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Tunnelling/Mining

A novel, non-circular Tunnel Boring Machine for Underground Mine Development

Dennis Ofiara and Mike Lewis

The mining industry excavates many more kilometers of tunnel each year than the civil construction industry, but the use of tunnel boring machines (TBM) in mining has been limited in decades past. This has changed in recent years. With their circular bores, the machines have thus far been unable to tackle a larger issue for mines. Typically a flat floor is needed for mining vehicles to traverse. A novel non-circular boring machine is now answering that need. Its rectangular cross section allows for use of typical mine trucks and other rubber-tired mine vehicles. It provides more useable space, and minimizes the amount of excavated rock. The machine is currently cutting an access tunnel at a silver mine in Mexico. This paper reviews the design and operation of the novel TBM, and describes possible future adaptations to provide safe, sustainable mine development.

Tunnelling • Mining • TBM • Non-circular TBM • Mechanised tunnelling • Innovation • Mexico

Ground Support with High Tensile Steel Mesh for Tunnelling and Underground Mining

Paul Braun

Traditional support and reinforcement systems such as shotcrete reinforced with electro-welded mesh or fibre concrete used in underground mining are limited in their capability against dynamic loads. High-tensile meshes Minax and bolts are an alternative solution. Large-scale tests have contributed significantly to this development.

Mining • Tunnelling • Rockburst • Safety • Steel wire mesh • Anchor • Support system • HSE • Large-scale tests • Research • Development • Reinforcement
TUNNELLING

Realistic large-scale Tests on self-healing Fresh-Concrete Composite Seal with swelling Nonwoven in Tunnel Construction

Frank Heimbecher, Stefan Thünemann, Adrian Pflieger and Chris Behr

To avoid damage to polymeric geomembranes for tunnels in conventional construction method, an innovative fresh-concrete composite seal (FCC seal) was developed and tested in realistic large-scale trials. The function of the swelling nonwoven laminated onto the geomembrane (GMB) is to create a bond between the GMB and the concrete inner shell and to self-heal leaks in the GMB and prevent water ingress and movement behind the membrane.

TUNNELLING • Waterproofing • Fresh-concrete composite seal • Polymeric geomembrane • Swelling nonwoven • Large-scale tests

Driving the Stuttgart Airport Tunnel – efficient Use of Resources using Tunnel Anchors made of high-strength Steel

Andreas Schiller, Sarah Gitzen and Darin Angelov

For the Stuttgart Airport Tunnel of Deutsche Bahn AG, anchors made of high-strength steel were used instead of conventional anchors of rebar steel. This contributed to efficient use of resources, to a reduction in CO₂, and to improvements in construction operation. It was therefore sustainable.

TUNNELLING • Anchor technology • Sustainability • High-strength steel • Resource efficiency • CO₂ reduction • Construction operation

TUNNELLING/IDEAS WORKSHOP

Prospects for visual Inspection of Tunnels using flying Drones

Ruslan Zuber, Zacc Dukowitz and Junio Valerio Palomba

Tunnel inspection is essential for ensuring the safety and integrity of these vital transportation corridors. Traditional methods, such as manual visual inspections or ground-based sensors, can be time-consuming and potentially hazardous for personnel. The use of flying drones, or unmanned aerial vehicles (UAVs), offers a safe and efficient alternative for tunnel inspection. With high-resolution cameras and other sensors, UAVs can provide detailed views of the tunnel’s condition, identifying any structural defects or damage that may pose a risk to users. They can also access areas that may be difficult or dangerous for human inspection, such as the tunnel ceiling or walls. Using UAVs for tunnel inspection can improve safety, efficiency, and cost-effectiveness, making them an increasingly valuable tool for tunnel maintenance and repair.

Tunelling • Surveying • Monitoring • Drones • Maintenance • Efficiency • Safety

ENERGY/GEOTECHNICS

Circular Construction of the Future with Pilot Project in Bremen

Strabag Group

Strabag’s Circular Construction & Technology Centre (C³) at Bremen’s former oil port in Germany shall establish a regional circular economy that preserves resources and avoids carbon emissions. A comprehensive sustainability concept for soil remediation, construction and operation forms the basis for the pilot project.

Geotechnics • Sustainability • CO₂ reduction • Climate • Remediation • Circular economy • Research • Development

MINING/ENERGY/IDEAS WORKSHOP

Postal Logistics Hub as a Coal Mine Restructuring Project – Ukrainian-German Ideas for the Post-mining Era

Oksane Vovk, Hennadii Haiko, Roman Kharchenko, Igor Sikorsky, Natalia Lubenska and Julia Tiganj

The world’s energy industry is going through a period of noticeable reductions in the production and use of hard coal. These reduction rates vary from fairly radical in the EU to very flexible and gradual in large Asian economies. Nevertheless, the general trend – as determined by the climate and environmental policy of the green transition – significantly limits the life cycle of the coal industry over time. The post-mining era in sustainable coalfield areas of the world requires systematic scientific methodology, educational efforts and technological, environmental and social transformations in many of these regions. Germany's experience in this field can provide the basis for the implementing regional transformation projects in several European coal-mining countries, notably Ukraine, and this will serve as a model for many other countries. The characteristics of the Germany and Ukrainian coalfield regions, along with individual projects aimed at transforming coal mining enterprises, testify to the expediency of developing cooperation between the two countries through post-mining programmes. Proposed measures for the post-war recovery and development of Ukraine envisage a radical renewal of the country’s energy and mining sectors, and it is probable that success here will rely primarily on German-Ukrainian projects. This article represents one potential concept for the restructuring of the Novovolynska No. 10 coal mine in the Volyn region of Ukraine and its transformation into a postal and logistics hub.

Mining • Energy • Coal • Climate • Post-mining • Coal • Ukraine
Green Solution – Metal Extraction in Chile without Nitrogen Oxide Challenge

Alexander Kraje

Mining giant wants to test a sustainable technology of the Kraje GmbH for recovery of nitrogen oxides in a test plant in Chilean Atacama Desert.

