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Mine shafts: improving security and new tools for the evaluation of risks

(MISSTER)

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FINAL SUMMARY

WP1: COLLECTION AND ANALYSIS OF CASE STUDIES

WPL: INERIS. Partners: UoN, GIG, KWSA, GEOCONTROL, MRSL

Objective

This work package deals with the collection of representative case history data concerning shaft instability events in Europe. Rather than being comprehensive of all events the case data needs to be representative of a range of potential behaviour in European conditions. The case files need to include as much detail as possible of the following: failure mode and consequences, previous treatments, structural and geotechnical details of shaft, final treatment.

This work package goes through:

- the identification of main characteristics to be supplied;
- the collection of representative cases by each partner;
- the analysis and synthesis of the data base.

Task 1.1 - Implementation of specifications for case files collection (INERIS)

In order to provide an international database relative to incidents directly involving mine shafts, a collection of incidents has been achieved by involved partners for their country.

To obtain the most representative cases, incidents which can be induced by the presence of a mine shaft have been reviewed and organised according to the following typology (based upon analyses of partners):

- a collapse of the shaft filling material column (a brutal and dynamic remobilisation of the filling materials as a consequence of:
  - a lack or undersizing of deep security workings in shafts stations (leading to the shaft filling materials flowing into the stations and old workings);
  - or a lack of filling material during filling process because of arching phenomena for example;
- a rupture of the shaft head leading to a « sinkhole » or subsidence. This may involve:
  - the surface closing structure failure;
  - the rupture of surface strata surrounding shaft head.
- a rupture of the shaft lining (brick, cast iron, concrete) as a consequence of fatigue of the lining or water deterioration;
- a rupture of deep security elements situated into the shaft (because of various causes like for example concrete segregation, or bad designing);
- a specific focus on water effect (flooding, infiltration, upper ground water);
- incidents due to particular geologic formations (soluble (halite, gypsum) or uncohesive (deep sand for example)) that may, under specific conditions, lead to cavities behind lining;
- a risk of release of mine gas.

Actually incidents can be the consequence of several phenomena. Consequently, study cases can illustrate one or several incidents cited above. Each one of these situations is illustrated by a reference case.

The selection of representative cases includes the collection of fundamental parameters that may, in one way or another, have played a role in the instability or the incident. The objective is to have a maximum of information on shaft and its context (geologic, hydrogeologic, geotechnical...). Table 1 below presents all the criteria that are informed.

Table 1 : Data for representative cases

Location	Lease name, municipality, coordinates
History	Use during mining operations (staff, ventilation…), Incident date, Opening/Closing date...
Geometry	Section (circular, rectangular), Diameter, Length / Width, Depth, Number of stages, First stage depth, Nature of closure stage (block, wall, concrete…)
Shaft status	Nature of head shaft lining, Deep lining nature, Head status (closed, open, collapsed…)
Geology	Geology cross section, Nature and thickness of non cohesive material around shaft head
Hydrogeology	Mine flooding piezometric level, Stabilized water (yes/no ?), Upper groundwater depth, Upper groundwater top piezometric level
Shaft closure (stowing, plug…)	Processing date, Processing nature, Shaft column remains empty after closure (yes/no) ?

Task 1.2 – Collection of case histories (INERIS, UoN, GIG, KWSA, GEOCONTROL, MRSL)

Each partner for its respective country performed the collection task according to the specifications identified in task 1.1 and data availability in its country.

Analysis of the data indicated that the most prevalent cause of failure is related to shaft filling material collapse (46%), followed by shaft head rupture (29%), water effects (14%), failure of the shaft lining (10%), and release of mine gas (1%). It should be recognised that the selection of failure scenario is subjective and that several scenarios may apply to a single failure incident. This data should therefore be interpreted with some consideration of these factors. These observations justify that main focus was directed toward filling material choice and operation as well as shaft lining monitoring, testing and modeling in MISSTER project.

To complete this case study task, 14 specific cases were studied in depth by the partners according to a common layout. This layout structures the information in different topics:

- Location and characterisation of the shaft(s);
- Geological and hydrogeological contexts;
- Description of the incident;
- Analysis.

These specific analyses constitute reference cases illustrating the main failure scenarii that may affect mining shafts.

Task 1.3 – Synthesis and dissemination to partners. Production of a database (INERIS)

Using information collected by the different partners, a database has been developed, bringing together 187 incidents occurred on mining shafts. This database is composed of 9 columns:

- Incident date: year in which the incident has been identified;
- Country: country in which the incident has been identified;
- Location: city or region in which the incident has been identified;
- Shaft name: when available, the name of the shaft concerned;
- Incident typology: nature of the incident as referred in this report
- Keywords: keyword(s) relevant to the identified case;
- Reference: Origin of the information. When available, a note or a report, detailing the example is provided (hyperlink);
- Language of reference: language used in the report or note;
- Photos: when available, one or more photos of the incident are provided (hyperlink).

The search of information can be done either by the type of incident or by keywords (for example: Brick lining, Filling material, Ground collapse, Remaining void after stowing, filling material, Shaft fill settled, Subsidence, Water and vibrations).

The purpose of this database is not to provide fields that detail: geology, hydrogeology and the characteristics of the shaft or of the collapse. The aim is to gather the expertise that has been built on the basis of these cases at a European scale. However those different details, mentioned above, are provided in the reports annexed to the database, when they exist.

This database makes it possible to collect and enhance the expertise available in the various cases of shaft incident that took place in Europe.

WP2: LOCATION AND CHARACTERISATION OF MINING SHAFTS

WPL: GIG. Partners: INERIS, KWSA, DMT, MRSL

Objective

Objectives of WP2 as defined in Technical Annex are :

Development or enhancements of new technologies in order to locate mining shafts :

- Analysis of existing techniques efficiency for locating mining shafts in particular contexts (urbanized areas);
- Test of new techniques.

Characterization of shafts key components :

- Evaluation of shafts lining during and after mining operations
- Monitoring of shaft closure process
- Evaluation of air conditions

Task 2.1 – Location of old mining shaft (MRSL, INERIS)

When mining operations terminate, the mine operator and/or local/public authorities is asked to guarantee the absence of hazards, notably adjacent to the old shafts. These shafts are old and invisible from the surface (covered with topsoil and/or backfill). These shafts are difficult to locate from the available data (e.g. old maps taken from the archives) so the area to be investigated may prove to be vast and may have been developed.

A **review of existing techniques** has been undertaken comparing merits of the following geophysical techniques for the detection of unknown mineshafts. The non-intrusive methods included are seismic refraction, surface wave seismic, ground penetrating radar (high-frequency electromagnetic methods), low-frequency far field electromagnetic methods (VLF), low-frequency near field electromagnetic methods (Slingram), direct current earth resistivity, microgravimetry and thermal infrared. The intrusive methods included are mono-frequency (electromagnetic) drilling tomography, radar tomography, radar reflectivity, seismic drilling tomography, and electrical methods.

Mine-shaft detection using geophysical methods essentially depends on the physical parameters (often heterogeneous and diverse) of the shafts in relation to the surrounding rock. As very little data exist on either the physical parameters of the backfill, or the surrounding rock, the methods were assessed based on a bibliographic search and experience on the detection of underground cavities other than shafts.

Advantages, disadvantages and necessary conditions for each technique have been identified in order to assist the operator in the choice of location method according to local conditions.

As no geophysical method can, on its own, enable an unambiguous conclusion to be drawn as to the presence of a shaft, the coupling of several methods can therefore prove beneficial, owing to their complementarity, both in terms of interpretation and implementation.

Lastly, it is advisable, before commencing a measurement campaign, to conduct a test on the site to be studied so as to adapt the chosen system, or validate (or not) the method (test on a shaft known prior to searching for a non-located structure).

An analysis of current practice in the area of **earth resistivity surveying** has been achieved with a view to identifying areas for improvement and progressing those areas. An examination of currently available hardware led to a proposed architecture that much improves on those currently available systems that employ smart, addressable electrodes. A high-level design was pursued, providing a "plug and play" solution with cost and ease-of-use benefits. A review is also presented of the method of "inversion" that is used to construct a model of the sub-surface from the measured resistivity values. Several approaches for making the technique more applicable to the detection of shafts are proposed.

In field tests for locating old mining shafts were carried out. Adapted techniques comprise :

- **Seismic tomography** using parallel boreholes in order to limit the number of drilling which is a major constraint in urbanized areas;
- **Surface seismic tomography**.

These tests enabled to compare techniques and check their effectiveness and relevance for the detection of old mining shafts in urbanized areas.

Task 2.2 – Development of a continuous shaft measurement system (DMT)

Within the project DMT has developed a laser scanning system for precise and almost complete survey of mining shafts. The developed probe is designed for mine shaft with a depth up to 2000 m. A shaft survey with the developed device provides an accurate geometrical model and point cloud of the shaft. Due to the technical properties of the integrated laser scanner and 360° camera the system provides also a photorealistic documentation of the shaft. The overall concept of a Continuous Shaft Measurement System is based on initial developments achieved in former RFCS PRESIDENCE project. Continuation of the development included all necessary improvements concerning the autonomous truck mounted winch and further works on the probe, e.g. integration of all necessary sensors. The modular concept ensures a stable fixing and easy access to every sensor.

Task 2.3 – Design and construction of a probe, in field tests of probes (GIG, KWSA, INERIS)

In addition to DMT shaft measurement system, three different probes have been developed in the framework of project MISSTER. They cover a wide range of situations according to shaft conditions.

The probe developed by GIG is designed for shafts with diameters from 3 to 12 m and depth to 1200 m. In case of smaller shafts or cavities, INERIS developed specific probes to face with problems of characterization and localization of underground cavities or old mine shaft when a direct inspection is not possible or difficult for safety reasons. It can reach cavities from the surface through a borehole or inspect directly the inside body of shafts. In the framework of MISSTER, the work is principally based on the development of the second probe for flooded void and the development of the data analysis systems to obtain direct results like cross section and also obtain a direct geo-referenced 3D point cloud to fit into existing GIS.

WP3: ANALYSIS OF CRITICAL SHAFTS CONSTITUTIVE ELEMENTS THAT INFLUENCE RISK OF FAILURE IN TIME

WPL: UoN. Partners: GIG, KWSA, GEOCONTROL, MRSL

Objective

As defined in Technical Annex:

To develop models representing structural and geotechnical performance of shaft structures including a range of potential failure modes typical of European conditions.

To compare different methods of treatment in terms of short and long term stability improvements of shafts including cappings, plugs, fills, and grouting.

Results will include: (1) evaluation of rock waste suitability used as filling material, (2) determination of technologies used for filling with desire material, and (3) optimisation of plugs and dams structure design based on used filling material.

Task 3.1 – Filling materials and techniques (GIG, KWSA, MRSL)

Task 3.1. covers a wide range of subjects, which are detailed described in the Deliverable Report 3.1. Within the framework of the task, basic operations associated with preparing for shafts closure with the most common methods of feeding filling materials are presented. In the further part of the research, laboratory tests and underground tests of filling materials before and after dropping into the shaft are shown. The scope of research covered grain-size analysis, evaluation of water permeability and leaching physic-chemical elements. On the basis of the obtained results a methodology of selecting filling materials for shafts closure, considering use of low strength materials, was prepared. It enables use of such materials as mining waste rocks, which has a positive influence on the costs associated with shafts closure. Selection of an appropriate filling material and backfilling technology has a significant influence on the possibility of reopening the closed shafts. The process requires numerous preparatory actions. In case of a shaft closed with a grainy material, they may be:

- disassembly of concrete slab closing the shaft,
- constructing a temporary steel headframe,
- constructing hoist machinery on the shaft frame,
- preparing bins for rock extraction,
- constructing a suspended deck with through holes for bins, air duct installation, pipelines etc.

Within the framework of that task, a new methodology of feeding material into the shaft was prepared as well. It enables to limit the degree of degradation of a filling material, which is especially important in case of materials of low strength. Moreover, the new method limits damages of the lining of a shaft and its equipment through directing filling material towards the bottom of a shaft. It is especially important when it is decided to reopen the closed shaft.

Task 3.2 – Linings cappings and plugs design and integrity (UoN, GEOCONTROL, MRSL)

The research conducted for this task focused on the analysis of the stability of shafts and in developing an understanding of the effect that time and harsh environmental conditions (weathering) have on the constituent elements of the shaft as well as the general behaviour and performance of the shaft. The work can be summarised into 3 categories: experimental tests on weathering (UoN and MRSL), numerical modelling of static and time-dependant scenarios of shaft behaviour (UoN and GEOCONTROL), and physical modelling of shaft failure mechanisms (UoN - not included in initial proposal).

Weathering experiments were conducted on shaft lining materials susceptible to degradation with time when exposed to harsh mine water environments. UoN performed a variety of lab experiments which focused on brick and concrete lined shaft materials. Material samples were immersed within baths of potable water (reference), a typical coal mine shaft water (based on data from the RFCS PRESIDENCE project), and a harsher acidic water. The materials were tested at four stages which spanned a duration of 48 weeks. Tests included uniaxial compressive strength (UCS), triaxial, four-point bending on brickwork beams, shear strength (bond), and scanning electron microscope in order to understand the effect of time and weathering on the mechanical properties of the materials. MRSL undertook a programme of weathering tests (immersion tests) related to concrete capping materials with different combinations of additives and reinforcement. Results were obtained which related strength and weight loss to the specific sample constituents.

The numerical modelling focused on static and time-dependant scenarios of mine shaft behaviour, considering the effect of progressive deterioration and potential final failure of a shaft lining. The modelling exercise was split between UoN and GEOCONTROL; UoN focused on brick-lined shafts whereas GEOCONTROL dealt with concrete lined shafts and specifically considered the influence of hydrogeological changes. UoN developed an equivalent property mesh for replicating brickwork behaviour which was based on results from the weathering experiments. Case studies were selected and modelled by UoN and GEOCONTROL to evaluate the effect of a variety of influence parameters, including (1) reduction of lining material properties due to weathering, (2) the shaft construction process and groundwater level fluctuation during construction, (3) flooding of the shaft, (4) dewatering, (5) shaft treatments and the effect of the reduction of strength and stiffness of the treatment materials, and (6) unequal horizontal stress conditions, and (7) point loading.

Physical modelling of reduced-scale shafts was undertaken by UoN using the Nottingham Centre for Geomechanics (NCG) geotechnical centrifuge. This work aimed to study the different failure mechanisms of shafts. In particular, a set of tests was conducted to compare the different mechanism of failure and observed ground displacements when an entire shaft loses support uniformly along its depth compared to when a shaft loses support at a discrete location near the rock-soil interface.

Task 3.3 – Shaft stability (GEOCONTROL, GIG)

Detailed results of task 3.3 are presented in the Deliverable Report 3.2.

Geocontrol'work has been focused on the use of two numerical codes (FLAC2D and 3D) to develop numerical analysis to quantify shafts stability. Comparisons have been carried out analysing several effects:

- Anisotropic natural stresses
- Rock wedges failures
- Shafts bottom collapses

Within the framework of the task, numerical investigations, developed by GIG, aimed at determining the stresses occurring in plugs and dams for different filling materials used for a shaft's closure were determined. In order to carry out the analysis a special program in FISH language has been developed. The obtained results showed that the height of filling column, at which the forces acting on the dams and plugs are stabilizing, depends not only on the friction coefficient (as in Jansen's theory), but also on the grain size of the material. The results of model studies have shown that for materials with the same physical properties (density, friction coefficient) the forces could stabilize at different height of filling column: from about 35 m (for material with median diameter of about 200 mm) to about 55 m (material with median diameter below 80 mm). The results showed also that the impact of void in the filling column on the forces exerted on the locking plug and dams are less significant than expected, but the increase of pressure in the filling column caused by water is much more important and could lead to locking plug and dams failure. Such failure could in turn threaten the stability of the entire shaft.

WP4: SYNTHESIS

WPL: INERIS. Partners: GEOCONTROL, MRSL

Objective

The mechanisms involving the collapse of a shaft are numerous and complex and the objective of the project is to analyse the components which lead to the collapse or incidents within shafts and propose new techniques and methodologies to improve safety conditions both during and after mining operations.

This WP will lead to the writing of a synthetic document in order to help actors in charge of mining shaft safety to identify key parameters that have to be taken into consideration in order to identify monitoring and treatment techniques in accordance to a targeted level of security.

Task 4.1 : Handbook

In Europe, mining situation is different depending on country and it is possible to find areas where shafts are all abandoned or in contrary still active. In these two cases, the most important point is to ensure their long term stability and avoid all possible failure caused by the shaft itself or due to an old closure treatment.

For abandoned mine shafts, some problems linked to deterioration of the sealing structure at the shaft head, or movement of backfilling material in the shaft have been observed. It is also common to find mine shaft opened even decades after mining activity. With time, it is also possible that mine shafts be localisable only thanks to mining map and not at surface.

So, there is a large range of situations (untreated, treated, localized, non localized...) or levels of risk (ground movement risk or physical injury risk), caused by the hazardous nature of the former works, for people in the vicinity of shafts or events which may occur (earth movements, gas emissions, others).

The techniques for closing mine working have evolved and improved thanks to feed-back on their relevancy, dimensions and durability. A handbook presenting good practices has been achieved. It presents the most frequently used techniques and their implementation conditions in terms of risk situations and contexts.

This handbook is intended for local or regional stakeholders in the post-mining area and for mine operators. It identifies all criteria which may influence the choice of a method for enhancing mine works safety, and recommends the best adapted techniques, in the light of these criteria, with practical presentation of the data in the form of information sheets.

This handbook refers to other MISSTER deliverables for specific topics.

Task 4.2 - Spreadsheet

Utilising the results from Work Packages 1 and 3, Task 4.2 investigated the potential to develop a computer application that could provide a risk profile for a given set of circumstances relating to the condition of a mineshaft lining. It was originally supposed that this tool might be a spreadsheet. However it was soon determined that a spreadsheet per se might not be the best tool for the task and it may be better to rely on an algorithmic programming language in a web-based environment.

There are several factors that can affect the movement or collapse of a mineshaft, including a change in the equilibrium of the fill or of the surrounding ground, and the overloading or shock to the fill or the surrounding ground. For example, the fill equilibrium might be affected by changes to the groundwater level, or to the saturation or consolidation of the fill; whilst overloading and shock can be caused by building and other structures, vibration from traffic and machinery, mining subsidence and blasting activities. Another key factor is the behaviour of the material surrounding the shaft, which can be affected by rainfall, temperature (frost heave) and ageing.

It was envisaged that an analytical tool could be developed that would have the potential to indicate, amongst other things, a safety factor associated with the tangential stress in the shaft lining, as a function of the above factors. Information on the properties of brick and concrete shaft linings, and their change in compressive strength with water ingress would be provided by the results of the earlier work packages.

The stated purpose of this task was to investigate the potential to develop such a tool. It was determined, by writing demonstration computer programs, that an ideal method of doing this would be to utilise a web-based tool that could be displayed on the screen of a PC or a mobile phone; and for the database of shaft material parameters to be specified in the form of simple text files.

SCIENTIFIC AND TECHNICAL DESCRIPTION OF RESULTS

OBJECTIVES OF THE PROJECT

This project addresses issues raised by mine shafts in terms of security both during and after mining operations.

The project aims are to:

- enhance the understanding of potential hazards that may affect mining shafts ;
- optimize safety conditions for operating shafts and enhance safety conditions of land surface near active and abandoned mining shafts ;
- develop tools to assess the likelihood of shaft deterioration and optimize closure methods.

The sub-objectives of the four individual Work Packages are as follows :

WP1 – COLLECTION AND ANALYSIS OF CASE STUDIES

This work package deals with the collection of representative case history data concerning shaft instability events in Europe. Rather than being comprehensive of all events the case data are representative of a range of potential behaviour in European conditions.

This work package goes through through:

- The identification of main characteristics to be supplied for representative cases;
- The collection of representative cases data by each partner;
- The analysis and synthesis of a data base.

WP2 - LOCATION AND CHARACTERISATION OF MINING SHAFTS

- Development or enhancements of new technologies in order to locate mining shafts :
  - Analysis of existing techniques efficiency for locating mining shafts in particular contexts (urbanized area);
  - Test and development of new techniques (seismic tomography, earth resistivity surveying…).
- Characterization of shafts key components through the development or optimization of probes.

WP3 – ANALYSIS OF CRITICAL SHAFTS CONSTITUTIVE ELEMENTS THAT INFLUENCE RISK OF FAILURE IN TIME

To develop models representing structural and geotechnical performance of shaft structures including a range of potential failure modes typical of European conditions.

To compare different methods of treatment in terms of short and long term stability improvements of shafts including

- Cappings
- Plugs
- Fills
- Grouting

WP4 – SYNTHESIS

Writing of a synthetic document (handbook) in order to help actors in charge of mining shaft safety including:

- Identification of possible failure modes associated with mining shafts and induced risk (risks scenarii, key parameters, qualification of the intensity of risks...);
- Review of monitoring techniques for the location, the characterisation and the anticipation of pre-identified risks ;
- Guidelines for improving shafts safety and recommendations on treatment techniques for shafts closure (taking into account economical aspects, safety level to be achieved, reversibility, methods of control of treatments, longevity of the reinforcements...).

DESCRIPTION OF ACTIVITIES AND DISCUSSION

WP1: COLLECTION AND ANALYSIS OF CASE STUDIES

WPL: INERIS. Partners: UoN, GIG, KWSA, GEOCONTROL, MRSL

Task 1.1 - Implementation of specifications for case files collection (INERIS)

In order to provide a representative analysis of cases relative to incidents directly involving mine shafts, a collection of incidents has been researched by each partner for their respective country. To obtain the most representative cases, a typology of the incidents which can be induced by the presence of a mine shaft has been undertaken. Various exchanges between all the partners allowed to define and to refine the different classes of incident.

The 9 different kinds of incidents and accidents considered are:

1) collapse of the filling material column

In the case of a shaft, collapse of the shaft filling material is a rough and dynamic remobilization of the filling material which propagates down abruptly and rushes into the old works, generating a collapse of the surface if no structure or protection was installed at the head of the shaft. Collapse of the shaft filling material occurs generally after a slow degradation of the conditions of the filling material, in particular during mine water rising within the shaft column after exploitation. These progressive modifications end in the establishment of a limit balance and the intervention of an aggravating factor can be enough to activate the dynamic mobilization of the column. Some collapses of the shaft filling material result from the formation of a void in the column during the dumping of filling material. These voids can result from the blocking of materials within the shaft column.

