine workings having several tens of years of existence, and sometimes more than one century.

Several mechanisms must be taken into account to evaluate the effect of time on mechanical stability.

Creep effect

When a geomaterial sample is loaded for a long time, failure can take place at a stress level much lower than that required for faste laboratory tests. This is due to a mechanical effect resulting in the propagation of micro-cracks in the rock sample. This “long-term strength” is often poorly understood, because its estimation requires “creep tests” that take a long time are more or less costly.

Creep effects depend on the nature of the specific rock. Some rocks appear very sensitive to this effect (salt, gypsum, clay, marl) some other exhibit less creep (e.g. granite, quartzite). Depending on the nature, it can be assumed that a reduction of strength of 20 to 50% can be obtained by standard laboratory creep tests.

Ageing effect

The ageing effect is a chemical process that contributes to modify the rock mass properties because of variations in the environmental conditions. The mechanism results, in particular, in the combined effects of oxygen and water present within the residual voids.

A strength decrease of about 50% was for example observed for Lorraine oolitic iron-ore in France (value evaluated from back-analysis of subsidence events that developed in that iron ore basin, see also Grgic et al., 2008). This is mainly attributed to the degradation of the calcareous cement, which ensures cohesion between the oolites.

Long term evolution of fracturing

The strength of a rock mass in abandoned mine workings closely depends on the degree of fracturing. This fracturing is likely to increase with time, because of environmental parameters (water circulation, atmospheric conditions: moisture, freezing).

5.5.2 Influence of water

Mine closure is very frequently accompanied by a modification in the rock mass water content because of the progressive flooding of underground mine workings resulting from the end of the pumping operations. Various phenomena may develop during the flooding phase: induced seismicity, surface instability development (limited uplift, continuous or discontinuous subsidence), chemical degradation of the water.

The effect of water on mine workings is difficult to evaluate because there are plausible arguments for both beneficial and damaging effects. The balance of these effects determines whether flooding is stabilising or detrimental in a given condition (e.g. nature of rocks, mining methods). We will summarise the discussion in presenting briefly the main mechanisms that rock mechanics experts usually consider to evaluate effects of water on mining stability. For each mechanisms, it is important to distinguish the flooding period (dynamic effect) and the stabilisation period (static effect).

Strength modification

Geomaterials have a higher strength when they are dry than when they are wet (Colback & Wiid, 1965). This strength drop may, for sensitive rocks, exceed 50% (Hamrol, 1961). This physical "moisturising effect" is related to the effect of the pore water pressures.

Water-sensitive rocks may then easily lose half of their strength from a completely dry state to fully saturated state.

Even before flooding, the rock mass is often near to saturation (80 % moisture content)because of water circulating around the cavities. The strength reduction from damp rock (20 %) to fully saturated rock (100 %) is much less significant than that from dry (0 %) to damp (20 %).

It can thus be considered that water naturally present in rock formations have probably already reduced the rock strength significantly and the flooding process will often only produce small additional effects (Hawkins & Mc Connell, 1992).

Nevertheless, certains rocks are very sensitive to water contact. Some rocks chemically or physically react with water and swell or becom desintegrated. Generally this concerns certain clay minerals (illite, kaolinite, montmorillinite) present within the weaker marl rock horizons (Van Ecckout, 1976). There may be areas of mines where the mine workings are mostly insensitive to water and other areas with structures in marls (pillars, roof, floor) with a significant degradation after contact with water.

The last effect of water on rock mass strength concerns the fact that rock mass contains natural joints, bedding planes and mining induced fractures (figure 5.2). When dry, these structures have frictional properties that help to hold them together. When wet, the friction is reduced as water lubricates the contacts. Additionally, if the water is under pressure, it can force the joint open thus reducing friction further. Rock Mass assessment techniques recognise these issues and take into account a significant strength reductions for rock mass properties in presence of water (Barton & al., 1974; Bieniawski, 1976).

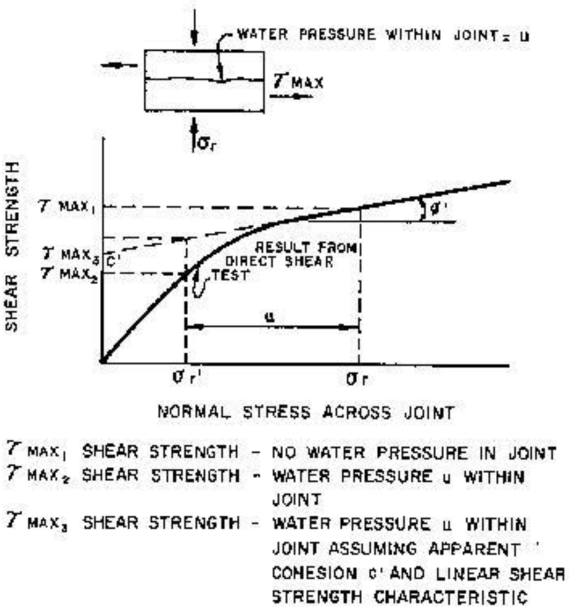


Figure 5.2. Influence of water pressure on shear strength of joints.

Stress modification

When the underground mining reservoir is flooded, the mine workings are subjected to a water pressure. The vertical effective stress is thus decreased, but the horizontal effective stress that has an important confining role is also reduced. According to the final water table level and to the shape of the pillars, the global effect may have, in some configurations, significant impact in terms of pillar stability. ??

On the contrary, in case of very impermeable rocks (intact salt for example), water (brine in case of a salt mine) does not penetrate into the rock mass. Flooding then generates pressure on pillars or cavities faces and may contribute to the stability improvement.

A rise of the water table level in the overburden above the abandoned mine workings may generate an increase in the stress within the mine workings. This phenomenon is sometimes known as “hydraulic overload”. Usually, this mechanism is only considered in the case of dynamic effects resulting from a sudden loading (heavy rainfall). This may affect shallow works, especially if mine workings are connected to surface by existing sinkholes. For deep mines, dynamic loading may result from the fracturing of an impermeable layer located in the upper overburden.

This is a very important point. Transient stages evolution from dry condition to flooding correponds to the most sensitive periods with respect to instabilities (Beckendam & Pöttgens, 1995). As a matter of fact, rock mechanics experts have observed that some surface problems takes place almost soon after flooding or pumping out of the mine prior to a new equilibrium state reached again (Smith & Colls, 1996**).** The changes caused by flooding and draining a mine has thus to be carefully considered (Goetz et al., 1994; Luckner, 1983).

5.5.3 Influence of geology and mining methods

Each mining site is unique because of its specific configuration and environment. It would be thus illusory, and sometimes even dangerous to define global and generic scenarios giving, for each site and without a specific analysis, the nature of hazards that may affect old mining sites.

Back analysis shows that key parameters have a first important role in the long-term behaviour of old mining works. Geology, the type of deposit and mining methods belong to those key parameters. They are generally closely related to each other since the choice of the mining method depends directly on the geological context.

Geological consideration

For generic mass fracturing scenarios as opposed to limited failure-mechanism occurrences, the extent of potentially risky zones increases quite logically with the size of the exploitation.

Geological configuration of the deposit

The geological configuration of the deposit influences the nature and the magnitude of the potential surface disorders (figure 5.3). Various configurations of deposits can be encountered.

The mining operations within sedimentary flat layers often constitute, when mining works are not very deep, the most unfavourable configuration in terms of disorder magnitude (in particular when the underground cavities are high) as well as surface extension of risky zones (several hundreds, and even thousands, of hectares for a single exploitation).

On the contrary, vein deposits and, more globally metal mines have a relatively limited ore thickness, a quite high dip and a strong surrounding rock mass. The principal risks for the safety of people and property located on the surface is thus often concentrated above crown pillars and represent relatively limited surface areas. The same applies to the majority of waste heaps whose side dimensions are often small.

For this type of extraction, the nature of the rock mass can play an important role in determining the nature and the magnitude of surface instabilities that may develop on the surface, as shown in the following diagrams (figure 5.3). Halfway between these two configurations, potential problems above sedimentary layers with middle to high dip must be studied on a case-by-case basis, in the light of other decisive parameters (thickness of the layer, mining method used).

Rock mass properties

The deposit and the rock mass properties have also a great influence on the long-term mine working behaviour. Evaluation of future behaviour should therefore address the following question : “which portion of the rock mass is mobilised by failure on the surface ?”.

Displacements within the rock mass at the periphery of shallow underground openings can be discontinuous, sudden and massive, irregular or piecewise and continuous. Considering the risk of sinkhole development, a limestone with a high strength or a granite overburden will prevent the instability progressing towards the surface if the mining depth is sufficient. On the contrary, soft or thin-bedded rock will be very favourable for the development of instabilities up to the surface.

The geological nature of the overburden may also influence the disorder type above an unstable room and pillar area. If there is a “stiff” horizon, (thick and strong layer), due to the progressive deflexion of the overlying strata, a part of the overburden weight is transmitted on the unexploited edges of the mining area. This phenomenon contributes to reduce the stress in the pillars. This made it possible to exploit some deposits with an extraction ratio much higher than the value calculated to ensure pillars stability.

Due to progressive convergence of the pillars (creep, ageing) the upper stiff layer bends more and more. Because it is not very deformable, its brittle fracture induces a sudden overloading that affects the pillars (Didier & Josien, 2003). The pillars collapse globally, resulting in a violent collapse of the overburden (sudden collapse). On the contrary, if the overburden is constituted by less strong layers, the entire overburden load is transmitting to the underlying pillars. Their convergence with time thus induces progressive and a more continuous surface subsidence.

Finally, tectonics and in particular presence of major faults or joints need to be carefully taken into account. The faults can indeed play an important role in the development of instabilities.

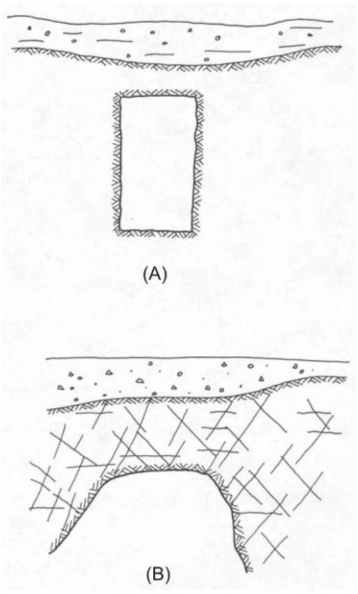


Figure 5.3. Common rock mass settings of shallow metal mine stopes: poorly jointed (A) and blocky (B).

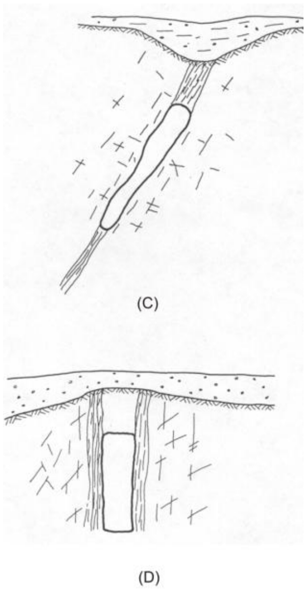


Figure 5.3 (continued). Common rock mass settings of shallow metal mine stopes: weak schistose orebody, competent walls (C) and massive orebody, weak schistose walls (D).

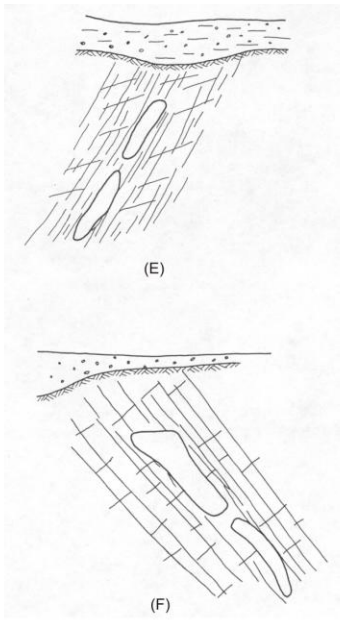


Figure 5.3. (continued). Common rock mass settings of shallow metal mine stopes: generally foliated, slaty (E) and well developed stratification (F).

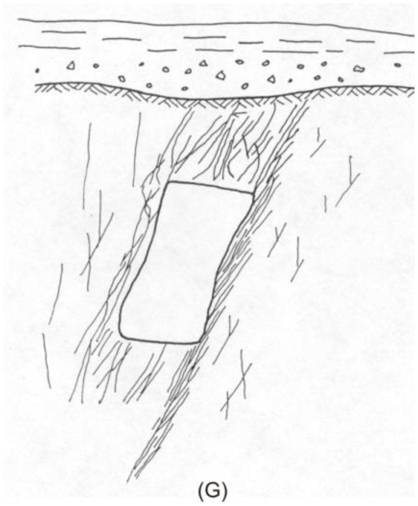


Figure 5.3. (continued). Common rock mass settings of shallow metal mine stopes: fault weakened, altered (G (Bétournay, 2004)).

Mining methods

The nature of the potential post mining disturbances is also related to the mining configuration. The choice of the mining methods directly influences nature, size and location of potential residual voids as well as the design of remaining mining works (pillars, cavities).

With respect to post-mining risk, the following distinction has to be made :

- mining methods ensuring a systematic treatment of the voids that have been created by ore extraction. This treatment may result from backfilling, caving or by a natural drift convergence ;
- mining methods leaving behind a large residual voids are likely to evolve and collapse in time.

The first conditions are likely to generate continuous subsidence, with sometimes an important magnitude, during the exploitation time-period but, also after mine closure, the surface movements are generally limited to readjustment of low amplitude. The second conditions, the collapses of the residual voids, which can occur just after mine closure or long time later, are likely to generate a continuous or discontinuous subsidence on the surface.

Without entering in detail, one should keep in mind the following general principles that have to be considered as elements of the risk assessment for different types of mining.

- The “massive mining” methods, like block caving or sub level stoping for example appear to be particularly sensitive to sudden or gradual subsidence of the surface. The main mechanism leading to those disorders is the deterioration or failure of the surface crown pillars.
- Steeper dipping tabular metal ore deposits yield piecewise failures that run through or close to surface crown pillars and impose surface subsidence only when the failure front is almost at the top of bedrock.
- In case of “deep level hard rock stoping” methods that are notably typical in gold and platinum mining, it is necessary to consider several kinds of potential failure mechanisms are to be considered :
    - ⇒ Failure of water plugs between adjoining mines as the water table rises
    - ⇒ Seismic events caused by lubrication of faults as the water table rises
    - ⇒ Failure of water plugs caused by post closure seismic events.
- In “Bord and pillar mining” methods, the most frequent problems encountered are :
    - ⇒ sudden or gradual subsidence caused by sudden or gradual pillar collapse
    - ⇒ sudden appearance of vertically sided sinkholes due to collapse of galleries.
- When shallow tabular seams are mined out by “high extraction” methods, one has to consider :
    - ⇒ Continued gradual subsidence due to compaction of goaf material
    - ⇒ Sub-surface erosion pot holes due to erosion of soil into cracks at the edges of subsided areas.

- The existence of vertical shafts requires the analysis of potential sudden appearance of sinkholes due to failure of plugs or backfill material running.
- In the case of inclined shafts, the major problem mechanisms are usually :
    - ⇒ Sudden appearance of sinkholes due to collapse of the shaft roof
    - ⇒ Sudden outflow of water due to plug failure or the failure of rock around the plug.

Table 5.5. Influence of the geological setting and mining methods on hazard predisposition

Hazard Probability (or Predisposition) ***Abandoned Mine Rock Mass Setting***	**LIKELY**	**MODERATE**	**UNLIKELY**
Lower dip coal seam (<35°) room and pillar mining	Shallow seam; sinkholes and troughs occurring	Shallow seam; few sinkholes or troughs. Deeper coal seam; rare trough development	Shallow coal seam with competent overlying beds. Deeper coal seam; no evidence of surface impact
Inclined coal seam (>35°) which outcrops at bedrock surface	Failure of hanging-wall crown		
Underground mining with weak post pillars	Pillar robbing or sizes too small (high extraction ratio); lack of boundary pillars; expanding surface subsidence	Pillar robbing; pillar sizes variable; rock composition variable; lack of boundary pillars; multiple seams. Expanding surface subsidence	
Under-ground metal mining in poorly jointed rock mass		Crown tensile failure with large stope span Induced siesmicity with large openings at depth	
Under-ground metal mining in blocky rock mass	Ravelling and plug drops, intense regional mining (low lateral ground stress); well-developed blocks Progressive hangingwall caving over steep sublevel caving	Block caving, low lateral ground stress; well developed blocks, large stope span	Ravelling and plug drops with local mining; poorly developed blocks or variably discontinuous rock unit
Underground metal mining in weak orebody, with competent walls	Chimneying in weak rock unit with dip >50° and low cohesion (<0.2 MPa)		Chimneying if weak rock unit decreases in dip and increases cohesion
Underground metal mining in competent orebody with weak walls	Chimneying in weak rock with dip >50° and low cohesion (<0.2 MPa); plug drops in intense regional mining		Chimneying if weak rock unit decreases in dip and increases cohesion
Under-ground metal mining in well developed rock mass stratification		Thin strata (e.g.<1 cm) failures in crown/hang-ingwall	Thicker strata failures; depth of opening more than ¼ stope span
Generally altered metal mine rock mass	Chimneying in weak rock unit with dip >50° and low cohesion (<0.2 MPa)		Chimneying if weak rock rock unit decreases in dip and increases cohesion
Under-ground rock mass subject to alteration	Chemical alteration of dominant mineral(s), sloughing		
Solution Mining	Large and shallow horizontal cavities; thin crown; unsatured groundwater		
Vertical shafts	Weak rock mass; well -developed blocks with steep joints; unlined shaft; water level near surface; partial or no fill		Lined shaft; unlined shaft with poorly jointed rock mass
Open pit		Weak rock mass; effective joint intersections; major joints with high dip; water table near surface; high steep walls	Fill placement to prevent failures
Mine Gas Emission	Unfilled shafts; permeable over-burden; gas source above water table; gas accidents since extraction; good connectivity of under-ground excavations	Limited exposure of producing geological unit; ineffective underground opening connectivity; few accidents since extraction	Limited exposure of producing geological unit; no gas reported during mine extraction; source below water; deep mine

5.6 HAZARD MAPPING

Hazard is a spatial concept, evaluated at a given point of land (Didier & al., 2007). It must therefore be mapped all over the studied area (figure 5.4) in order to locate the sectors that appear to be the most sensitive to potential problems.