Conventional and mechanised Shaft sinking – System Comparisons and innovative Developments

Thomas Ahlbrecht

Conventional shaft sinking by drilling and blasting was for many years the most hazardous of all mining operations. New techniques and technical developments have now made shaft construction work much safer and more efficient. Yet there is still room for further improvement. This paper describes the current state of the art and the experiences that have been acquired in the field of mechanical and conventional shaft sinking and presents innovative ideas along with the latest developments in this sector.

Extracting Raw Materials from old mine-waste Heaps – ReMiningPlus Project for the environment-friendly Recovery of recyclates from a Tailings Facility

Jana Pinka and Arite Werner

The BMBF-funded project ‘³ – Strategic metals and minerals – innovative technologies for resource efficiency’ involved the preparation of an official register, or cadaster, of the largest mining waste dumps in the German Free State of Saxony. The aim of the investigations was to supply the economy with strategically relevant metals and minerals from disused mine holdings such as heaps and tailings dams. A reference example is used to describe the project’s strategy and potential.
Focus on Nature and Climate – a Turning Point and constructive Cooperation
Dr.-Ing. M.A. Katrin Brummermann

A close connection with nature and respectful interaction despite diversity are important keys for a turning point in climate protection.

Geotechnics • Tunnelling • Mining • Energy • Raw materials • Nature • Climate • Turning point

I just read in the daily press about the speech robot ChatGPT with the ambiguous title “The Typewriter” and the subtitle “Homework at the press of a button”. Am I completely out of touch with the times if I write on the special topic of nature and climate without a language computer and artificial intelligence? I’ll do it anyway.

In Germany, an independent jury selected Zeitenwende - turning point (in history) as Word of the Year 2022 and Klimaterroristen - climate terrorists as Taboo Word of the Year from suggestions submitted by the public. The word of the year was used by Chancellor Olaf Scholz in his speech after the outbreak of the war in Ukraine. People – including those in politics and the media – used the taboo word for climate activists and equated them with terrorists.

In times of increasing urbanisation, use of technology, and all-inclusive holidays, many of us have less and less direct contact with nature. And yet nature provides a habitat for plants and animals, is of great recreational value for us humans and is really important for the environment and the climate. But I observe a turning point just the same. Awareness of the need for climate protection is increasing – not least due to the efforts of climate activists. Actively taking action is also typical of the professionals working in our geotechnical engineering, tunnelling, mining and raw materials industries. We provide the infrastructure and the necessary raw materials that our societies need. We plan, we survey, we construct, we extract raw materials and process these. In a word: action – we take action. So we are probably basically in sympathy with people who are actively committed to protect-

For future generations, climate protection is even more crucial than for those currently working or already retired. Much more practical action and positive interaction is therefore needed. For the challenges ahead, we need to ensure the development of young professionals in our sectors. We need to win them over, pass on existing expertise and integrate their valuable new ideas into shaping the future. A positive, open, but also constructively controversial cooperation is an important basis for this.

I see it as the task of the specialist press and the daily press, but also of the social media, to take really seriously this responsibility of open and honest communication between different generations and people. I hope that this issue of GeoResources Journal, with its particular focus on nature and climate, will contribute in some way to this, and I wish you an interesting read and rewarding sojourns in nature – preferably with wide-eyed children. And even with a good contact with nature, our homework on climate protection will require more than the press of a button; we need inner conviction and perseverance.

Katrin Brummermann

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The Circular Economy – more than just Recycling

Dr.-Ing. Dipl.-Bergingenieur Helmut Spoo, Dr. Spoo Umwelt Consulting, Aachen, Germany

The transition to a circular economy is unavoidable if we are to protect our climate and our environment. The conventional mining industry must become more environment friendly. Waste volumes need to be reduced and the circular economy driven forward. Products are increasingly becoming important sources of raw materials. Joined-up thinking must also mean thinking holistically by tracking the product design and production process right through to the use and re-use phase.

Mining • Raw materials • Resource efficiency • Environmental protection • Climate protection • Product development • Circular economy

Reducing Waste Incineration and forcing the Pace of the Circular Economy

The days when throwing stuff away was cheaper than recycling it are now over. We need the circular economy to keep products affordable. And this is also all about climate protection and supply capability. Every tonne of raw material that passes through the circular economy is one tonne of self-reliance. We need to think ahead. Our philosophy has to be: what is optional today will be compulsory tomorrow.

High-quality recycling can make an effective contribution here. Closed material cycles ensure that CO₂ remains bound within products and materials. Moreover, according to the waste hierarchy material recycling takes precedence over energy recovery (‘recovery’ sounds better than ‘incineration’) and thermal processing in waste incinerators. We are burning far too much.
And it should not be forgotten that every combustion process – whether it takes place in a waste incinerator, in a power station with co-incineration of waste or in a rotary kiln – generates CO₂ emissions. It is therefore vital that we should be burning as little waste as possible and only as much as is necessary.

**Products as Raw Materials Repositories**

What therefore could be more logical than to see products and equipment as ‘raw materials repositories’ and to set about recovering the materials they contain at a high quality level, and ideally in such a way that they have the same properties as primary raw materials? This is precisely what the ‘Product Mining’ label aims to do – though with a much reduced environmental impact and lower CO₂ emissions. Causing less environmental damage and ensuring climate protection while at the same time maintaining competitiveness is a massive challenge, but it is something that we have to tackle together.

If we are to tap into the product ‘repository’ we have to make it far more accessible. This means avoiding unnecessary composites, non-separable connections, adhesive bondings and so on. Important information on the materials used and on any harmful substances that may be present will be included as part of the product passport so that these data are made available within the supply chain, and more particularly for the benefit of the recycling industry.