2) failure of the shaft head

Many shafts were closed by old techniques presenting no guarantee of sustainability. Some old mine shafts were closed by a single on-surface or near-surface wooden platform, eventually completed by filling material on the shaft head but leaving the whole column empty. Some structures, such as more recent concrete slabs, can break when they are subjected to excessive loads (motor vehicle transit, building…), or when surface ground materials on which they rest fail.

3) failure of the shaft lining

The most frequent failures of the shaft lining result from a decrease of its resistance or from an increase of the pressure of grounds. When the strength of the lining is exceeded, the lining (bricks, stone blocks, concrete, cast iron and steel) deforms and eventually breaks. It may collapse in the shaft with part of the surrounding ground.

The decrease of the mechanical properties of a lining material with time is an inevitable phenomenon resulting from the progressive ageing of the constituent materials. Shaft backfilling operations made without sufficient precautions may also damage linings. Stones or blocks dumped from the surface opening are subject to free-falls of several hundreds of meters and can sometimes damage sections of the lining. Also, closure structures badly or insufficiently designed may sometimes stress the shaft lining.

4) failure of deep closure structure located into the shaft galleries

Galleries or mining works with connecting shafts may have been closed before the shaft was backfilled in order to avoid spreading of the backfilling material in the galleries. Structures generally consist of walls in hollow blocks, metal dams or concrete plugs. For old mining shafts, galleries may have been closed with remaining items but without particular design. Because of various causes, for example concrete segregation or poor lining design, a rupture of this deep closure structure can occur allowing the filling material to spread into the galleries, resulting in a collapse of the shaft.

5) rupture due to water effect

When an inflow of water occurs in a shaft, either by the rise of water levels, or by infiltration, this can become a triggering factor:

- of failure of the filling material. The additional water within the column of the shaft adds weight and may reduce fill strength due to pore pressure generation, thereby disturbing the equilibrium state within the column and generating failure.
- of the rupture of the shaft lining, by increasing pressure on the lining.

6) rupture due to particular geologic formations

The presence of particular geological formations, such as soluble horizons (gypsum / salt) or soil seams lacking cohesion which are susceptible to flow (sand for example) may induce the creation of voids behind the lining. This void may destabilize the lining of the shaft and induce its collapse.

7) risk of gas release

The presence of harmful or potentially explosive gases (monoxide and carbon dioxide, methane…) in old mining works can result from:

- A concentration of gas in the rock which is released into cavities generated by the mining;
- The decomposition or the chemical weathering of materials or products which remain
- within the mine.

Shaft may constitute a preferential flow path from mine working up to the surface for gas. The release on the surface can occur during the exploitation, but also during the phase of filling the void after the end of the works (the gases migrating to the surface by piston effect).

These gases can migrate to the surface according to various phenomena:

- thermal variation, due to the difference between gases' temperature or openings altitude;
- Variations of the external atmospheric pressure: gases dilate in period of decline of the outside barometric pressure. On the contrary, in case of increase of the external pressure, the air rushes into the mine;
- Rise of water levels: under its effect, gases are pushed upward through the openings of access. The level of the underground aquifer can vary according to the seasons or the precipitation and induce slow or rough rises of gas.

8) Impact of surface development

Occasionally, a brutal collapse may occur in the vicinity of a mining opening due to the constraints applied on surface. Several causes are likely to lead to these instabilities of the ground level. For example, an overload on the surface, in the immediate surroundings of the shaft head, such as storage of exploited material, heavy vehicles or construction. Vibrations generated by explosions or blasting near the shaft head or by intense circulation of very heavy vehicles can also cause instability.

9) risk of subsidence due to remobilisation of filling material or surface development

Occasionally, a slow and progressive remobilisation of the surface layer (shaft backfilling material and low cohesive ground material) occurs in the vicinity of a mining opening. Settlements occur within the backfilling materials as a result of compaction. Under the effect of outside disturbances (on-surface overload, vibratory stress) or due to a remobilisation of filling materials, grounds or backfill material can settle and induce movements of low amplitude (generally the maximum amplitude is a few decimetres).The results are mainly surface differential settlement that may affect buildings and infrastructure.

Task 1.2 – Collection of case histories (INERIS, UoN, GIG, KWSA, GEOCONTROL, MRSL)

Let us note that in reality, incidents can be the consequence of several phenomena or a combination a previous listed elements. Partners proceeded to the collection of cases including fundamental parameters that may, in one way or another, have played a role in the instability.

During data collection, it appeared that sources of information are variable according to the countries. For example, in England, the Coal Authority provided a data base which includes 1023 mine shafts related hazards whose 322 cases involving collapses of shafts. In other countries, data are often more scattered and required to gather archive data. The collection work carried out through MISSTER project underlined the great heterogeneity of historical data availability among countries.

Thanks to the great numbers of entries in the Coal Authority database, a statistical analysis has been carried out. An analysis of the database found that there were 322 cases involving collapses of shafts. The failure modes of many cases could not be identified based on the limited information. So, only 143 cases with clear information about the failure mode have been included in the final database. These 143 cases were reviewed and organised according to the main failure scenarios identified in task 1.1.

(1) shaft filling material collapse;

(2) shaft head rupture (behaviour of strata surrounding shaft head);

(3) a failure of shaft lining;

(4) rupture of security elements (e.g deep plugs);

(5) a specific focus on water effects;

(6) incidents due to particular geological formation (e.g. gypsum, quick sand);

(7) release of mine gas.

The distributions of the cases at each failure scenario are shown in Figure 1. It is recognized that the selection of failure scenario is subjective and that several scenarios may apply to a single failure incident. The data in Figure 1 should therefore be interpreted with some consideration of these factors.

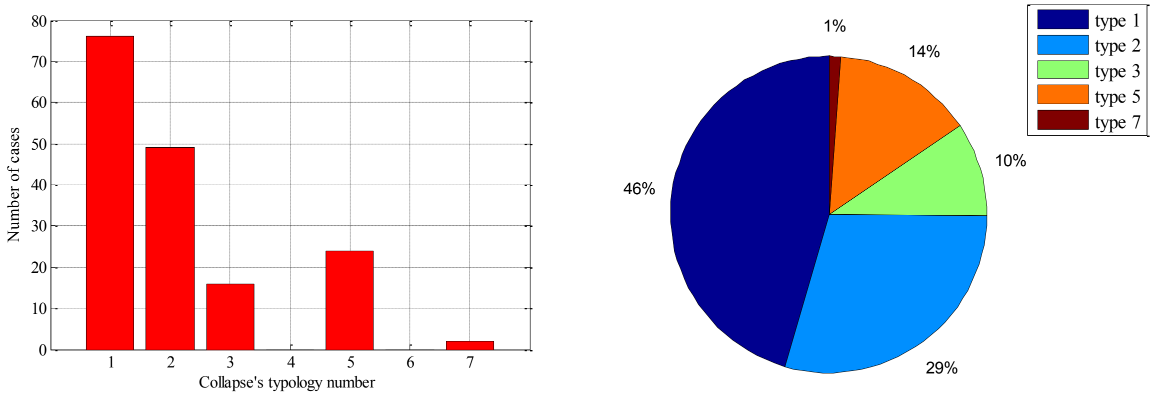


Figure 1 : The distribution of shaft failure scenarios.

This statistical analysis underlines the important role of backfilling material, lining, strata surrounding shaft head in shafts instabilities.

14 specific cases were studied in depth by the partners to illustrate the scenarii identified in task 1.1 according to a similar layout. Analyses are presented in Deliverable 1 and underline the following key points:

(1) Old shafts whose characteristics and modes of treatment are poorly known are of particular concern. When the position of the shaft and the materials used for backfilling is unknown, different problems arise:
   a. shaft stability is not guaranteed;
   b. land use planning is complicated by the presence of a not located shaft requiring to perform shaft location search.

(2) It is often possible to find in same area, shafts whose characteristics and methods of treatment are similar. Securing process should anticipate the presence of close similar shafts;

(3) During the backfilling process, the compared monitoring of backfill material volume and residual depth of shaft is of great importance to avoid or detect any void creation within shaft column. This phenomenon explains a number of backfill collapses, even longer after shaft closure;

(4) Collapse of backfilled shaft column does not systematically induce a collapse of strata surrounding shafts. When these two events occur, it is not possible to forecast how much time may separate the two events (hours, weeks, months or even years). It mainly depends on the nature of the lining (concrete lining are expected to better resist the pressure of the surrounding strata than a wood structure for example).

(5) The nature of strata surrounding shaft head strongly determines the extension of surface collapse. A competent rock around shaft head limits collapse diameter. An uncohesive material (sand…) may induce a collapse with a great diameter (> 10 m).

(6) Modification of hydric or hydraulic conditions within shaft column may compromise a shaft stability (watering or dewatering of filling materials within shaft, modification of air circulation and humidity…);
(7) Attention must be drawn to the concentration of weight around the shafts caused by surface structures (airlocks, fan drifts, fan houses for example);

Task 1.3 – Synthesis and dissemination to partners. Production of a database (INERIS)

Using information collected by the different partners, a database has been developed, bringing together 187 incidents occurred on mining shafts. This database (detailed in Deliverable 1) is composed of 9 columns:

- Incident date: year when the incident has been identified;
- Country: country where the incident has been identified;
- Location: city or region where the incident has been identified;
- Shaft name: when available, the name of the shaft concerned;
- Incident typology: nature of the incident as referred in Task 1.1 typology;
- Keywords: keyword(s) relevant to the identified case;
- Reference: Origin of the information. When available, a note or a report, detailing the example is provided (hyperlink);
- Language of reference: language used in the report or note;
- Photos: when available, one or more photos of the incident are provided (hyperlink).

The search of information can be done either by the type of incident or by keywords (for example: Brick lining, Filling material, Ground collapse, Remaining void after stowing, filling material, Shaft fill settled, Subsidence, Water and vibrations).

The purpose of this database is not to provide fields that detail: geology, hydrogeology and the characteristics of the shaft or of the collapse. The aim is to gather the expertise that has been built on the basis of these cases at a European scale. However those different details, mentioned above, are provided in the reports annexed to the database, when they exist.

This database makes it possible to collect and enhance the expertise available in the various cases of shaft incident that took place in Europe.

Many cases are from United Kingdom as the Coal Authority owns a database. In other countries, such database does not exist and most work within MISSTER dealt with the collection of scattered data in archive or existing reports. As a consequence, provided database is not claimed to be exhaustive but gathers already a wide range of risk scenarii.

Task 1.3 led to Deliverable D 1 : "Synthesis and database containing ordered case files of representative shaft incidents in Europe" – Amelie LECOMTE (INERIS), Mike BEDFORD (MRSL), Alec MARSHALL (University of Nottingham), Slawomir BOCK (GIG), Andrzej MADRZA (KWSA), Agustin MUÑOS NIHARRA (GEOCONTROL) – September 2012.

WP2: Location and characterisation of mining shafts

WPL: GIG. Partners: INERIS, KWSA, DMT, MRSL

Task 2.1 – Location of old mining shaft (MRSL, INERIS)

Review of existing techniques for locating shafts

When mining operations terminate, the mine operator and/or local/public authorities is asked to guarantee the absence of hazards, notably adjacent to the old shafts. These shafts are old and invisible from the surface (covered with topsoil and/or backfill) and therefore difficult to locate from the available data (e.g. old maps taken from the archives). For example, in the North and Pas-de-Calais coal basins, a statistical study comparing archived coordinates and actual coordinates proved that actual location of shafts often differ by up to 20 m and sometimes much more (Charbonnages de France, 2003). Amongst the available processes for locating these vertical structures, partners reviewed the existing geophysical methods, both intrusive (by drilling) and non-intrusive.

Mine-shaft detection using geophysical methods essentially depends on the physical parameters (often heterogeneous and diverse) of the shafts in relation to the surrounding rock. As very little data exists on either the physical parameters of the backfill, or the surrounding rock, the methods were assessed based on a bibliographic search and experience on the detection of underground cavities other than shafts (Fauchard et al, 2004, INERIS/LCPC 2005 and Lagabrielle, 2010).

For each method the principle of operation, the measured data, the expected results, the typical areas of application, and the limitations are discussed. In addition, case studies show examples of each method's application.

The non-intrusive methods included are seismic refraction, surface wave seismic, ground penetrating radar (high-frequency electromagnetic methods), low-frequency far field electromagnetic methods (VLF), low-frequency near field electromagnetic methods (Slingram), direct current earth resistivity, microgravimetry and thermal infrared. Non-intrusive geophysical methods may be used outside of urban areas and enable a large expanse of terrain to be investigated. The main non-intrusive methods and their area of application are summarised in Table 2.

Intrusive geophysical methods enable the investigation radius to be extended around the drilling, surface disruptors to be overcome, and prospecting to be conducted beneath houses. The main intrusive methods (mono-frequency (electromagnetic) drilling tomography, radar tomography, radar reflectivity, seismic drilling tomography, electrical methods), according to the objective sought and the site configurations, are summarised in

Table 3.

In order to be efficient and best define the area to be investigated, the mine-shaft detection phase using geophysical methods must always be preceded by preliminary reconnaissance operations: investigation phase (gathering of information in archives) and surface-indication search phase (topographical anomalies, remnants, etc.) This data will enable the most appropriate method for the case in question to be chosen and the gridding required for executing the measuring points to be defined.

Table 2 : Summary of non-intrusive geophysical methods for detecting old shafts

Technique	Shaft type	Urban environment	Sensitivity to noise	Decoy source	Necessary conditions for detection	Disadvantages
Microgravimetry	empty shaft diameter > or = 3 m	yes but high constraints	human activity, earthquake, impact	mass heterogeneity of the ground	known topography to the nearest cm in z	many difficult-to-interpret measuring points required
Very high-resolution seismic reflection (SHR)	flooded empty cavity	no	human activity, earthquake, impact, surface waves	heterogeneity of the surface terrain, decompressed zone	presence of a reflecting horizon (water table for example)	indirect detection method requiring many difficult-to-interpret measuring points
	not appropriate for detection of vertical constructions such as shafts					
Seismic refraction	shaft closed with a concrete slab, then drowned	no	human activity, earthquake, impact, surface waves	heterogeneity of the surface terrain, decompressed zone	presence of refracting horizons (water table for example) increasing speed media several parallel profiles speed contrast between fill and TN	indirect detection method requiring many difficult-to-interpret measuring points
	not appropriate for the detection of vertical constructions such as shafts					
Surface wave seismic surveys	small cavity close to the surface	yes	human activity, earthquake, impact, surface waves	-	depth of waves sufficient to reach the top part of the shaft (cap, slab..)	difficult-to-interpret indirect detection method
	not appropriate for detection of vertical constructions such as shafts					
Geological radar	shaft closed by a reinforced concrete slab or a concrete or cast iron cap, flooded shaft	yes but high constraints	low except if antennae are not shielded	heterogeneity of surface terrain decompressed zone presence of houses, trees	surrounding rock over 100 Ωm presence of reflecting or refracting horizons (water table for example) at a shallow depth under the shaft closing system wave depth sufficient to reach the top part of the shaft (cap, slab…)	indirect detection method to be avoided if clayey layers are present in surrounding rock difficult to interpret
Slingram	shaft backfilled with clayey materials cast iron cap or shaft fitted or closed with a reinforced concrete slab	no	electric lines and closures	metal environment	largely conductive medium significant contrast in conductivity between fill and surrounding rock	many measuring points required interpretation mainly qualitative and highly subject to disruptive elements
Low-frequency electromagnetism in far field	empty or conductive shaft (cast iron cap or shaft fitted or closed with a reinforced concrete slab)	no	radio emitter metal environment	metal environment	reception of the emitters significant contrast in conductivity between fill and surrounding rock	many measuring points required interpretation mainly qualitative and highly subject to disruptive elements
Infrared	shaft empty or very little filled	no	human activity	wooded surface, water	summer flight after 17H winter flight at end of night	need for aircraft
Electric panel	flooded shaft in a low conductive surrounding rock waterless shaft in clayey surrounding rock	no	-	resistivity jumps	significant contrast in resistivity between fill and surrounding rock	difficult to interpret many measuring points required
Gamma or alpha rays	shaft empty or filled with material other than TN	no	human activity	wooded surface atmospheric conditions (humidity, temperature, wind…) artificial concentration under building	radioactive radiation of the fill >> TN background noise	difficult to interpret many measuring points required
	not appropriate for shaft detection					

Table 3 : Summary of intrusive geophysical methods for detecting old shafts

Technique	Shaft type	Necessary conditions for detection	Disadvantages
Seismic tomography (wave speed)	shaft empty or encased in concrete or cast iron	significant contrast between fill and surrounding rock drill holes tubed and filled with water good coupling between the tubing of the drill hole and the surrounding rock the empty, flooded or filled shaft is a heterogeneity where the propagation speed of the mechanical waves is lower than that of the	many measurements required difficult to interpret detection in the drill hole plane only
Radar tomography (wave speed)	empty shaft	electrically resistant surrounding rock (> 100 Ω.m) the empty shaft is a heterogeneity where the electromagnetic wave speeds are higher than in the surrounding rock. A backfilled shaft would be a heterogeneity in which the speed is slower	detection in the drill hole plane only
Electromagnetic tomography (propagation mode, wave attenuation)	empty or backfilled or flooded shaft	electrically resistant surrounding rock inclinometric measurements of the soundings	detection in the drill hole plane only difficult to interpret
Low-frequency electromagnetic tomography (diffusion mode)	shaft filled or flooded	the empty shaft is a more resistant heterogeneity than the surrounding rock a shaft filled with water or backfilled is more conductive	detection in the drill hole plane only difficult to interpret
Bore hole radar in reflection	empty or backfilled or flooded shaft	electrically resistant surrounding rock	omnidirectional antennae no information on the azimuthal location of the anomaly
Electric boring methods	shaft filled or flooded	the empty shaft is a more resistant heterogeneity than the surrounding rock a shaft filled with water or backfilled is more conductive	

The geological and climatic conditions, urbanisation, etc. are all factors that influence and limit the application of the geophysical methods for detecting old shafts. None of the geophysical procedures described above enable unequivocal location in urban areas or in areas disturbed by human activity. Certain methods provide indications to be verified by sounding or shovel trenching. In all cases, the use of a geophysical method must be considered as a stage in mine-shaft reconnaissance methodology. Its main objective is to define the risk areas on the surface where drillings will be set up.

As no geophysical method can, on its own, enable an unambiguous conclusion to be drawn as to the presence of a shaft, the coupling of several methods (microgravimetry and seismic, for example) could therefore prove beneficial, owing to their complementarity, both in terms of interpretation and implementation.

Lastly, it is advisable, before commencing a measurement campaign, to conduct a test on the site to be studied so as to adapt the chosen system, or validate (or not) the method (test on a shaft known prior to searching for a non-located structure).

Mine shaft exploration using seismic tomography

Seismic tomography is frequently used as a tool for investigating wave velocity variations in different geological environments. Developments made over the past few years have improved sources, sensors and the quality of the tomographic image with, in particular, a higher resolution. Since Bois et al (1971), tomography has been widely used in various fields, and in particular in medical imaging (ultrasounds), where structural information bears no comparison with the information that can be obtained in subsoil. Effectively, velocity contrasts in the human body are very low and predictable compared with those that can be observed in subsoil (Rector et al, 1996). Washbourne et al, 1998, showed that it is more difficult to highlight a geological anomaly than a physiological anomaly. The main differences lie in the seismic ray coverage, dispersive and anisotropic wave propagation and in the multiple ray paths. In sedimentary rock, tomographic data will inevitably contain multiple paths, guided waves, reflected waves and wave conversions, which will make the inversion work even more complicated.

Despite these problems, Louis et al (2005) used seismic tomography between shafts on an archaeological site to explore natural or man-made cavities. Similarly, within the context of the mining basin of the Nord-Pas de Calais, this involves demonstrating whether abandoned shafts can be detected using seismic tomography. Two experiments were therefore carried out on two different sites in the municipality of Fresnes-sur-Escaut with a first shaft known as Saint Germain not located but having surface indications and a second backfilled shaft known as Soult 1, the dimensions and location of which were perfectly known.

Discovering a shaft in an area where there were none led us to interpret the seismic anomaly as the effect of a shaft, all the easier as this anomaly had the same contours and orientations as an indication of surface subsidence. Shaft exploration using power shovels at the location of this anomaly proved the contrary. This anomaly is probably related to a more altered chalky area.

A second seismic tomography carried out in the known Soult 1 shaft coverage area eliminated any ambiguity on the seismic response of a shaft within this context. Its seismic signature on the clayey host rock is clearly very different with an absolute amplitude of more than 1,000 m/s and an extension of several metres beyond the exact shaft coverage area. The anomaly observed on the Saint Germain is much slower (approximately 400 to 500 m/s). It is therefore encouraging to note that seismic anomalies from different sources can be distinguished. The accuracy on the shaft's location would therefore be possible to at least one metre.

These results and the various method robustness tests show that the tomographic image keeps a resolution of approximately one metre in ¾ of the system's coverage. Therefore, the triangle of poor resolution located on either side of the system should be taken into account. The same applies to the low velocity coverage where the discrimination of a low velocity anomaly has now been considered as difficult to achieve. This resolution is compatible with the size of the shafts explored.

Seismic tomography has shown at this stage that it was able to highlight a velocity anomaly corresponding to the shaft coverage area. As the tomography method was adapted to the objectives, in particular, by increasing the resolution, the interpretation of its results must be improved and the confidence that can be placed on these results must be assessed, in particular, when choosing seismic anomaly verification boreholes. In particular, prior to operational implementation of this method, the cause of the symmetrical seismic anomaly should be checked with that corresponding to the Soult 1 shaft. Simulations show that this anomaly could be the symmetrically to both the presence of silt surface and the transverse anisotropy which is in chalk (Figure 2).