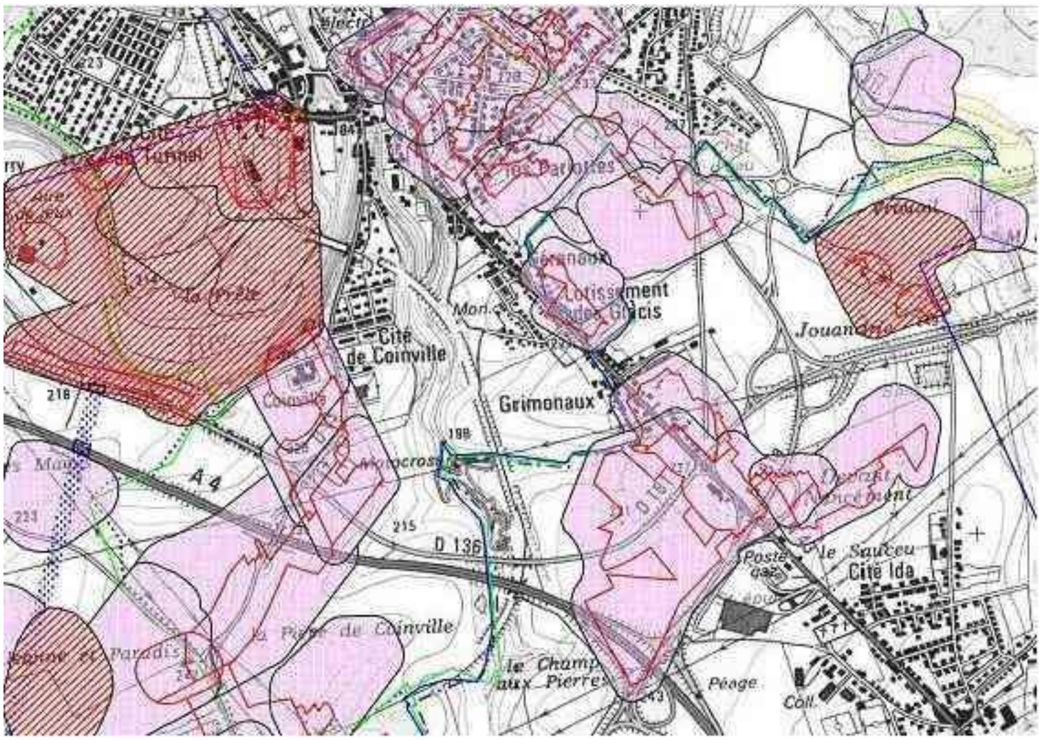


Figure 5.4: Example of a hazard map above disused mines (Source INERIS).

Post-mining hazard maps are the reference objects for all stakeholders of a particular site. The hazard mapping contours are based on natural technical parameters (e.g. geology, mine workings). They therefore have no reason to follow administrative contours.

In order to ease maps utilisation, each hazard category, such as geomechanical disorders or mine gas emissions, has to be incorporated into a different map. Zones of incomplete or missing information may be highlighted.

Extension of effects on surface

Because they are dedicated to land use development, hazard maps are plotted on surface and not underground. The hazard maps should contain a projection, on surface, of all known mine workings. They may also contains, if necessary, hydrogeological, geological and major structural geology features (e.g. water body contours, faults). It is also necessary to take into account the possibility of lateral extension of damage or nuisances resulting from phenomenon initiated underground and developing towards the surface (e.g. angle of influence for subsidence, diffusion on surface for gas emission).

Managing the uncertainty of localisation

Due to the old age of most available maps, there is generally some uncertainty concerning their accuracy. Thus each map has to be qualified by indications of accuracy as well as adequacy with present co-ordinate system. This means identifying a certain margin of uncertainty. Depending on the context, this uncertainty may vary from a few metres to several tens of metres. This margin of uncertainty must therefore be added to the extension of predictable surface events. Since this is a margin of uncertainty and the events predicted within this margin are identical to those characterising the central zone, the hazard levels should be identical for both zones.

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6 HAZARD MANAGEMENT METHODS

6.1 TREATMENT

6.1.1 Backfilling

The safest and most durable hazard management method is the rehabilitation of underground works in zones where the most harmful consequences of subsidence are expected and where the consequences are the most serious. The most efficient protection in such zones is assured by backfilling of underground works. Different backfilling methods have been used. They can be grouped in Hydraulic, Pneumatic or Hand Packing.

- In Hydraulic backfilling, the material is mixed with water and pumped or flowed down under gravity effect to the desired position.
- In Pneumatic backfilling, the crushed material is blown down into the cavities with compressed air. A binder, such as cement, may be added by spraying the dry material with a weak cement and water mixture. Alternatively, water may be added to the dry mixture at the nozzle of the pneumatic pump.
- The third basic method is hand packing of large lumps of waste material.

Depending on the circumstance, backfilling can either be performed from underground or from surface. The following table summarises the important elements of the different methods.

Table 6.1. Important Elements of Different Backfilling Methods

Method	Requirements	Advantages	Disadvantages
Hydraulic, underground	Accessible underground Dams and barricades to be constructed Run-off water to be handled Pump installation to be provided Water and crushed fill material must be available	Position of placement certain Quality of placed material can be tested	Expensive Handling of contaminated run-off water Vulnerable due to blockage and breaking of pipes Requires men to work underground
Pneumatic, underground	Accessible underground Crushed fill material must be available	Position of placement certain Quality of placed material can be tested Independent of pump installations	Expensive Transport of material
Hydraulic, surface	Water and crushed fill material must be available Pump installations must be provided Holes must be drilled to underground workings	No underground work is required Only method if underground access is not possible Can be done in flooded areas, albeit a slow and uncertain process.	Position of placement is uncertain Contaminated run-off water must be handled Run-off water can go anywhere Difficult to test quality of placed material Environmental risk if pipes break Expensive
Hand packing	Fill material must be available Transport of men and material must be available	Position of filled material is certain Quality of placed material can be tested and controlled	Labour intensive Requires underground work Has seldom been done in modern times on large scale

Once backfilling has been done, the material removal is pratically unfeasible, even if of a poor quality.

The method has to be selected on the basis of accessibility, availability of a suitable back fill material and costs. Backfilling has been used as a method to stabilise underground workings, but is normally reserved for high-risk areas because of its high costs.

Figure 6.1. Underground stower

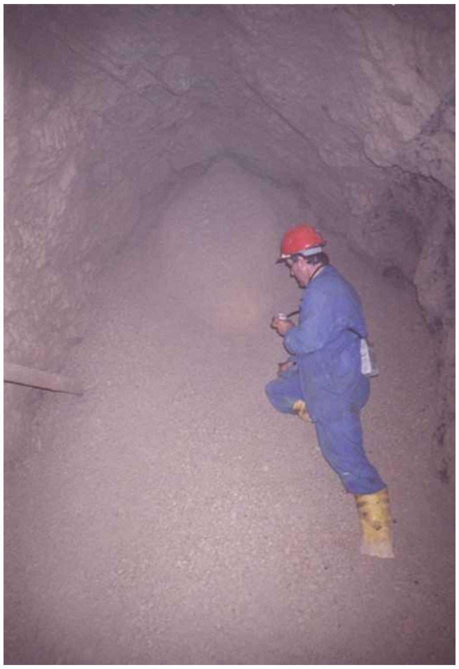


Fig 6.2. Reinforced backfill

(By courtesy of Bojan Rezùn)

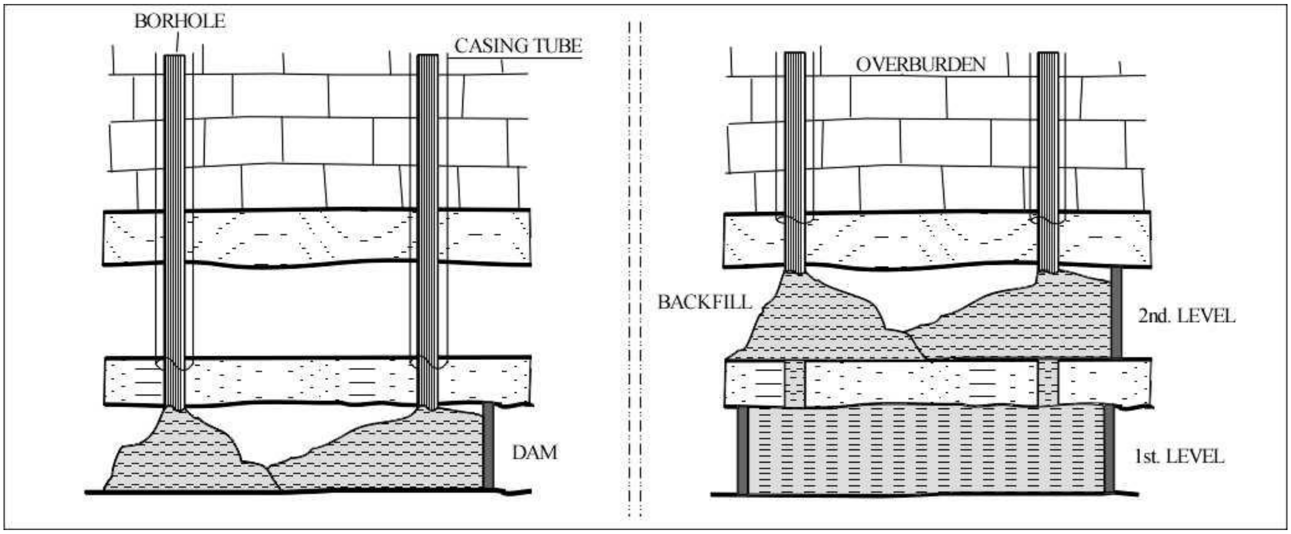


Fig. 6.3. Backfilling of underground works on several levels through boreholes.

Fig. 6.4. Mixing plant, pumping station and control centre on surface (By courtesy of Bojan Rezùn).

Fig. 6.5. Injected paste in abandoned underground area (By courtesy of Bojan Rezùn).

6.1.2 Geosynthetics

Geosynthetics are the products that have at least one component manufactured of synthetic or natural polymer usually in form of a band, belt or three-dimensional structure. Typical polymers are polyester (PET) with low elongation and high strength, polyvinylalcohol (PVA) with high strength, extremely low elongation and a high chemical resistance and polypropylene (PP) with very high chemical resistance and acceptable elongation. Some companies also offer geosynthetics made from aramid with very high strength and high chemical resistance.

Geosynthetics as geogrids or geotextiles can be a cost-efficient engineering solution for collapse hazards. A lot of work has recently been done on this issue in different countries; the opinions on the best material and the design method may be different. Within the scope of this guideline, only some of them can be mentioned.

One of the conceptual roles of geosynthetic reinforcement is limiting surface deformations due to subsidence as given in figure 6.6. The objective is to avoid collapse due to the failure of an underground mining cavity and to only allow for a reduced depression at the surface. For this, one or more layers of geosynthetics can be put into the ground bridging a possible cavity.

British Standard BS 8006 is one example of design method. Some other design procedures and simple design charts can also be consulted (Bonaparte & al., 1987, Giroud & al., 1990; Blivet & al., 2002). The most realistic design can be investigated using numerical methods, considering the influences such as volume increase, wall roughness, deformation induced by pull out and lengthening in the anchored zone.

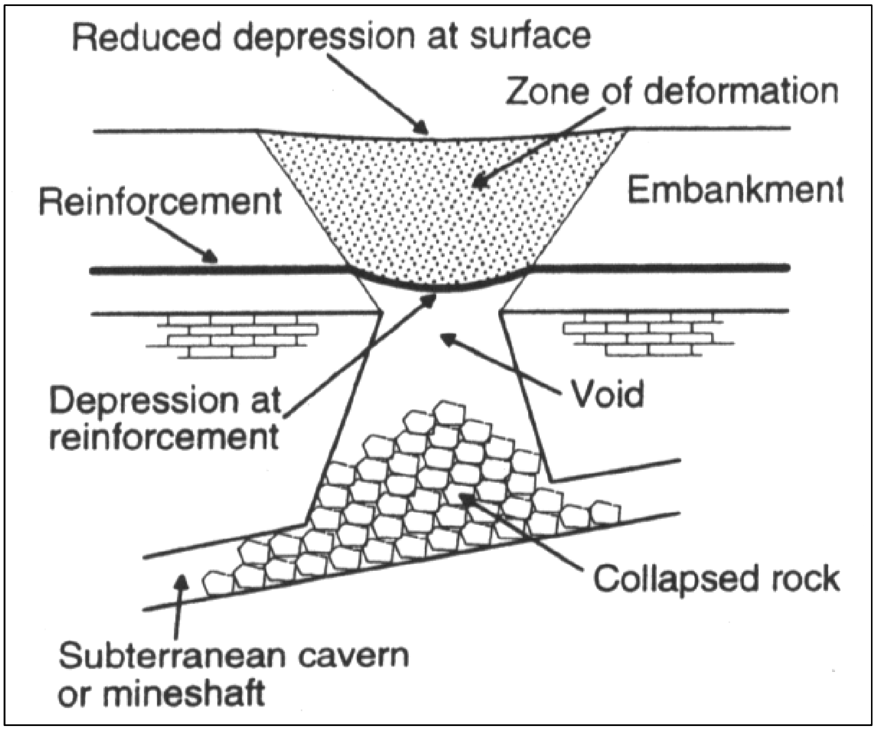


Figure 6.6. Conceptual role of geosynthetic reinforcement (From British Standart, 1995)

Geosyntethic reinforcement can be designed for collapse areas as a long-term or short-term solution, e.g. the geosynthetic can be designed so that to span a collapse feature for example for one month.

If the geosynthetic reinforcement is designed as a long-term solution, only the long-term tensile strength of the chosen material may be used in the design calculations. For example the long-term tensile strength of aramid material is only about 30 % of its short-term tensile strength.

Short-term solutions can be effective when an additional monitoring system (e.g. extensometers) is installed. Monitoring systems can be a helpful for the construction of new roads in areas prone to collapse : the road then can be closed before the collapse reaches the surface. The working lifetime of the geosynthetic material must be longer than the planned lifetime of the surface construction (roads or the like).

When constructing a geosynthetic reinforcement, great attention has to be given to a proper handling of the geosynthetics since they can be very sensitive to too much sunshine (lack of UV-stability). They also can be easily damaged by the compaction of coarse and cornered material during installation. In most cases, the limit of economic efficiency of geosynthetic reinforcement is reached at expected collapse feature diameters of about 6-8 m.

6.1.4 Shaft treatment

Old mine shafts can be stable for a very long time depending on the surrounding rock and the shaft filling. Within the overburdein shafts tend to fail as soon as the shaft support (e.g. wood) decays and looses stability. Often such old mine shafts only have an insufficient filling or even no filling at all (figure 6.7). Collapses above shafts can develop very quickly; they correspond to a significant risk to the ground surface and to public safety.

Figure 6.7. Old mine shaft with wooden supports and no shaft filling (Source IHS, Aachen)

In many cases, the exact location of a shaft is unknown and first the shaft has to be found before it can be remediated. The search grid of borings must be dense enough so that the shaft can not be missed. In figure 6.8 the shaft diameter is exactly known and its location unknown, so the grid density *x* only must be below the value of $2^{1/2}$ D / 2.

When using small vertical core borings or penetration tests, the driller must be roped up to a fixed point, just in case a collapse is triggered by the investigation works. When a drilling rig is used for large core borings, it should be placed outside the assumed shaft location and the shaft should be searched using inclined core borings.

In both cases, a search grid is placed on the assumed shaft location and its vicinity.

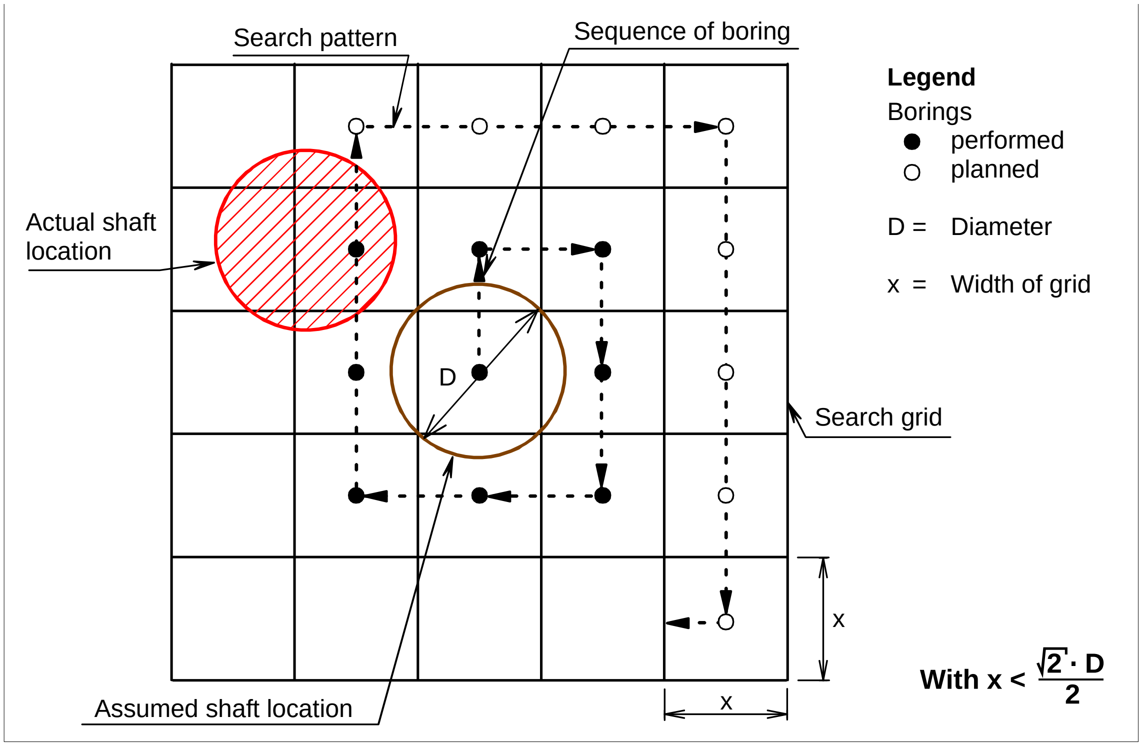


Figure 6.8. Search pattern for a shaft with a known diameter using small vertical borings or penetration tests (Modified after Jones, 2001).

Geophysical methods can face reliability problems for the detection of shafts if there is partial filling in the shaft, which has similar geophysical properties to the surrounding soil.

Several techniques of treatment of old mine shafts and an important litterature are available on this matter (NCB, 1982; U.S. Bureau of mines, 1995). Among them, two recommended methods for the treatment of old shafts are described below. One consists of installing a reinforced concrete slab on the rock surface as a foundation for the overlaying soil. The other method is grouting of the shaft filling in order to stabilise the filling itself. Reinforced concrete slabs are more cost-efficient if the rock is near to the surface. If the excavation pit is too deep, injection is to be preferred.

Reinforced Concrete Slabs

Reinforced concrete slabs can be an effective treatment method for abandoned shafts. Reinforced concrete slabs are placed over the shaft opening directly connected with the surrounding stable rock. They prevent an upward migration of the cavity to the ground surface.