As well as knowing their product standards designers must also be prepared to engage with themes such as the Circular Economy and Green Deal, including for example VDI Directive 2243 ‘Recycling-oriented product development’. The latter outlines detailed measures for the ‘Design for Recycling’ initiative. Recycling of this kind also means taking account of aspects such as ‘grey energy’, i.e. the energy that is expended during the production process.

Operating under the European label ‘Product Mining’ my Aachen-based company Dr. Spoo Umwelt Consulting offers analysis services for all kinds of products, whether it involves determining the raw material composition or preparing a product passport. I hope that by using my expertise in the primary mining sector I will be able to make product mining a success and in this way make a useful contribution to climate and environmental protection.

**Circular Product Design**

**Smartphones**

A good example of a circular product design is the Shift6m smartphone that is currently being explored as part of the BMBF ‘loop-PHONE’ research project. This device is durable, fully modular and repairable. A life cycle assessment has been carried out and the product passport with all key information, including raw material content, is in preparation.

**Cement Production**

We absolutely need to take a closer look at our different industries and exploit any potential that exists for reducing CO₂ emissions. Cement production is a particularly energy-intensive industrial process and a significant source of CO₂ release. The ‘Up Cement’ project currently under way in North Rhine-Westphalia, Germany has set itself the important objective of eliminating the release of CO₂ during the calcination of limestone in the cement manufacturing process and reactivating the separated cement at a lower temperature level.

**Aluminium Production**

Primary aluminium production is another important, energy-intensive process that also has a major environmental impact. By separating the different aluminium alloys more efficiently and managing them in a more application-oriented way we can make significant energy savings and at the same time reduce CO₂ emission levels. This will almost completely eliminate the need for primary aluminium to be added in order to dilute any unwanted elements.

**Conclusions on the Transition to a resource-efficient and climate-neutral Economy**

Profound changes are needed if the circular economy and the transition process are to lead to a resource-efficient, climate-neutral economy. An effective circular economy starts at the product stage and not at the waste material stage. Barriers that exist in standards and other regulations need to be removed. If products are to find their way back into economic circulation at the end of their useful life we also need to draw up clear end-of-waste criteria.

The German Federal States are being called upon to ensure that all current legal regulations are implemented in full. The Commercial Waste Ordinance is a good example of what is needed here, and the enforcement of this inherently sensible regulation will have the effect of avoiding and reducing commercial waste levels and in this way will help to protect and conserve valuable resources.

The circular economy poses an exciting and seminal challenge that is of huge relevance for all mankind. Optimum implementation will call for joined-up thinking and indeed for some ‘thinking outside the box’. It will take a team effort – so let us work together and apply all our skills and capabilities to the task.

Helmut Spoo

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Building watertight with a fully bonded System – Ground Sealing at the Senckenberg Campus in Görlitz

Dipl.-Ing. (FH) Marco Bloch, Sika Deutschland GmbH, Stuttgart, Germany

1 Motivation
Basements are increasingly being designed as watertight concrete structures, or ‘white boxes’. However, more aggressive environments and more complex construction methods, along with shortcomings in planning, execution and monitoring procedures and deficiencies in building regulations, have seen a marked increase in cases of damage and defects in watertight structures of this type [1, 2]. This situation is aggravated by the fact that basement levels are now generally subject to much higher usage requirements. One way of compensating for the weaknesses and problems that can strike watertight concrete structures when affected by pressurised water or fluctuating water levels or when located in radon areas or in aggressive groundwater zones is to use a fully bonded waterproofing system. While these well-established fully bonded systems have been widely employed in Germany since 2005, and on international level during the last 25 years, improved and new innovative technologies are now becoming increasingly available in this sector. These new systems, when used in conjunction with recognised concrete building methods, can create crack-bridging and watertight composite structures with no lateral water migration. After presenting a brief introduction to the concept, principle and mode of operation of fully bonded systems and outlining the complex nature of the planning process involved this paper uses the example of the fully bonded system installed at the Senckenberg campus in Görlitz, Germany to provide further illustration of the technique.

2 Concept, Principle and more of Operation of fully bonded Systems

2.1 Concept
Fully bonded systems are used to create an effective and continuous bond between the geosynthetic membrane and the watertight concrete structure so that cracks in the concrete can be bridged and any large-scale ingress of water due to local leakages can be effectively averted. This technology is designed to prevent the following:

- Moisture-related usage restrictions on basements
- Damages to permanent fixtures and other stock and furniture
- Structural damages that could in the worst case damage its stability
- Expensive downtime for repairs to be undertaken
- Costly renovation work resulting from poor accessibility to damaged areas

This applies especially to high-value usages [3] and when the damage occurs in the active utilisation period.

2.2 Basic Construction
Fully bonded systems are available from various suppliers and most generally have the following layer construction (Fig. 1):

- Waterproofing layer, e.g. with flexible synthetic membranes and professionally made joints for sealing against pressurised water and bridging over cracks
Bloch: Building watertight with a fully bonded System – Ground Sealing at the Senckenberg Campus in Görlitz

The concrete is poured directly up against the fully bonded system so that the composite layer is able to create a full-surface mechanical connection between the concrete and the waterproofing layer. In other instances, such as when installation is undertaken after pouring, alternative systems with an adhesive bond can be used.

3 Complexities of the Planning Process

Planning watertight structures is a complex task that calls for the expertise and collaboration of different specialist disciplines, such as concrete technology and structural engineering. It may also require a knowledge of structural physics, building technology and – because of external factors – geotechnical engineering. If the planning engineers are to produce suitable, effective and efficient sealing systems and watertight structures they not only have to fully understand the structure itself but must also appreciate how the geological factors and other relevant environmental conditions interact with one another.

4 The Senckenberg Campus

4.1 General Background

The Free State of Saxony began construction works on the Senckenberg campus in Görlitz in September 2021. The construction project is scheduled for completion at the end of 2023. The complex itself comprises five building units and connections leading off to other neighbouring buildings and units in the inner courtyard (Fig. 5). Existing historical and listed buildings are currently being renovated and incorporated into the complex.