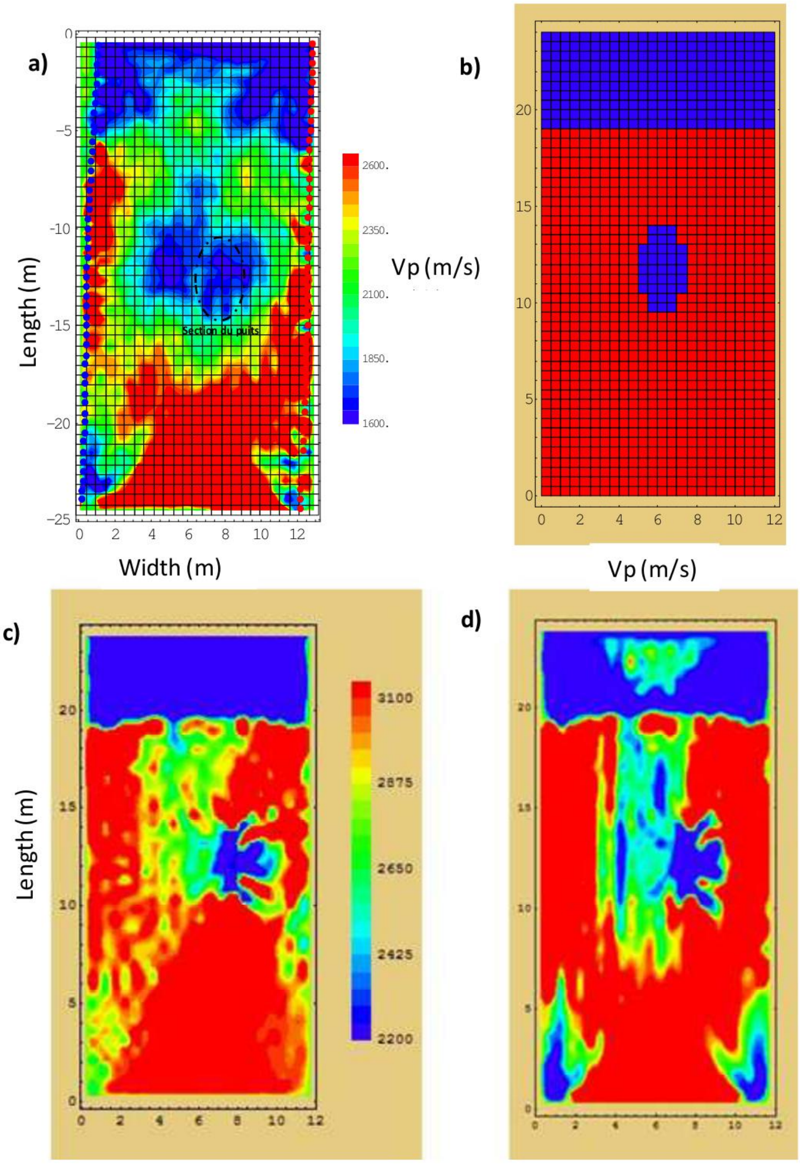


Figure 2 : Example results of mine shaft exploration using seismic tomography a) experimental tomographic image with calibration of the explored shaft section and inversion on 25x50=1250 cells, b) synthetic modelling with low velocity layer on the top (silt) and at the place of the shaft (1800 m/s), c) synthetic inverted result, d) synthetic inverted result with 15% transversal isotropy

<u>Electrical Resistivity Methods – Equipment Design</u>

In the framework of the "MISSTER" Project a novel "plug and play" architecture for smart electrodes, offering major cost, productivity and ease-of-use benefits, has been devised. A top-level electronic design capable of achieving this has been produced and the associated software algorithm has been demonstrated. In parallel, as reported previously, research has also been carried out into the software technique of inversion that is required to interpret the results of an earth resistivity exercise, and approaches for optimising it for the detection of mine shafts have been developed. This completes the research phase as envisaged for this project. Once a commercial opportunity has been identified, an engineering team would be capable to translating the output of this task into a component-level design and production software as a product development exercise.

Task 2.1 led to Deliverable D 2.1 : "Shafts location techniques review and results of geophysical tests" – Mike Bedford (MRSL), Cyrille Balland & Catherine Lambert (INERIS) – June 2012.

Task 2.2 – Development of a continuous shaft system (DMT)

The overall concept of a Continuous Shaft measurement System is based on initial developments achieved in former RFCS PRESIDENCE project. Continuation of the development includes all necessary improvements concerning the autonomous truck mounted winch and further works on the probe integrating all necessary sensors.

The continuous shaft system consist of following modules:

- Telemetry Unit: control of all sensors and network connection to the ground control
- Camera Unit: 360° high resolution panoramic color photo
- Inertial Measurement Unit: detects the rotation and the oscillation of the probe during a measurement sequence in the shaft
- Battery Unit: power supply for all integrated sensors
- Scanner Unit: including the laser scanner, a sensor for collision control and gas sensors

The housing of the probe gives protection to all elements. It is a robust construction of steel and brass in an aerodynamic shape that minimizes the effects of ventilation winds and the resulting turbulences. The total length is less than 2m with a maximum diameter of 324mm at the scanner unit - the total weight is 175kg. The tool was cut down into single elements that are mounted piece by piece while hanging on the wire at the shaft entry. Its slim and compact design allows to access shafts in difficult situations (e.g. access through an air lock). The system is divided into five sub units which can be combined in various ways. The order of the units in between telemetry unit at the top and scanner unit at the bottom can be arbitrary selected. Thus configurations with or without Camera Unit or Inertial Measurement Unit can be chosen, or a minimal set of Camera Unit and Battery Unit is possible. This modular layout also allows the implementation of further sections with other sensors that may be desired at a later time.

One part of the Continuous Shaft Measurement System is the DMT-owned truck with a winch, which works as control center. To control all sensors during a shaft measurement a control software was designed. The software offers general information about the health status of the main components, a graphical display of Scanner and Swiss Ranger data samples in real time and additional information about depth, winch speed and power status.

A major part of the project was the development of the processing software. As a first processing step the recorded data had to be converted into a format readable by Leica Cyclone. Also for the generation of 2D unwrapped images a software module was developed as there is nothing suitable on the market. The software developed by DMT for processing and analysis is able to do preliminary evaluations and also to export data to standard laser scanning software.

For a virtual shaft access and inspection DMT has develop a special visualization tool which is optimized for the shaft scanner data.

The software developed by DMT for processing and analysis creates own evaluations and exports data for standard laser scanning software (Figure 3). Examples of results from the on-site inspections are shown on Figure 4, Figure 5 and Figure 6.

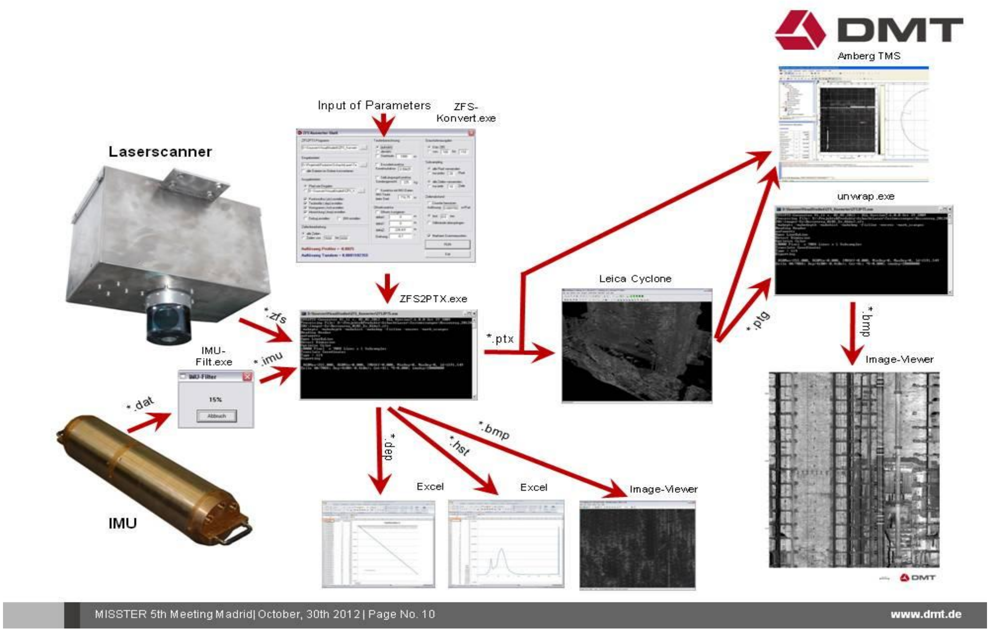


Figure 3: Workflow of data processing

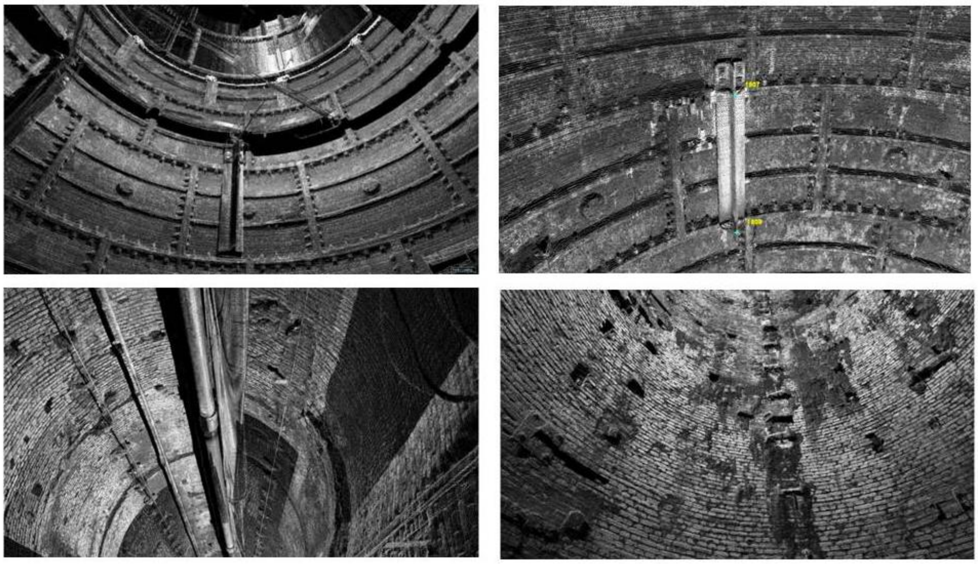


Figure 4: Scan data (inside view) as displayed in Leica Cyclone

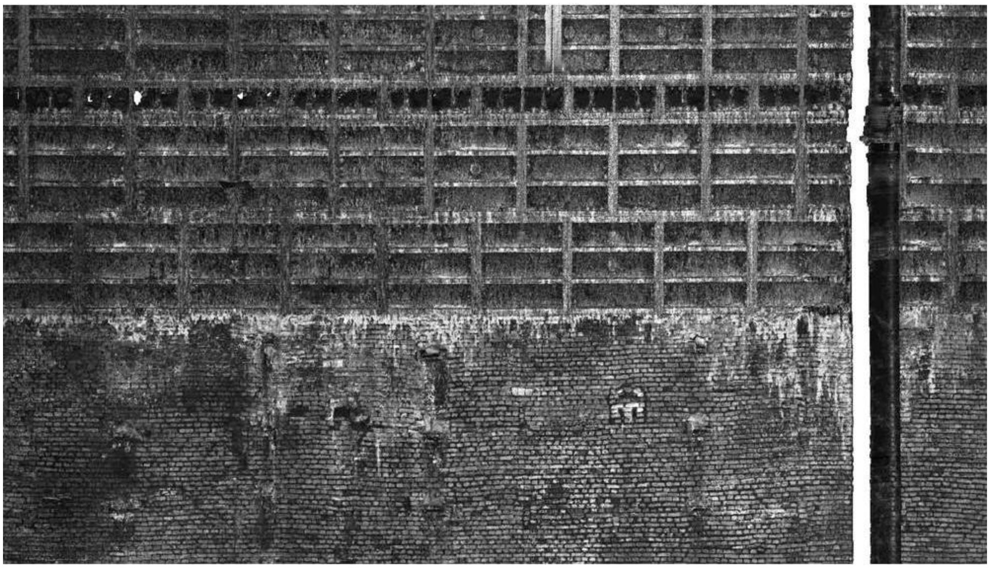


Figure 5: Unwrapped image of scan data (transmission from tubbing to brick lining)

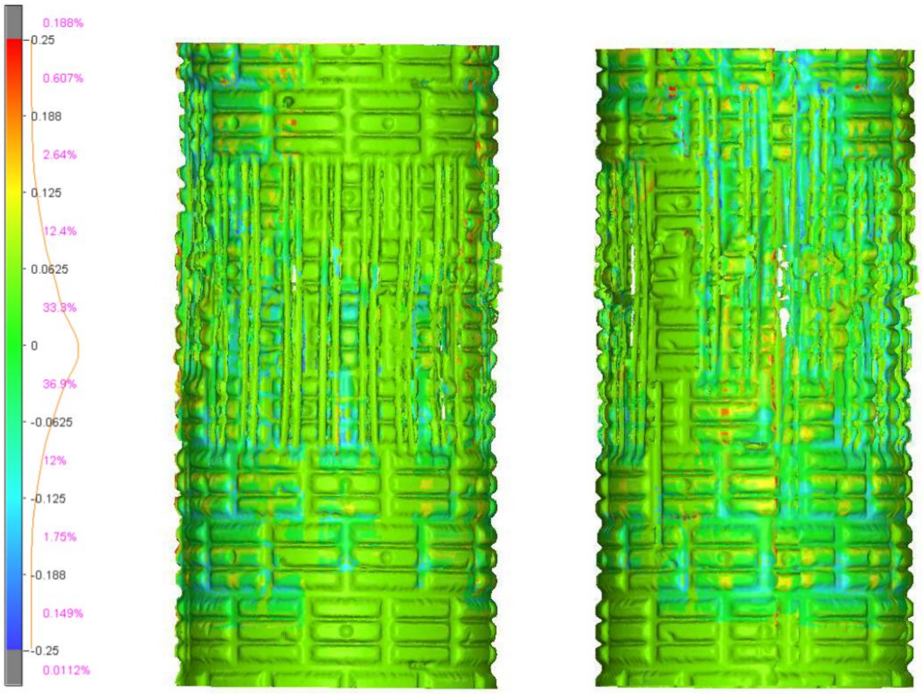


Figure 6: Test of a local deformation analyses between two campaigns

Corresponding Deliverable is D 2.2 : "Guideline for continuous shaft measurement system, visualization software" - Soenke RAPP (DMT) - June 2013.

Task 2.3 – Design and construction of probes, in field tests of probes (GIG, KWSA, INERIS)

In addition to DMT probe previously presented, three different probes have been developed in the framework of project MISSTER (Table 4). The probe 1 (DMT) – Shaft survey system was developed in the framework of Task 2.2. and is described in the Deliverable Report 2.2.

GIG and INERIS probes are described in Deliverable D 2.3 : "Design and construction of a probe and field tests" - S. BOCK (GIG), L. CAUVIN (INERIS) - June 2013.

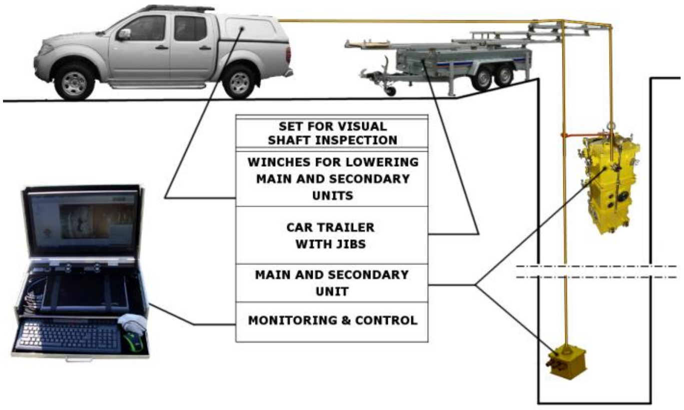
Table 4 : The comparison between developed probes

Parameter	Probe 1 (DMT) Shaft survey system	Probe 2 (GIG)	Probes 3 & 4 (INERIS)
Weight of probe	200 kg	100 kg	5 kg / 3 kg
Total weight (probe, winches, car, ...)	~ 14 100 kg	~ 3 300 kg	150 kg
Dimensions of probe	2520 × 380 × 340 mm	1000 × 320 × 320 mm (main unit) 320 × 320 × 320 mm (secondary unit)	540 × 100 mm / 500 × 80 mm
Minimum - maximum diameter of shaft/cavities	1.0 - ~150 m	3.0 – 12.0 m	0.1 m – 20 m (Laser) 0.1 – 40 m (Video)
Maximum reachable depth	2600 m	1200 m	140 m
Explosive atmosphere (ATEX)	No	Yes	No
Underwater research	No	No	Yes (1 bar / 14 bar)
Video recording	Limited	Very good	Very good
Geometry - laser scanning	Excellent	Limited	Good
Additional sensors	CH_4, O_2, Temp.	CH_4, O_2, CO	None

GIG and INERIS probes are described through information sheets that follow.

PROBE 2 (developed by GIG)

Description: Complete set for remote shaft inspection



General concept of the set for visual shaft inspection

The main probe is equipped with 4 cameras emplaced every 90° on the perimeter and an additional camera located at the bottom of the probe.
The video signal is transmitted on the surface (WIFI), which allows to supervise the tests. A small, portable winch has been entrenched within a mobile platform (a 4×4 Nissan Navara car). During the tests continuous records of the air-conditions, distance between the probe and the lining (four laser distance meters) and the depth, at which the probe is located, are carried out.
The secondary unit is composed of only one module. It is equipped with a video camera located at the bottom of the module, light source (LED), system for measuring the composition of the atmosphere in the shaft and signal transmitter (WIFI).

Each of the two winches for lowering main and secondary unit are equipped with a steel rope (1200 m of length) and rope spooling system. The winches speed can be control continuously from 0,0 to 1,5 m/s. During the shaft inspections the winches are secure mounted in the cargo area of a car - Nissan Navara.

Winches for lowering the main and secondary units a) mounted in the car, b) unmounted for maintenance and service

Car trailer with jibs
a) folded and prepared for transport, b) fully extended and placed over the shaft

Car trailer is equipped with depth-encoders, WIFI antenna and special jibs enabling precise guidance of the probe anywhere in the area of the shaft.

The probe allows:

- Visual recording of the entire circumference of the shaft lining (1280x1024, 30 fps)
- Visual recording from camera directed into bottom of the shaft (1280x1024, 30 fps)
- Distance measurements using laser markers (directed in four directions)
- Continuously measurements of the air composition (methane, oxygen, carbon monoxide)
- More than two-hour running time using the internal power supply,

The monitoring&controls unit allows:

- Live preview on the surface from all of the video cameras
- Winch control (speed, position of the main and secondary unit)
- Control of the light sources and cameras in the units (turning on/off, adjusting of parameters)

The probe is intended to be used in an explosive environment (ATEX Certificate)

PROBE 2 (developed by GIG)

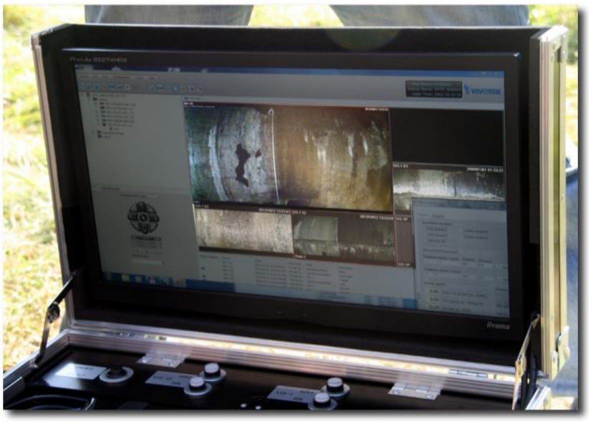
Usage examples

Preparations for remote shaft inspection

Car trailer with probe mounted for transport

The removable roof protecting from rain and snow

Monitoring&Control Unit

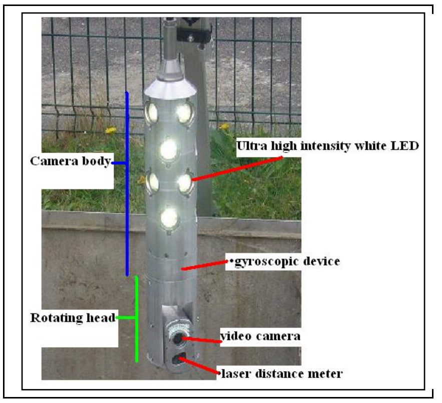


Live preview of recorded images

Example image recorded during shaft inspection

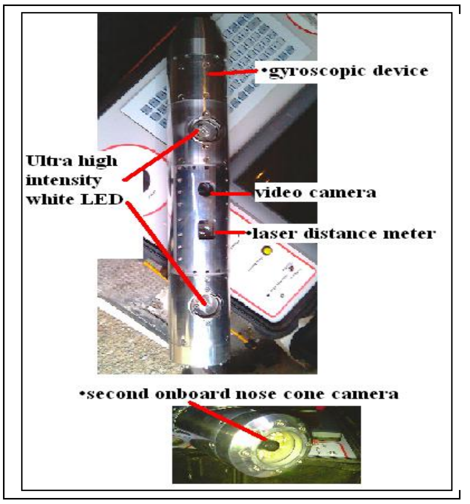
PROBES 3 and 4 (developed by INERIS)

Description: Laser cameras for dry and flooded voids



Camera for dry voids (probe 3)

The probe is built to work in dry conditions or in accidental immersion (<100 kPa). It requires a drilling of 125 mm diameter.
The lightening is composed of 12 ultra high intensity white LEDs fixed in the body of the camera. The rotating head can move in 360° in the azimutal plane and 155° in elevation (zenith). The head position is located in three directions in reference with the camera body by pitch and roll sensors and a gyroscopic device. The video camera and the laser distance meter are situated in the rotating head.
When the diameter of the access in the shaft or in a void is more than 140 mm and the void is dry, the system is able to product video and pictures, manual laser measures and automatic laser measures (3D point-cloud).



Camera for flooded voids (probe 4)

The probe is built to work in flooded conditions (max <1400 kPa) like in some old mine shafts. It requires a drilling of 100 mm diameter.
The body of the camera is totally cylindrical. The rotation of the head in only an azimutal plane (360°) is located in direction in reference with the camera's body and by a gyroscopic device.
The video camera and the laser distance meter are situated in the rotating head between 2 directives ultra high intensity white LED.
A second onboard nose cone camera used to view the borehole with an additional white LED light source is situated in the front of the body.
When the diameter of the access is between 100 and 140 mm and the void is dry, the system is able to produce video and pictures and manual laser measures in an azimutal plan. In flooded voids only the video and pictures are available.