It is not recommended to use concrete plugs within the overburden which are not based directly on the rock surface because such concrete plugs can become hollow from the basis since cavity migrate in time (Didier, 2007).

In the reinforced concrete slab, a refill opening should be installed with a control shaft going up to the ground surface (figures 6.9 and 6.10). The control shaft then is filled with gravel. In a monitoring programme, the filling of the control shaft and the filling of the deeper old shaft can be controlled with regard to sagging. If necessary, the gravel is refilled.

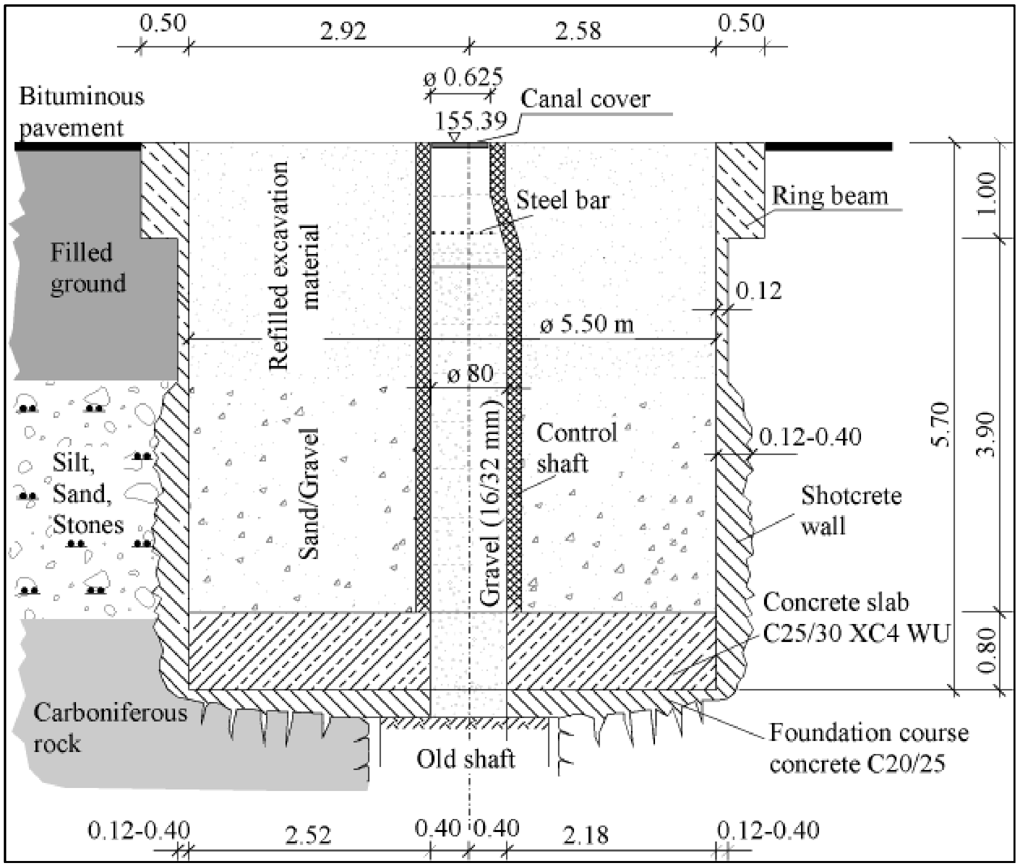


Figure 6.9. Example of solution of an excavation pit with an old shaft and a reinforced concrete slab (all values in cm except where indicated otherwise; Heitfeld et al., 2006)

In the areas where a lower level of security can be applied (e.g. in a forestry area), the control shaft can be omitted (figure 6.11). The disadvantage of this solution is, that the usable lifetime of a reinforced concrete slab is finite and the condition of the remedial construction can not be controlled without such a control opening.

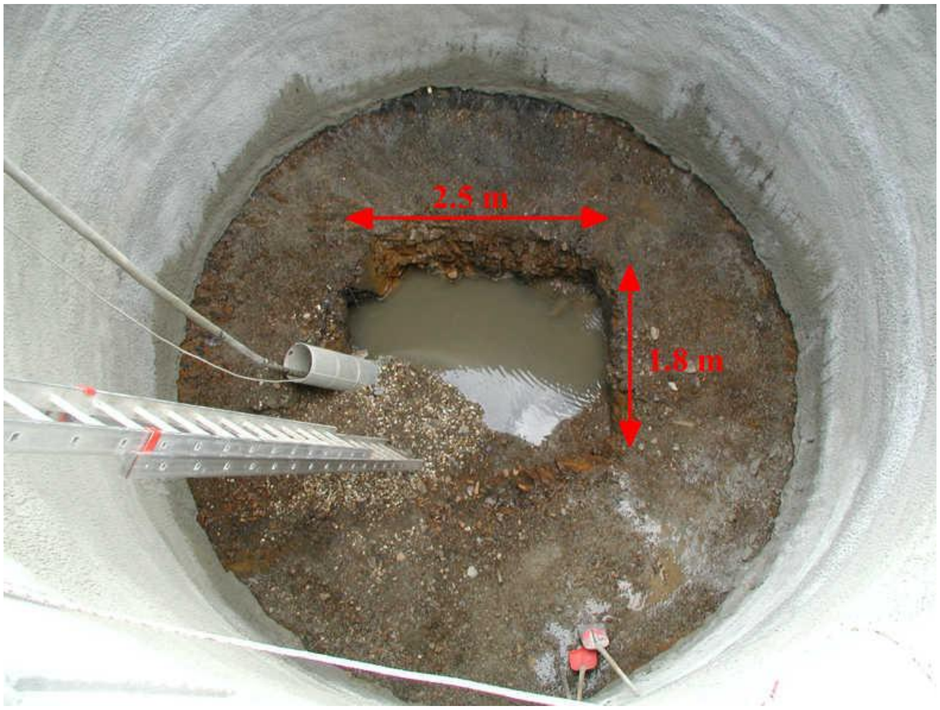


Figure 6.10. Bottom of an excavation pit with old extraction shaft contours (Heitfeld & al., 2006).

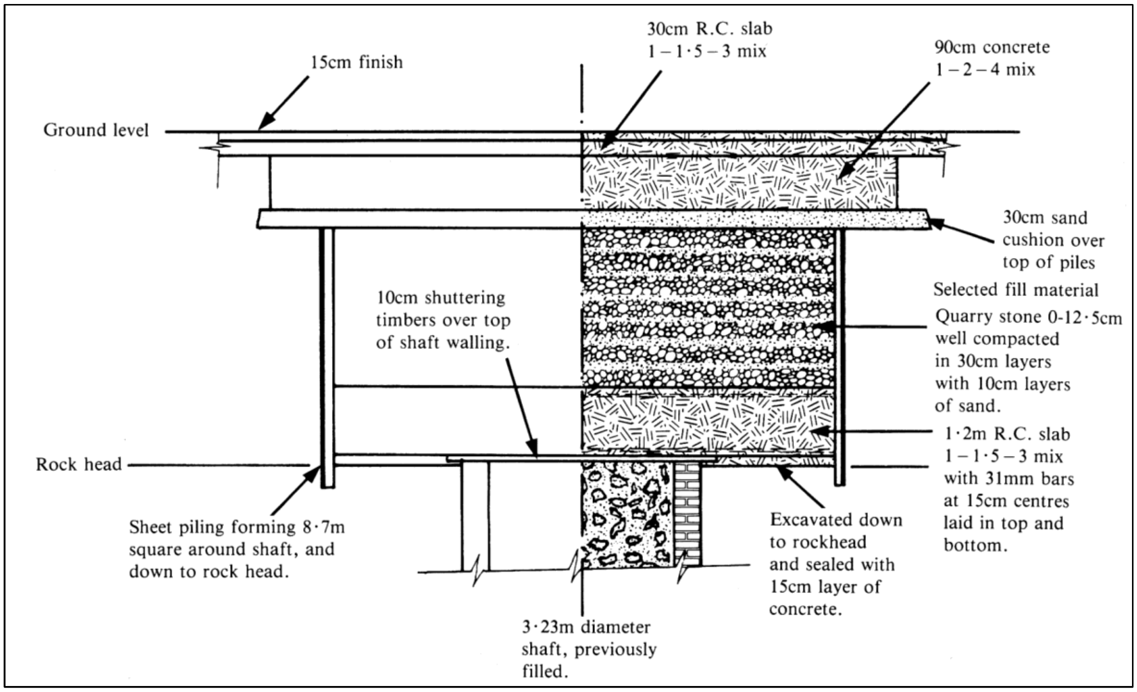


Figure 6.11. Details of rafting used to cover an old shaft located within a St. Helens industrial concern (Dean, 1967).

In low security level areas (e.g. forests), a fence around the shaft hazard zone also can be set up.

Two more examples of engineering treatment solutions for old mine shafts with pre-cast or cast-in-place concrete caps can be found in Bétournay, 2004.

Forces from suction (potential backfill run out within the shaft column) and overload (potential passage of a machine on surface) have to be considered in the calculations. When designing a concrete slab above a shaft with a depth of more than 100 m, one should also consider bounce forces (in case a partial shaft filling fails and drops down into the empty shaft) (Hollmann & al., 1976; Wojtkowiak & Didier, 1999).

In places where a critical amount of mine gas might reach the surface via the shaft, ventilation installations have to be placed into the concrete slab in order to avoid the risk of explosion. Such works have to be performed by skilled personal and according to the safety standards and requirements.

Shaft filling stabilisation

If a shaft filling is present and the surface rock is too deep to build a concrete slab economically, the filling can be stabilised by grouting the shaft filling down to the bottom of the shaft.

In many cases, the shaft filling might be reached partially by the platform within the shaft. Usually this can not be recognised by first boring detecting the shaft. Hence a vertical investigation boring is needed in the shaft filling which then can be used as an injection boring. Due to this vertical boring, such a platform may fail and break into the lower parts of the shaft together with the shaft filling. This would mean a significant hazard to the driver and his drilling rig. Hence, it is strongly recommended to perform such works from a steel platform which bridges the shaft (figures 6.12 and 6.13).

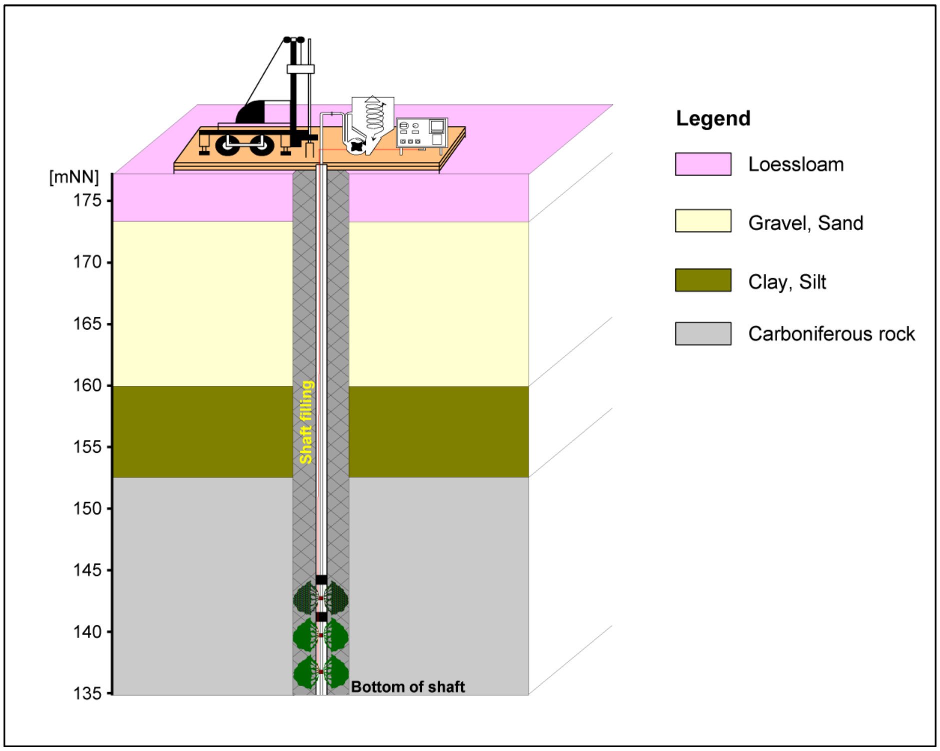


Figure 6.12. Injection into a shaft filling from a steel platform (Source IHS, Aachen)

Figure 6.13. Steel platform positioned above a shaft (Source IHS, Aachen).

Usually more than one injection boring is needed to stabilise the fall shaft filling. Stabilisation of the shaft filling can be assumed sufficient when three conditions are fulfilled:

- The cement injection rate decreases down to negligible volumes and the injection pressure reaches its limit.
- The comparison between the theoretical pore volume and the injected grout volume shows a satisfactory balance.
- The control core boring detects no residual hollow.

6.2 LAND USE MANAGEMENT

When, for technical or economical reasons, it is not possible or relevant to treat existing mine workings by backfilling or grouting, it is of major importance to manage properly land use of undermined sectors. Two approaches may then be complementary: a preventive one that consists in defining regulatory measures to avoid or reduce risky situations and a curative approach that consists in managing existing goods subjected to high risk.

6.2.1 Preventive regulation and mapping

For most national, regional or local authorities in charge of preventing consequences of abandoned mines for people property, one of the major objectives is to give information to the population on potential risk areas in order to prevent new building in such areas.

As an example of procedures available world-wide, a short overview of the French “ Mining Risk Prevention Plans (MRPP)” is given below.

The main purpose of a MRPP is to take risks into account within land-use management (Didier & al., 2007). MRPP procedure usually is applicable in sectors exposed to high levels of risk. However, it can also be implemented, as a preventive measure, within zones, which may constitute a risk in the future and, therefore, in zones within which urban development must be limited to avoid an increase of risk level. Thus, the MRPP process is mainly focused towards the future constructions through the idea of "prevention".

MRPP identifies zones, which are directly or indirectly exposed, taking into account the nature and magnitude of the risk. Within these zones, instructions based on town planning and construction regulations are defined. They have to be applied to each building project, concerning new installations as well as existing property and activities. MRPP can also be used to define general measures for prevention, protection and safety, that must be taken into account by public authorities and/or private individuals, particularly concerning measures linked to personal safety and the organisation of rescue.

It is a powerful regulatory tool because it takes the form of public preventive restriction. It is appended to Local Urbanism Plans (established within each French town) and takes priority if the two documents are not fully compatible. There are also many administrative tools assuring MRPP application, starting with penal sanctions in case the rules defined by MRPP regulation are not followed.

An MRPP is performed in four main stages :

- The data collection phase of an MRPP is designed to collect all available information (including further investigations if they are strictly necessary). It requires an on-site investigation and consultation of archives. In this phase, an "information map" is produced (figure 6.14). This map is used as a basis for diffusing essential information to the population, because it helps to justify the prevention procedure undertaken by summarising the disorder and harmful effect which has affected the site in the past.

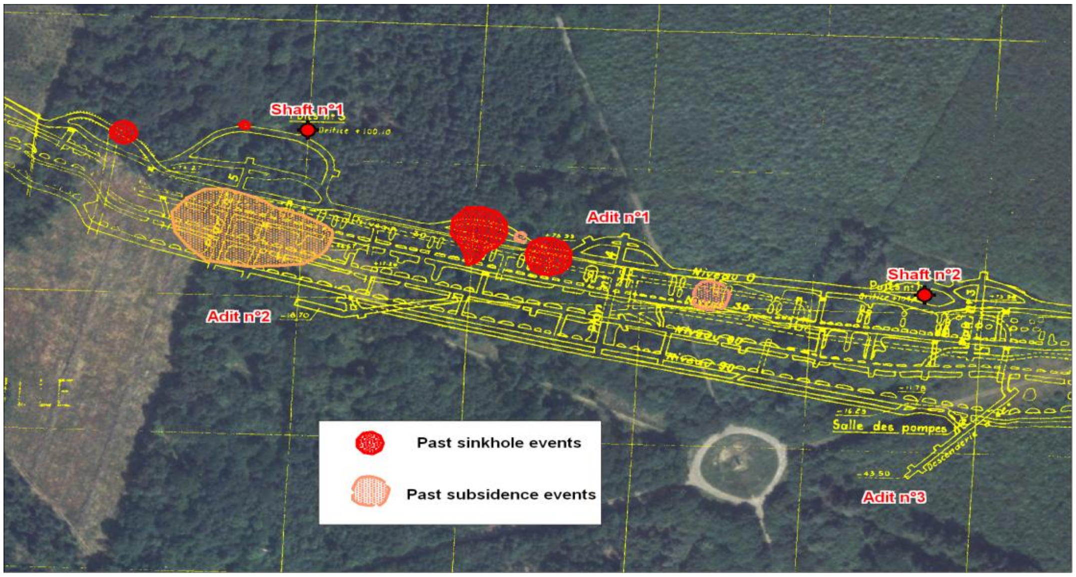


Figure 6.14. Example of an information map (Source INERIS).

- The hazard evaluation phase is intended to locate and list the zones exposed to potential phenomena, according to the intensity of the predictable events and the zone's predisposition to their development. This evaluation does not include the type of surface occupation. It ends with the drafting of maps, which locate the hazard zones identified by the evaluation procedure.
- The people and property assessment stage includes drawing up an inventory of all existing factors in areas subject to one or more risks and identifying the potential future projects, which could develop as a result. It is used to identify populations subjected to a non-zero risk level, particularly listing the most sensitive equipment or public establishments. It results in the production of a map including all the factors concerned.
- The regulatory zoning phase defines homogeneous zones in terms of prohibitions, instructions or recommendations concerning land use, for both new and existing projects.

The last "regulatory zoning phase" constitutes, without any doubt, the main part of the procedure. This is explained in more in detail.

Mapping hazard and drawing up a regulatory zoning plan are two specific procedures with fundamentally different objectives. Whereas the first identifies the different types of disorder likely to develop on the surface and locates them, the second marks out the limits of the zones within which homogeneous instructions can be defined to ensure the safety of people and infrastructure, now and in the future.

The risk zones are marked by cross-referencing hazard and factor maps, i.e. combining the type and intensity of predictable disorder with the occupation of surface land. Apart from exceptions, definition of the different zones is based on constructibility criteria (e.g. zones which are non-constructible or constructible under certain conditions). As for hazards, the aim is to avoid multiplying the number of zones, to facilitate the legibility of the maps. For this purpose, the number of zones selected are often limited to three or four (a white zone within which requirements are minimal or non-existent, a red one for sectors considered to be non-constructible and one or two blue ones in which urbanisation remains possible but with more or less severe constraints and restrictions).

Generally speaking, priority will be given to the development of a new urban area in zones outside areas with mining-related risks. However, although this rule can be applied relatively strictly for areas not yet urbanised, constraints may be relaxed locally in urbanised areas with mining-related risks over a major part of the area occupied by the communities in question. In this case, building permits may be given in low risk zones. The regulatory zoning plan must be drawn up as far as possible on a scale, which is compatible with studies performed during the risk evaluation and factor assessment phases.