The interior spaces of the overall structure, comprising a total surface area of some 8,300 m², are destined for high-quality use as a museum (the Senckenberg Museum of Natural History Görlitz), a research institute and a teaching and educational centre for TU Dresden. The complex has ample room for valuable collections, laboratories, office workstations, classrooms and workshops.

Given that the assumed water level was above the top of the foundation slab the new buildings had to be designed to resist hydraulic pressure and were required to meet watertight specifications in accordance with the German Guideline on Water Impermeable Concrete Structures [4]. In view of the sensitive nature of the events to be held in the complex of buildings the latter also had to be designed for maximum resistance to moisture and damp.

4.2 Sealing with the fully bonded system

A ‘white box’ of watertight concrete was combined with a fully bonded system in order to minimise the project

![Fig. 4: Effect produced by using fully bonded systems – (left) mechanical bond and (right) adhesive bond (not drawn to scale) [1]](image)

![Fig. 3: Lateral water migration in a waterproofing system without a bond to the watertight concrete (top) and when using a fully bonded waterproofing system (bottom) [1]](image)

![Fig. 2: General arrangement of fully bonded systems with their watertight bond to the concrete structure and, by way of comparison, the conventional loosely laid waterproofing system. With the conventional loosely laid system any perforation of the membrane will allow water to spread between the membrane and the concrete and if continuous cracks are present this water will then penetrate into the interior of the structure. With a professionally installed fully bonded system, however, this lateral water migration cannot take place and the water is only able to extend into a very small area immediately around the perforation zone.](image)
risks [5, 6]. The innovative fully bonded system chosen for the job featured a special bonding layer [7]. This ‘hybrid bonding layer’ combined three action mechanisms:

- **Adhesive bond** between the bonding layer and the concrete structure is created by the adhesive force of a special polymer mixture (immediately after pouring)
- **Mechanical gripping** of the setting concrete due to the surface roughness of the bonding layer (immediately after pouring)
- **Mechanical needling effect** due to the cement particles in the bonding layer, which creates a strong bond with the concrete structure (after pouring this increases with time).

The use of thermoplastic polyolefins (TPO) in the bonding layer means that overlap joints can be sealed by thermal jointing (Fig. 6). Thermal jointing is the best possible joint sealing solution for fully bonded waterproofing systems.

The combination of fully bonded membrane with a product solution for the sealing of joints and transitions ensured a waterproofing system resistant to lateral water migration (Fig. 7) that was installed to a very high standard by the Bautzen-based contractors Hentschke Bau working together with the certified waterproofing company August Reiners of Wüstenbrand.

5 Conclusions and Outlook

When it has been completed and is fully up and running the Senckenberg campus in Görlitz, along with its precious collections and other high-value goods, will be very well protected from the risks posed by flooding.

The success of the operation depends not only on the high quality of the system used but also, more crucially, on the professionalism and teamwork displayed by all involved. Consequently, the German Concrete Association is now working on a set of DBV Guidelines for fully bonded waterproofing systems that will cover all aspects of this construction method and will lay down rules for its future application. These Guidelines are expected to become available in 2023.
6 References


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The mining industry excavates many more kilometers of tunnel each year than the civil construction industry, but the use of tunnel boring machines (TBM) in mining has been limited in decades past. This has changed in recent years. With their circular bores, the machines have thus far been unable to tackle a larger issue for mines – the need for a flat floor. While the mining industry excavates many more kilometers of tunnel each year than the civil construction industry, typically a flat floor is needed for mining vehicles to traverse.

An innovative type of non-circular boring machine is now answering that need with its ability to cut a rectangular profile in hard rock (Fig. 1). This cross section allows for use of typical mine trucks and other rubber-tired mine vehicles. It provides more useable space, compared to a circular profile, and minimizes the amount of excavated rock that must be hauled out of the mine. This machine uses typical disc cutters to cut the rock (Fig. 2) and has a support structure similar to an open type TBM; however, the cutting geometry is entirely different. The machine is currently cutting an access tunnel at a silver mine in Mexico.
of the fleet of mine trucks and other rubber-tired mine equipment. Robbins and their agent, Topo Machinery, worked with Fresnillo to develop a suitable Mine Development Machine proposal. Equally important to the machine design was the deployment and operation of the machine on a day-to-day basis, which Topo and Robbins formed a partnership to undertake.

3 Mechanical Rock Excavation, circular and non-circular

Circular, full-face rock TBMs are well-developed tools, but are not often used in mining, considering the many kilometers of mine tunnels that are driven each year. This is for a variety of reasons: difficult mobilization/demobilization in deep mines, inaccessibility to sharp curves and steep gradients that are part of the standard mining plans, and the fact that the mines usually desire a flat tunnel floor, not a circular profile. The TBM industry has made strong efforts to overcome the obstacles. A full face circular TBM remains the most efficient machine for mechanical excavation of tunnels in rock. However, if a flat floor is imperative, it must be created by secondary methods if a circular full face TBM is used to drive the tunnel.

Several secondary methods can be considered to create the flat invert roadway. These include follow on slashing of the bottom haunches by drill and blast, or by rock splitting. A precast floor can be set, or concrete can be poured in place to create the floor. Alternatively, crushed rock can be used to fill the circular invert to create the road. This invert space can sometimes be used for drainage pipes or drain channels beneath the slab to create the road. This setup can help offset the penalty of having to construct the flat bottom. However, the resulting cross section is often still not the most efficient for the intended use.

Many types of rock excavation machines have been introduced to cut a non-circular cross section with a flat bottom. Roadheaders in particular have become more capable in recent years. Robbins Mobile Miners were first used in the 1980s and 1990s, and more recently have been trialed and are under further development. Several other machines using partial face excavation with disc cutter technology have been tried. Unfortunately, most of these machines have been abandoned by the mines due to low productivity or high cutter wear.