The general specifications:

- Built in 3 parts (cameras, winder on a trolley, remote control unit) to be transportable in a small van, the total weight is less than 100 kg
- Based on two interchangeable cameras (for dry and flooded voids)
- Can be used directly on its own wheel (the trolley of the winder was built to get through a standard house door) or with a tripod
- Independent power supply and separation of the power supplies of the winder and the control unit allowing the integration of an inverter that guarantees the safeguard of the data and the restoring of the camera in the event of power incidents
- The system is able to automate the measure cycles (max 1800 measuring point at each cycle) of the laser distance meter

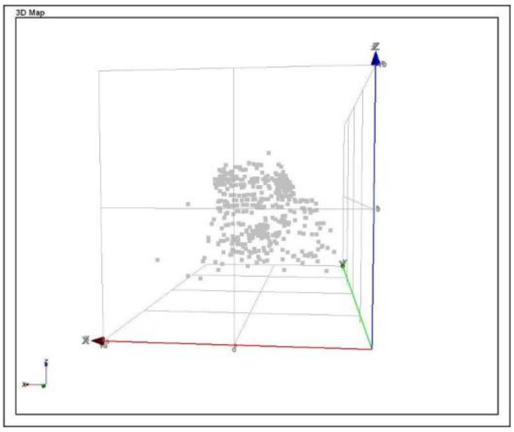
PROBES 3 and 4 (developed by INERIS)

Usage examples

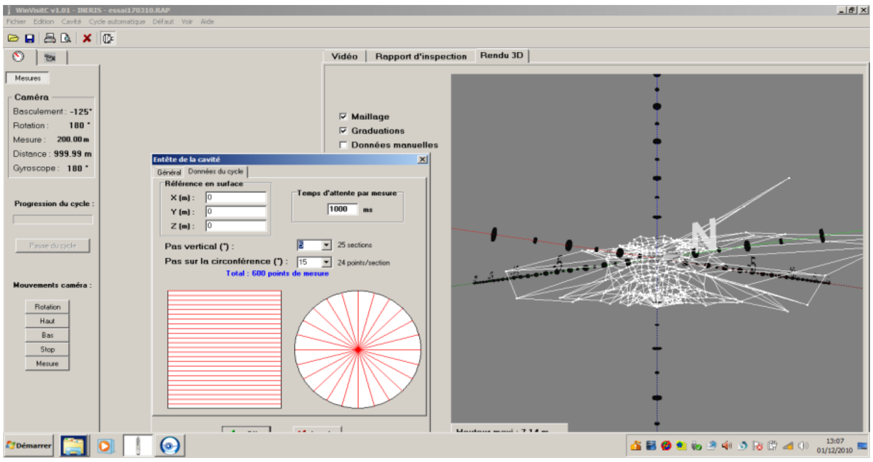
Inspection of cavities and shaft with the winder located directly at the top of the shaft or at the top of a borehole

Digital picture taken by the acquisition card (example of closure of the head of an old schaft)

Inspection of cavities and shafts using a tripod or a deviation pulley



Point cloud of the body of an old shaft



Remote control software with visible results of 3D scanning process

WP3: ANALYSIS OF CRITICAL SHAFTS CONSTITUTIVE ELEMENTS THAT INFLUENCE RISK OF FAILURE IN TIME

WPL: UoN. Partners: GIG, KWSA, GEOCONTROL, MRSL

Task 3.1 – Filling materials and techniques (GIG, KWSA, MRSL)

Task 3.1 corresponding Deliverable is D 3.1 : "Evaluation of new materials and techniques for shaft filling or consolidation" - S. Prusek, S. Bock, J. Dziura (GIG) – June 2012.

The objectives of this WP include the evaluation of rock waste suitability used as filling material and the determination of technologies used for filling with desired material. Objectives also include comparison of different methods of treatment in terms of short and long term stability improvements of shafts including cappings, plugs, fills, and grouting.

Abandoning a shaft is a complicated task as shafts, being the link between the surface and an underground network of workings, disturb hydro-geological and gaseous conditions in the rock mass. Therefore, the method used to abandon the shaft must take into consideration that conditions (Sztelak, 1991). Because of various functions of shafts, their closure technology and preparatory works shall be prepared individually, taking into consideration maximum safety of the conducted works.

Within the framework of the task a range of works, realized in preparation for shaft closure, is presented. It should be noted, that in other countries because of different conditions, different than described here, additional works may be conducted. They may be forced by specificities of a particular shaft, or equipment used in its closure. Nevertheless, it seems that the works described within the scope of the task are the basic steps that have to be undertaken in case of the simplest methods of abandoning shafts i.e. where the filling material is fed directly or indirectly. The range and description of that tasks are included in the Deliverable Report of WP3.1, Chapter 2 - Shafts preparation methods for abandoning and filling techniques.

An important issue in the shafts closure is the choice of appropriate material for its filling. In the framework of task 3.1, Polish and world scientific publications have been analysed and additional underground and laboratory tests have been conducted on materials with diverse properties, that is:

1. Blast furnace slag (graining from 4.0 to 200.0 mm)
2. Metallurgical slag (graining from 4.0 to 200.0 mm)
3. Granite (graining from 31.5 to 200.0 mm)
4. Dolomite (graining from 31.5 to 63.0 mm)
5. Mining waste rock I (graining from 2.0 to 45.0 mm, 70% of clay-type rocks)
6. Mining waste rock II (graining from 31.5 to 200.0 mm, 70% of clay-type rocks)
7. Mining waste rock III (graining from 4.0 to 200.0 mm, 70% of clay-type rocks)
8. Waste mixture (graining from 50.0 to 100.0 mm, mixture of mining waste rock and metallurgical slag)
9. Mining waste rock IV (graining from 31.5 to 63.0 mm, 70% of clay-type rocks)
10. Metallurgical slag (graining from 31.5 to 63.0 mm)
11. Granite (graining from 31.5 to 63.0 mm)

Each of the materials subjected to these tests were divided into two parts. The first part (about 2 tonnes) was directly transported to the laboratory at Główny Instytut Górnictwa (GIG) with the object of determining its water permeability. The second part of the material (about 8 tonnes) was delivered to the place of the underground test. The underground tests were carried out at the partially closed shaft „Żeromski" of the colliery „Piekary" which is a mine owned by Kompania Węglowa SA. The material was supplied in portions of about 2 tonnes until it was possible to take a sample by means of a steel bin of 1.0 m^3 in volume from the shaft bottom. The tests were performed in the active part of the shaft over its length up to a depth of 303 m for the first 8 materials and up to a depth of 190 m for the next 3 materials.

The material recovered from the shaft was transported to the laboratory at the Central Mining Institute where its grain size distribution and water permeability were determined. Moreover, before the underground tests were commenced, there were material samples taken for the purpose of executing complementary analyses of their grain size distribution. The obtained values of the median diameter and the degradation coefficient for the example materials are presented in

Table 5.

Table 5 : Obtained values of median diameter D_M and degradation coefficient i_M for the materials under test

Material	D_{M0}	D_{M1}	i_M
	mm	**mm**	**-**
Blast furnace slag(1)	58.0	16.0	3.6
Metallurgical slag I(1)	44.0	9.1	4.8
Metallurgical slag II(2)	32.8	17.9	1.8
Granite I(1)	51.0	14.9	3.4
Granite II(2)	32.5	19.2	1.7
Dolomite(1)	38.3	13.7	2.8
Mining waste rock I(1)	12.4	9.2	1.3
Mining waste rock II(1)	38.8	9.0	4.3
Mining waste rock III(1)	20.2	11.1	1.8
Mining waste rock IV(2)	22.0	8.1	2.7
Waste mixture(1)	48.9	15.5	3.2

(1) material tested in the 1st stage of underground tests (depth 303 m)
(2) material tested in the 2nd stage of underground tests (depth 190 m)

Coefficient of grain degradation i_M is defined as a ratio of the typical grain size in a given material (D_M) before it has been dropped into the shaft to the same after dropping:

$i_m = D_{M0}/D_{M1}$

where:

D_{M0} – median diameter for which sum of minus mesh fractions makes up 50% of sample (for material before dropping into shaft)

D_{M1} – median diameter for which sum of minus mesh fractions makes up 50% of sample (for material after dropping into shaft)

On the basis of the presented test results, it can be concluded that changes in grain size of the tested materials were greatly differentiated. In case of the eleven tested materials, the value of degradation coefficient i_M changed within the range between 1.3 and 4.8. The biggest degradation of grains in the group of tested materials occurred in metallurgical slag I dropped from the height of 303 m. The smallest changes in grain size occurred in mining waste rock I of relatively fine initial grains (D_{M0} = 12.4 mm).

The obtained results confirmed earlier views that degradation of a material depends on its strength parameters – materials of different strength and similar initial grain distribution (e.g. dolomite and mining waste rock II) showed different levels of degradation after dropping them into the shaft. In case of the same type of material and different grain distribution there was a distinct correlation between the initial size of grains and the degradation coefficient. Together with the increase in the share of coarse grains, the degree of degradation of the material also increased after dropping it into the shaft.

Underground tests in Żeromski shaft were conducted for two heights: 303 m and 190 m. In case of materials with good strength parameters (UCS > 50 MPa), such as *granite* or *metallurgical slag,* decrease in the height caused decrease in their degradation. Degradation coefficient for metallurgical slag I and II, dropped from the height 303 m and 190 m, decreased from 4.8 to 1.8. Such a significant difference resulted undoubtedly from slightly different grain distribution of the tested materials (median of the grains was respectively: 44.0 and 32.8 mm), yet the height of drop played a role too, as the value of grain median also changed. As far as materials dropped from the height of 303 m were concerned, in all cases the average median of grains was approximately 12 mm. Both in case of metallurgical slag, and granite, after the drop from the height of 190 m, medians of grains were respectively 17.9 and 19.2 mm.

No similar correlation was observed in case of materials with low strength parameters (*UCS* < 30 MPa). In case of comparable materials, like mining waste rock III and mining waste rock IV, dropped from the height of 303 m and 190 m, similar degree of degradation was observed. A slight increase in degradation of the material dropped from 190 m (mining waste rock IV), in comparison with mining waste rock III, was probably caused by a bigger share of coarse grains which were further refined. Also the value of material grain median, after dropping from the height of 190 m (8.1 mm), shows that the changes in grain size of the materials for the two heights are comparable. It allows to conclude that further increase in the height of drop does not have a significant influence on further degradation of low strength materials.

Because of the unique character of the studies and the need to conduct them in a way, which does not disturb the process of shaft abandonment, the tests were limited to these two heights only (303 m and 190 m). In spite of the previous statements, it is advised to continue the studies for other heights of drop to confirm the obtained data.

The sequential laboratory test, to which the samples were subjected, was determination of water permeability. A special testing stand has been developed and made for the purpose of determining permeability within the framework of the „MISSTER” project. The basic component of the stand is a steel cylinder with a diameter of 1.0 m and a height of 2.0 m. Filling material permeability is determined by measuring the following parameters: volume of flow, time of flow and water table level in the measuring cylinder. The values of the parameters are recorded by the measuring sensors and transferred to a computer. A diagram of the measuring system for determining water permeability of filling materials and the testing stand developed at the Central Mining Institute are presented in Figure 7.

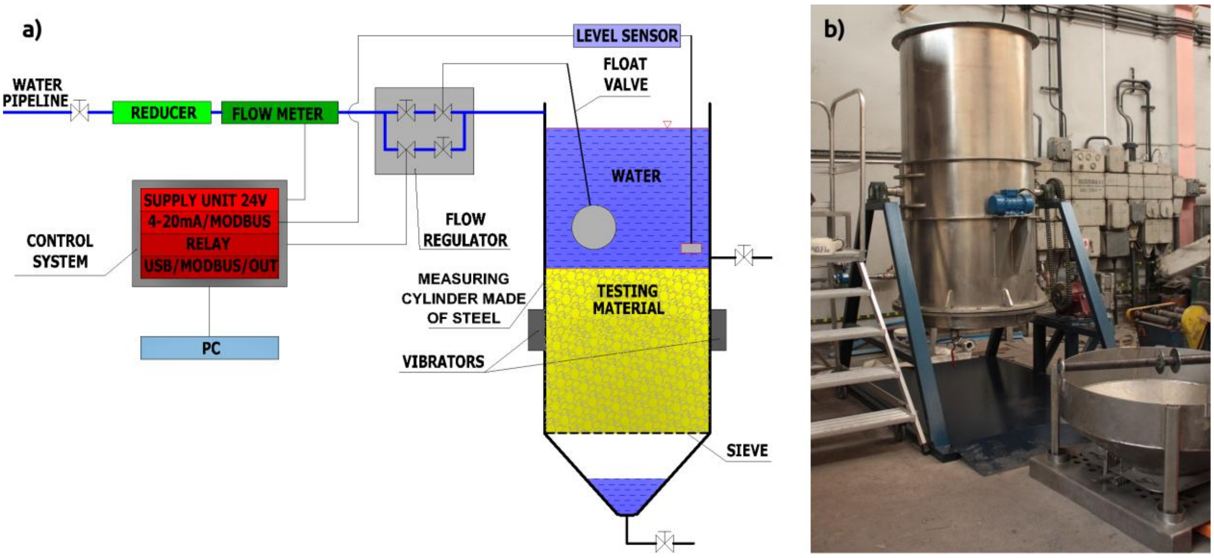


Figure 7 : The testing stand developed at the Central Mining Institute
a) Schematic depiction of stand for measuring water permeability,
b) View of stand for measuring water permeability

The stand makes it possible to measure water permeability using the constant- and variable-gradient methods in a range of hydraulic conductivity from 10^{-3} m/s to 10^{-8} m/s. The values of hydraulic conductivity for tested materials are presented in Table 6.

Table 6 : Results of water permeability tests

Material	Hydraulic conductivity m/s	
	Before	**After**
Blast furnace slag(1)	$2.24 \cdot 10^{-3}$	$2.04 \cdot 10^{-3}$
Metallurgical slag I(1)	$2.17 \cdot 10^{-3}$	$6.02 \cdot 10^{-4}$
Metallurgical slag II(2)	$1.96 \cdot 10^{-3}$	$1.63 \cdot 10^{-3}$
Granite I(1)	$2.48 \cdot 10^{-3}$	$1.80 \cdot 10^{-3}$
Granite II(2)	$9.12 \cdot 10^{-4}$	$7.92 \cdot 10^{-5}$
Dolomite(1)	$2.48 \cdot 10^{-3}$	$2.12 \cdot 10^{-3}$
Mining waste rock I(1)	$2.48 \cdot 10^{-3}$	$2.13 \cdot 10^{-3}$
Mining waste rock II(1)	$2.47 \cdot 10^{-3}$	$2.13 \cdot 10^{-3}$
Mining waste rock III(1)	$2.48 \cdot 10^{-3}$	$2.42 \cdot 10^{-3}$
Mining waste rock IV(2)	$2.30 \cdot 10^{-3}$	$2.23 \cdot 10^{-3}$
Waste mixture(1)	$2.27 \cdot 10^{-3}$	$2.25 \cdot 10^{-3}$

(1) material tested in the 1st stage of underground tests (depth 303 m)

(2) material tested in the 2nd stage of underground tests (depth 190 m)

On the basis of the obtained test results it may be concluded that, after dropping into Żeromski shaft, hydraulic conductivity of most of the tested materials decreased probably due to the change in their grain size (degradation of grains resulting from dropping the material into a shaft). It should be also noted that the changes in hydraulic conductivity were not significant. It is probably because, in spite of changes in grain size of the materials after dropping them into the shaft, in all of the cases grain distribution similar to the one of coarse-grained materials was observed. A decrease in water permeability coefficient by approx. 10-30% was observed after dropping the materials into the shaft. In case of granite II a significant decrease in hydraulic conductivity occurred as the sample was mixed with some fine grained material. Probably during the underground tests, as a result of the filling material colliding with shaft steelwork and lining, the sample was mixed with fine grained material used in shaft liquidation.

On the basis of the obtained data it was concluded that the tested materials (except granite II) both before and after the drop into the shaft, remained in the group of good hydraulic conductivity materials (values between 10^{-3} and 10^{-4}).

Additional tests of the influence of soaking clay rocks on hydraulic conductivity were conducted for the already tested mining waste II, the material with the highest contents of clay among the materials tested within the framework of the project. First hydraulic conductivity of the material was assessed and then it was left in a measuring cylinder filled with water. After 24 hours another test of hydraulic conductivity was performed. In both cases the same value of hydraulic conductivity was obtained ($k = 2.39 \cdot 10^{-3}$ m/s). The results showed that soaking clay substances in the tested mining waste did not influence significantly its water permeability. Nevertheless, during the tests of filling materials containing clay rocks it is advised to conduct tests of water permeability, as it was shown above i.e. after leaving the material covered with water in a measuring cylinder for 24 hours.

In the next stage, influence of compaction of the material on its water permeability was tested to reflect conditions during shafts closure. On the basis of earlier numerical calculations with PFC3D software conducted within the framework of task 3.3. of the present project, final compaction of the material for mining waste II was evaluated by determining the change of height of backfill column (5 cm per meter). Considering the factor, to evaluate the influence of material compaction on water permeability, the tested material (mining waste II) was compacted in the measuring cylinder until the same change in height was obtained. Then its water permeability was evaluated. The obtained results show a slight decrease in hydraulic conductivity, by approximately 2% - from $2.39 \cdot 10^{-3}$ to $2.34 \cdot 10^{-3}$, due to compaction of the material. On the basis of the conclusions it may be stated that in case of low pressure in the backfill column of the shaft – up to approximately 2 MPa (Janssen, 1895; Stałęga et al., 1998) – compaction of a coarse grained material, should not have significant influence on its water permeability.

The next test, which some of the materials were subjected to, was a leachate analysis, which allowed to evaluate influence of the materials on pollution of groundwater. It is an important issue as, for economic reasons, materials like mining waste rock, metallurgical slag, fly ash etc. are used to backfill shafts. The analysis was conducted according to the standard PN-Z-15009 (Solid waste. Preparing leachate) and was performed by leaching contaminants in a given sample with distilled water. Additionally tests with mine water, taken from Ziemowit coal mine, were performed, with (7- and 14-day) prior soaking the tested materials and without soaking them. Chemical composition of the mine water is presented in Table 7.

Table 7 : Chemical composition of mine water used in tests of filling materials influence on groundwater pollution

Indication	Unit	Value
pH	pH	7.0
chlorides (max)	mg/l	10640
sulphates (max)	mg/l	909
ammonium ions	mg/l	3
manganese	mg/l	0,33
potassium	mg/l	127
sodium	mg/l	5309
calcium	mg/l	362
iron	mg/l	0.88

The obtained results do not reflect the total contents of a given component in tested samples, yet they let estimate potential threat that a given material may pose for the environment.

Samples of the following materials were the subject of the research on the influence of filling materials on groundwater pollution:

- Blast furnace slag
- Metallurgical slag
- Mining waste rock
- Granite
- Dolomite

Values of contents of physic-chemical elements obtained through chemical analyses were compared with the boundary values provided in the Regulation of the Minister of the Environment of 23 July 2008 on criteria and methods of assessment of the status of groundwater (OJ of 2008 No. 143, item 896). The analysis shows that in some cases the contents of physic-chemical elements were exceeded. To compare the obtained results the measured content of physic-chemical elements in reference to their acceptable values, considering contents of the elements in the used mine water, were presented in a graphic form. An example of such comparison is presented on Figure 8. Due to significant discrepancies between the obtained values the graphs are presented in logarithmic scale.

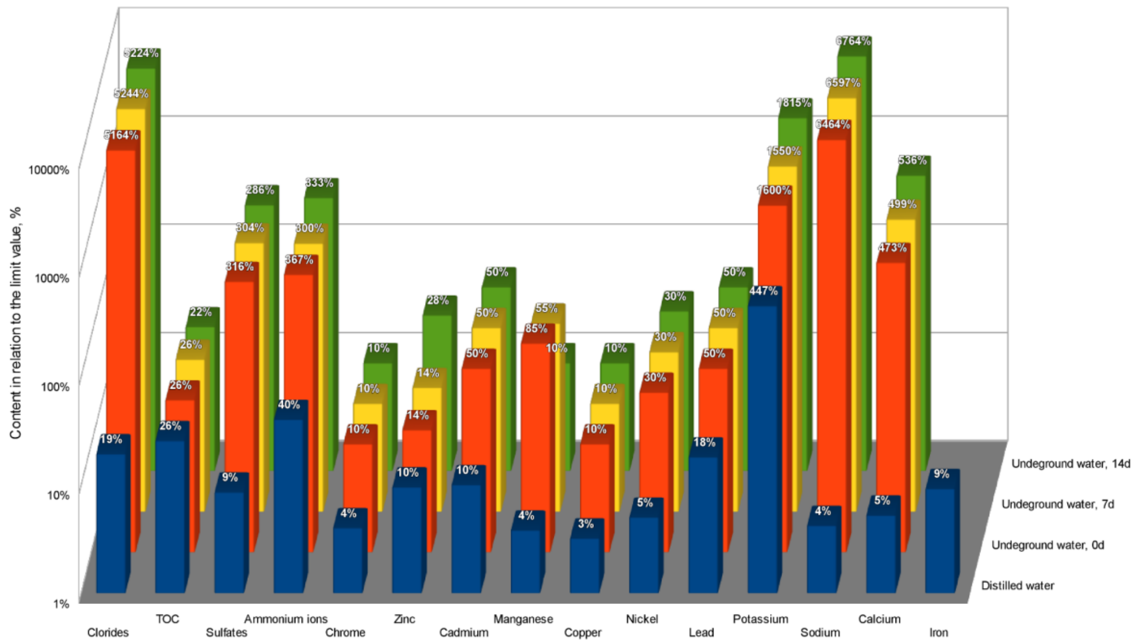


Figure 8 : Percentage of measured values in reference to acceptable values for blast furnace slag

On the basis of the obtained results it may be concluded that in case of the analysis of the leachate according to the standards, i.e. with distilled water, it is acceptable to fill shafts with granite and dolomite as well as mining waste rock. Maximum values of the measured indicators were:

- 55% of TOC acceptable value for granite,
- 41% of TOC acceptable value for dolomite,
- 58% of sulphates acceptable value for mining waste rock.

In case of the two remaining materials (blast furnace slag and metallurgical slag) a significant exceedance of potassium (respectively 565% and 447% of acceptable values) was observed. Other indicators did not exceed acceptable values. Completely different results were obtained with the use of aggressive mine water. The highest exceedances of acceptable values were observed in case of metallurgical slag (chlorides exceeded by 5664% in relation to the acceptable values). A total of six elements in the material showed exceedances and for four of them they were over 500%.

Similar exceedances of acceptable values were observed in case of blast furnace slag and mining waste rock. The maximum exceedances were respectively 6764% of the acceptable value for sodium and 7592% of the acceptable value for chlorides. The results obtained for mining waste rock are particularly interesting. With the use of distilled water, no exceedances of physic-chemical elements contents were observed whereas with the use of aggressive mine water the analysis of leachate showed results comparable with the ones obtained for blast furnace slag and metallurgical slag. In case of the samples of granite and dolomite, independently on the water used, no exceedances of physic-chemical elements contents were observed.