At the same time, as the regulatory zoning plan is drawn up, the State Service in charge of drafting the MRPP draws up the regulation which defines the regulatory provisions applied to each zone within the regulatory zoning area. These measures are mainly intended to improve the safety of people and property in zones subject to mining-related risks and prevent increasing vulnerability of property and activities in the most exposed zones, reducing it if possible.

The regulations must be as simple and operational as possible to make it easier for the public to understand and adopt them. It is generally presented by type of regulatory zone (e.g. red, blue, white) after defining the general measures applied to all the sites within the limit of the MRPP.

For each zone, it is usual to organise the measures in two groups: those designed for existing property and those intended for future projects. The different measures may have the form of prohibitions, obligations or simple recommendations.

For successful drafting and application of the MRPP, all available expertise (administrative, technical and political) must be combined. A “dialog procedure” must therefore be systematically used between State Services and local authorities, to facilitate understanding, appropriation and participation of local authorities in the risk prevention policy. It is essential to obtain the participation of local representatives when drawing up the regulatory zoning plan and regulations because they are the main authorities who will be in charge of applying them on a daily basis and explaining them to the population.

6.2.2 Damage Compensation and Preventive Evacuation

In most countries, the mining operator, when it still exists, is responsible for the damages that can result from his activity, without any time restriction (even after mine closure). It is his responsibility to compensate victims of mining damage. It has to be proven that the resulting damages can not be attributed to another origin.

In several countries however, in order to avoid that victims may not be compensated in case of concession-holder disappearance or insolvency, the legislator expected the State to deal, in this specific context, with the victims’ compensation.

In case a major mining hazard seriously threaten public safety, the property exposed to this risk may be expropriated while the protection and/or prevention measures are more expensive than the expropriation costs. This statutory process is restricted to the cases of major risks and extreme urgency. Due to very strong socio-political constraints, this step is the ultimate risk management solution, when any other possibility is inadequate (for technical or economical reasons). During the last few years, about hundred houses have been expropriated throughout France and people have been relocated in other residences.

6.3 MONITORING

6.3.1 Ground Movements Monitoring

The monitoring of ground movements resulting from subsidence development in areas worked by long-wall mining or caving methods and from progressive failure of the underground rock mass to the surface may, be required for environmental safety or urban development.

Ground movements may be monitored using direct or indirect techniques. Direct techniques may involve inclinometers, extensometers of mechanical or fibre-optic type, Time Domain Reflectometry (TDR), geodetic measurements or differential GPS technique, as well as visual inspection. Indirect methods may involve aerial photogrammetric methods or the InSAR method.

The most important aspect in monitoring is the long-term reliability and repeatability of measurements because the measurements must be carried out over a long period of time, (several years). When ground movements are accelerated, the measurement intervals may be shortened and the combination of several techniques may be necessary. A brief outline of the major techniques is presented in the following paragraphs.

Direct Measuring Techniques

Inclinometers

An inclinometer basically measures the deviation of inclination of each segment of the casing (figure 6.15). The ground movements are converted to displacements on the basis of measured deviations and location of each casing segment. The device consists of an inclinometer casing, a traversing probe and a readout unit. The casing is permanently installed in a borehole. Important features of the casing include the diameter of the casing, the coupling mechanism, groove dimensions and straightness, and the strength of the casing.

The traversing inclinometer probe is the standard device for surveying the casing. Recently, some traversing probes are equipped with fiberoptic sensors. The traversing probe obtains a complete profile because it is drawn from the bottom to the top of the casing. The first survey establishes the initial profile of the casing. Subsequent surveys reveal changes in the profile of the casing, if a movement has been detected.

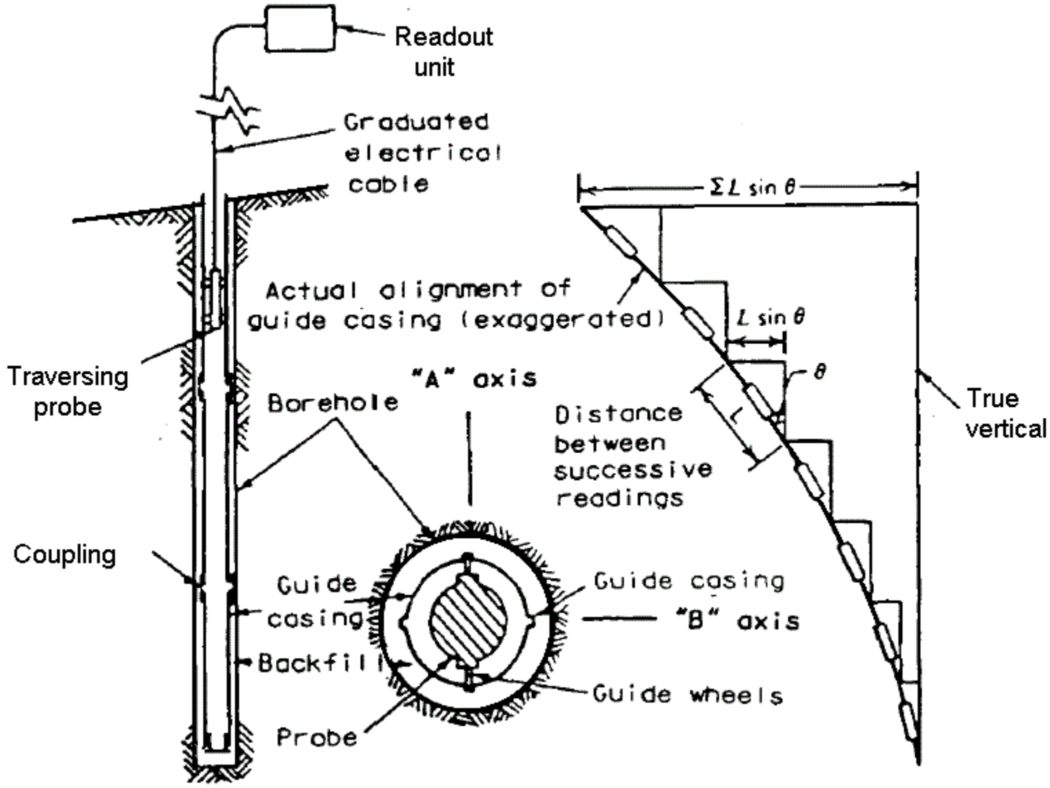


Figure 6.15. Ground movement measurement by an inclinometer.

Extensometers

An extensometer monitors changes in the distance between one or more anchors fixed to the ground and a reference head at the borehole collar (Figure 6.16). Components of an extensometer include anchors, rods or wires with protective tubing, and a reference head. The anchors, with wires or rods attached, are installed in a borehole.

A borehole is drilled to a depth at which the strata is thought to be at a stable equilibration. It is then lined with a steel casing with slip-joints to prevent crumpling as subsidence occurs. An inner pipe rests on a concrete plug at the bottom of the borehole and extends to the top. This inner pipe then transfers the stable elevation below to the surface. The wires/rods span the distance between the anchors and the reference head, which is installed at the borehole collar.

Measurements are taken at the reference head with a sensor or a micrometer, which measure the distance between the top (near) end of the anchor and a reference point. A change in the distance with respect to initial measurement indicates a movement. It may be referenced to a borehole anchor that is installed in stable ground or to the reference head, which can be surveyed. In recent years, fiberoptic extensometers have been developed and applied in practical monitoring of ground movements.

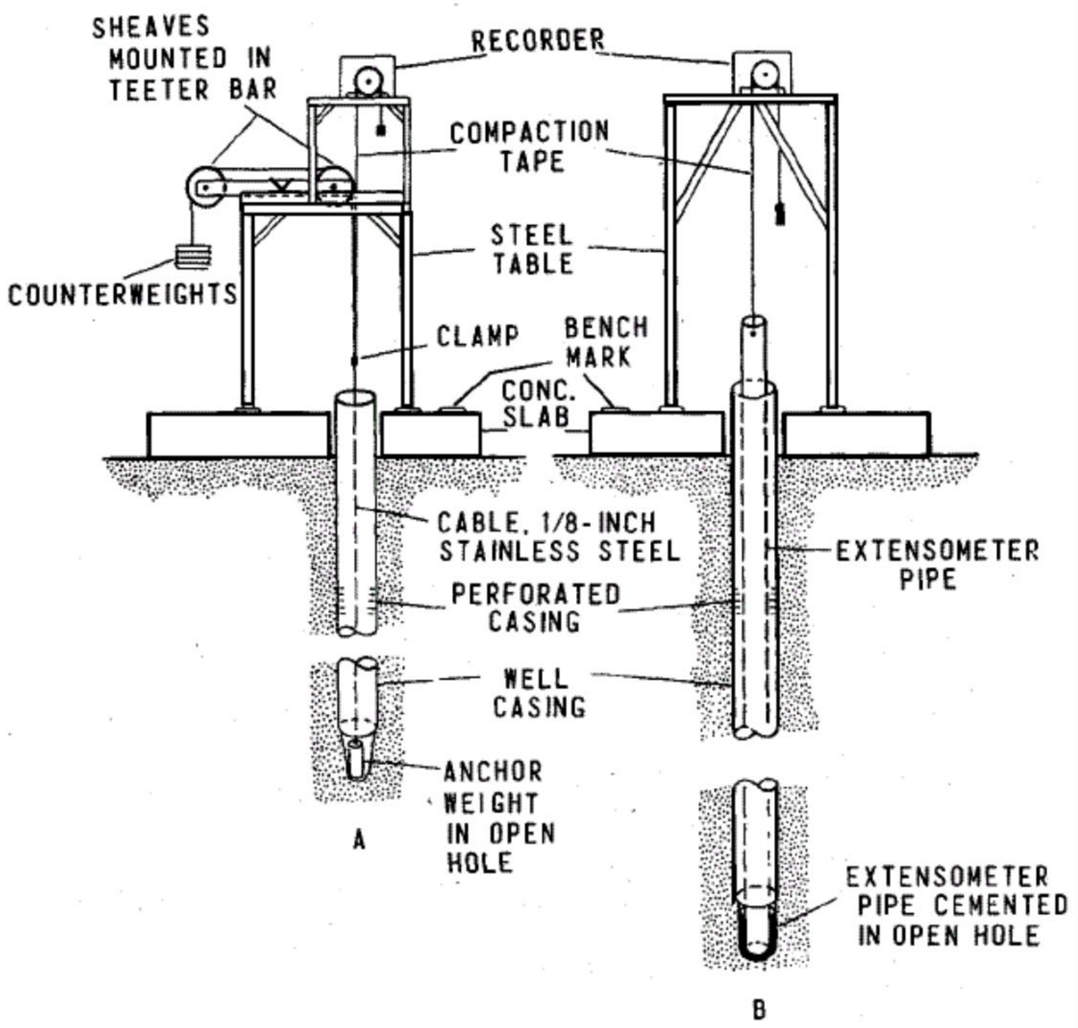


Figure 6.16. Illustration of ground movement measurement by extensometers.

Optical levelling technique

Ground movements may be systematically measured using optical levelling devices (Figure 6.17). For this purpose, a network of levelling points is established and measurements are performed at certain time intervals. The repeatability of the measurements obtained from different surveys and different loops and stability of the monuments with respect to its local environment are the main criteria for this technique. The levelling technique can provide very precise height differences up to a few millimetres level of accuracy. This technique is relatively flexible to be implemented in areas, which have usually dense housing, building and/or vegetation. The benchmarks can also be easily located. Data processing and analysis of the measured results can be done easily.

Although it yields very accurate height differences, the levelling technique is relatively slow and time consuming in its execution, especially when precise levelling procedures are being implemented. Its operation also depends on time, weather and also environmental conditions along the levelling routes. It should be also noted that the monitored points should generally be associated with a certain benchmark located on a stable zone outside the subsiding area. When the subsiding area is large, then connection to the stable benchmarks is another limiting constraint for implementation of the levelling technique.

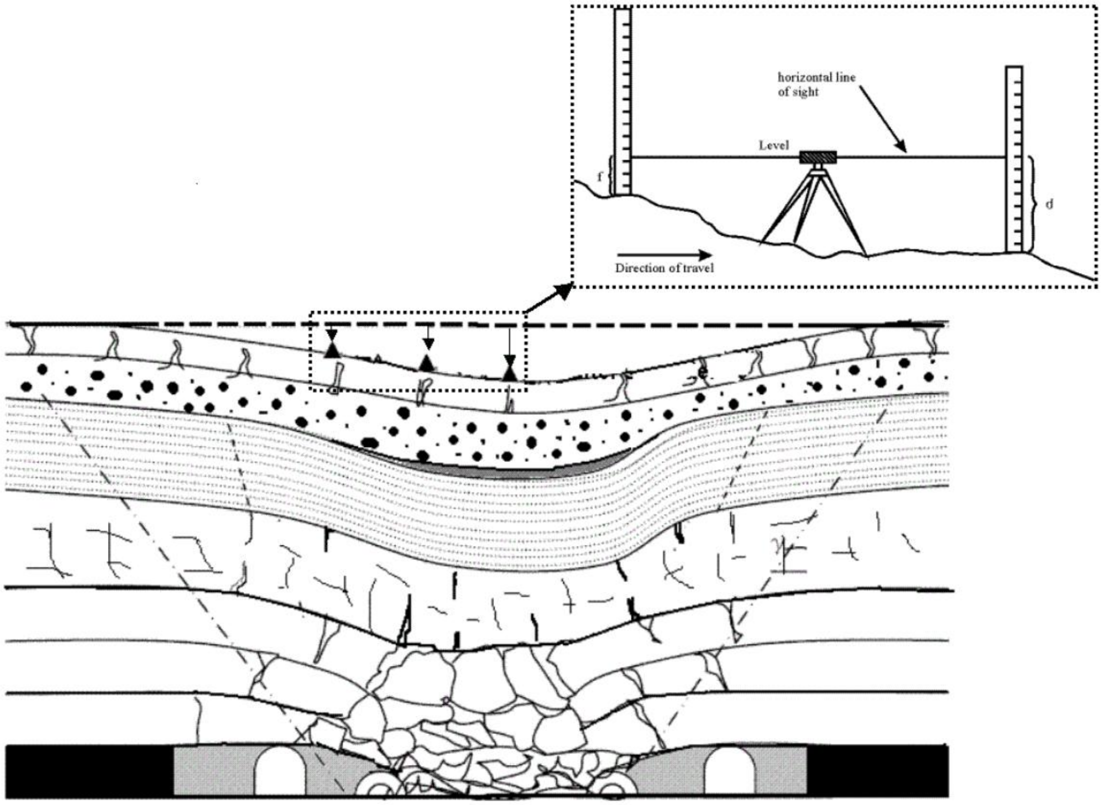


Figure 6.17. An illustration of ground movement measurement by levelling technique.

GPS levelling technique

GPS technique has also been applied to subsidence measurements in recent years (Figure 6.18). First, a network of GPS stations is established. The GPS survey is carried out at the stations using dual-frequency geodetic-type GPS receivers. There are several advantages of using GPS technique as:

- GPS provides three-dimensional displacement vectors with two horizontal and one vertical components so that the subsidence is obtained three dimensionally ;
- GPS provides the displacement vectors in a unique co-ordinate reference system, so that it can be used to effectively monitor subsidence in a relatively large areas ;
- Only differential GPS may provide displacement vectors with a several millimetres precision level, which is relatively consistent in time and space, so that it can be used to detect even relatively small subsidence signals ;

- GPS can be utilised in a continuous manner, day and night, independent of weather condition so that its field operation can be flexibly optimised.

However, surveys by differential GPS technique may show slightly worse standard deviations due to the signal obstruction by trees and/or buildings around the station. Therefore, the real precision level of the survey with signal obstructions and/or multi-path may be in the order of 1-3 cm while for the surveys with good signals it would of several millimetres.

The problem may result from the destruction or alteration of observation monuments inside the urbanised areas. Furthermore, expertise in GPS data acquisition and precise data processing is required for accurate detection of ground subsidence.

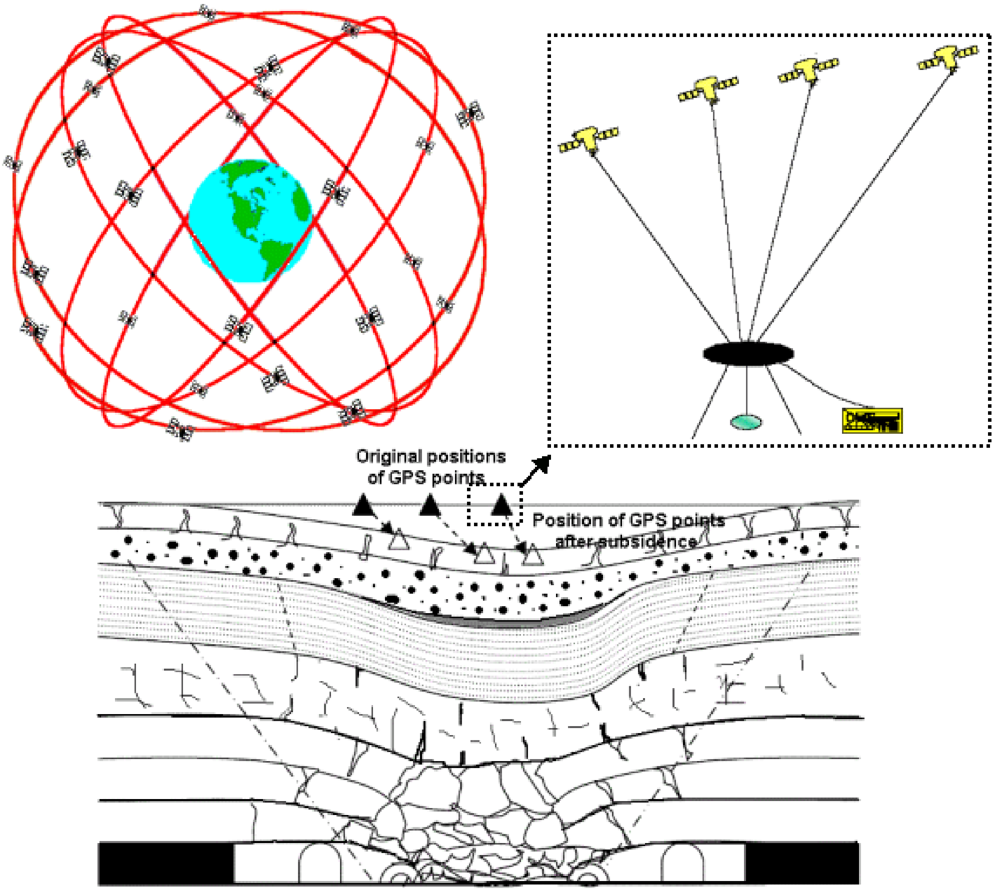


Figure 6.18. An illustration of ground movement measurement by GPS technique

Indirect Techniques

Aerial Photogrammetry

Aerial photographs are taken at certain time intervals with scales, such as 1:5000 or 1:10000, for determination of relative ground deformations. The area of interest must be covered with photographs, which must be continuous and should have an overlapping ratio of, at least, 60 percent (Figure 6.19). Data on the internal elements and inner factor of the camera used in aerial photography are required for making possible the geometrical analysis. Points used in the national triangulation network and water level points are used as permanent signals references.