If the main intention is to develop a roadway tunnel, and additional cross sectional area is not needed for ventilation flow or other purposes, then the most efficient cross section is rectangular. The comparison below shows a rectangular cross section compared to a circular tunnel that has the same floor width (Fig. 3). The circular tunnel has 30% more excavated area per lineal meter. This means more muck to hoist and dispose. An efficient way of mechanically excavating a more or less rectangular profile remains much sought after in the mining industry. While the civil tunneling industry has been much more accepting of circular tunnels, an efficient rectangular machine could also be useful for many civil applications.

4 Evolution of the MDM Cutting Concept

Besides roadway tunnels, a mechanically excavated cross section is very useful to mine ore bodies that are in seams with parallel tops and bottoms. Such deposits are called “reefs” and are typical in platinum mines and other minerals. Mining the reef in deep platinum mines is very difficult and dangerous work. Many efforts have been made to mechanize reef mining as an alternative to drill and blast.

One such effort was the “Reef Mole”. This machine was conceived and developed by John Gibson and Andy Anderson, long time Robbins engineers who formed a new company after retirement. The machine was built and excavated in a platinum mine in South Africa. This machine cut out a 1 m x 5 m rectangle to excavate the ore.

The cutting action was performed by a swinging cutter head, rather than a rotating cutter head, as on circular TBMs. The head was swung horizontally by hydraulic cylinders, to create the rectangular cut. Strong grippers locked the machine within the excavated reef to resist the significant cutting forces. The geometry of the machine was arranged so that the cutters swept across the semi-circular shaped face with nearly constant penetration to provide the most effective cutting action. A vacuum system was used for muck removal.

The Reef Mole cut effectively in the very hard rock of the platinum reef, however, the machine was regarded as “experimental” by the mine. Thus, it did not get any priority for resources such as power, water, ventilation, haulage, personnel, etc. – all of which are precious commodities in a deep operating mine. Though promising, the Reef Mole was never fully utilized by the mine.

4.1 The MDM Design

As the need for mechanically excavated development tunnels at Fresnillo was discussed further, a machine concept evolved using a swinging cutterhead, similar to...
the Reef Mole. The goal was to produce a rectangular cross section, 5 m wide and 4.5 m high. In this case, the cutter head was swung vertically about a horizontal axis. A robust front gripper cylinder was located on this axis of rotation. This provided good stabilization and direct reaction of cutting forces. The gripper anchored within the vertical side walls of the cut. The machine was designated as MDM5000, for Mine Development Machine. A drawing of the machine is shown in Fig. 4 and a close-up of the cutting action on the rock face in Fig. 5.

Swinging the cutterhead about the horizontal axis gave the opportunity for the head to push the cut muck rearwards, onto a muck apron, much like the muck apron on a roadheader. The apron covered the full 5 m width. Twin loading wheel “propellers” to each side of center pushed the muck towards the hopper in the center of the apron. A chain conveyor pulled the muck from this hopper and conveyed it to the rear of the MDM. Belt type conveyors are usually preferred for TBM type equipment, however, the conveyor is located low in the MDM, near the tunnel floor. It was thought that a belt type conveyor would constantly be running through the inevitable muck accumulated beneath and would suffer too much wear. Also, The MDM was intended to be used on steeper gradients. In such gradients, the net inclination angle of the conveyor in the MDM would be too steep to allow effective conveyance by a belt (Fig. 6).

The MDM is significantly front heavy due to the configuration of the machine, and the overhung cutterhead. This would cause the MDM to tip forward about the front fulcrum shoe in the muck apron. Significant rear structure and machine length was needed to counter the overhung weights and cutting forces. The rear of the MDM had a “Main Beam” which mimics the main beam of a typical hard rock TBM. It also had a rear gripper and thrust cylinders to advance the machine by skidding on the front fulcrum. The rear gripper and torque cylinders provided steering effect, much like on a hard rock TBM.

5 Mining Machine or Rectangular TBM?

The mining industry wants excavation equipment that is powerful and highly productive, yet lightweight and easily mobile. The MDM was developed as much as possible with these goals in mind. From the photo (Fig. 7), you may get the impression these goals were superbly met. You see a strong rock cutterhead on a very mobile, tracked carrier. However, this is only one module of the MDM. It is being transported down the mine ramp road on a special tracked carrier. The MDM was transported down the ramp as three main modules. You can see from Fig. 4 of the entire MDM that significant structural and mechanical elements are needed to deliver the high cutting forces that provide efficient hard rock excavation – a setup typical of hard rock TBMs.
If a lighter, more mobile machine is needed, these systems would have to be greatly abbreviated, and perhaps left behind on the tunnel floor and connected to the excavation machine with umbilical cables. Such a machine would have much less power and productivity.

6 MDM Roof Support Systems

Immediate, effective roof support was a strict requirement at Fresnillo. Like other TBMs, the MDM was equipped with a hydraulically operated roof shield that provided protection over the front gripper area, where there was no space available for roof support activities. Special high tensile wire mesh (“Minax”) for mine support and rock bolts were installed just aft of the roof shield (Fig. 8). The mesh was brought to the front of the MDM in rolls. Each roll was long enough to provide coverage across the width of the roof, and down each side to about springline. The mesh panels were 1.4 m wide to provide overlap at each row of roof bolts. Roof bolt spacing was 1.24 m. This spacing was chosen as it was adequate for effective support in the anticipated conditions. Also, the roof bolt spacing corresponded to the spacing of the hanger chains on the conveyor, which was used for muck removal.

The forward roof bolters and positioners were hydraulic percussive type drills supplied by Fletcher. These drills installed the bolts across the width of the roof. In addition, there were rear drills, supplied by TEI, that installed bolts into the side walls. The TEI drills could also be turned forward and articulated to drill a re-con hole into the face, or a series of holes into the face for spiling or pre-excitation grouting.