Results of the analyses with the use of mine water, without soaking and with soaking for 7 and 14 days, for each of the tested materials were very similar. In case of the tested materials there was no significant difference in the contents of physic-chemical elements, thus the tests could be performed without additional soaking. Moreover, on the basis of the obtained results, it was concluded that an analysis of leachate with distilled water (i.e. according to the standard of PN-Z-15009) is insufficient to assess influence of the used filling material on groundwater pollution. Such an evaluation is possible when the analyses are supplemented with tests with the use of the water, which actually occurs in the liquidated shaft.

Detailed description of test results and conclusions are included in the Deliverable Report of WP3.1., Chapter 3 - Laboratory and in situ characterisation of filling materials.

On the basis of the conducted literature analyses and obtained results of both underground and laboratory tests within the framework of MISSTER project, it is proposed to use filling materials which meet the following criteria:

- grainy mineral material of grain size between 20 and 120 mm and grain median D_M = 100 mm, free of undersize particles,
- compression strength of at least 30 MPa,
- insoluble and non-flammable,

- without toxic compounds,
- no risk of leaching harmful and hazardous elements,
- meeting requirements of acceptable level of radioactivity.

The above requirements ensure creating a safe, water permeable backfill column. They can be met by using such rocks as: granite, gneiss, basalt or dolomite. The conducted tests showed that there is a possibility to use a grainy material of different qualities than the ones mentioned in Point 1 and 2, i.e. of low strength parameters (UCS < 30 MPa) and different grain size distribution, to shafts closure. It may therefore be for example a waste materials from coal or steel processing (mining waste, metallurgical slag, blast furnace slag etc.). Using them is economical, yet it requires additional tests. Within the framework of task 3.1 of MISSTER project a range of necessary tests was specified, together with methodology of filling material selection. The first of the required tests, specified in the methodology of low strength materials selection is an analysis of their grain distribution, and then laboratory tests of their water permeability. It is considered that the condition of water permeability is met if the backfill column made from a given material is able to filter the total amount of water supplied to the shaft. In practice it means that the backfill column should have water permeability coefficient between $1 \cdot 10^{-3}$ and $1 \cdot 10^{-4}$ m/s. If the obtained result is satisfactory, then the water permeability test should be repeated with a sample of grain distribution reflecting the material after dropping, i.e. considering its degradation, resulting from the strength parameters, chosen technology of feeding into the shaft, and existing steelwork of the shaft. The degree of material degradation can be assessed with analytical methods (Frolik, Rogoż, 2006) or with numerical methods e.g. with PFC3D software.

The next important feature of the applied material is its lack of influence on groundwater pollution. The conducted tests showed that an analysis of leachate with the use of distilled water (i.e. according to the standard PN-Z-15009) is insufficient. It is necessary to supplement the tests with an analysis with the use of water that may flow into the liquidated shaft. The material meets the criterion of lack of influence on groundwater pollution if the contents of physic-chemical elements obtained in chemical analyses of leachate do not exceed boundary values. The boundary contents of the elements are specified in the Regulation of the Minister of the Environment of 23 July 2008 on criteria and methods of assessment of the status of groundwater (OJ of 2008 No. 143, item 896). Because of the proposed modification of guidance of PN-Z-15009, the leaching tests with the use of mine water should be conducted for waste materials, and low strength parameters materials, as well as homogeneous materials like granite or dolomite.

The filling material is considered appropriate for shafts closure if it meets all of the above-mentioned requirements.

Selection of an appropriate filling material and backfilling technology has a significant influence on the possibility of reopening the closed shafts. The process requires numerous preparatory actions. In case of a shaft closed with a grainy material, they may be:

- disassembly of concrete slab closing the shaft,
- constructing a temporary steel headframe,
- constructing hoist machinery on the shaft frame,
- preparing bins for rock extraction,
- constructing a suspended deck with through holes for bins, air duct installation, pipelines etc.

The most often used equipment to load rocks into the bins is a material handler. It can also remove such elements as platforms, ladders, frames, guides etc.

Shafts closure is most often conducted by filling it with a grainy material fed into the shaft with a conveyor or directly from a lorry. It often leads to devastating a shaft lining and elements of its equipment. It also increases probability of occurrence of voids, cavities, cornices of a filling material etc. in the backfill column. Moreover, the method of feeding increases the degree of filling material degradation due to numerous collisions of the material's stream with equipment within a shaft. Such refined material may not meet the requirements posed to maintain filtering properties in the backfill column. Free fall of grainy materials, especially solid rocks, may cause sparking on impact with elements of shaft steelworks. Consequently, it may cause an explosion of methane migrating along the shaft. To limit or eliminate the hazards and enable use of low strength parameters materials to shafts closure, within the framework of task 3.1 a new method of feeding material into the shaft was prepared. The main idea of the new method of feeding the material is to place in an optimum place of shaft section (best in the axis of the shaft) tubular tanks that direct the stream of the filling material. They enable feeding the material in portions in short intervals. The top and bottom dampers (placed on both ends of the tubular tanks), opening under specific load, are used as dosing elements. It allows feed into the shaft a portion of material that is subject only to gravitation. In consequence, it limits occurrence of disturbances in the flow of material and collisions with a shaft steelwork and its lining. Tubular tanks are mounted on the charging hopper where the material is transported with a conveyor. Additionally it is advised to feed small amounts of water, which maintain high humidity of the portioned material. Optionally, to ensure continuity of feeding material into the shaft additional sequentially filled tanks may be installed.

Detailed description of that methods is included in the Deliverable Report of WP3.1., Chapter 4 - A new backfilling methodologies.

Task 3.2 – Linings cappings and plugs design and integrity (UoN, GEOCONTROL, MRSL)

The research conducted for this task focused on the analysis of the stability of shafts and in developing and understanding of the effect that time and harsh environmental conditions (weathering) have on the constituent elements of the shaft as well as the general behaviour and performance of the shaft. The work can be summarised into 3 categories: experimental tests on weathering (UoN and MRSL), numerical modelling of static and time-dependant scenarios of shaft behaviour (UoN and GEOCONTROL), and physical modelling of shaft failure mechanisms (UoN - not included in initial proposal).

Corresponding Deliverable is D3.2 : "Numerical modelling results including characterization of brickwork and stonework. Static and time dependent numerical modelling for the evaluation of treatments effectiveness" - Dr A. Gullón, Eng. A. Muñoz, Eng. J. Vaca (GEOCONTROL), Malcolm Purvis (MRSL), S. Prusek, S. Bock, J. Dziura (GIG, KWSA), Dr Alec Marshall, Dr Wenbo Yang, Dr Yudan Jia, Dr Rod Stace, Dr Dariusz Wanatowski (UoN) – June 2013.

Weathering

Weathering experiments were conducted on shaft lining materials susceptible to degradation with time when exposed to harsh mine water environments. UoN performed a variety of lab experiments which focused on brick and concrete lined shaft materials. Material samples were immersed within baths of potable water (reference), a typical coal mine shaft water (based on data from the RFCS PRESIDENCE project), and a harsher acidic water (Table 8). The materials were tested at four stages which spanned a duration of 48 weeks (Table 9). Tests included mass loss, uniaxial compressive strength (UCS), triaxial, four-point bending (FPB) on brickwork beams, interface strength (bond), and scanning electron microscope (SEM) in order to understand the effect of time and weathering on the mechanical properties of the materials.

Table 8 : The concentration of the main chemical components for the solutions

	Mg mg/l	Na mg/l	Cl mg/l	SO4 mg/l	PH
Mine water (PRESIDENCE report)	31	15.7	13	360	6.0
Mine water (group 3)	40	14.5	12	353	5.2
Aggressive acidic solution (group 4) (phase 0 to phase 1)	400	724	600	3273	2.1
New aggressive acidic solution (group 4) (phase 1 to phase 3)	400	724	600	8182	1.3

Table 9 : Lab tests programme for determining the weathering effects on the test material.

	Phase0 before Weathering	Phase 1 16 weeks	Phase 2 32 weeks	Phase 3 48 weeks
Samples in air	FPB, SEM, UCS Triaxial, IT			
Samples in potable water		FPB, SEM, UCS, ML Triaxial, IT	SEM, ML	FPB, SEM, UCS, ML Triaxial, IT
Samples in mine water		SEM, UCS Triaxial, ML	SEM, UCS Triaxial, ML	SEM, UCS Triaxial, ML
Samples in aggressive acid water		FPB, SEM, UCS, ML Triaxial, IT	FPB, SEM, UCS, ML Triaxial, IT	FPB, SEM, UCS, ML Triaxial, IT

With :

UCS = Uniaxial compressive strength, ML = mass loss, FPB = four-point bending, SEM = scanning electron microscope, IT = interface strength (bond).

Results from the SEM tests proved ineffectual in showing effects of weathering on the constituent materials.

Mass loss tests indicated that brick materials suffer mass loss in both potable and acidic mine water. The degree of mass loss of cementitious materials (mortar and concrete) was notably higher in the aggressive acid water compared to the mine water and potable water tests.

UCS tests showed little effect of weathering on the strength and stiffness of bricks. Though there was considerable scatter in the data from the UCS tests on concrete and mortar, some trends in the data were noted. The UCS results on the mortar samples showed no statically significant effect on the strength of the samples due to the imposed weathering. There was, however, a notable decrease in the stiffness of the samples which was attributed to the opening of micro-cracks due to the weathering process. The mortar samples in the aggressive acid were not able to be tested by UCS at phase 3 due to near-complete deterioration of the samples, hence it can be said that the strength of the mortar wen to zero at this stage. For concrete, similar to the mortar results, acid attack had more effect on the surface than the interior of the concrete samples. This conclusion was based on the significant reduction of stiffness of the concrete with the weathering phases. The results suggest that concrete could resist the acid attack for a short time period however after long time immersion in aggressive acid environment, the behaviour of concrete could be considerably changed under uniaxial compressive load. Figure 9 shows a summary of strength and stiffness data obtained for the mortar and concrete samples.

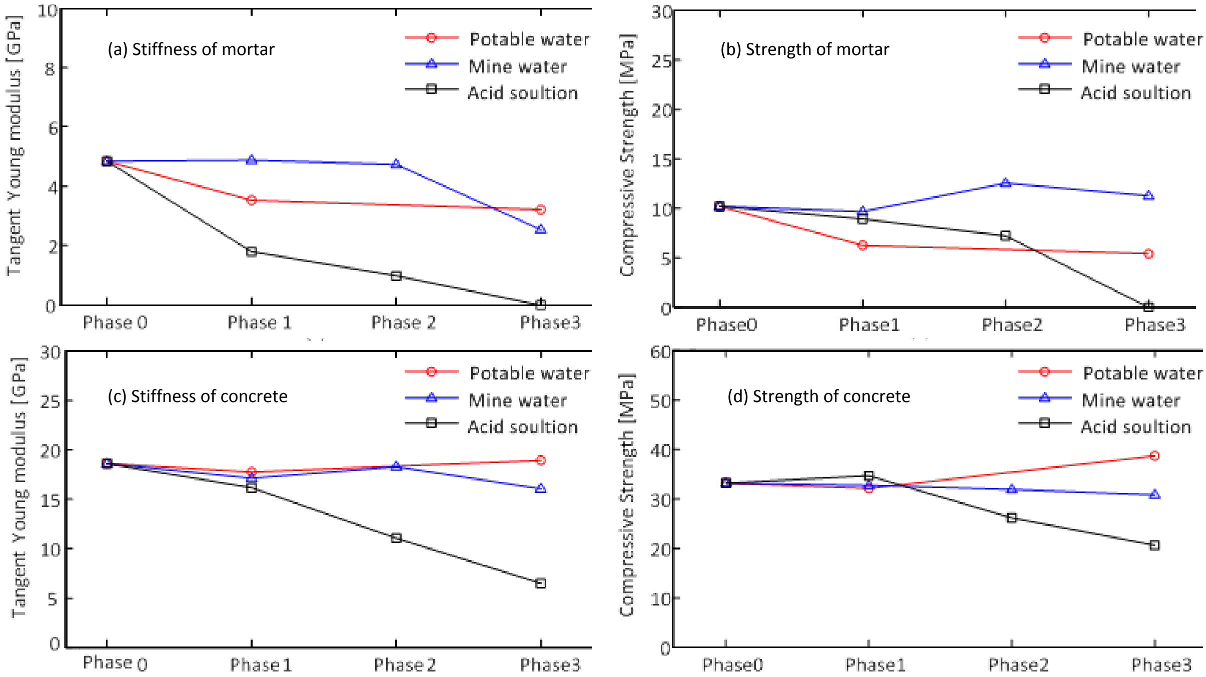


Figure 9 : UCS results for stiffness and strength change of concrete and mortar due to weathering

Triaxial tests were conducted on the brick, mortar and concrete samples. From the test data obtained, it was found that the effects of potable and mine water on the strength of all three materials was limited; small variation of strength are observed even after 48 weeks. For mortar and concrete in the aggressive acid solution, a considerable reduction of strength was observed after immersion of samples in the acid solution for 48 weeks (a large part of the mortar was dissolved in the acidic solution after 48 weeks therefore zero strength of mortar samples at all confining pressure was assumed). It was found that the strength of mortar and concrete samples were close at phases 0, 1 and 2. However a large decrease of was observed at phase 3. This observation differs from UCS data which showed a gradual reduction of strength for mortar. The reason for this difference could be that at the early stages of weathering, the main effect of acid attack on the mortar and concrete is to cause micro cracks on the samples. These micro cracks were closed by applying a confining pressure in the triaxial test and the weathering effect is hidden. However, at phase 3, the test samples were significantly weathered (dissolving materials and forming large cracks) and a sudden drop of strength was observed.

The four-point bending tests on brickwork beams produced no clear trend of varying flexural strength due to weathering. This observation could be due to two reasons. Firstly, the mortar may have been protected from weathering by the brick. The brick was shown to be little affected by the weathering process applied. The exposed surface area of the mortar in the brickwork beams was quite small therefore the bulk of the mortar may not have been exposed to high degrees of weathering. A longer duration of the weathering process for the brickwork beams was required. The second reason could be that due to the complexity of the configuration of the brickwork beams, the samples could have large variation themselves so the weathering effect may not be obvious.

The interface tests provided data related to the bond strength between mortar and bricks. The samples in potable water showed a reduction in bond strength of approximately 25% from Phase 0 to 3. For samples in the aggressive acid tank, a continuous decrease of bond strength was found. An almost linear reduction was observed with time, with nearly 50% strength reduction at Phase 3 compared to Phase 0. At phase 3 only half of the original bond strength was measured.

MRSL undertook a comparative study between modern reinforcement systems and conventional steel rebar reinforced concrete. This involved testing the structural strength of the two systems both before and subsequent to immersion in “aggressive water” (acidic mine drainage).

A methodology of producing test samples to cover a number of different reinforcement and concrete additive scenarios as shown in Table 10 was developed. All samples were tested in 3 mediums i.e. air, potable water and acid water to enable a comparison of results.

Table 10 : Fibre / Steel Reinforcement Concrete Testing Matrix

Reinforcement Additive	None	Steel Mesh (5mm)	Rebar	Steel Fibres	Synthetic Macro Fibre	Crimped Synthetic Macro Monofilament Fibres
Water Only	√	√	√	√	√	√
Superplasticiser	√			√	√	√
Integral Water Repellant	√	√	√	√		
Corrosion Inhibitor		√	√	√		
Superplasticiser (Ext Slump Life)				√	√	√

The additives chosen were as follows:

- Superplasticiser - used in a wide range of ready mix concrete applications where high strength, high workability and high durability are required.
- Integral Water Repellent - stable dispersion of stearate and other water repellent compounds provide hydrophobic, water-repelling properties forming an internal barrier against water transmission.
- Corrosion Inhibitor chemically inhibits the corrosive action of chlorides on reinforcing steel and prestressed strands in concrete containing a minimum of 30% calcium nitrite.
- Superplasticiser (Ext Slump Life) produces extended slump life over normal superplasticisers allowing long and difficult pours to be achieved.

The test samples (150x150mm cubes- 60 in total) were mixed by hand after accurately weighing out the proportions of aggregate, sand, concrete, water and additive to ensure a consistent product. A standard procedure was used to ensure compatibility of the periodic tests results and covered pH of immersion fluid, weighing and compressive strength testing. The simulated mine water was created by mixing 0.01 molar sulphuric acid to potable water in an acid-proof container to the required pH. A baseline test was also initiated using drinking water having a nominal pH of 7. One sample cube of each was retained without immersion for comparison purposes. Continuous testing of the immersion solutions was undertaken to establish alterations in the chemistry. The compressive strength testing was undertaken using a calibrated Schmidt hammer rather than "destruction" testing which would have required casting a greater number of test cubes. Documentation indicates a minimum number of 9 readings to establish a mean value for the compressive strength. In the testing a minimum of 12 readings (2 per face) was employed.

The test cubes which were not immersed were weighed at regular intervals. The final weight of these samples indicated a reduction of circa 0.2% average. In all probability the loss in weight could be attributable to insufficient initial curing before recording of data as the addition of additives would not appear to influence these readings. Test results for the first 6 month immersion period indicated that the immersed test cubes all gained some 3% of their initial weight due to ingress of water with the highest subject to the use of a superplasticiser additive. The increase in weight thereafter varied very little and at the cessation of immersion increase of some 3.3% on average was recorded. The results indicated that the two additives which allowed a greater ingress of both potable and acid water into the test cubes were superplasticiser and the integral water repellent. The best results were obtained by the corrosion inhibitor and superplasticiser with an extended slump life.

In summary the average loss in weight of the test cubes immersed in potable water was some 0.7% less than the pre immersion values whilst the average figure for those in acid water reduced by 1.5%. There was little difference between the results for different additives for the potable water with the cubes treated with superplasticiser ext slump showing the least loss in weight. This product also had the highest performance for the acid water test cubes followed by the normal superplasticiser. The cubes with no additives showed the greatest loss in the acid water.

The Schmidt hammer data gave an indication of the change in compressive strength relative to reinforcing material for the samples immersed in acid water. The samples without any reinforcement showed the greatest loss in compressive strength with over 18% loss as compared to 15% in potable water. The reaction of the monofilament fibres was similar to that of the steel fibres whist the macro fibres closely matched the results from the steel mesh. The performance of these latter samples "stabilised" after some 12months whilst the other samples only obtained this after a further period of 3 / 4 months. The results of compressive strength from the use of synthetic fibres were closely grouped with the exception of the cube with macro fibres reinforcement with a superplasticiser additive. The steel fibres performed better with no additive with the corrosion inhibitor showing less of a reduction in compressive strength than either the integral water repellent or superplasticisers. The use of additives for the concrete cubes with conventional reinforcement materials appeared to be beneficial in maintaining a lower loss in compressive strength as opposed to the samples with no additives. A comparison of the effectiveness of the use of fibre reinforcements as opposed to conventional illustrated that use of the former is not detrimental to the compressive strength of concrete when subject to immersion in acidic water.

The use of a number of different additives designed to reduce ingress of water within the test cubes failed to identify one prominent product although it should be noted that in both the potable and acidic waters the plasticiser with extended slump properties appeared to outperform the normal plasticiser but only by a margin of 0.5%. With respect to the compressive strength this product also indicated an improved performance over the superplasticiser when used with the manmade fibres.

Numerical modelling

The numerical modelling focused on static and time-dependant scenarios of mine shaft behaviour, considering the effect of progressive deterioration and potential final failure of a shaft lining. The modelling exercise was split between UoN and GEOCONTROL; UoN focused on brick-lined shafts whereas GEOCONTROL dealt with concrete lined shafts and specifically considered the influence of hydrogeological changes.

UoN developed an equivalent property mesh for replicating brickwork behaviour which was based on results from the weathering experiments. The laboratory FPB test data on brickwork beams conducted by UoN were used to validate small scale 3D numerical models using FLAC3D. A parametric study on the effects of the material stiffness and strength properties on the deflection of the beam was carried out. The modelling results showed that the stiffness and tensile strength influence the flexure strength of the brick beam significantly, and cohesion and friction angle have little effect. In order to obtain equivalent uniform material mechanical properties, the constitutive Strain-Softening (SS) model was chosen for the composite material brickwork in the 3D model. This constitutive model is based on the MC model but allows for a reduction of strength properties after the onset of plastic yield. As shown in Figure 10, a good fit between the equivalent material numerical model and experimental FPB test results was obtained.

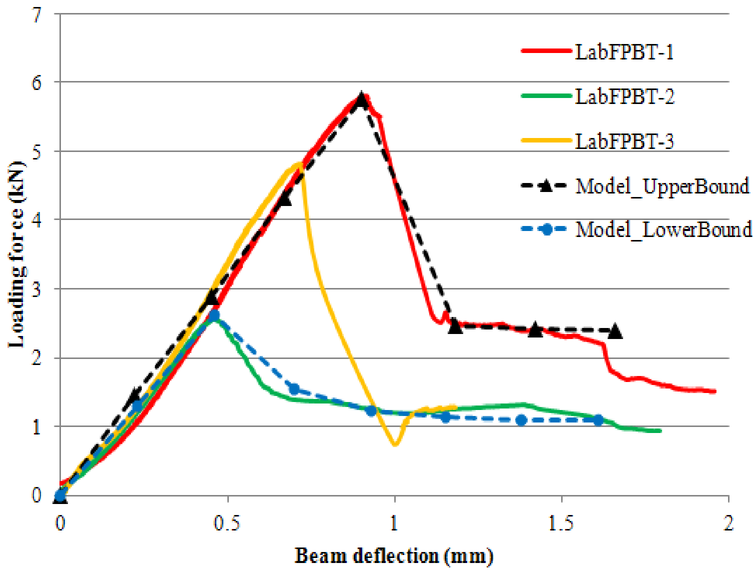


Figure 10 : Force-deflection curves for FPBT on brickwork beam from numerical models & laboratory tests

A case-study 3D numerical model was based partly (first 54 m) on the geology at the Bolestaw mine shaft (bobrek-centrum colliery, Poland) was developed. The modelling mainly focused on a stability analysis of a brickwork liner at shallow depth (< 60 m). A series of numerical simulations was undertaken to evaluate the effect of (1) reduction of lining material properties due to weathering, (2) unequal horizontal stress conditions, (3) shaft treatments and the effect of the reduction of strength and stiffness of the treatment materials, and (4) point loading on the lining.