The selection of control points is a very important factor for the determination of their spatial coordinates. It is essential to determine the control points independently in the field. In addition, the coordinates would be better determined from differential GPS.

Control points are generally marked by white plates on the ground so that they can easily be distinguished on the aerial photographs. They are assumed to be stationary points. Measurement points, which are the points on the ground surface in the area of interest, are marked on photographs taken at certain intervals.

In aerial photogrammetry, relative precision depends upon the scale of photographs and their inner factor (the precision in determining the coordinate system of photographs). Precision of measurement by aerial photogrammetry, for example in the *'Bundle'* method, is the standard deviation value of residuals. The vertical relative precision is generally 6 times the horizontal relative precision. Generally horizontal absolute precision is smaller than the absolute horizontal relative precision.

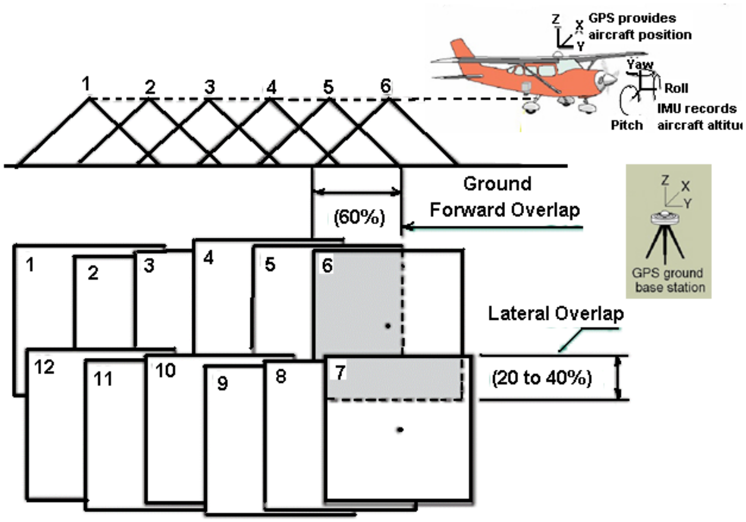


Figure 6.19. An illustration of the fundamental concept of aerial photogrammetry technique

Interferometric Synthetic Aperture Radar (InSAR) Technique

Although it is a relatively new technique, InSAR technique has a great potential for long-term monitoring of mine subsidence problems. Similar to aerial photogrammetry, SAR images of the same area taken at certain time intervals are needed (Figure 6.20).

Several methods can be required to monitor mining subsidence with InSAR technique. Several InSAR images of the same area are used to generate an interferogram. It shows the surface topography as well as the subsidence occurred during a given period.

A DEM of the area is then used to remove the topography from the interferogram and to generate a “differential interferogram”. This shows the surface height changes occurred during the period due to the mining subsidence. From the differential interferogram, the points affected by the same surface subsidence are extracted and contoured as lines of "iso-subsidence" which are overlaid onto a satellite image. This combination gives valuable information for the assessment of the actual and potential damage caused by subsidence.

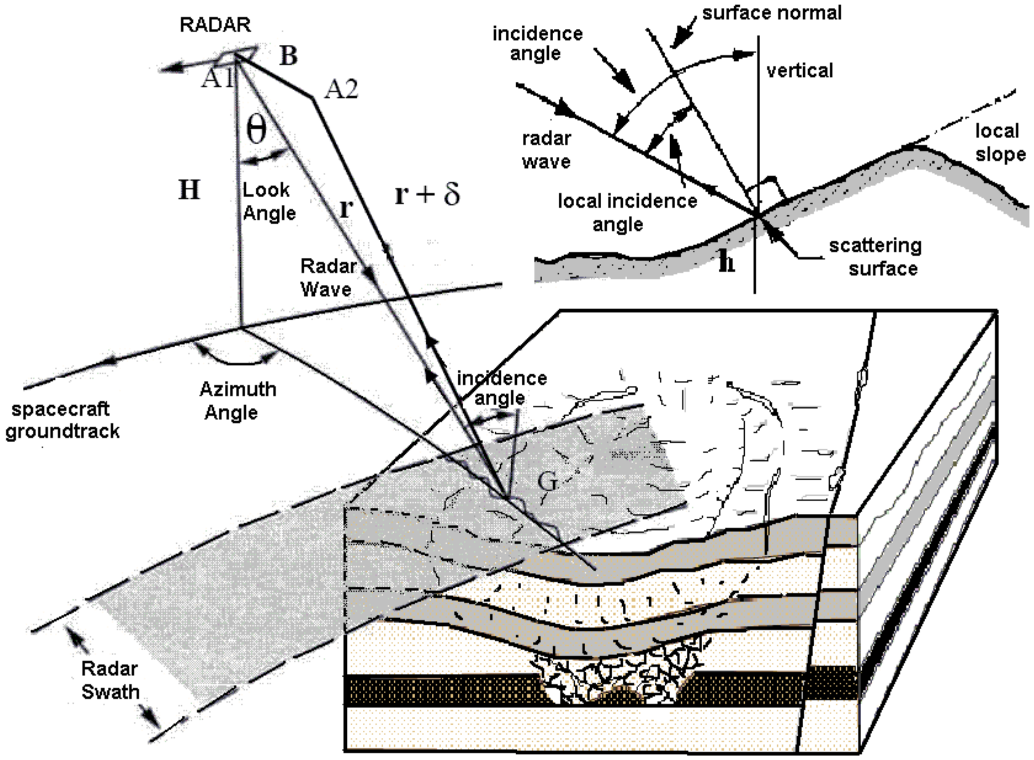


Figure 6.20. An illustration of ground movement measurement by InSAR technique

The InSAR technique yields the subsidence information on a regional scale (Ge & al., 2003, Haynes & al., 1997, Wright & al., 1999). However, its accuracy is restricted to several centimetres. The use of InSAR technique for studying subsidence phenomena is expected to be increasing with more Radar satellites in space (e.g. ERS, Radarsat, Envisat and ALOS) and more InSAR data processing packages available (e.g. Atlantis, Gamma, Vexcel, Roi-Pac and Doris).

To use InSAR technique for ground subsidence, multi-temporal radar images of the area are needed together with InSAR processing softwares and hardwares. An expertise in image processing is also required. Time frames for studying land subsidence will also be imposed by the passing times of radar satellites over the studied area. In the context of data processing, the potentially rapid environmental changes of urban areas or dense vegetation sectors, combined with relatively dynamic atmospheric conditions can also limit the potential of InSAR for accurate detection of land subsidence.

6.3.2 Monitoring mine-induced seismicity to identify potential instability sources

Degradation and creep phenomena of surrounding rocks of abandoned mines may result in the failure of roof and/or pillars. As described before, these failures may sometimes lead to catastrophic events at the ground surface like huge and sudden collapses or subsidence troughs, which may affect or destroy structures and cause casualties.

The seismo-acoustic monitoring principle consists to monitor the occurrence, location and magnitude of such failures and their progress in time (Couffin & al., 2003). Collected data may then be used to warn authorities responsible for public safety, if necessary.

These systems consist of sensors (e.g. accelerometers, geophones), A/D digitisers and data-acquisition and data processing units. Figure 6.21 shows an example of designed by NIOSH (Swanson & al., 2002). Sensors can be fixed into boreholes, competent rock surfaces or steel wave guides fixed into rocks.

Seismic signals are either transmitted via cable to an A/D converter attached to a data acquisition unit or digitised near the sensor and data transmitted to a data acquisition unit. In each case, the data acquisition systems collect waveform files either continuously or in a triggered event-capture mode. Data received from the data acquisition unit are processed by a data-processing unit to obtain the location and magnitude of seismic events associated with rock cracking.

Some advanced systems also identify the source characteristics of the seismic events. The rate of seismic energy release may be used to warn the local authorities and people of the collapse risk.

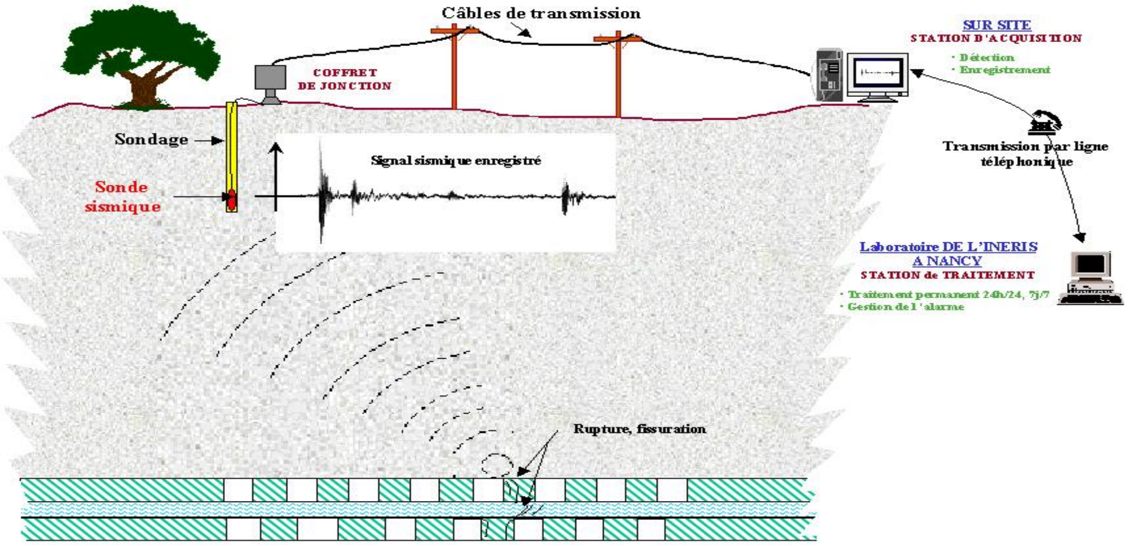


Figure 6.21. An illustration of induced seismicity by abandoned mines (Source INERIS).

6.3.3 Monitoring of abandoned mines located in areas sensitive to earthquakes

In countries with high seismicity, earthquakes may lead to ground amplifications above abandoned mines or cause the collapse of overburden. Such events are reported in Japan and the USA. For example, the recent M6.2 event near Yamoto town during the Miyagi-ken Hokubu earthquake caused severe damage to abandoned lignite mines resulting in sinkholes and discharge of muddy underground water to the ground surface (Aydan & al., 2004).

A severe ground amplification may also result from the abandoned mines exploited by room and pillar method, as shown by physical and numerical models.

Urban areas with abandoned room and pillar lignite mines (i.g. Mitake in Gifu Prefecture, Yamoto in Miyagi Prefecture of Japan) are very much concerned with the risk above disused mine workings (Figure 6.22). The monitoring system for this purpose is basically similar to those used for monitoring mine-induced seismicity. Nevertheless, sensors are installed at different depths to monitor the amplification characteristics as well as surface ground movement. At least three or four sensors (one is 10-20 m below the extracted seam, two just below and/or above the seam and ground surface) are installed and triggering is carried out.

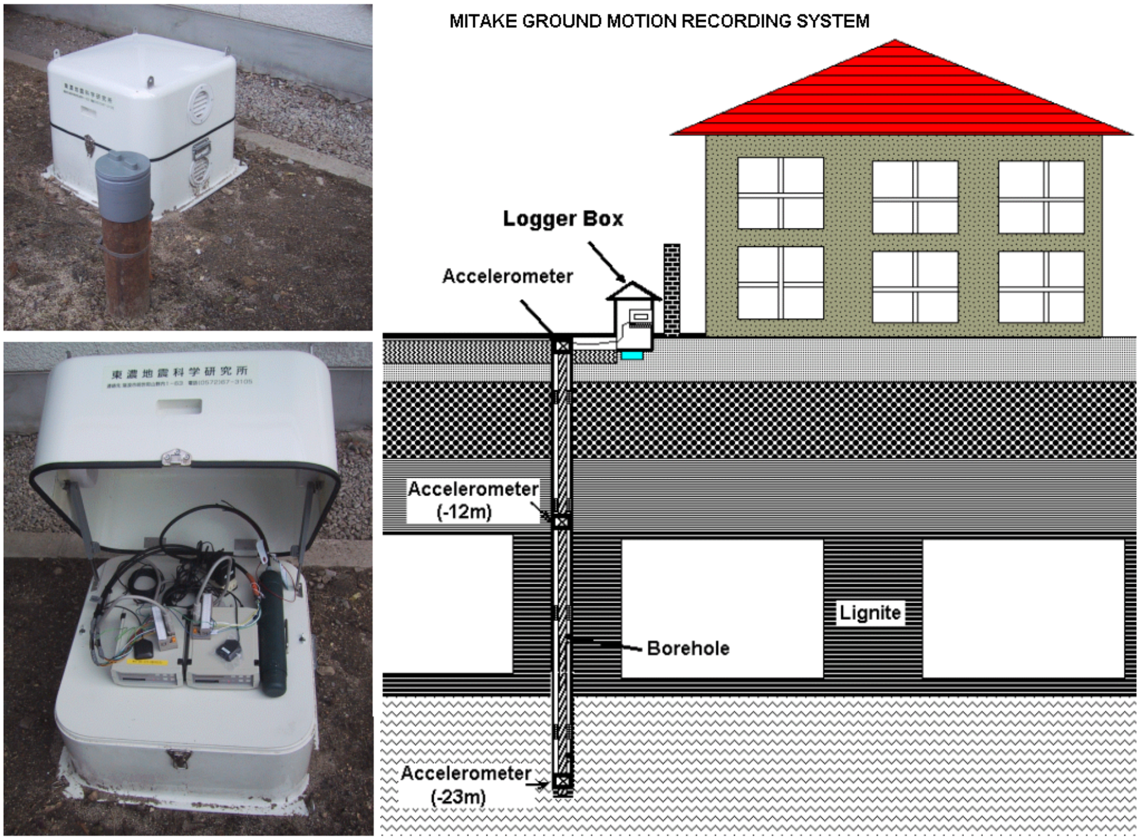


Figure 6.22. Strong motion monitoring system at Mitake Lignite Town
(Mitake Abandoned Mine Mitigation Committee, 2005)
(the system is operated by Tono Geoscience Center))

6.3.4 Time Domain Reflectometry Monitoring for Abandoned Mines

Time Domain Reflectometry (TDR) is an electrical pulse testing technique (Dowding & al., 1989; O’Connor & al., 1999). Ultrafast rise time voltage pulses are sent along a rigid co-axial cable from a cable tester unit (Figure 6.23). Pulse reflections from all changes in geometry along the cable (breaks, tight deformations, etc.) are superimposed on the input pulse and returned as a reflected “signature”. The characteristics of a TDR signature are not only defined by the magnitude of cable deformation but also by the type of deformation imposed to the cable (shear, tension, combination). This provides a powerful means of delineating the failure mechanism and the progress of the location and development of the failure front towards surface, by covering the rock mass in three dimensions using several cables. Stand-alone remote systems, multiplexing of several cables and data storage systems are possible, as well as the manual use of the read-out unit on site. Installation of the cable is straightforward: they are placed in drill holes and then fully grouted. The orientation of the cable placement is only limited by site and drilling equipment restrictions.

Each displacement along the length of the cable is registered with an accuracy of about 2.5 cm. A very close match can be made between the location of cable movement and rock mass features in the rock core from the borehole. When the cable is severed, the remaining upper portion is still functional.

TDR has been successfully applied to a variety of geotechnical needs: measurement of soil moisture, water level as well as soil and rock mass stability assessment. The latter includes abandoned coal, gypsum and metal mine failures (O'Connor & al., 2007; Aston & al., 1994).

TDR is not as accurate as extensometers, but its basic advantage has on the fait that it can measure displacements along and across the instrument over the entire length of the cable, at a lower cost. Signal attenuation limits the length of the cable to about 100 m for quantifiable readings, although lengths of 600 m can still provide indications of movement.

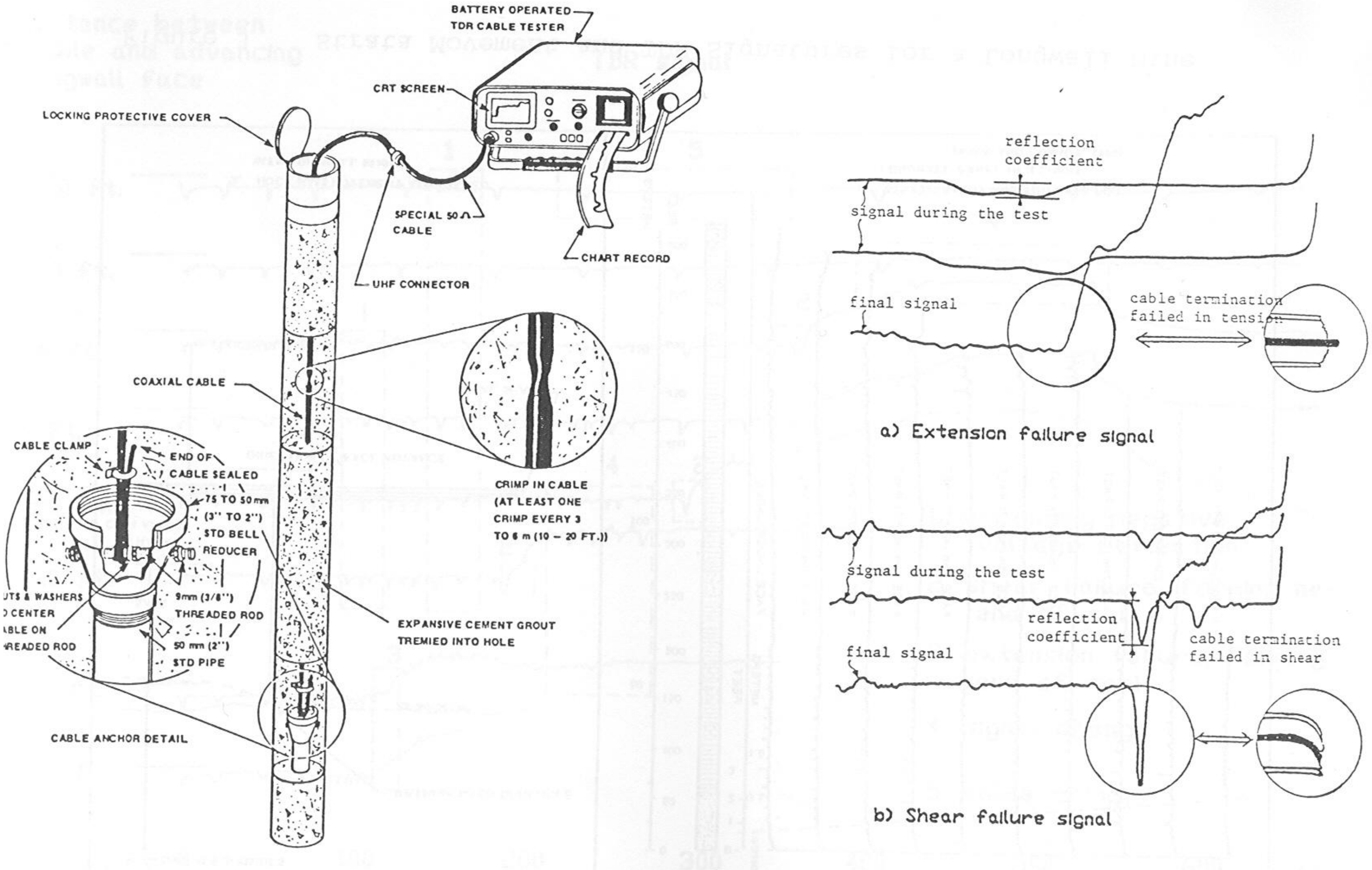


Figure 6.23. Schematic TDR installation and signal properties (O'Connor & al., 1989)

6.3.5 Monitoring techniques under scientific and experimental development

Soft rocks mechanical properties are influenced by water content change. The compressive strength and elastic modulus of this kind of rocks generally decrease with the increase of water content. Rock degradation effect due to the cycles of wetting and drying causes the flaking of rock near the surface and the fall under the effect of gravity. This process is repeated continously, which subsequently causes the long-term reduction of the supporting area of the pillars. Therefore, it is of first interest to monitor the environmental parameters such as temperature, humidity, air pressure within the abandoned mines and water content, temperature variations in surrounding rocks in association with the degradation process.