7 MDM Muck Removal

A Robbins extensible tunnel conveyor system was used to remove the muck produced by the MDM. The conveyor system was chosen for several reasons. The con-
veyor had high capacity and did not introduce any exhaust pollution. Also, there was not enough room for high capacity mine trucks to pass within this tunnel. A further consideration was that the tunnel conveyor is able to safely remove muck at fairly high gradients. Future MDM tunnels are planned with up to 7% gradient to develop deeper levels of the mine.

The tunnel conveyor was mounted in the center of the crown (Fig. 9). This left more room for vehicles and for installation of piping and other utilities within the tunnel. Also, this central position allowed the tunnel conveyor belt to be routed all of the way forward to the discharge of the MDM chain conveyor. A separate transfer conveyor, and additional transfer point were not necessary.

The tunnel conveyor structure was added continuously as the MDM mined forward, within the protection of the Installation Window. Personnel were thus not exposed to the moving belts. As mentioned before, the tunnel conveyor was suspended by chains attached to the roof bolts. No additional bolts in the roof were needed to suspend the conveyor.

The belt storage cassette paid out conveyor belt as the MDM mined forward, so the tunnel conveyor was continuously extensible. The cassette was fairly long so adequate space had to be prepared underground. The tunnel belt carried muck out of the tunnel, over the cassette, then to the main drive unit. The conveyor discharged at the main drive into a cross conveyor system, which could then selectively discharge muck into either of two 450 m³ silos created by raise mining. The silos discharged into a loading area, where electric trains were loaded for transport to the shaft skip.

8 MDM Transport and Mobilization Underground

The MDM needed to be transported from the surface to the –695 m level of Fresnillo mine via the existing main ramp tunnel. This was an 8 km long trip down the ramp. This ramp had limited cross section, undulating bottom, steep gradients, and many sharp radius curves. The MDM was assembled as completely as possible on the surface, and transported down the ramp in three main modules: the cutterhead, the front main frame, and the rear gripper section. A special, tracked carrier was developed by Fletcher Mining Machinery, in collaboration with Robbins engineers. The carrier had multi-axis articulation so the modules could “duck and weave” to miss obstructions in the mine ramp, much like a person spelunking in a cavern passageway.

An assembly and launch cavern was developed at the first MDM tunnel site on the –695 m level. The cavern was long enough to accommodate the full MDM and backup system, and the continuous conveyor cassette. This cavern required significant excavation to prepare, but allowed the MDM and the conveyor to be used immediately, from the first cut of the MDM (Fig. 10).

The cross section of the assembly and launch cavern was only slightly larger than the 5 m x 4.5 m dimen-
has a better ‘angle of attack’ to allow for more efficient mucking (Fig. 11). Observations are that the new design has resulted in quicker cycle times and aids in muck removal. Originally, each cycle would take 32 swings and 22 minutes; this has been reduced to 26 to 28 swings and 18 minutes.

- **Muck apron**: Cylinders have been added to the muck apron to enable it to be forced down and avoid raising up as muck accumulates in the invert. Other improvements are being investigated to improve the robustness of the chain conveyor.

### 10 Conclusions

The MDM is excavating rectangular profile development tunnels at Fresnillo. Most mines have regarded such new equipment as “experiments”, and have not devoted adequate resources such as power, water, manpower, muck haulage, ventilation, etc. Fresnillo has devoted the necessary resources, and all parties are determined to make the MDM do the job it was intended to do.

The MDM is cutting the desired rectangular, flat invert profile. The MDM has passed zones of bad ground and high water inflows. Traditional mining methods have been used to augment the MDM ground support capabilities in particularly bad areas, so that the MDM could proceed through.

With its first use has also come some overall observations: due to the cyclic, swinging cutting action, the machine has lower productivity compared to a traditional, rotary TBM that cuts a circular profile. While there are still many benefits, most prominently a flat roadbed, the comparisons must be carefully evaluated for any significant mine excavation considering using this method.

The MDM is not the “lightweight, mobile rock excavation machine” that the industry covets. Such a lightweight machine may be possible, and development will surely be undertaken due to the demands of the mining industry. However, such a machine will surely have a penalty of decreased productivity.

### 11 References

The article is based on a paper for the WTC 2022.

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**Fig. 11:** Scraper design – original above and improved below
Ground Support with High Tensile Steel Mesh for Tunnelling and Underground Mining

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Background

Mining is getting deeper, and rockburst is a growing risk in underground excavations around the world. Especially in mining tunnels, when in search of the mineral strata, tunnels are deepened more and more, until reaching depths greater than 1,000 m and more. However, seismicity events and associated rockburst can occur even at lower depths. Traditional support and reinforcement systems such as shotcrete reinforced with electro-welded mesh or fibre concrete used in underground mining are limited in their capability against dynamic loads. The development of diamond-shaped lightweight steel wire meshes Minax® [1] of very high strength in recent years has offered alternative design solutions (Fig. 1).

Research and Development

In order to fully understand the behaviour and capacity of various ground support systems using these Minax meshes, the Swiss Company Geobrugg has carried out many full-scale dynamic tests in its own test centre in collaboration with universities and mines from all parts of the world (Fig. 2).

The need to increase the energy dissipation capacity in the support system designs of different mines has been present for many years ago. With this goal in mind, systematic studies have been carried out, aiming to improve the performance of the single elements and the complete reinforcement systems. In addition, the development of diamond shaped lightweight steel wire membranes of very high-tensile strength, in recent years, has given a great boost to this trend. These powerful flexible solutions combined with suitable anchors (Fig. 3) have undoubtedly been a huge step towards solving situations where protection against dynamic load is imperative.
energy capacity surface support. Distribution of the impact loads during the stopping process to the different elements of the bearing support system depends on the strength and flexibility of the mesh and the bolt resistance and its pattern.