Results from the analysis illustrated the relationship between the strength and stiffness of the shaft lining and the magnitude and modes of deformations that took place. Figure 11 indicates results from a baseline model and results obtained when the lining strength and stiffness were significantly reduced (case 2-1), where a significant increase in shaft lining displacements was observed. When filling material is included, however, even if the lining strength and stiffness are reduced significantly, the lining displacements are not substantially increased (model 4-0). Uneven horizontal stress conditions were found to have considerable detrimental effects on the shaft lining displacements. The effect of point loading on the shaft liner was performed by applying a distributed load approximately 1.5 times greater than the vertical stress over a small section of the lining at a depth of 46 m (where strata of clay and sand/gravel meet and larger displacements occur). The maximum displacement in the model were approximately 3 times that in the baseline model, the shaft liner closure is uneven and the displacements surrounding the shaft were asymmetric. Uneven loading and deformation pose a serious threat to the stability of a circular shaft structure.

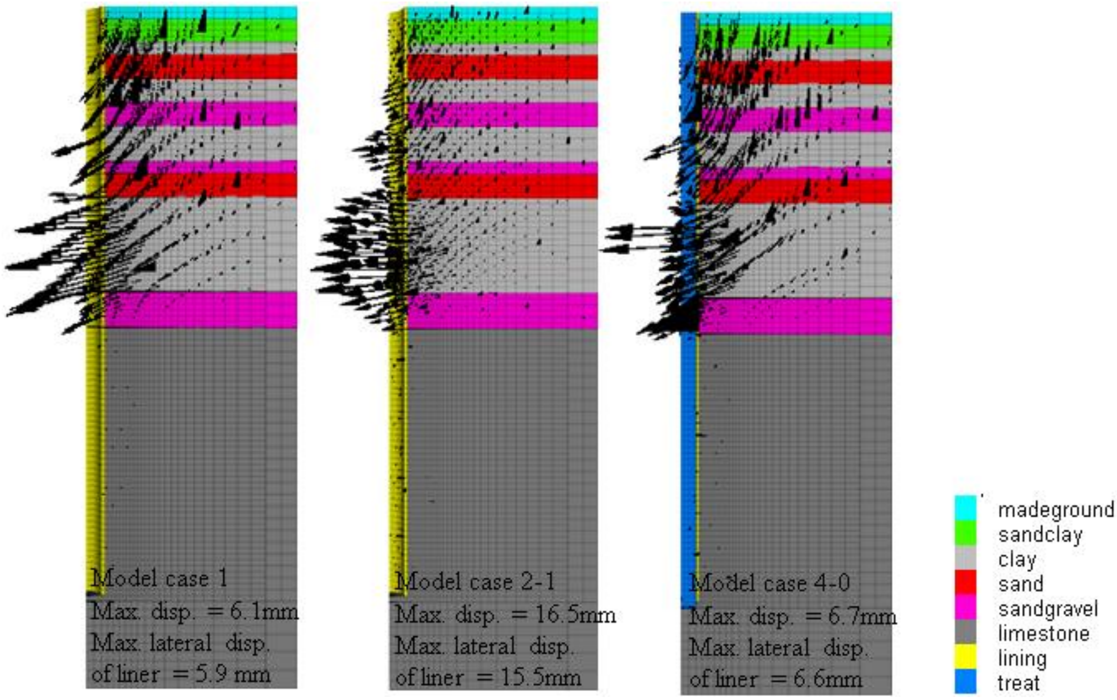


Figure 11 : Displacement vectors of Model case 1, 2-1 and 4-0

GEOCONTROL performed 3D numerical analyses of how the properties of a lining of a shaft are affected with time (concrete weathering). Another aspect that was considered is the deformation induced on the surface due to hydrogeological changes (flooding and drainage).

For the studies of the influence of hydrogeological changes on surface and concrete weathering, a case study analysis using FLAC3D was undertaken. A variety of models were tested to reproduce the progressive weathering effect on a shaft's structure. The models that were carried out included 3D shaft models with progressive reduction of lining material properties, due to different weathering agents such as chemical and physical attack, and 3D shafts models where hydrogeological changes were produced, including (i) the shaft construction process and groundwater level fluctuation during construction, (ii) flooding of the shaft, and (iii) dewatering.

The first case study corresponded to Herrera 2, 80cm thick concrete shaft. This is the main access of a Spanish colliery of the Company Hulleras de Sabero SA, abandoned in 1991. The calculations confirmed (1) that the shaft had no stability problems even when it was flooded, (2) that the water table could only break the shaft lining if it remained empty and if the water load was very high (unlikely situation), and (3) variations on the water table (due to seasonal changes) did not produce surface settlements. With these results, it was seen that this shaft did not lose its stability with the pass of time (in a normal scale), so it was decide to select a new shaft to study.

As the previous case did not have any instability, the Boleslaw Shaft from Bobrek-Centrum colliery (Poland), which on the 6th of September 1975, suffered a catastrophic failure, was modelled. An increased outflow of quicksand at a depth of 24 meters occurred, creating a crater on the western side of the shaft, causing a collapse of the shaft bank building. This shaft was constructed within a superficial soil layer of 63m and was closed a long time ago. The dimensions of the model were slightly different from reality because it was decided to study a more generic shaft dimension. Accordingly, the model had a slightly lower diameter of 5m and a continuous concrete lining of 0.7 m. Two FLAC-3D models were developed; the first to model the area near the surface and the second to model a deep location of the shaft (Figure 12, Tables 12 and 13).

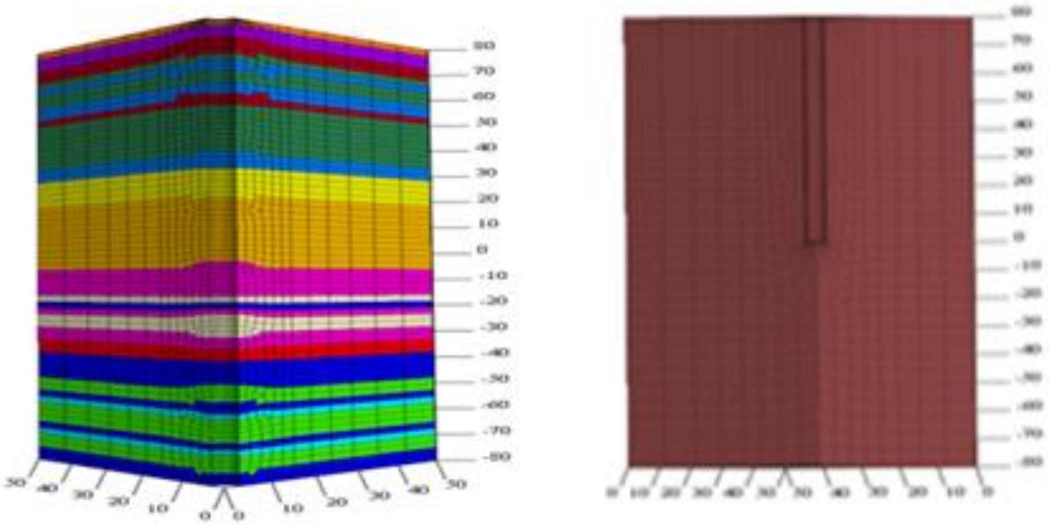


Figure 12 : Cross section of both models with geological properties (Model 1: Multicolor; Model 2: Brown)

2: Brown)

Table 11 : Geological properties for Model 1

Materials	Density	Young's modulus	Poisson's ratio	Cohesion	Friction angle	Dilation angle	Tensile strength
	Kg/m^3	MPa		kPa	°	°	kPa
Made Ground (Dust)	1200	1.0	0.45	3.1	10	0	0
Sand	1700	40.0	0.3	2.0	32	10	0
Clay	1450	8.0	0.33	31.0	21	0	0
Sand & Clay	1600	24.0	0.31	16.0	26	5	0
Sand & Gravel	1700	50.0	0.25	0	35	8	0
Mudstone	2.400	3.700	0,26	4.580	25	0	458
Clay shale	2.400	3.700	0,26	4.940	28	0	494
Limestone	2.650	9.000	0,22	700	48	0	70
Sand Gravel and Clay	1700	50.0	0.25	0	35	8	0
Dolomite	2.700	13.000	0,22	1.100	51	0	110
Arenaceous shale	2.650	1.200	0,25	600	36	0	60
Claystone	2.400	9.000	0,21	5.910	35	0	591
Coal	1.800	1.600	0,3	4.400	18	0	440

Table 12 : Geological properties for Model 2

Materials	Density	Young's modulus	Poisson's ratio	Cohesion	Friction angle	Dilation angle	Tensile strength
	Kg/m^3	MPa		kPa	°	°	kPa
Sandy shale	2.400	4.500	0,26	4.310	32	0	431

After analyzing the results, it was concluded the following (1) the shaft rupture was not produced by the lining overstress of the ground loads since this would have caused a failure at at a greater depth than observed, (2) the safety factor (SF) evaluation concluded that the lining had a very good SF, confirming the hypothesis that the cause of failure couldn't be just by the ground load, and (3) the loss of support by deterioration of the concrete from weathering over time and the presence of humidity, didn't justify the shaft failure, except when the reduction was very complete (around 90% lost). The calculations showed that the shaft from Boleslaw did not collapse due to the lining overstresses of the ground loads, and the collapse was probably not due to the deterioration of the concrete. Therefore, a possible rupture mechanism involving a perched water table, the cracking of a discrete location of the lining which induced a drainage point. The proposed uneven hydrostatic loading was shown to cause considerable tensile bending strains within the lining that may have been the cause of the lining failure.

Physical Modelling

Physical modelling in the UoN Nottingham Centre for Geomechanics (NCG) geotechnical centrifuge allows for the study of failure mechanisms of shaft linings near the ground surface. Experiments were conducted to study the behaviour of superficial soils and shaft linings during a collapse event and to determine the effect of discrete weakened zones within the shaft lining on the resulting subsidence.

The tests were performed in a dry silica sand using an axisymmetric container with a diameter of 490mm and depth of 500mm (Figure 13). The container enabled pictures to be taken during the tests so that digital image analysis could be used to measure soil displacements. Two model shafts were built; (1) the baseline test to simulate the loss of lining support along the full shaft length (Figure 13a), and (2) the weak zone test to simulate the loss of lining support at a discrete location near the soil-rock interface (Figure 13b). The model shafts were 90mm in diameter in model scale, corresponding to a prototype shaft of 7.2m diameter. The gradual loss of shaft lining support was modelled in the experiments by reducing the internal air pressure within the sealed membranes of the model shafts.

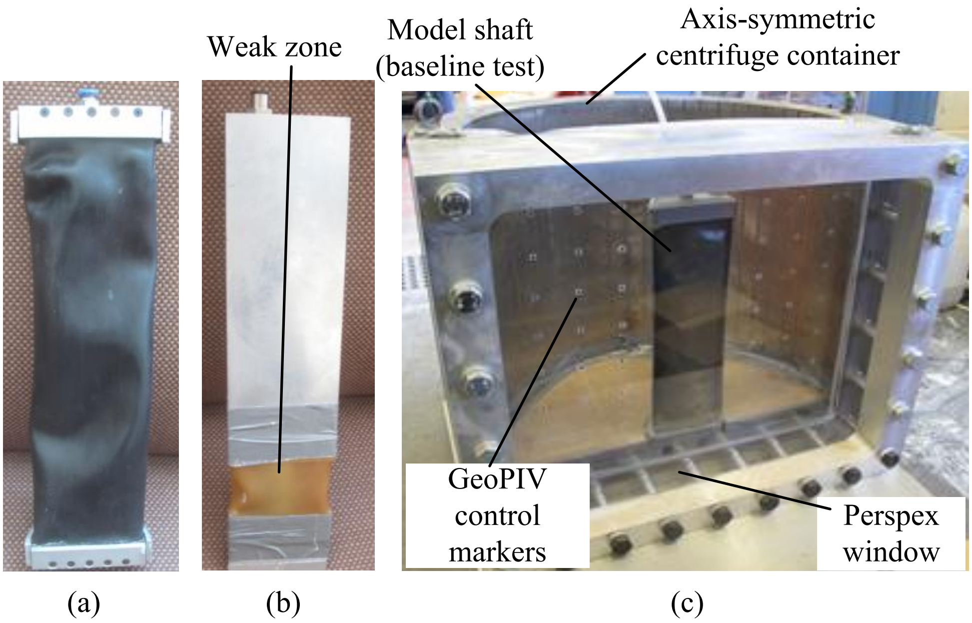
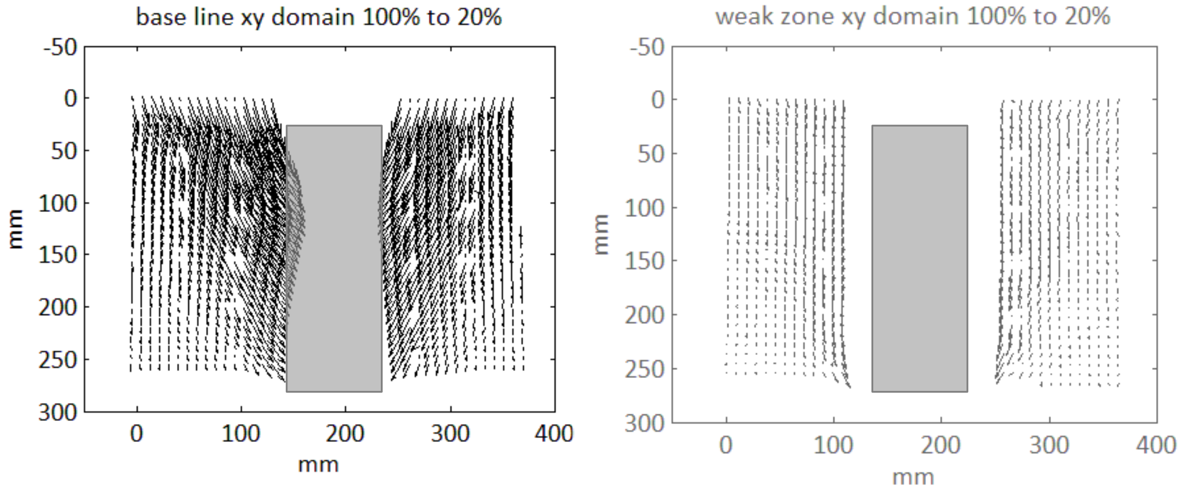


Figure 13 : (a) baseline test shaft, (b) weak zone shaft, (c) view of axis-symmetric container with baseline test shaft

For both tests, the vertical displacement of the soil is larger than the horizontal displacement. For the baseline test, after reaching a normalized shaft pressure of 50%, a pattern of soil displacement initiated in the ground and the magnitude of displacements increased significantly with further reduction of shaft pressure. For the weak zone test, a clear pattern of displacements was observed only when the shaft pressure was reduced to 20% of the original air pressure. Different failure mechanisms were observed from the two tests (Figure 14). For the baseline test, the main displacements were in an area just above the mid-level of the shaft, a large subsidence bowl formed, and horizontal displacements were significant. For the weak zone test, most displacements occurred very locally around the weak zone, a small subsidence bowl formed, and horizontal displacements were insignificant. The soil displacements at the ground surface for both tests showed that the vertical surface displacement of soil is clearly larger than the horizontal displacement. This suggests that the vertical surface displacement is more sensitive to the movements of the shaft lining compared to the surface horizontal displacement.



(a) baseline test (b) weak zone test

Figure 14 : Displacement of soil around shaft when shaft internal air pressure reduced to 20% of its original value for (a) baseline test, and (b) weak zone test.

Task 3.3 – Shaft stability (GEOCONTROL, GIG)

Parametric analysis (FLAC modeling)

Three comparisons have been done by FLAC modeling to analyze the shaft stability, focusing on:

- Anisotropic natural stresses.
- Rock wedges failures.
- Shaft bottom collapse.

For the **anisotropic natural stresses analysis** four different cases were studied, both in 2D and 3D modeling:

Case	**K_{0x}**	**K_{0y}**
1	1,5	1,5
2	1,5	3
3	0,5	0,5
4	0,5	1

K_{0x} : ratio horizontal in x axis direction/vertical stresses
K_{0y} : ratio horizontal in y axis direction/vertical stresses

Figure 15 is an example of the analysis of yelding in the case 4 using 2D and 3D modelling.

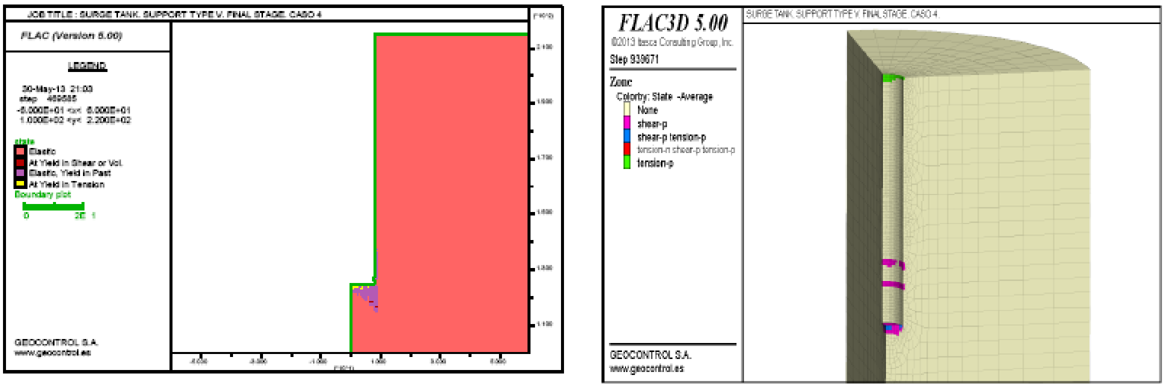


Figure 15 : Expected yielding of case 4 in 2D and 3D.

With the results it can be finally concluded:

- The varieties of result imply that in models where the stress field is not symmetric, it must be made for their study a 3D model.
- An increase of k0 implies an increase of displacements that are also increased if the k0 are non-symmetric.
- An increase of k0 also implies an increase of Z displacements in the bottom of the shaft

About the **rock wedges failures analysis**, different modeling have been developed using classical cinematic stability in comparison with 3DEC.with these conclusions.

There are several calculation systems for the sizing of the necessary support for the stabilization of the blocks that can be generated during the excavation.

The capacity for analyzing the wedges using classic cinematic stability analysis in comparison with numerical methods (3DEC) is completely different. The cinematic analyses are much faster and easier to use than the numerical methods, and allow an analysis that is the proper one to determine which blocks can present instability risk.

On the other hand, the program 3DEC provides sufficient capacity to fully analyze the behavior of fractured rock masses with the possibility of generating blocks capable of falling or sliding. Numerical methods offer the most generalized media for stress calculation around excavations.

It has been demonstrated that the stability of the wedges in relatively large depths may be affected by the anchoring effect of the tensional field that surrounds them. The normal stresses to the planes of the joints that form the wedge can mobilize sufficient shear strength to keep the wedge in its place.

The results can allow the reduction in a totally justified way the support to install in an excavation.

Finally to analyze **the shaft bottom collapse** a 3D model with FLAC3D about a real and representative shaft case in the Barcelona’s subway has been carried out. Figure 16 shows the calculation model developed.

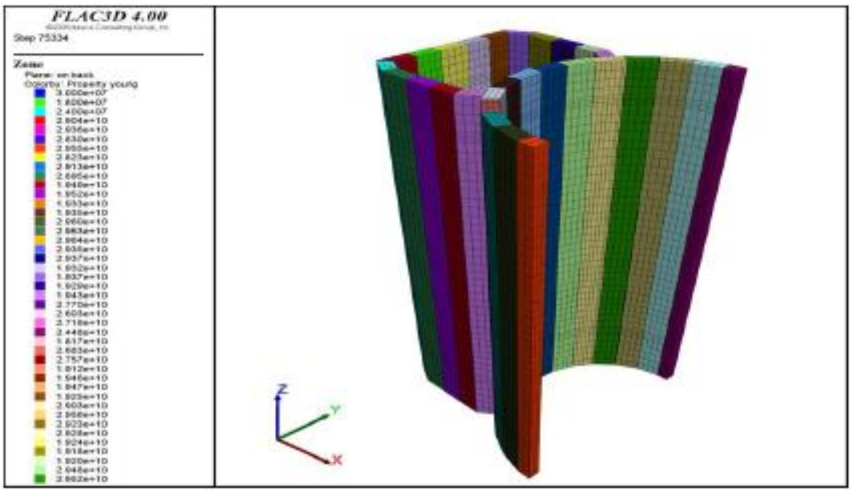


Figure 16 : Calculation model of the shaft in Flac 3D.

The main conclusions are:

- Results show a lifting in the terrain at the bottom of the shaft of 30 centimetres, but it is also demonstrated the absence of seepage at the backfill of the shaft.
- The modelling of this problem with FLAC3D has been proved to be a very useful tool.
- In coal mining is very strange that this could cause a serious problem while in the civil sector, especially in subway constructions in urban areas, is a serious problem.
- It is recommended to make a deep study using FLAC3D for modelling the behaviour of the shaft bottom to solve this type of problems.

Impact of filling material on dams and plugs (PFC modelling)

The results obtained and observations made during the laboratory and underground tests of filling materials constituted the basis for calibrating numerical models developed in program PFC3D. In order to carry out the analysis of the stress occurring in the dams and plugs during shafts closure, a special program in FISH language has been developed. The shaft and inset geometry could be prepared in almost any CAD programs and then - with help of a special subroutine - imported directly to the PFC3D. An example of imported geometry is shown in Figure 17.

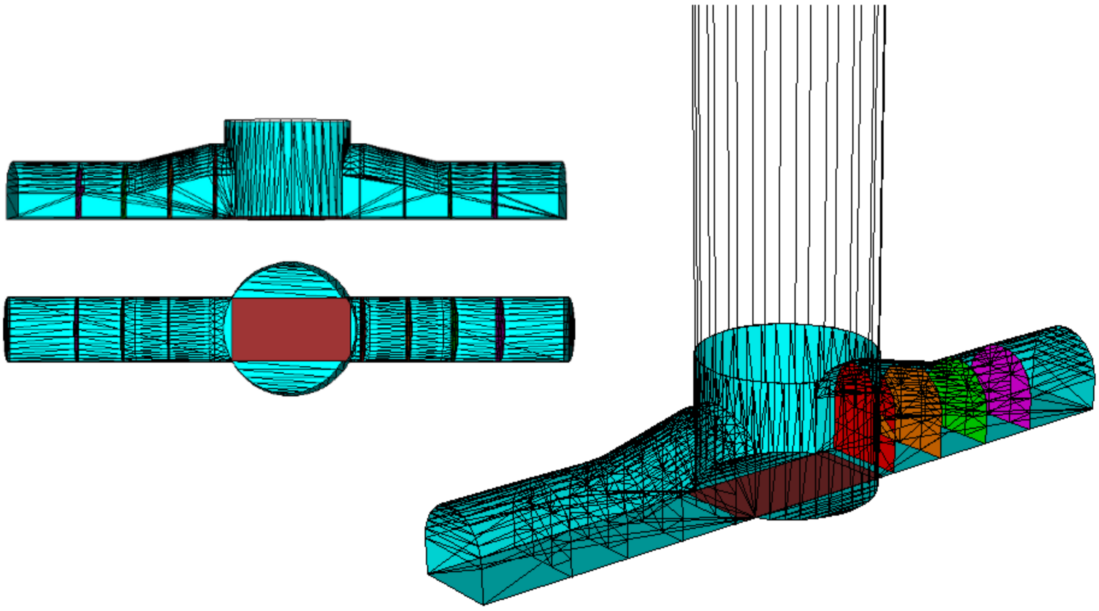


Figure 17 : View of the imported insets geometry with the variable location of the dams at level 190 m

An important feature of the developed program is the ability to simulate filling material taking into account its granulometric curve. Another developed subroutine, based on the data entered by the user (the percentage of grains in each class of size), periodically generates portions of the material with the appropriate grain composition. An example of the generated portion of the filling material with properties of granite tested in the framework of "MISSTER" Project in WP3.1, is shown in Figure 18.