It is also known that, when rocks subjected to high stresses start to fail, the mechanical energy accumulated within the rock is transformed into different forms of energy according. About of transformation involve the variations in electrical potential, magnetic field, heat release and kinetic energy in the surrounding rock mass. Recent experimental studies on various types of rocks by Aydan and his co-workers (Aydan & al., 2001, 2003), including some from abandoned mines indicated variations in parameters mentioned above during deformation and fracturing processes. Therefore, they may be used in the assessment of the short-term stability of abandoned mines.

The real-time multi-parameter measurement system involves electric potential (EP) variations, acoustic emissions (AE), temperature and water content of rocks (RT), temperature, humidity and air pressure within the abandoned lignite mines above the ground water table (Aydan & al., 2005b; figure 6.24). The rocks around abandoned mines above the ground water level are much more prone to degradation due to environmental variations in time (Aydan & al., 2005a). The temperature, humidity and air pressure sensors are installed at certain distance from the mine entrance to monitor the spatial distribution and variations in time. Temperature and water content sensors are also installed at several depths in some selected pillars and monitored in time.

Geo-electric potential monitoring devices and electrodes are set up within the abandoned mine. It is generally useful to install the devices close to geological discontinuities such as faults and fracture zones, which are much more sensitive to stress changes within the surrounding rock mass. When rock mass is damp or saturated, the electrical resistance of ground is in the order of kΩ. Therefore, it would be sufficient to use devices, whose impedance is in the order of MΩ. Otherwise, it would be necessary to use devices having impedance in the order of GΩ. Therefore, the measured electric potential variations by the devices are directly related to those of the surrounding rock mass. The amplitude and orientation of geo-electric potential variations are used to infer the likely location and magnitude of sources of instability.

The AE system is limited only to counting AE events (Tano & al. 2005). It may be useful for long-term monitoring of rock fracturing in abandoned lignite mines (figure 6.24). Pulse signals, which correspond to AE waves exceeding certain threshold are discriminated through a pulsar and recorded onto a pulse counter (logger) as AE rate counts. Such limited specification of the rate counting reduces the system cost so that it is capable of using two AE systems as one set. One of the AE systems is called an active unit while the other one is called a dummy unit. The active unit is directly attached to the rock mass while the dummy AE sensor is not in contact with the rockmass. If signals are counted on both systems, the count of the active unit is neglected from the measured data. This active-dummy counting system increases the reliability of the AE monitoring and checks the noise condition in the field.

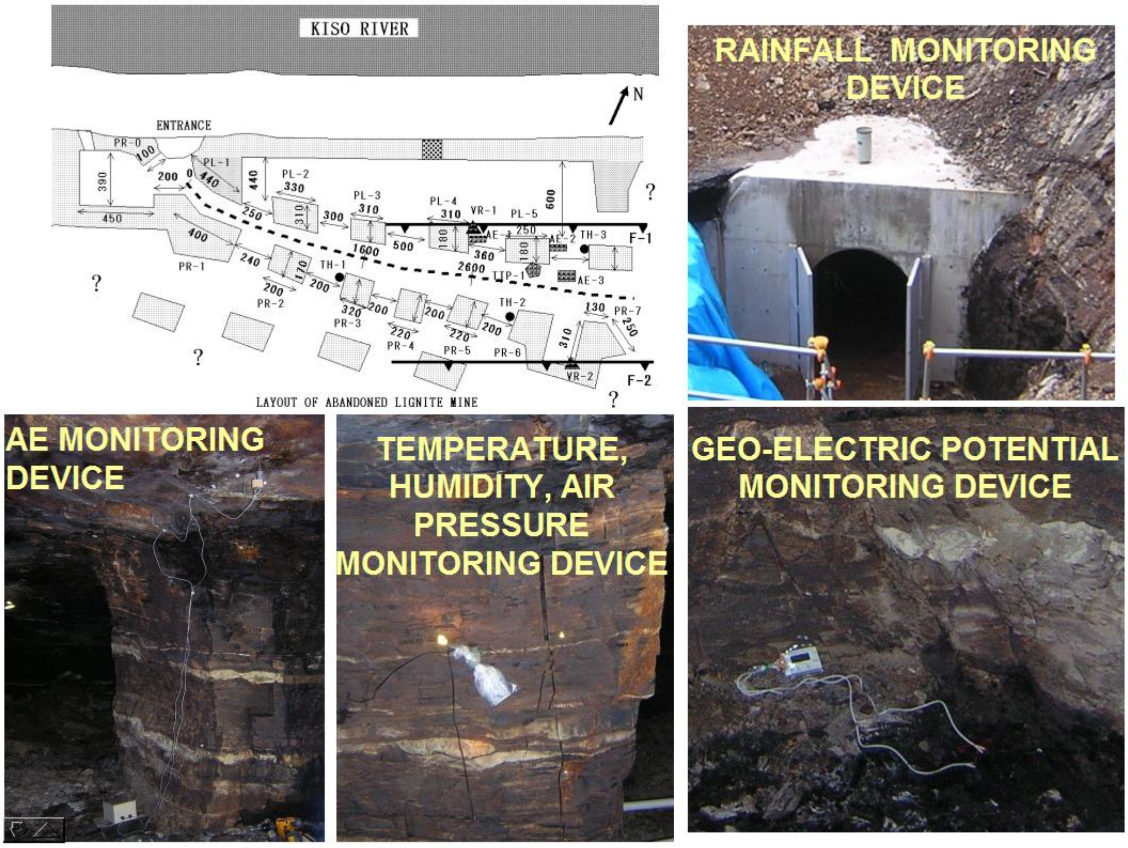


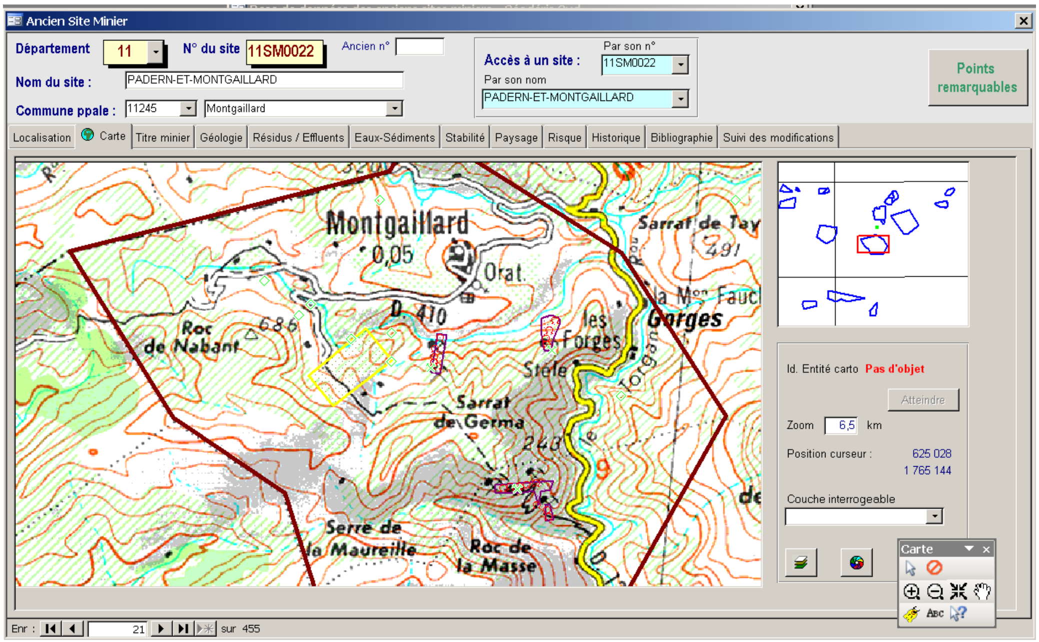
Figure 6.24. Application of multi-parameter system for monitoring degradation and long-term response of surrounding rock mass at an abandoned lignite mine (from Aydan et al.. 2005b)

6.4 DATABASE MANAGEMENT

6.4.1 Importance of data management

Acquisition, management and validation of available data constitute an important step in a risk prevention policy. For this reason, it is essential to build a database able used for management.

As an example, GEODERIS, (French public body in charge technical support to Administration on mine closure issues), has developed and exploited, since 2001, a database on abandoned mining sites (figure 6.25). This tool, dedicated to the different stakeholders involved in post-mining (e.g. administration, cities, experts), aims to identify, classify, organise and make exploitable the data available on abandoned mining sites. The database and its structure are in constant evolution in order to fit different requests from various users.



Département 11
N° du site 11SM0022
Nom du site : PADERN-ET-MONTGAILLARD
Commune ppale : 11245 Montgaillard
Accès à un site : Par son n° 11SM0022
Par son nom PADERN-ET-MONTGAILLARD
Id. Entité carto Pas d'objet
Zoom 6,5 km
Position curseur : 625 028 1 765 144
Enr : 21 sur 455

Figure 6.25. A typical screen-print of the Geoderis post mining database.

The database integrates data on mining titles (e.g. concession perimeters, agreement for exploration task) and mining sites (sector of exploitation known with more or less a degree of precision). It gathers administrative (beginning and end of the mining titles, information on owner) and technical (e.g. mining methods, depth) information related to underground or open-cast mines. Data concerning mine openings (shafts, adits) as well as mining waste deposits (tailings, spoil heaps) are also collected. The database also makes it possible to gather information on geology and characteristics of the ore deposit as well as information concerning past events with mining origin (e.g. number, nature, date of appearance).

It is possible to bind a mining site or a mining title to various types of documents (photographs, maps, letters) like to the results of analyses undertaken on the site (expert report, zoning of risk), see figure 6.25. The database, developed under ACCESS®, allows visualisation of the various elements (e.g. titles, sites, works, zones of risks). The tool is of a very simple and intuitive use, not requiring any particular knowledge of specialised software (Dommanget, 2006).

6.4.2 Example of abandoned coal mines database in Korea

The closure of 336 coal mines during the last two decades in Korea has caused safety and the environmental problems such as ground subsidence, acid mine drainage (AMD), and deforestation. To solve these problems the Korea Mine Reclamation Corporation (former Coal Industry Promotion Board), KMRC has continuously carried out mining-related damage restorations and environmental improvements.

Also, KMRC launched a project to construct an Abandoned Mine Geological Information System, called AMGIS for the abandoned underground coal mines in 2003. This system was developed for management and prevention for mining-related damages. The AMGIS project aims to develop an expert system, which can support decision-making policy for rehabilitation in abandoned underground coal mine areas and can provide basic geological data for regional construction works as well as for building a database.

KMRC collected and managed data for 52 abandoned underground coal mines for two years and developed application programs to analyse and estimate the mining-related damages. Figure 6.26 shows the system configuration of the AMGIS. The server side consists of ArcSDE for management of spatial database and Oracle RDBMS. The client side consists of workstations where the client applications based on ArcGIS are loaded.

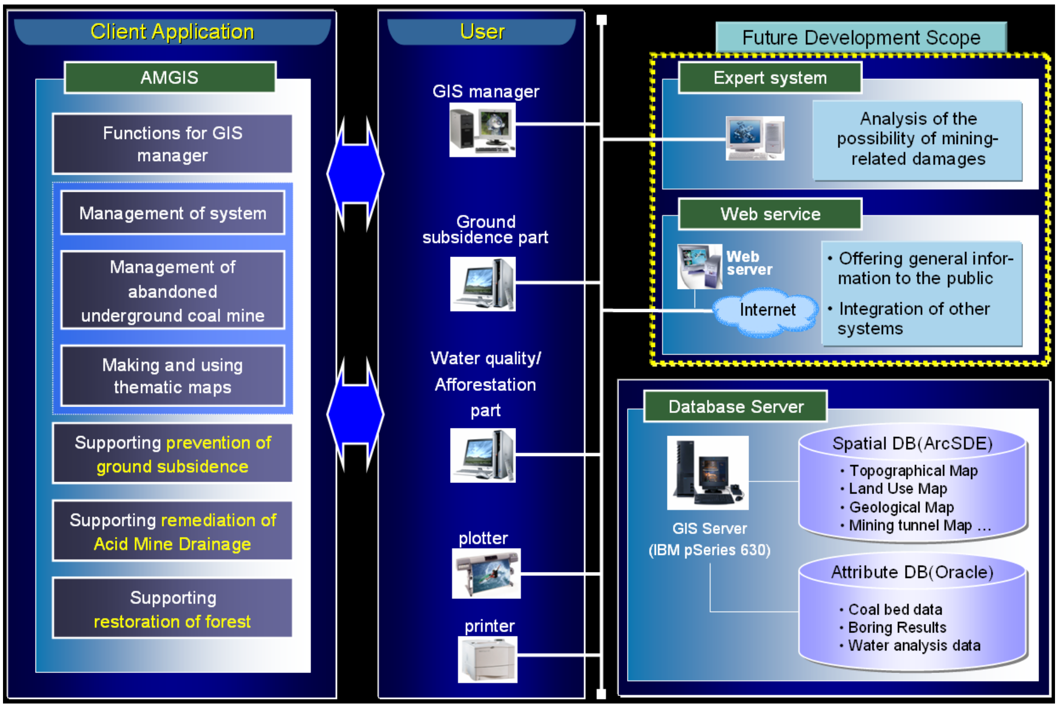


*Figure 6.26. System configuration of AMGIS (*Lee et al., 2005).

Spatial Database

Spatial database of AMGIS contains the following information.

- Topographical map: road, railroad, river, building, administrative districts, height contour etc., 1:5,000 scale, published by NGII (National Geographical Information Institute).
- Land Use map: represents the land use based on land registration map, 1:5,000 scale, published by NGII.
- Geological map: e.g. geological unit, boundary, structural line, strike and dip; 1:50,000 scale, published by KIGAM (Korea Institute of Geoscience and Mineral Resources).
- Mine Lot map: represents mining land registration, overlay of unit and free style mine lot map.
- Mining Tunnel map: represents the location, depth and width of shafts, drifts, and mine opening. Especially, mine openings were surveyed by GPS for the use of Ground Control Points.
- Satellite Image: Ikonos and landsat-7 ETM+ image.
- Spatial data obtained from mining-related damage prevention projects: e.g. areas of investigation, reinforcement work and remediation facility, cross-lines for geological and geophysical interpretation and borehole locations.

Attribute Database

Attribute database of AMGIS contains the following information.

- Abandoned underground coal mine information: e.g. mining record and various information about shafts and drifts.
- Geological Interpretation data: e.g. coal beds, field survey data and cross-section interpretation.
- Geophysical Prospecting data : e.g. seismic, electrical resistivity and GPR.
- Borehole data: e.g. Standard Penetration Test (SPT), water pressure test, Goodman jack test, Rock Mass Rating (RMR), BIPS and Numerical Analysis.
- Mechanical Measurement data: e.g. Multi Point Borehole Extensometer (MPBX), Slope Inclinometer.
- Reinforcement Work data: e.g. grouting material, reinforcement method.
- Wastewater Purification data: e.g. information of facilities, water quality and pollution status.
- Forest Restoration data: e.g. ruined status, afforestation information.

Application module

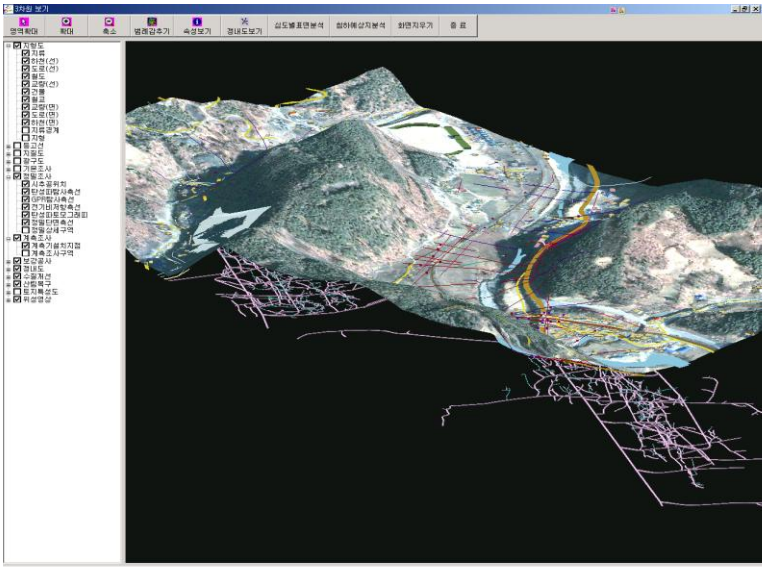
AMGIS can be served as an useful tool to do the following works.