Given the characteristics of a structure that attempts to reproduce the conditions of a mine, boundary conditions are generated, which do not allow a direct correlation of the results obtained in the test with the results expected at the mine. However, it allows comparisons between systems and elements of fortification and helps to advance our understanding of the complex problem of ground support.

The new ground support designs, developed over the last few years, consist of high-tensile steel wire mesh Minax, anchors and shotcrete. Because of the use of high-tensile steel wire (min. 1,770 MPa) and the flexibility of the chain-link mesh, such a support system can be applied in areas with very high static and dynamic stress.

Proven in Practice

On several rockburst occasions worldwide (Fig. 5), it was clearly demonstrated that this type of design, with high-tensile chain-link mesh Minax, allows high energy absorption of the dynamic loads from periodic rockbursts, depending on the magnitude of the incident usually without any maintenance requirements, which is both fundamental for guaranteeing miners’ safety and essential to increase the productivity of mining development ultimately.

With this successful test series of a reinforcement system (shotcrete with mesh, bolt and a second mesh with cable bolts) under dynamic conditions, Geobrugg can add experimental antecedents to the theory and confirm that this type of support is with no doubt a huge step forward in increasing the safety in underground mining.

References


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Realistic large-scale Tests on self-healing Fresh-Concrete Composite Seal with swelling Nonwoven in Tunnel Construction

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1 Introduction

Experience shows that, when subjected to water under pressure, waterproofing systems in tunnel construction using polymeric geomembranes (GMB) often require remedial work in order to achieve the contractually required watertightness (Fig. 1). The reasons for this can be found in both the design and the execution. The trades which come after the installation of the sealing system, such as reinforcement installation or concreting of the inner shell, can cause damage to the sealing system. As a result, damp and wet spots often appear after completion, and can only be eliminated by costly injection measures. These measures can be either local, or they can involve the introduction of injection material in specific blocks behind the inner shell. The classic structure of the sealing system consists of a protective nonwoven (≥ 900 g/m² mass per unit area) on the outer face and a loosely laid GMB with a thickness of 2 mm for sealing systems not subjected to water pressure, or 3 mm thickness when water pressure is present [1]. The sealing system is divided into chambers using welded-on external water stops. In the event of damage and water ingress, this prevents water movement over the whole area between the GMB and the cast-in-place concrete inner shell.

The development of a new type of reactive Fresh-Concrete Composite seal (FCC seal) is aimed at repairing damage to the polymeric geomembrane in a “self-healing” manner and, in the event of such damage, preventing water movement between the GMB and the inner shell [2].

The solution consists of a substrate (e.g. a polymeric geomembrane) onto which a nonwoven fabric containing swelling polymers is laminated. During concreting, the nonwoven bonds into the in-situ concrete inner shell. In the event of water ingress, the swelling properties of the nonwoven create an additional sealing barrier and prevent longitudinal or transverse movement of the water through the bond with the GMB (Fig. 2). Local damage, e.g. perforations in the GMB caused by reinforcement bars, is closed up, resulting in a self-healing effect.

2 How the swelling Nonwoven works

The new FCC seal with its swelling nonwoven took account of extensive development work under realis-
3.1 Preliminary Investigations into the Barrier Behaviour of the FCC Seal

Damage to the geomembranes often occurs during execution, as explained above. A frequent cause are, for example, exposed reinforcement bars in the area of voids in the concrete in the ridge area. These damage the KDB in the ridge area of tunnels subjected to water under pressure once dewatering during the construction phase is ceased. As soon as water pressure acts on the geomembrane from the outside, it is pressed against the reinforcement bars. This can perforate or tear the geomembrane, enabling the ingress of underground water between the geomembrane and the inner lining, and thus into the tunnel itself. The FCC seal can prevent or at least reduce such water ingress. In the meantime, numerous investigations into the effectiveness of FCC sealing have been carried out under tunnel-specific boundary conditions, and extracts from these are described below.

3.2 Large-scale Tests under realistic Installation Conditions

To replicate the surface properties encountered in bored tunnelling, several large-scale tests were carried out with the maximum permissible unevenness and roughness according to ZTV-ING Part 7 [1]. This was achieved by applying a realistic shotcrete surface as a simulated outer shell to a test structure, a concrete pipe with an outer diameter of 3.10 m (Fig. 5). Damage to the sealing system was simulated with the aid of reinforcement bars passed through the GMB in order to determine the self-healing behaviour of the swelling nonwoven under pressure in a practical manner in both short- and long-term tests. The test set-up allows the following investigation parameters:

- Variation of the water pressure up to 2.5 bar in individual variable test steps
- Several test areas, approximately 2.00 x 1.25 m\(^2\) (L x H) in size
- Reproduction of realistic types of damage such as perforation of the GMB by rebars
- Establishing the extent of the reduction in water flow along and transverse to the sealing system as a function of the damage and the water pressure
- Investigation into the short- and long-term behaviour of the sealing effect

The fibres of the swelling nonwoven used in the studies are made of polypropylene. These fibres incorporate so-called superabsorbers, which swell on contact with water and thus create a sealing effect.

The superabsorbers are weakly cross-linked, insoluble polymers. When they come into contact with water, they swell and form a hydrogel. Superabsorbers can absorb many times their own weight in water without releasing the water again later. They are optimised for maximum water absorption, unlike most other polymers, whose water absorption is very low [2]. On the left of Fig. 4, some fibres of a nonwoven are shown in their original state under the microscope. After water has been added, the superabsorbers are clearly visible on the right.

Fig. 3: Detailed section of an FCC seal on a concrete inner shell

Fig. 4: Swelling behaviour of the nonwoven fibres with superabsorbers – left original state, right after 30 seconds swelling

Fig. 5: View of the shotcrete surface
Fig. 6: Test setup – left cross-section (diameter $D_{\text{outside}} = 3.10$ m), right detail 1

Fig. 7: Installation damage (rod diameter 16 mm) on the FCC seal (left: Single damage, right: Total area)

Fig. 8: Position of the sounding boreholes and distance from the respective point of damage in cm

Fig. 9: Damaged area with the location of a sounding borehole.