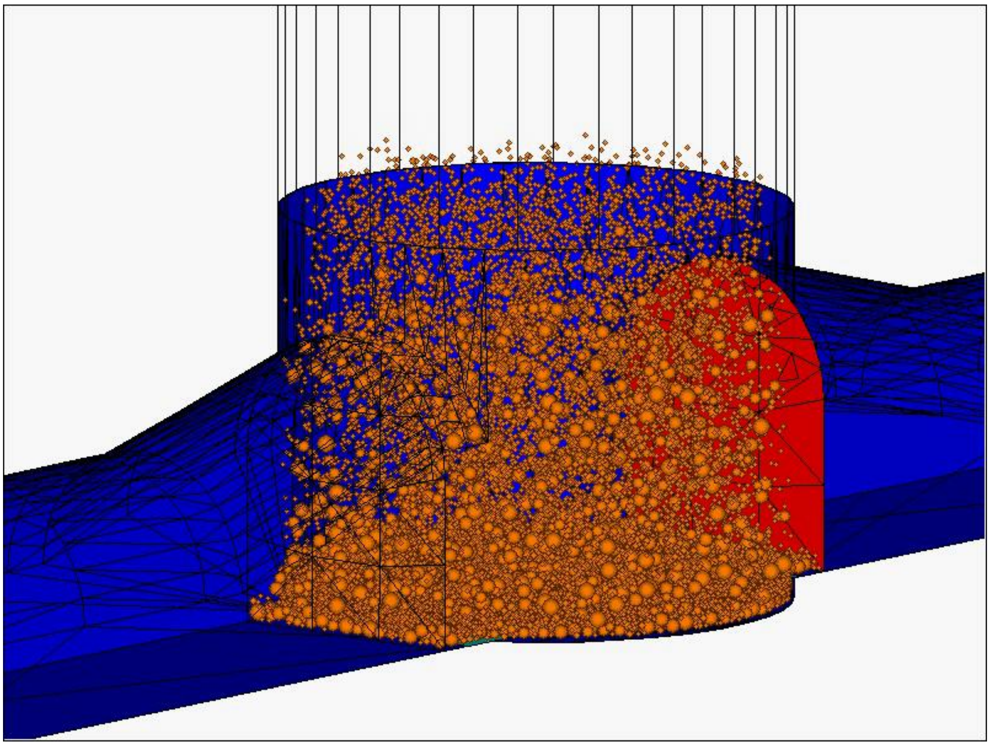


Figure 18 : Example of generated material with a defined grain size distribution and other physical properties (density, friction coefficient)

That subroutine is periodically repeated until the desired filling column is generated. Additional subroutines have been also developed to monitor the height of the filling column and its impact (forces) acting on the dams and the locking plug (Figure 19 and).

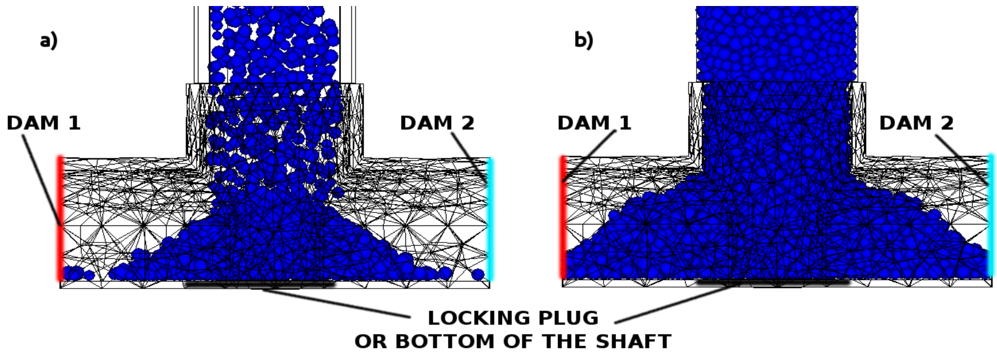


Figure 19 : Sequential stages of simulation of shaft filling – mouth view in shaft insets area. a) Initial stage of filling, b) End stage of filling.

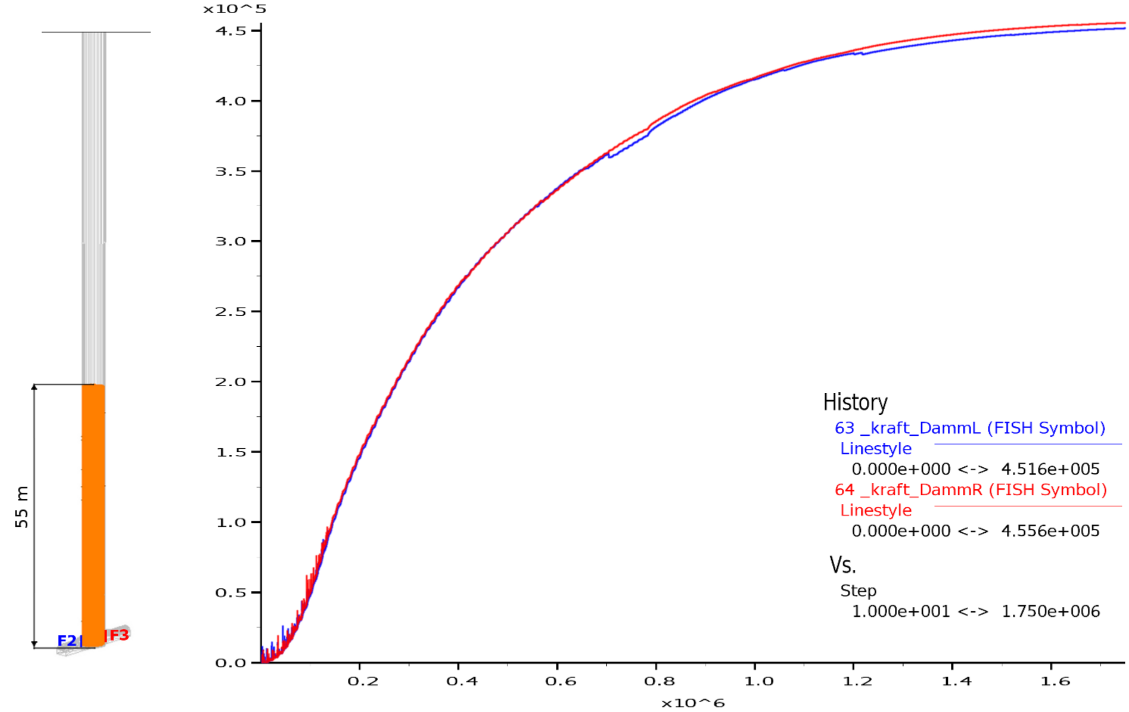
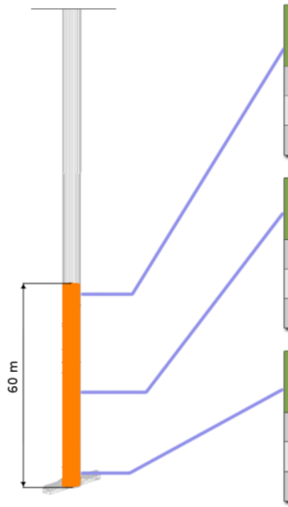


Figure 20 : Example of changes in the forces acting on the dams depending on the height of filling colum

The developed program allows also monitoring of compaction in the filling column and changes of the stress-strain state at any point (
Figure 21).



Depth: -135 m (5 m)	Stress x	Stress y	Stress z
x	**-4.512e3**	5.180e-1	4.199e1
y	4.847e-1	**-4.474e3**	1.714e1
z	4.143e1	1.711e1	**-8.607e3**

Depth: -160 m (30 m)	Stress x	Stress y	Stress z
x	**-5.474e4**	6.677e1	-5.177e1
y	6.677e1	**-5.503e4**	-1.003e2
z	-5.177e1	-1.003e2	**-1.274e5**

Depth: -185 m (55 m)	Stress x	Stress y	Stress z
x	**-7.314e4**	1.354e2	2.382e2
y	1.354e2	**-7.280e4**	2.599e1
z	2.382e2	2.598e1	**-1.467e5**

Figure 21 : An example of the state of stress in the three selected points in the filling column (MPa)

Another subroutine was developed to allow export of the final results to an external file and hence to perform detailed analysis of displacements and stresses for a given dams geometry using FLAC3D. An example of such calculations for a typical dam with a thickness of 0.35 m is presented in Figure 22.

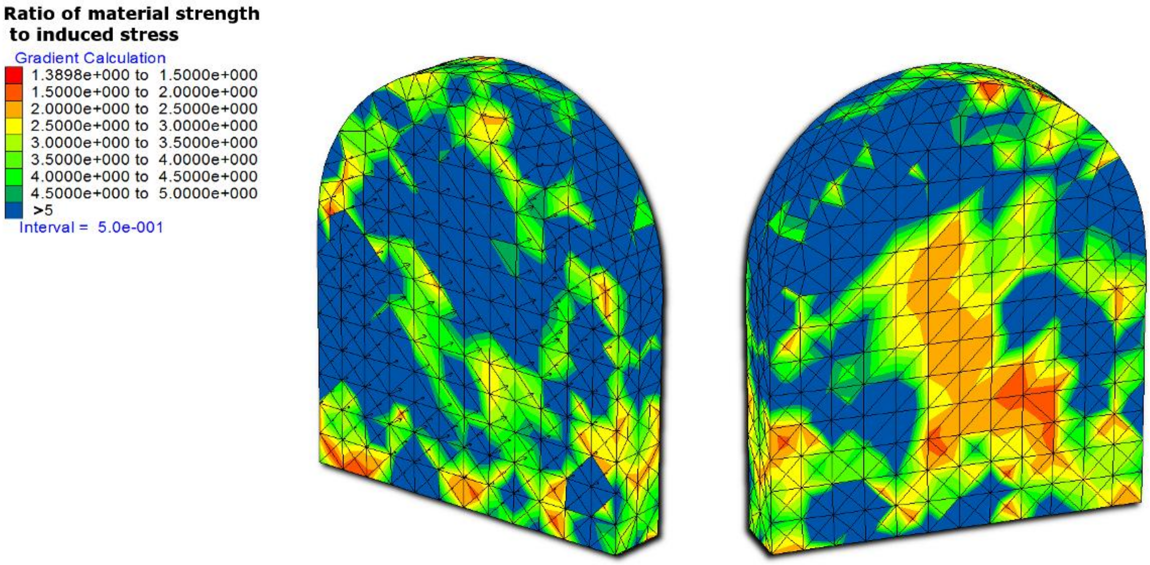


Figure 22 : Example of strength analysis using FLAC3D based on results from PFC3D

WP4: SYNTHESIS

WPL: INERIS. Partners: GEOCONTROL, MRSL

Task 4.1 – Handbook (INERIS, GEOCONTROL)

Through MISSTER project, a systematic analysis of risks raised by the presence of mining shafts was developed. It consisted of:

- Mining shafts risks identification, typology definition and hierarchy (WP1) ;
- State of the art, enhancement and adaptation of techniques for shaft location (Task 2.1) ;
- Development or enhancements of probes and measurement systems for shaft column characterization (Tasks 2.2 & 2.3);
- Enhancement of filling materials and techniques (Task 3.1) constituting one of the most commonly used techniques for shaft closure ;
- Better knowledge and laboratory data relative to lining or treatment material weathering with time combined with numerical and physical modelling (task 3.2).

The topics covered through MISSTER made it possible to establish a handbook intended for local or regional stakeholders in the post-mining field as well as mine operators. This handbook constitutes Deliverable D4 : "Handbook to best practices for mine shaft protection" - Amelie LECOMTE (INERIS), Agustin MUÑOS NIHARRA (GEOCONTROL) – June 2013.

This handbook covers steps for identifying and choosing best available techniques for shafts protection.

It consists of:

1) A concise reminder of risks raised by the presence of shafts, referring to Deliverable 1 for examples of shafts incidents and accidents;
2) Prerequesites necessary for appropriate treatment of shaft :
    - A reminder of treatment objectives;
    - Parameters to be collected:
        - Position of mine shafts, with reference to Deliverable 2.1 for helping in best location techniques choice if required;

- Ease of access to the site;
- Nature and extent of local issues, future use of the land;
- Geometric characteristics of the shaft to be treated, referring to Deliverables 2.2 and 2.3 for information on data acquisition thanks to existing probes;
- Condition of mine works;
- Connections with other mine –works, presence of voids or infrastructure;
- Geology;
- Hydrogeology;
- Materials degradation referring to Deliverable 3.2 for weathering effect estimation for example;
- Potential presence of gas;
- Need or wish to preserve access to underground mine works;
- Preservation of fauna, flora and the environment
- Costs.

Last step is the identification of best practices for securing a shaft which is of interest for both active operators (anticipation of future closure) and post mining situations.

It is based on information sheets (one by technique) which are intended to set out the techniques that can be used in situations where there is a varying degree of risk of physical injury or of "ground movements", and with a view to raising awareness to the post-treatment residual risks.

These information sheets briefly describe:

- the contexts and risk situations in which a technique can be used;
- the most important design-sizing criteria for the required site conditions;
- the prerequisites as well as the complexities which may significantly increase the costs of the works.

The purpose of these information sheets is to provide a better understanding of use of the techniques and to assist in choosing the most well adapted. The decision-making power is that of the owner, who may be called on to consider criteria other than the purely technical ones referred to here.

An explanation for the various items in the sheets is given below.

Treatment technique: generic name for a method or technique which could incorporate several variants.

Equivalence table: at the top of the sheet, a table allows rapidly reviewing the appropriateness of the technique for the risk situation encountered, the ease/simplicity of its implementation and the cost. These scores assume the process has been performed according to professional standards and the principles set out in the sheet. The scoring system is as follows:

★★★ : very suitable technique

★★ :	Technique appropriate but other techniques may be more appropriate or modifications/adaptations may be necessary
★ :	Technique poorly adapted or to be reviewed
Θ :	Technique unsuitable for this criterion
⌿ :	Technique to be prohibited for this situation

Thus, for example, a score ★★★ for an economic criterion denotes that a technique is economically advantageous.

Risk situation: a table rapidly displaying the appropriateness of the technique for one or more risk situations encountered, a focus on physical injury and risks linked to ground movements (the term "ground movements risk" is used for ease of reading). This section presents the issues present close to the works, and the situation/degree of risk which in consequence justifies or favours use of the technique.

Required site conditions: describes the main conditions at the site, notably, access to the shaft allowing use of the technique.

Treatment principle: a brief description of the principle of the technique. The design-sizing criteria are described on the back of the sheet.

Maintenance/Monitoring: briefly describes maintenance, surveillance and repairs necessary for durability of the protection.

Post-treatment residual risks: indicates the risks which subsist or may subsist after treatment, or which are not treated by the considered technique. This heading frequently includes the risk of emissions of mine gas, for which some techniques are inoperative, or others requiring adaptations, structures or supplementary works.

Protected species: indicates whether the technique is appropriate given the presence and wish to preserve protected species, notably bats and crawling animals.

Pre-requisites: indicates the main pre-requisites necessary for the choice and design-sizing of the technique, these aspects having been detailed in Chapter 4.

Design-sizing: a heading which tackles the important points and criteria relative to the choice of a precise technique, the constituent material and the design-sizing of the structure.

Most frequent complexity criteria: lists the main constraints which may require prior or supplementary works with a modification of the overall cost of the technique.

As an example, information sheet relative to backfill and referring to Deliverable 3.1 is presented in Figure 23 and Figure 24.

Treatment technique

Backfill

Risk of physical injury	Risk of "ground movements"	Risk of "gas emissions"	Economy	Ease/Simplicity
★★★[2]	★★★	★	★/★★	★★

Risk Situation (Risk diagnostic)	
Physical injury risk: The shaft presents an established risk of physical injury and the risk of falls must be eliminated "Ground movement" risk: 1/Absence of local challenges 2/Reduced local challenges (path little used, agricultural activity constrained by the presence of the mine-works)	 Source : CdF

Site conditions required:	Empty shaft, accessible or close to useable tracks, manageable adjacent area, availability of back-fill material
Principle of treatment:	Backfill consists in strengthening the entire shaft lining by absorbing some of the horizontal thrust of the surrounding land. It allows sealing off the mine head, and if appropriately performed, significantly reduces the risk of collapse. Monitoring process and stations strengthening should be controlled during this treatment
Maintenance/Monitoring	Monitoring level of back-fill for several years, or during the water submersion period
Residual risks after treatment:	"Ground movements" risk: compaction "Mine gas" emissions risk
Protected species:	Technique not appropriate to preserve protected species roosting in the shaft (certain bats)

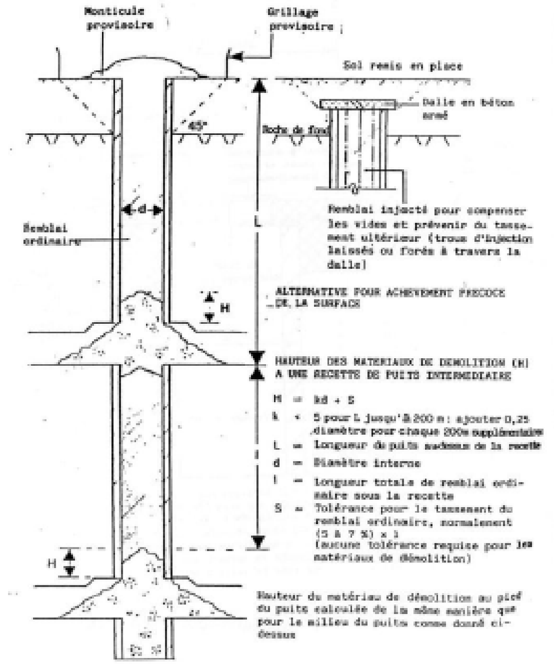
Pre-requisites

- Preliminary visual inspection
- History of back-fill/problems with works (if the shaft was previously back-filled)
- Underground connections to the shaft, assessment of potential gas emissions
- Gas measurements, Piezometric measurements

Figure 23 : Example of information sheet for Backfill (first page)

Technical aspects

Design-sizing



Principle of controlled back-filling of a mine shaft (National Coal Board, 1982).

Controlled back-fill of the shaft is recommended.

Materials to be preferred:

- grainy mineral material of grain size between 20 and 120 mm and grain median D_M = 100 mm, free of undersize particles,
- compression strength of at least 30 MPa,
- insoluble and non-flammable,
- without toxic compounds,
- no risk of leaching harmful and hazardous elements,
- meeting requirements of acceptable level of radioactivity.

The above requirements ensure creating a safe, water permeable backfill column. They can be met by using such rocks as: granite, gneiss, basalt or dolomite. There is also a possibility to use a grainy material of different qualities (i.e. of low strength parameters and different grain size distribution), such as waste materials from coal or steel processing. Using them is economical, yet it requires additional tests (Deliverable 3.1 of MISSTER project).

Techniques and controls

Shafts closure is most often conducted by filling it with a grainy material fed into the shaft with a conveyor or directly from a lorry.
It is essential to back-fill the first metres from the base of the shaft using coarse materials to guarantee a stable base for the superimposed back-fill, and avoid fine material flowing into the former works. All levels of the shaft with connections should be back-filled using coarse materials. These sections should start below the floor of the service area and block off the opening to the latter and continue up to an adequate height above the top of the service area. The same material is appropriate for filling water submerged shafts. The use of concrete may be appropriate in certain cases (reduction of voids, increased strength, capping block at the top to avoid any surface compaction).
During the back-filling operations, the alignment of back-filling conditions, the quantities of material deposited and the pre-defined quantities must be regularly verified by measuring the height of the back-fill. For water-submerged shafts, the water displaced by the back-fill may rise up and special precautions should be adopted for its removal (pumping) as the back-fill rises up the shaft.

Most frequently-encountered complexity criteria (excluding accessibility to the mine-works)

- Stability of the mine-head in the presence of heavy plant: safety distance, system for spreading loads
- Disassembly of equipment blocking the shaft (avoid residual voids in the works)
- Use of anti-explosion systems if there is gas
- Effect of falling materials if water is present;
- Adaptation of materials if shaft is deep and there are many service areas (see above)

Figure 24 : Example of information sheet for Backfill (second page)

Task 4.2 – Spreadsheet (MRSL)

Utilising the results from Work Packages 1 and 3, this task investigated the potential to develop a computer application that could provide a risk profile for a given set of circumstances relating to the condition of a mineshaft lining. It was originally supposed that this tool might be a spreadsheet. However it was soon determined that a spreadsheet per se might not be the best tool for the task and it may be better to rely on an algorithmic programming language in a web-based environment.

There are several factors that can affect the movement or collapse of a mineshaft, including a change in the equilibrium of the fill or of the surrounding ground, and the overloading or shock to the fill or the surrounding ground. For example, the fill equilibrium might be affected by changes to the groundwater level, or to the saturation or consolidation of the fill; whilst overloading and shock can be caused by building and other structures, vibration from traffic and machinery, mining subsidence and blasting activities. Another key factor is the behaviour of the material surrounding the shaft, which can be affected by rainfall, temperature (frost heave) and ageing.

Development of an Analytical tool

It was envisaged that an analytical tool could be developed that would have the potential to indicate, amongst other things, a safety factor associated with the tangential stress in the shaft lining, as a function of the above factors. Information on the properties of brick and concrete shaft linings, and their change in compressive strength with water ingress would be provided by the results of the earlier work packages.

The stated purpose of this task was to investigate the potential to develop such a tool. It was determined, by writing demonstration computer programs, that an ideal method of doing this would be to utilise a web-based tool that could be displayed on the screen of a PC or a mobile phone; and for the database of shaft material parameters to be specified in the form of simple text files.