- System administration:
    - registering and editing users and codes
    - managing the system privileges of users
    - setting up the work areas and group layers
    - managing functions of spatial and attribute data
- Management of abandoned underground coal mines:
    - searching and editing abandoned underground coal mine data and maps(mine lot map and geological map, etc.)
    - making the charts and reports of abandoned underground coal mine data
- Management of abandoned underground coal mining-related damages (Figure 6.27) :
    - managing the mining-related damages data and prevention work results
    - searching and viewing the individual survey and prospecting data

행 정 구 역: 강원(도계)
사 업 지 역 명: 고사리지역
침하지번호: 07
용 역 명: 고사리지역 지반보강공사 실시설계 보고서
침 하 지 명: 고사리지역
수 준: ml
연 장: 116 m
폭: 75 m
깊 이: m
균 열 방 향: °
심 도 차: m
침 하 상 태: 남풍갱주변
침하지관리:

Figure 6.27. Surface subsidence control module.
*General information (left) and restoration work history (right) (*Lee et al., 2005).

- Making thematic maps :
  - Making the various complex maps of mining layers
- 3–D visualisation of mining tunnel map (Figure 6.28) :
  - Visual analysis between underground tunnels and surface facilities



☑ 지형도
☑ 지류
☑ 하천(선)
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☑ 건물
☑ 철교
☑ 교량(면)
☑ 도로(면)
☑ 하천(면)
☐ 지류경계
☐ 지형
☐ 등고선
☐ 지질도
☐ 광구도
☐ 기본조사
☑ 정밀조사
☑ 시추공위치
☑ 탄성파탐사측선
☑ GPR탐사측선
☑ 전기비저항측선
☑ 탄성파토모그래피
☑ 정밀단면측선
☐ 정밀상세구역
☑ 계측조사
☑ 계측기설치지점
☐ 계측조사구역
☑ 보강공사
☑ 갱내도
☑ 수질개선
☑ 산림복구
☐ 토지특성도
☑ 위성영상

*Figure 6.28. 3-D satellite image merged with underground mine tunnels (*Lee et al., 2005)

- Analysis of the possibility of ground subsidence (figure 6.29) :
  - 2-D and 3-D cell-based analysis considering the depth between each cell and underground tunnels
  - theoretical analysis using the theory of angle of draw and the theory of volume expansion.

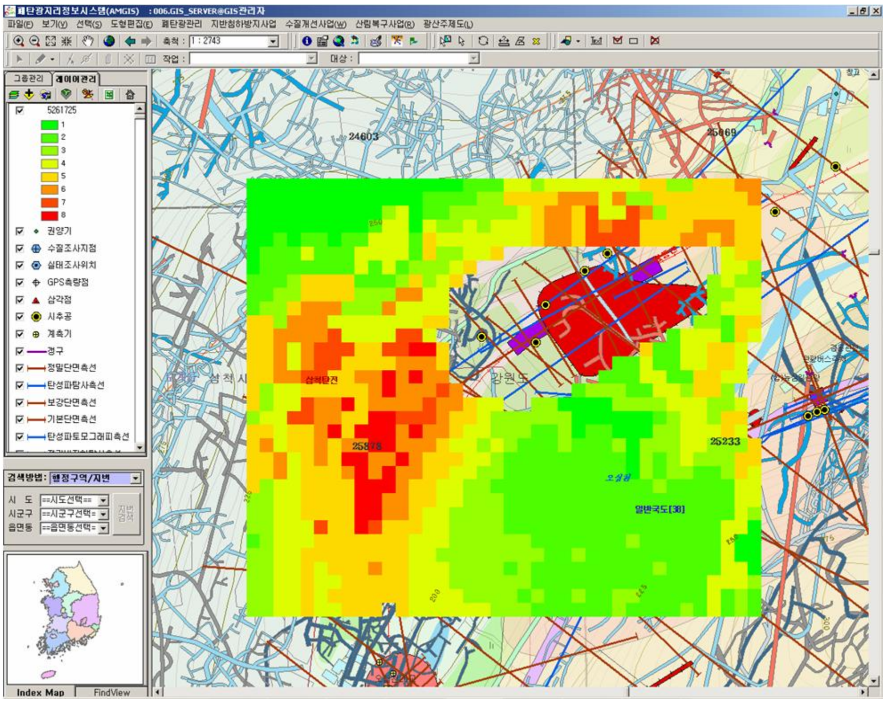

Figure 6.29. Subsidence risk map obtained from 2-D cell-based analysis. The red cells represent the areas where the subsidence could occur with high probability (Lee et al., 2005).

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LIST OF APPENDICES

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Appendix A

Mine gas emission to the surface.
Phenomenon and mechanisms

Mine gas emissions at the surface are likely to endanger people and property, which almost exclusively concerns, underground mining operations. Three unfavourable factors need to combine to produce risky situations:

- cavities forming an underground reservoir;
- presence of dangerous gases;
- possibility of gas accumulation and migration towards surface at significant concentrations.

During operations these gases are diluted and evacuated by the ventilation system. After halting mining operations, if not completely flooded, mining spaces form a more or less confined underground reservoir in which mine gasses can accumulate at high concentrations. Depending on the ore extracted and the gases present in the deposit, the residual mine atmosphere may differ greatly in composition from one site to another.

These mine reservoirs do not usually have a distinct limit or shape. They are still sets of "elementary" cavities however, more or less interconnected. The available voids may sometimes represent considerable volumes. For coalmines, this volume may reach several million m^3, or several tens of millions of m^3.

1 DESCRIPTION AND EFFECTS OF THE PHENOMENON

Depending on the type and composition of mine gas, surface gas emissions may constitute several risks or nuisances to people and property (Tauziède et al., 2002). One may particularly note the risk of asphyxia, intoxication or irradiation and finally, the risk of inflammation or explosion. These risks are increased when the mine gas is confined, i.e. not or only slightly diluted. They are evidently less important for diffuse emission into the open air.

Mine gas generally is a mixture of gases of various origins at variable concentrations. Some gases are of endogenous (contained in the deposit before extraction) origin (firedamp, carbon dioxide, radon), others of exogenous (produced by chemical transformation of the deposit or certain elements of the mineral, during or after extraction) origin (carbon monoxide, carbon dioxide, hydrogen sulfide, for example).

The main constituents of mine gas, described below, do not represent the same level of risk for people and property on the surface. However, the dangers of each constituent do combine. So the same concentration of toxic gas will be more dangerous in a gaseous mixture with other toxic gases (or an oxygen deficit) than if it would be alone.

1.1 METHANE (CH_4) AND ITS HIGHER HOMOLOGUES (ETHANE, BUTANE, PROPANE)

Methane is the main constituent of firedamp, a gas essentially found in solid fuel mines, and to less extent, in salt or potash mines. It can also be found in oil, bituminous limestone, bituminous schist and bauxite mining operations.

In *coal or lignite mines*, methane usually is the predominant gas (up to 95% or more). Other gases (ethane, butane, propane, nitrogen, carbon dioxide, etc.) may also be present in variable proportions from one seam to the next, but usually at low concentrations. In some specific cases, CO_2 may replace CH_4 as the predominant constituent of firedamp.

Firedamp is "trapped" in the material mined (coal, lignite, bituminous schist…) in adsorbed form, and to a lesser extent in the pores of the surrounding rocks, as free gas. During operations, because of land relaxation, it is readily released from coal and rocks. Nevertheless, significant quantities of firedamp remain in the unexploited areas. Gas emission, even slow, can therefore last for a long time, until a new balance is established, which will be different for each site.

Methane is an odourless, colourless, tasteless gas. It is about half as heavy as air and therefore tends to accumulate in higher areas and migrate towards the surface. It is a non-toxic gas, physiologically inoffensive in that its presence does not lead to a reduction in atmospheric oxygen leading to a risk of asphyxia (see below). Essentially it is its inflammability (or explosivity) which makes methane such a dangerous gas.

A binary mixture of air and methane may explode directly when the concentration of methane is between 5% (lower explosive limit) and 15% (upper explosive limit). Ignition of such a mixture causes thermal and mechanical effects, which are hazardous to humans and can cause damage to property.

1.2 CARBON DIOXIDE (CO_2)

Carbon dioxide, which is probably the most frequently detected gas in old underground mine workings, may have several sources.

In some coalmines, firedamp is detected which consists entirely or partly of CO_2. Like methane, this gas is present in adsorbed form, in coal. It can be explained by more or less significant replacement of the original methane, following volcanic activity after constitution of the coal deposit. Carbon dioxide may also be due to combustion (underground fires) or slow oxidation of organic materials. This is the case for coal and lignite mines, but may also concern any other type of underground installation, where organic material is present, though to a lesser degree. It may also be of human origin (supporting wood for example). Finally, another source of CO_2 may be the action of acid water on carbonaceous rocks. This situation may be found in many mines, no matter what the extracted mineral is.

Carbon dioxide is a colourless, odourless gas. It is about one and half times heavier than air. It therefore tends to accumulate in low, unventilated areas. Non-inflammable, CO_2 is very slightly toxic at low concentrations but quickly becomes dangerous, even in the presence of oxygen, if its concentration increases. For example, in French mining regulations, the concentration of 1% in air is the first threshold limiting the duration of exposure during work. It is toxic in the blood system and particularly the respiratory system. Replacing oxygen in the air or diluting it can also involve the risk of asphyxia for anyone exposed to it.

1.3 CARBON MONOXIDE (CO)

In disused mining works, this gas essentially results from the usually slow, low temperature oxidation of coal, hydrocarbons and any other organic material that have been abandoned underground. This oxidation can last very long until there is a lack of oxygen, which interrupts the chemical reaction.

CO also is generated during combustion. It is usually found in old coal or lignite mines. These materials are indeed sensitive to spontaneous combustion, when a slight draught of fresh air flows through the mining works.

CO is colourless, odourless and tasteless, highly diffuse and with a density close to that of air. It is inflammable when mixed in air at very high concentrations (above 12%), which are very unlikely to be encountered. Its high toxicity makes it very dangerous. It obstructs the transport of oxygen in the blood by irreversibly binding to haemoglobin. In French regulation, a concentration of 50 ppm (0.005%) in air is the maximum value for prolonged human existence. At high concentrations of about 1000 ppm, it is very quickly fatal.

1.4 HYDROGEN SULFIDE (H_2S)

Hydrogen Sulphide can be detected in all types of old mining works because it may come from the decomposition of old supporting wood, the reaction of acid water on pyrite present in the ore or surrounding rocks, or the action of certain bacteria on sulphates.

Hydrogen Sulphide is a colourless gas with a characteristic unpleasant odour of rotten eggs, which does not increase with concentration. The odour, which can be detected at very low concentrations (0.1 to 0.2 ppm), is attenuated or even disappears at high concentrations by "anaesthetising" the sense of smell. It is slightly heavier than air. Like carbon monoxide, it is inflammable when mixed with air at high concentrations (more than 4%), which cannot be found in a post-mining context. It is a highly toxic gas, attacking the human nervous system at fairly low concentrations. A concentration of 5 ppm (0,0005%) in air is the limit not to be exceeded for prolonged human life in French regulations. It is fatal at higher concentrations.

1.5 RADON

Radon comes from the natural decay of radium, product of the connection between uranium and thorium. Isotope ^{222}Rn, the precursor of which is ^{226}Ra, obtained from ^{238}U, and is the most commonly found in the atmosphere.

Obviously, radon can be found in old underground uranium mines, but is also in other underground cavities of any kind if the surrounding ground contains even tiny quantities of uranium (a few mg/kg). This is the case in acid magmatic rocks as well as in certain metamorphic or sedimentary rocks such as schists and above all coal and lignite. If underground mining cavities are poorly ventilated, their atmosphere may contain high concentrations of radon.

Radon is the heaviest gas. It is odourless and colourless. It is a radioactive element, which can be dangerous to humans when inhaled. Its effects increase the risk of lung and bronchial cancer.

In the open air, its concentration (dependent on meteorological conditions and ground characteristics) is low because it is diluted by the wind. On the other hand, in an inadequately ventilated building, it can accumulate and reach high concentrations, which, in the event of prolonged exposure, may generate a risk of inhalation of its short-lived descendants. The complexity of managing this risk has led to the definition of values of radioactivity per volume for public buildings (from 400 and 1000 Bq/m^3 in France) to implement corrective actions to reduce this level of exposure.

Unlike the gases described previously, radon is not a "product" of mining activity. It is already in the ground before mining starts. However, the effects of mining activity, mentioned above (increase in ground permeability, communicating structures) are likely to modify the way in which radon is emitted at the surface. It can be emitted into the outside atmosphere in a more concentrated and localised form and at a higher rate than before the mining operations started.

1.6 DEOXYGENATED AIR

Mine gases may be present in underground mine workings at extremely variable concentrations. Methane and carbon dioxide can therefore be found at concentrations, which are several or several tens of percent. Other gases are usually only present at much lower concentrations.

Their accumulation leads to a reduction of oxygen content in the mining atmosphere. Note also that partial or total disappearance of oxygen is relatively common, without any accumulation of gases of mining origin (in this case the mine gas is essentially composed of nitrogen).

Oxygen deficit situations are likely to be encountered in all kinds of mining operations, particularly coal mines. Mine gas therefore represents a risk of asphyxia for humans. An oxygen-poor atmosphere leads to a disturbance of the respiratory and blood systems of anyone exposed to it. A strong deficit can rapidly lead to death. For example, French mining regulations have fixed the minimum concentration of oxygen in the atmosphere of underground workings at 19% (the normal level in air is about 21%).

2 INITIATING MECHANISMS

Several mechanisms, acting alone or in combination, may generate mine gas emissions at the surface. Apart from specific diffusion mechanisms as well as transport of dissolved gases in water, the migration of gases to the surface is mainly controlled by the mechanisms which contribute to the existence of a positive pressure between an underground mine reservoir and the outside atmosphere.

Indeed, if mine gas in underground cavities is at, even slight, excess pressure, relative to the outside atmosphere, it will tend to migrate to the surface. All things being equal, the greater the difference of pressure, the more significant the mine gas flow.

2.1 GAS PRODUCTION IN OLD WORKINGS

Various physicochemical mechanisms may produce gas emissions and pressurisation of the underground reservoir. For gases like carbon monoxide, hydrosulphide or radon, the quantities produced are small and do not cause any significant increase in gas pressure in the reservoir. On the other hand, the production of carbon dioxide from carbonate rocks and particularly the desorption of firedamp (methane or carbon dioxide) from coal must be considered likely to cause a notable increase in the internal pressure of an underground mining reservoir.

In "firedamp-prone" coal seams, unextracted coal can contain considerable quantities of firedamp (5 to 15 m^3 of methane or 10 to 20 m^3 of carbon dioxide per tonne of coal, or more) with pressures that can reach 1 to 2 MPa. It is therefore theoretically possible for pressures of this order to be reached in old coal mines through desorption of residual firedamp. This phenomenon, although slow, can last a long time after extraction.

2.2 EXPULSION BY RISING WATERTABLE

Flooding the mining reservoir gradually reduces the volume of residual cavities available, with the effect of evacuating the mine gas present. Depending on the duration of this flooding (which can vary from several months to several decades) and the total volume of the cavities, this transient phase may appear crucial considering the risk of mine gas emission to the surface.

2.3 VARIATIONS IN ATMOSPHERIC PRESSURE

Variations in atmospheric pressure also contribute to a difference in pressure between the underground reservoir and the external atmosphere. In case of a meteorological depression, the underground mining works may be temporarily in a condition of relative over-pressure that could generate (or accentuate) gas emission to the surface.

2.4 NATURAL VENTING

In certain configurations, there may be a natural gas flow between the underground reservoir and the outside atmosphere. This mechanism, well known by miners and largely used by them, it may be called “natural venting”. The reason for this is that there is a difference in temperature between the earth and atmospheric air and a difference in altitude between several mine entrances (adits, shafts and cracks).

Under standard climatic conditions, a certain thermal gradient between the outside atmosphere and the underground mine workings may provoke air circulation through the mining reservoir, depending on the season. In winter, cold air penetrates through adits into the lower parts of the mine. It is heated during its passage through the mine and exits into the atmosphere at high points. In summer, it is usually the opposite.

2.5 TRANSPORT OF GAS DISSOLVED IN WATER

Gases likely to be found in an underground mining reservoir have very different characteristics of water solubility. Underground water present in mining works can therefore enter into contact with mine gas and dissolve its constituents. This dissolution takes place at variable degrees according to the gas concerned. Mine water will thus be likely to contain and carry a large amount of carbon dioxide and hydrogen sulphide and much smaller quantities of other gases. Radon will also be easily carried in water and rapidly released into the atmosphere. The solubility of a given gas in water decreases with the temperature of the water and rises in proportion to its pressure. During natural outflow, the temperature of the water may rise and its pressure may fall steeply. These two factors lead to the release of a part of the dissolved gas. For example, water initially at 10°C and saturated in gas with an over-pressure of 10 bar (i.e. 100 m of hydraulic load), may lose about 0.5 m^3 of methane and 12 m^3 of carbon dioxide per cubic metre when the pressure is released.

The dangers of this situation are clear and accidents linked to the release of gas have already happened in the past.