Deriving the Stress in the Wall of a Mine Shaft

A concrete cylinder subjected to a uniform radial pressure around its outer circumference will develop an internal compressive stress tangential to the circumference. If the pressure is applied suddenly, the concrete will react elastically and the stress near the interior wall of the lining will be greatest and gradually reduce towards the outer wall. This situation is described by the Lamé or ‘thick wall’ formula. Conversely, if the pressure is high, and applied slowly, the concrete may react plastically and the stresses will tend to redistribute themselves evenly across the thickness of the concrete wall. A number of formulas have been developed to account for this plastic or visco-elastic property of concrete; one such is the Huber formula, which is similar to Lamé’s but with a different factor applied to the pressure term in the equation. Deriving the Stress in the Wall of a Mine Shaft, where a formula for a ‘safety factor’ F is derived, namely...

$$F = \frac{\sigma_l}{2P}\left(1 - \frac{1}{\left(1 + \frac{2t}{d_i}\right)^2}\right)$$

1 psi : 6.9 kPa

1MPa : 145 psi

As an example, suppose that, as above, the concrete has σ_ℓ = 3,500 psi and the external pressure is P = 200 psi. The lining thickness is 450 mm and its diameter is 6 m. The quantity t / d_i is 0.075 (or 1/13.3) and so the formula gives F = 2.13. At its most basic, the tool therefore asks the user for the following data...

- Lining thickness, t
- Shaft diameter, di
- Estimated compressive strength of the lining, σ_l (as modified age and condition of the shaft – WP3 data)
- External pressure, P.

Development of a Demonstration Program

It would not be appropriate to go into exhaustive detail of the computer software here. A demonstration was arranged as an HTML page on a web server. The size of the page was adjusted so that it could be viewed on a standard mobile phone with a screen width of 240 pixels. Provided a 3G mobile phone has a suitable 'data package' it is possible to access the Internet without difficulty even if it is not a smart phone. Additionally, it was demonstrated that the files could be downloaded to a PC via FTP and loaded onto a phone via its USB cable using a data transfer application, thus avoiding the need for a live Internet connection.

The features of the web page included a number of 'housekeeping' functions designed to make this Application tool more 'user-friendly' and to 'fail' in a safe manner. These included auto-versioning, file existence checks, and testing for JavaScript and web cookies. These checks are not always performed in web-based applications but were considered to be more important in this application because of the sometimes limited functionality of phone-based browsers and because of the requirement to successfully transfer an entire suite of files to the phone, in order to operate 'off-line'. The GUI presented to the user comprises an HTML form element and resulted in a typical display as Figure 25 below.

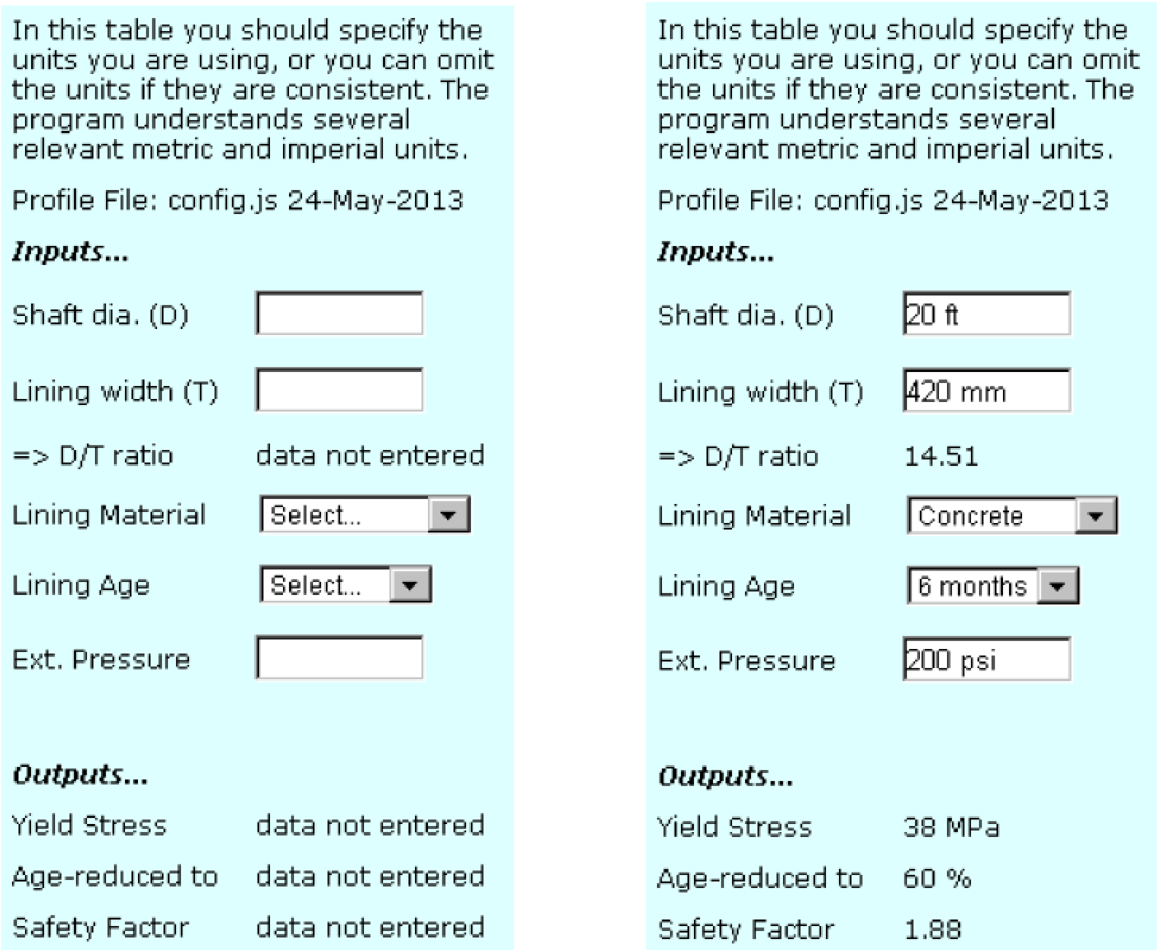


Figure 25 : Demonstration of Shaft Risk Profile Tool: Screen Captures.
Left: initial form. Right: after data has been entered.

CONCLUSIONS

WP1: Collection and analysis of case studies

WPL: INERIS. Partners: UoN, GIG, KWSA, GEOCONTROL, MRSL

A typology of shaft incidents and accidents scenarii has been established. A database of 187 incidents and accidents has been produced by the partners for their country. This database is not exhaustive of all events relative to shaft accidents but covers a wide range of contexts and scenarii. It gathers the available expertise on shafts accidents with rich content (reports, pictures, analyses…). This database provides a first preview on data quality, details available and also on the heterogeneity of the known cases, by country.

It constitutes a common base for stakeholders involved in coal shafts security and risk assessment. The distribution of shaft failure scenarios show that in many cases, the most frequently scenarios encountered are collapse of the filling material column and failure of the shaft head. Let us note also that lining quality and water effect are often aggravating factors. It was expected to disseminate the database on MISSTER website. However problems of data diffusion have been highlighted by several partners. A version accessible only by the partners is available on http://www.misster.eu.

14 cases have been deeply analysed, underlining weak points and key points that may, in a way or another, play a significant role in the assessment of shaft security and stability. This work was presented by a paper presented on April 24, 2012 at the 3rd International Conference of Shaft Design and Construction in London and detailed in the Deliverable D1.

WP2: Location and characterisation of mining shafts

WPL: GIG. Partners: INERIS, KWSA, DMT, MRSL

Task 2.1 – Location of old mining shaft (MRSL, INERIS)

A review of geophysical methods for the location of old mining shafts has been carried out. This will help operators in charge of old mining shaft location to choose appropriate method according to local context as each techniques was described and its domain of validity detailed.

In urbanised areas, where there is a strong need of old shafts location for securing existing structures or developing new ones, no geophysical method can, on its own, enable an unambiguous conclusion on the presence of a shaft (or its absence).

Let us note that it is advisable, before commencing a measurement campaign, to conduct a test on the site to be studied so as to adapt the chosen system, or validate (or not) the method (test on a shaft known prior to searching for a non-located structure).

Two methods have been studied and/or developed in this project to locate the shaft: electrical resistivity tomography (ERT) and seismic tomography.

Location testing made from the seismic tomography method allowed the observation of velocity anomaly corresponding to the shaft. However, the test has been performed by knowing the location of the shaft, so it was easier to associate the signal to the shaft. The perspective of this work is to test the method under unlocated conditions to validate this method.

In the framework of the "MISSTER" Project a novel "plug and play" architecture for smart electrodes, offering major cost, productivity and ease-of-use benefits, has been also devised. A top-level electronic design capable of achieving this has been produced and the associated software algorithm has been demonstrated. In parallel, research has also been carried out into the software technique of inversion that is required to interpret the results of an earth resistivity exercise, and approaches for optimising it for the detection of mine shafts have been developed. Once a commercial opportunity has been identified, an engineering team would be capable to translating the output of this task into a component-level design and production software as a product development exercise.

Task 2.2 – Development of a continuous shaft system (DMT)

A complete shaft survey system is available (called Probe 1 within MISSTER project). Components have been developed and/or updated and integrated. Control software has been designed and developed. Workflow for deployment and data communication between all components has been tested under lab conditions and in practical tests in Lohberg Shafts of RAG Deutsche Ruhrkohle AG. Software for processing and conversion into suitable output formats has been developed. At the end of the project a system is available to do continuous shaft inspections at a low risk with objective results in an efficient way.

Task 2.3 – Design and construction of a probe, in field tests of probes (GIG, KWSA, INERIS)

New probes for remote inspection of mine shafts have been developed and optimised.

A prototype of the Probe 2 has been already tested. Based on the results from underground tests some additional mechanical improvements have been developed and integrated. The results from underground tests have been presented on a workshop meetings organized in GIG on the 9th Nov 2012 and 14 Jun 2013. Support engineers from the mines, designers from the mining equipment producers as well as mining authorities took part in the workshops.

Probes 3 and 4 – developed by INERIS – has been already conducted to underground tests. Tests were carried out in shafts under 30 m of water. The viewing distance was estimated between three and five meters in water.

The four probes and measurement systems (tasks 2.2 and 2.3) cover a wide range of situations in terms of air condition, shaft depth, video capacities, etc.

WP3: ANALYSIS OF CRITICAL SHAFTS CONSTITUTIVE ELEMENTS THAT INFLUENCE RISK OF FAILURE IN TIME

WPL: UoN. Partners: GIG, KWSA, GEOCONTROL, MRSL

Task 3.1 – Filling materials and techniques (GIG, KWSA, MRSL)

Within the framework of this task, basic operations associated with preparing for shafts closure with the most common methods of feeding filling materials are presented. In the further part of the research, laboratory tests and underground tests of filling materials before and after dropping into the shaft have been performed. The scope of research covered grain-size analysis, evaluation of water permeability and leaching physic-chemical elements. On the basis of the obtained results a methodology of selecting filling materials for shafts closure, considering use of low strength materials, was prepared. It enables use of such materials as mining waste rocks, which has a positive influence on the costs associated with shafts closure. Within the framework of that task, a new methodology of feeding material into the shaft was prepared as well. It enables to limit the degree of degradation of a filling material, which is especially important in case of materials of low strength. Moreover, the new method limits damages of the lining of a shaft and its equipment through directing filling material towards the bottom of a shaft. It is especially important when it is decided to reopen the closed shaft.

Task 3.2 – Linings cappings and plugs design and integrity (UoN, GEOCONTROL, MRSL)

In order to improve ground stability, the normal treatment is to pressure grout the inaccessible voids. The results of the tests performed for the evaluation of grouts have been analysed in terms of evolution over time of weight change and changes in unconfined compressive strength for the samples subjected to various environments (air, potable water and acid water). The most significant results have been obtained for acid water resulting in a significant decrease of compression strength. The results also indicate that the UW grout is a more stable material relative to conditions which may be found in mine shafts.

In order to compare the durability of different reinforced concretes and additives, a testing methodology has been developed. Samples are immersed in an acid solution in order to evaluate deterioration effect with time. The results indicated that the two additives which allowed a greater ingress of both potable and acid water into the test cubes were superplasticiser and the integral water repellent.

The average loss in weight of the test cubes immersed in potable water was some 0.7% less than the pre immersion values whilst the average figure for those in acid water reduced by 1.5% with little difference for different additives.

Results show that the samples without any reinforcement showed the greatest loss in compressive strength with over 18% loss as compared to 15% in potable water.

A testing methodology has been developed to evaluate degradation and weathering of brick, mortar, concrete and brickwork. It is difficult to see the weathering effects on the brick samples due to the large variation of brick samples themselves. For concrete samples, a clear decrease in the stiffness due to acid attack is shown. For Mortar samples, a significant reduction of stiffness of the samples in the acid solution is observed. Acid attack seems to have more effect on the surface than the interior of the samples. Results also suggest that concrete could resist the acid attack for a short time period however after long time immersion in aggressive acid environment, the behavior of concrete could be considerably changed under uniaxial compressive load.

Physical modelling has been developed for the study of failure mechanisms of shaft linings. A significant effort has been concentrated on setting up the experiments in centrifuge with a high acceleration up to 80 g. Different failure mechanisms and induced displacements were observed according to the presence or the absence of a specific weak zone in the lining.

Numerical modelling have been undertaken to simulate static and time-dependant scenarii of mine shaft behavior, considering the effect of progressive deterioration and potentialfinal failure of a shaft lining. Brick-lined shafts and concrete lined shafts were simulated.

For example, modeling was used also for the back analysis of Boleslaw catastrophe (Poland) in 1975 (WP1). The results indicate that lining failure could not be caused just by ground load but by a combination of significant weathering and humidity effect resulting to 90% strength loss

Task 3.3 – Shaft stability (GEOCONTROL, GIG)

Detailed results of task 3.3 are presented in the Deliverable Report 3.3.

Within the framework of the task, numerical investigations aimed at determining the stresses occurring in plugs and dams for different filling materials used for a shaft's closure were determined. In order to carry out the analysis a special program in FISH language has been developed. The obtained results showed that the height of filling column, at which the forces acting on the dams and plugs are stabilizing, depends not only on the friction coefficient (as in Jansen's theory), but also on the grain size of the material. The results of model studies have shown that for materials with the same physical properties (density, friction coefficient) the forces could stabilize at different height of filling column: from about 35 m (for material with median diameter of about 200 mm) to about 55 m (material with median diameter below 80 mm). The results showed also that the impact of void in the filling column on the forces exerted on the locking plug and dams are less significant than expected, but the increase of pressure in the filling column caused by water is much more important and could lead to locking plug and dams failure. Such failure could in turn threaten the stability of the entire shaft.

WP4: SYNTHESIS

WPL: INERIS. Partners: GEOCONTROL, MRSL

Task 4.1 – Handbook (INERIS, GEOCONTROL)

The techniques for closing mine working have evolved and improved thanks to feed-back on their relevancy, dimensions and durability. A handbook presenting good practices has been achieved. It presents the most frequently used techniques for mine shaft protection and their implementation conditions in terms of risk situations and contexts.

This handbook is intended for local or regional stakeholders in the post-mining area and for mine operators. It identifies all criteria which may influence the choice of a method for enhancing mine works safety, and recommends the best adapted techniques, in the light of these criteria, with practical presentation of the data in the form of information sheets.

This handbook refers to other MISSTER deliverables for specific topics.

Task 4.2 – Spreadsheet (MRSL)

The conclusion of Task 4.2 was that it was certainly feasible to use a web-based computer application as a tool to provide a risk profile for a given set of circumstances relating to the condition of a mineshaft lining. It had also been demonstrated that the tool could be run on a mobile phone (not requiring a smart phone) and that a simple text-based database of shaft data could be utilised.

EXPLOITATION AND IMPACT OF RESULTS

ACTUAL APPLICATIONS

The expertise developed through the systematic analysis of risks induced by mine shafts is of great interest for operators in charge of mine operations or post mining issues.

By defining a typology of failure scenarii, illustrated by representative cases and building a database of shafts incidents and accidents, WP1 provide stakeholders a framework for a better anticipation of risk control.

WP4 provide a methodology for assisting decision makers in identification of risks induced by shafts, evaluation of securing objectives according to local context and definition of best available techniques for shaft treatment.

WP4 handbook has been discussed and enriched with French (Central and Local) Authorities in charge of mines. Until recently in France, regulations required systematically a heavy and expensive treatment of any mine shaft regardless of the local context (in terms of urbanization or geology for example). In addition, the recent European guidelines for the conservation of protected species added constraints in terms of shafts closure. Indeed, some shafts now constitute privileged access of specific chiroptera species requiring an open passage through shafts.

WP4 handbook is actively used by French Local Authorities to define best shaft treatment taking into account local context. It enables to justify the use of treatment techniques better adapted to local contexts and sometimes less expensive than what was previously regulatory required.

The continuous shaft system is currently used for periodical shaft inspection of the Lohberg Shafts in Germany. Several mining companies have requested a service with this device. Two projects will be realized soon:

- Potash shaft Rössing Barnten K+S Inc. Germany (complete 3D-Documentation of an abandoned shaft, 2014);
- ONTRAS VNG Germany (complete 3D-Documentation of two abandoned mine shaft which are currently used as underground gas reservoir.

Probe 2 (developed by GIG) is currently used in periodical shaft lining examinations. Probes 3 and 4 are periodicaly used since 2010 in France:

- Bauxite mine, Mazaugue, Var : shaft inspection (2013) ;
- Coal mine, Plan d'Aups, Var : flooded shaft inspection (2013);
- Chalons-en-Champagne, Marne : inspection de tête de Crayère (2012) ;
- INERIS/Montlaville, Oise : inspection of walls of a large diameter drilling (2012);
- Avilly-Saint-Léonard, Oise : Verification of the status and condition of an old shaft, (2011);
- Laon, Aisne : Verification of the status and condition of a shaft (2012/2013).

TECHNICAL AND ECONOMIC POTENTIAL FOR THE USE OF THE RESULTS

The review of existing techniques for locating shafts achieved during MISSTER project constitutes a basis which assists operators in charge of shaft location to choose best available techniques according to local specificities.

Location of old mining shafts in urbanized areas raise an important issue in terms of security for actual structures and people as well as land planning. Currently, no techniques clearly appeared unambiguously enabling old shaft location. Promising results of seismic tomography may constitute a perspective for future development but within a coupling of location methods framework, as suggested by D2.1 conclusions.

The performed investigations in Poland confirmed the usefulness of the developed program and additional subroutines developed in the framework of Task 3.3 and their usefulness for design of shafts closures, especially for strength calculations of dams located in the area of inlets

PATENTS

Probe 2 (developed by GIG) : Two patent applications have been already submitted to the Polish Patent Department:

- Zestaw do wizualnej inspekcji szybów (Set for Visual Shaft Inspection)
- Sonda do zdalnej kontroli geometrii obudowy i wyposażenia szybu (Probe for remote control of the geometry of the lining and shaft equipment)

New method for shaft closure (Task 3.1) : a patent application has been submitted to the Polish Patent Department: "Sposób i urządzenie do podawania ziarnistego materiału zasypowego do likwidowanego szybu kopalnianego" ("Method and device for granular backfill feeding into the liquidated mine shaft").

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LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVATIONS

2D :	Two dimensional
3D :	Three Dimensional
ATEX :	ATmosphères EXplosibles
Bar :	100 000 Pa
CA :	The Coal Authority
CH_4 :	methan
CIRCABC :	Communication and Information Resource Centre for Administrations, Businesses and Citizens.
cm :	centimetre
CO :	Carbon monoxide
D3.1 :	Deliverable 3.1
d_i :	Shaft diameter
D_M :	Median diameter
F or SF :	Safety Factor
FISH :	Programming language
FLAC :	Finite Difference program for engineering mechanics computation
FPB :	Four-point bending
GIG or CMIPL :	Glowny Instytut Gornictwa
GIS :	Geographic Information System
GPa :	Giga Pascal
H :	hour
i_M :	Degradation coefficient
INERIS :	Institut National de l'Environnement Industriel et des Risques
IT :	Interface strength
kg :	kilogram
kPa :	kilo Pascal
KWSA :	Kompania Weglowa S.A.
LCPC :	Laboratoire des Ponts et Chaussées
LED :	light-emitting diode
Leica Cyclone :	3D Point Cloud Processing Software
m :	metre
m/s :	metre per second
m^3 :	cubic metre
mg/l :	miligram per litre
ML :	mass loss
mm :	millimeter
MPa :	mega Pascal
MRSL :	Mines Rescue Service LTD
O_2 :	dioxygen
OJ :	Official Journal
P :	External pressure
Pa :	Pascal
PFC3D :	Particle Flow Code in 3 Dimensions
SEM :	Scanning electron microscope

SS :	Strain-Softening
T :	Lining thickness
Temp. :	Temperature
TOC :	Total organic carbon
UCS :	Uniaxial compressive strength / Unconfined Compressive strength
UoN :	The University of Nottingham
VLF :	Very low frequency
Vp :	P wave velocity
WIFI :	Wireless local area network
WP :	Work package
WPL :	Work package Leader
σ_l :	Estimated compressive strength of the lining
Ω :	ohm
NCG :	Nottingham Centre for Geomechanics

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Mine shafts constitute a key element of mining because they are crucial for access to underground workings, necessary for the proper functioning of mining operations and a remaining trace of former mining activity on surface.

MISSTER project contributes to enhance the knowledge and identification of failure modes. New diagnostics tools have been developed to take into consideration shaft location accuracy problems, geotechnical and gas hazards, effect of time on the shaft stability and closure methods and techniques.

The present document constitutes the final report covering the 36 months period of the project from 01/07/2010 to 30/06/2013.

In the framework of MISSTER project, the following achievements are described in this final report:

- a typology of incidents or accidents relative to mining shafts;
- a back analysis of a representative shaft incidents in Europe and a database of incidents that gather the available expertise and enables statistical analysis;
- a review of existing techniques for locating old shafts;
- the development and enhancements in the area of electrical resistivity method and seismic tomography for locating shafts;
- development, optimization and improvement of four complementary “probes” or measurement systems for shaft inspection;
- laboratory and underground tests for the choice of appropriate material and technique for shaft filling;
- specific tests for the evaluation of the resistance of grouts, and degradation of brick, mortar, concrete and brickwork panels with time in mine water;
- physical and numerical modeling to evaluate shaft stability;
- preparation of a handbook of good practices for mine shafts treatment.

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