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Appendix B

Investigating techniques and information collected

Investigating Technique	Penetration of the rock mass	Sampling of the rock mass	Information	Quantification	Qualification
Transit surveying	no	no	Underground void detection		
			Void geometry		
			Condition of mine pillars		
			Filled workings		
			Discontinuities		
			Orientation of discontinuities		
			Weak zones		
			Rock quality		
			Geology, map confirmation	✓ (rock outcrops)	
			Rock properties		
			Bedrock surface		
			Groundwater flow		
			Movements	✓ surface breakthrough, subsidence, changes with time	
			Surface location of underground access	✓	
			Soil density		
			Soil stratigraphy (sampling)		
			Soil permeability		
			Soil shear strength		
			Soil modulus of elasticity		
			Other sampling		

Investigating Technique	Penetration of the rock mass	Sampling of the rock mass	Information	Quantification	Qualification
Visual surface investigation (including mine portals)	yes	no	Underground void detection		✓ (breakthroughs)
			Void geometry		
			Condition of mine pillars		
			Filled workings		✓ (breakthroughs)
			Discontinuities	✓ (rock outcrops)	
			Orientation of discontinuities	✓ (rock outcrops)	
			Weak zones	✓ (rock outcrops)	
			Rock quality	✓ (rock outcrops)	
			Geology, map confirmation	✓ (rock outcrops)	
			Rock properties		
			Bedrock surface	✓ (rock outcrops)	
			Groundwater flow		
			Movements		✓ (breakthroughs)
			Surface location of mine openings		✓
			Soil density		
			Soil stratigraphy (sampling)		
			Soil permeability		
			Soil shear strength		
			Soil modulus of elasticity		
			Other sampling		

Investigating Technique	Penetration of the rock mass	Sampling of the rock mass	Information	Quantification	Qualification
Underground visual investigation	yes	no	Underground void detection	✓	
			Void geometry	✓	
			Condition of mine pillars	✓	
			Filled workings	✓	
			Discontinuities	✓	
			Orientation of discontinuities	✓	
			Weak zones	✓	
			Rock quality	✓	
			Geology, map confirmation	✓	
			Rock properties		
			Bedrock surface		
			Groundwater flow, course	✓	
			Movements	✓	
			Surface location of underground access		
Percussion drilling	yes	no	Underground void detection	✓ (point location)	
			Void geometry	✓ (point location)	
			Filled workings	✓ (point location)	
			Discontinuties		
			Orientation of discontinuities		
			Weak zones		✓
			Rock quality		✓
			Geology, map confirmation contact		
			Rock properties		
			Bedrock surface	✓ (point location)	
			Groundwater		
			Movements		
			Surface location of underground access		

Investigating Technique	Penetration of the rock mass	Sampling of the rock mass	Information	Quantification	Qualification
Diamond drilling	yes	yes	Underground void detection	✓ (point location)	
			Void geometry	✓ (point location)	
			Filled workings	✓ (point location)	
			Discontinuties	✓ (rock core evaluation)	
			Orientation of discontinuities	✓ (rock core evaluation)	
			Weak zones	✓ (rock core evaluation)	✓ (penetration rate)
			Rock quality	✓ (rock core evaluation)	✓ (penetration rate)
			Geology, map confirmation	✓ (rock core evaluation)	
			Rock properties	✓ (rock core evaluation)	
			Bedrock surface	✓ (point location)	
			Groundwater		
			Movements		
			Surface location of underground access		
			Soil density		
			Soil stratigraphy (sampling)		
			Soil permeability		
			Soil shear strength		
			Soil modulus of elasticity		
			Other sampling		

Investigating Technique	Penetration of the rock mass	Sampling of the rock mass	Information	Quantification	Qualification
Borehole visual examination (video-camera)	yes	no	Underground voids	✓ (point location)	
			Voids geometry		
			Conditions of mine pillars		
			Filled workings	✓ (point location)	
			Discontinuities	✓	
			Orientation of discontinuities	✓	
			Weak zones	✓	
			Rock quality	✓	
			Geology, map confirmation	✓	
			Rock properties		
			Bedrock surface	✓ (point location)	
			Groundwater		✓
			Movements		✓
			Surface location of underground access		
			Soil density		
			Soil stratigraphy (sampling)		
			Soil permeability		
			Soil shear strength		
			Soil modulus of elasticity		
			Other sampling		

Investigating Technique	Penetration of the rock mass	Sampling of the rock mass	Information	Quantification	Qualification
In situ testing	yes (test dependent)	yes (test dependent)	Underground void detection		
			Void geometry		
			Condition of mine pillar		
			Filled workings		
			Discontinuties	✓ (rock core evaluation)	
			Orientation of discontinuities	✓ (rock core evaluation)	
			Weak zones	✓ (rock core evaluation)	
			Rock quality	✓ (rock core evaluation)	
			Geology, map confirmation	✓ (rock core evaluation)	
			Rock properties	✓ (Borehole rock mass modulus; in situ stresses)	
			Bedrock surface	✓ (rock core evaluation)	
			Groundwater	✓ (water chemistry)	
			Movements, concentration of gases	✓ (instrumentation)	
			Surface location of underground access		
			Soil density	✓	
			Soil stratigraphy (sampling)	✓	
			Soil permeability	✓	
			Shear strength	✓	
			Soil modulus of elasticity	✓	
			Sampling	✓ (groundwater, gas)	

Investigating Technique	Penetration of the rock mass	Sampling of the rock mass	Information	Quantification	Qualification
Geophysics	yes (borehole application)	no	Underground void detection		✓ (location)
			Void geometry		✓
			Condition of mine pillars		✓
			Filled workings		✓ (location)
			Discontinuties		✓
			Orientation of discontinuities		✓
			Weak zones		✓
			Rock quality		✓
			Geology, map confirmation		✓ (comparison between on-site types)
			Rock properties		
			Bedrock surface	✓	
			Groundwater		✓
			Movements		✓
			Surface location of underground access		✓
			Soil density		
			Soil stratigraphy (sampling)		
			Soil permeability		
			Shear strength		
			Soil modulus of elasticity		
			Sampling		

Appendix C

Main geophysical methods adapted to locate disused mine workings

Generally, the geophysical methods, which are applied for surveying and assessing post mining sectors, can be divided into four groups. The usefulness of each method is analysed separately on the base of its technical or economic value and results of performed tests.

Geoelectrical and geomagnetic methods

Those methods utilise the difference between electrical properties of soils and rocks, likewise the difference between their natural geologic and anthropogenic features. The basic properties comprise parameters describing electrical field propagation in media. In particular the following parameters:

- Specific, electric resistivity (ρ) – electro-resistivity methods,
- Specific, electrical conductivity (σ) – electro-magnetic methods,
- Relative, dielectric permittivity (ε) – ground-penetrating radar.

Electroresistivity methods

The resistivity methods have various variants of measurements, which have their specific names. They are widely applied within post-mining areas. They can be applied both for preliminary assessment of geological conditions in specific areas and for recognition of structural features in soils and bedrock (figure 1).

The measurements can be performed either on the surface or in boreholes and drillings (electro-tomography, resistivity logging). The depth range of the method is practically not limited. It depends mainly on the power of the current generator and type of electrodes, being applied. The method is still in development and its research possibilities are being improved. Generally, for geology recognition Vertical Electroresistivity Soundings (VES) or multilevel Electrical Resistivity Tomography (ERT) are used. The last method, as being currently implemented to practice, needs special equipment and software. This factor has a great influence on costs of geophysical services

One of the most frequently applied geophysical methods in rock massive assessment is the Profiling Electroresistivity (PE) method. This method is very often used in two or three level depth variants, which gives at result plane distribution of measured, specific apparent resistivity data on various depth levels. The DC or low frequency AC field is input to the geologic environment through steel or copper electrodes, driven into ground. Depending on the surface, technical availability the measurements are performed on profile lines or lines grid. The layout of measurement points forms regular (if possible) or irregular nets.

There are various, electronic devices for resistivity measurements. In the past, there were only single channel units. Nowadays, the multi channel units are available on commercial market. The multi channel technology gave a speed up to numerical modeling progress. Various commercial software are available for 2D and 3D modeling of geologic structures by techniques of numerical inversion of the measured data. In last years also, techniques for electrical tomography imaging have been developed (ERT). This can be applied for multilevel measurements on the surface likewise for measurements between boreholes. Due to high costs of the multi channel equipment, use of this method in post-mining areas is still not common.

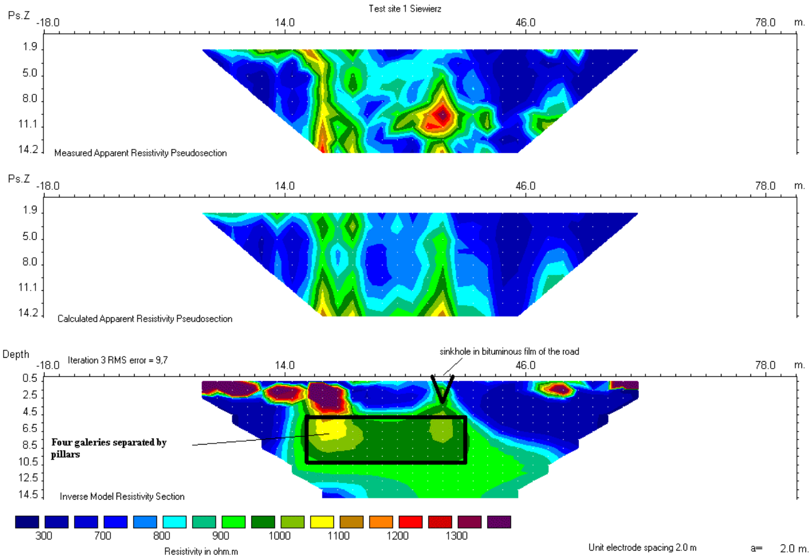

Figure 1 Models of resistivity distribution in geological strata in the vicinity of an abandoned silver mine in Poland (a - traditional pseudosection of apparent resistively values, b – calculated pseudosection for model blocks, c – inverted model of specific electro-resistivity distribution) (source GIG).

Electromagnetic methods (EM)

The principles of these methods are similar to electro-resistivity methods in the measured, electrical parameters (specific electrical conductivity: σ). The electromagnetic field in the geologic strata is created by induction. The primary, medium frequency alternating EM field is emitted to ground from various coil/dipole devices. The secondary field response is measured by a similar like emitter device. The depth of penetration depends on spacing between coils (emitter – receiver) and frequency of electric field being applied. The method allows for rapid measurements. The results are roughly similar to those being obtained from electro-resistivity surveys. Nevertheless, the penetration depth is lower.

Ground penetrating radar (GPR)

The ground penetrating radar is a technology for imaging rock structure (figure 2). The method uses high frequency pulses, which are emitted to the ground from specially designed transducers with very high-transmitting rates. The pulses propagate in the geological environment, where they can be reflected at interfaces (discontinuities) between media with different values of dielectric permitivity and conductivity. Reflected pulses return back to the surface where they are recorded in the time domain by transducers.

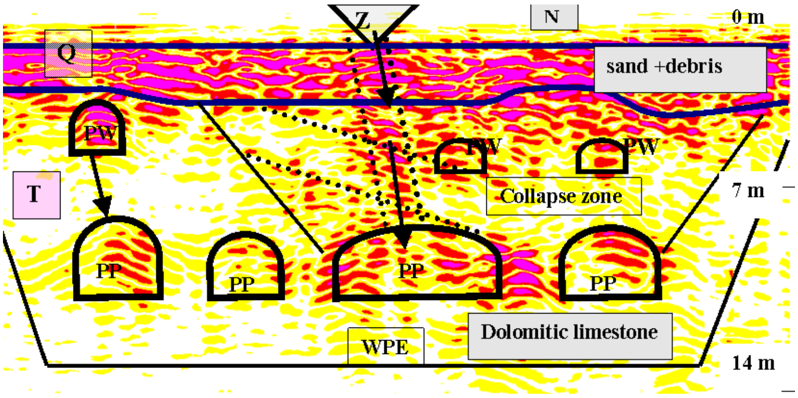

Figure 2 Structure of geological strata vicinity of abandoned silver mine in radar echogram. Black line marked by symbol (WPE) shows the area of image from PE measurements seen on fig.2. (PP-primary voids, adits, PW – secondary voids, Z – sinkhole location, Q – quaternary sediments, T- Triassic sediments (source GIG).

The elapsed time is a function of reflector depth and electric properties of rock strata. The method is in rapid development in regard to equipment and software. The GPR data can supply very valuable information about rock structure and voids location.

Gravimetric methods

Those methods are based on local and regional gravity field changes caused by density variations (γ) in the rock mass. Each irregularity in distribution of rock density generates its own gravity field. The distribution of earth's attraction force depends mainly on the difference between the density of the anomalous body and the density of the enclosing body (figure 3). This distribution is also a function of shapes, sizes and depth of irregularity, usually called a disturbing body - specific geological structures (e.g. folds, faults,) or man made heterogeneity (e.g. voids, washouts, deformations).

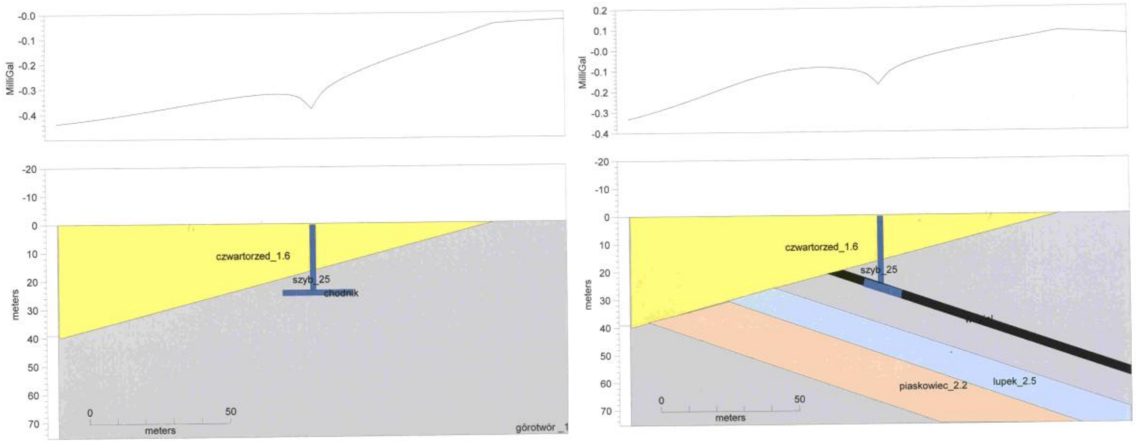

Figure 3 The local gravity field response for two geological cross sections with shaft and gallery (quaternary overburden marked by yellow polygon, below quaternary sediments - uniform – on the left and stratified bedrock-on the right) (source GIG).

Two modes of measurement surveys in grid lines on the surface followed by leveling survey of points are utilised (the earth attraction force, the gradient of earth attraction force). They give best results for old shafts detection and assessment of backfilled mining works. There are many methods of data interpretation and modeling of rock massi structures. The cost of gravimetric survey is relatively higher compared to geoelectrical surveys due to precise leveling needed.

Geothermic methods

Geothermal methods are based on variation of natural heat flow in the anisotropic and non-homogenous rock mass (figure 4). Present application of this method to post-mining management is mostly limited to location of old mining shafts and areas affected by underground fire hazards (self-heating of coal). Measurements may be carried out by airplane, camera or may be performed in shallow (1-2 m deep) or medium depth (20 – 50 m) boreholes.

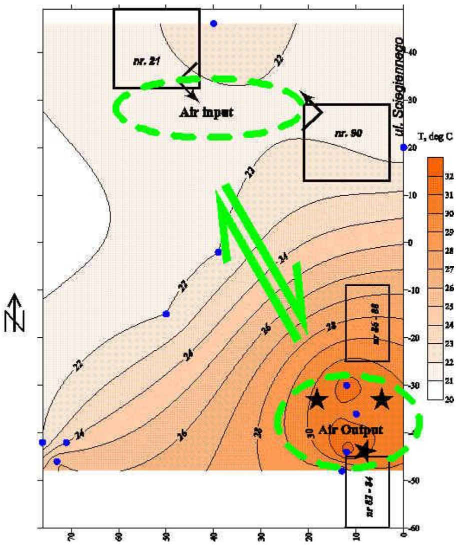

Figure 4 The temperature of soil at depth 0.7 m and air circulation scheme within bedrock strata (green color) over abandoned coal mine in Poland (urban area in Katowice). Arrows mark directions of building displacements. Stars mark sinkholes (source GIG).

Seismic methods

Applications of seismic methods are based on variations of elastic waves velocity and attenuation (α) in anisotropic and non-homogenous rock masses. The surface measurement methods (refraction, reflection) fit well on first geotechnical parameter investigations (figure 5). Measurements performed between boreholes or between borehole and the surface, based on direct seismic waves, appear to be much more effective. As an advantage, application of seismic methods gives information about the mechanical state of the bedrock. The relatively high costs of seismic measurements in boreholes are mainly conditioned by drilling costs.

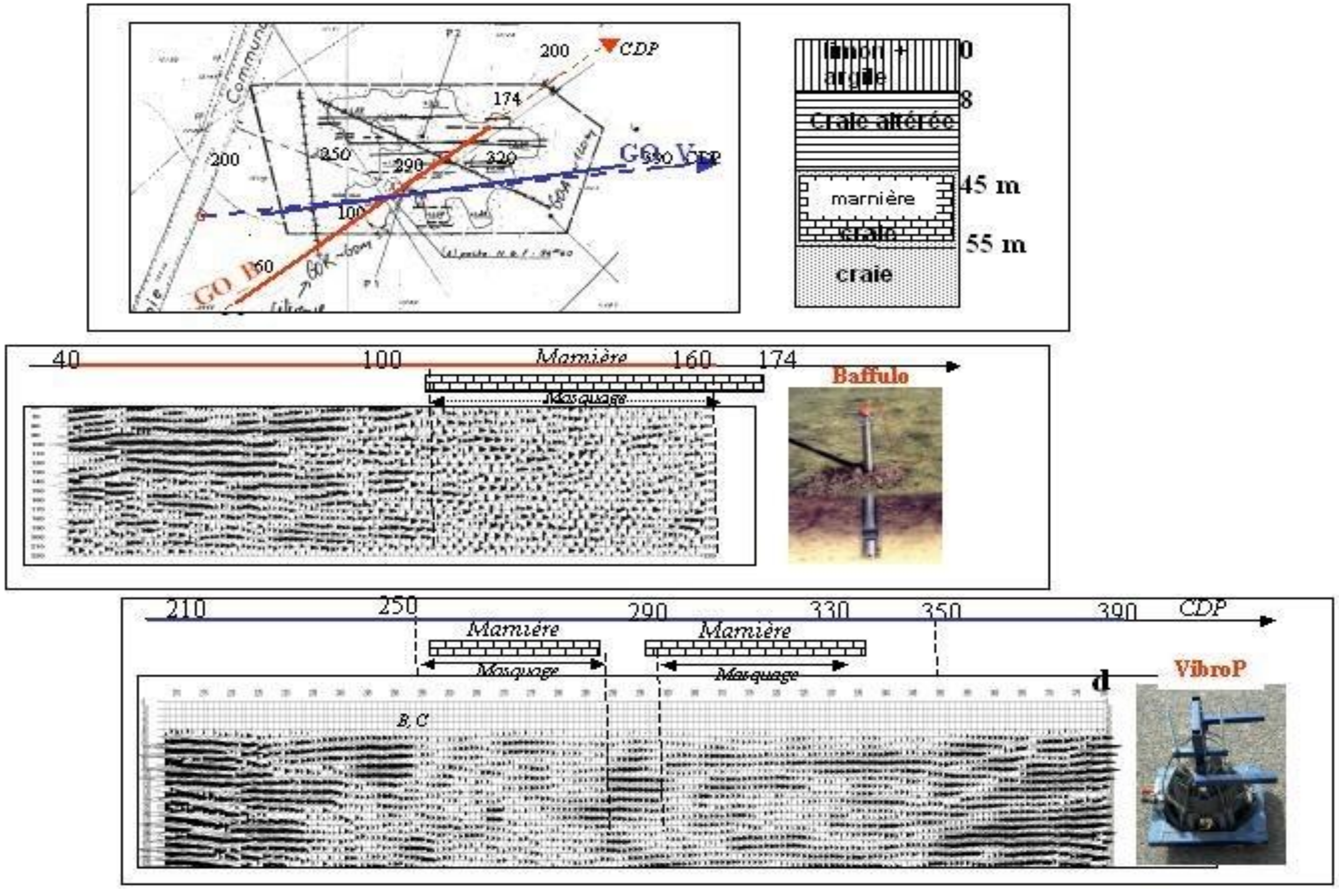

Figure 5 Seismic reflexion High Resolution of Goderville chalk mine (depth around 45 m). Tests with several sources (source INERIS).

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