To detect water leaks resulting from installation damage, sounding boreholes were placed at defined intervals (Fig. 8). These sounding holes were connected in stainless steel pipes to the FCC seal before concreting, i.e. they had contact with the laminated swelling nonwoven. Fig. 9 shows a damaged area with the location of a sounding borehole. This ensured the detection of any leaks.
Distances of 15, 30 and 60 cm between the sounding holes and the damaged areas were chosen in order to map possible water spread in the swelling nonwoven at these different distances. Assuming that water spread is approximately circular, in each case three sounding holes were in the direct area influenced by damage.

3.3 Results

The results in Fig. 10 show that an initially detected release of water was confirmed in all but one of the sounding holes. After approximately 56 h (measurement no. 4 in Fig. 10), however, no further water release was measured. Even under increasing water pressure, no further water release was measured via the sounding holes.

In the second test run, the pressure was increased in a manner similar to the first test, but up to a maximum pressure of 250 kPa. Fig. 11 shows the results of the flow measurement over the entire period. It can be seen that in the first pressure stage there was no measurable release of water in the sounding holes.

In the second pressure stage at 150 kPa, two sounding holes showed a slight water release after a total of approximately 170 h (measurement no. 9 in Fig. 11), and this tended towards zero after a further 20 h (measurement no. 12 in Fig. 11).

After the increase to 200 kPa, a release of water was measured in every sounding hole except one. The maximum flow rate was 0.51 l/h (measurement no. 15 in Fig. 11). In the space of 95 h, the water release in all sounding holes reduced to negligible amounts (measurement no. 21 in Fig. 11). And even after the pressure was further increased to 250 kPa, no further significant amounts of water were measured.

4 Conclusion

The investigations show that the FCC seal can prevent water ingress between the GMB and the in-situ concrete inner shell in the case of perforations of the GMB by reinforcement bars. Although water movement was detected around the sounding holes, the water flow reduced to a negligible level during the course of the test. This positive “self-healing effect” was observed and proven in both experiments.

The substrate consisted of a shotcrete surface typical of those met in practice, with maximum unevenness and roughness in accordance with ZTV-ING Part 7 [1]. Despite this – for the FCC sealing system unfavourable boundary condition, the large-scale test demonstrated that a “self-healing process” sets in both along and transverse to the sealing layer. The spread of water is hindered by the swelling properties of the laminated nonwoven bonded to the cast-in-place concrete. Furthermore, it was shown that the self-healing process remains permanent even at changing pressures of up to 2.5 bar.
For practical applications, the large-scale tests carried out under realistic conditions have provided positive results for future use. They show that on the fresh-concrete composite seal investigated, it is possible to guarantee class 1 sealing in accordance with ZTV-ING Part 7 even when the polymeric geomembrane is perforated by re-bars. The water leakage rate can be reduced significantly or even completely in the case of local perforations.

5 References


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Driving the Stuttgart Airport Tunnel – efficient Use of Resources using Tunnel Anchors made of high-strength Steel

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Introduction

Sustainability: only a few years ago it attracted scarcely any interest in the construction sector, and especially in tunnelling. Now the focus is increasingly on sustainability in both construction products and methods. Thus, it can be observed that there is a greatly increasing tendency among contractors and clients to use sustainable building products to reduce the CO$_2$ footprint. Whereas classic construction products have long characterised tunnel construction, in recent years innovation has also become increasingly important in tunnels. For some years now, the use of high-strength SN anchors with a yield strength of 900 N/mm$^2$ and a tensile strength of 1,050 N/mm$^2$ has made a contribution to reducing CO$_2$ emissions [1]. In the course of driving the Stuttgart Airport Tunnel, high-strength SN anchors were successfully used and enjoyed great popularity, not only with regard to the environment.

The Stuttgart Airport Tunnel is part of the extensive Stuttgart-Ulm project and is being constructed as a single-track, twin-tube tunnel using conventional excavator driving (Fig. 1). The 1,200 m long west and east feeder lines and the 440 m long new underground station pass under the A8 motorway and the sites of the Stuttgart trade fair and airport. In addition to the tunnels themselves, five shafts were sunk in the area of the new station.

Innovative high-strength Anchors

Due to its design consisting of a steel tension member, anchor nut and anchor plate, the SN anchor is one of the simplest anchors in tunnel construction (Fig. 2). Conventional SN anchors with the usual diameter of 25 mm, such as those used in German-speaking countries, usually consist of a steel tension member made of conventional rebar steel with a yield strength of 500 N/mm$^2$ and a tensile strength of 550 N/mm$^2$. These have a separate metric thread at the anchor-head end for the application of an anchor nut.

In contrast to conventional anchors, the new high-strength SN anchor with a diameter of 18.6 mm is made using steel with a yield strength of 900 N/mm$^2$ and a tensile strength of 1,050 N/mm$^2$. Its outer shape follows that of a hot-rolled threaded steel bar with an endless-screw coarse thread (Fig. 3). In the course of the manufacturing process, the technological properties, such as
yield and breaking load, ultimate load, shear strength, corrosion resistance or bond strength, are adjusted so that when used in SN anchors [1] they are comparable to those of conventional products.

But there is one major difference. With a yield strength of 900 N/mm² and comparable technological properties, high-strength SN anchors have a mass 44 % less than SN anchors made of rebar steel that have been in common use until now.

**Sustainability**

In their areas of application, high-strength SN anchors make a significant contribution to reducing negative environmental impacts and conserving resources, and thus help to achieve sustainability goals. The CO₂ savings already start with the transport to the construction site. 44 % less steel mass means around 80 % greater truck loading in terms of tunnel anchors per linear metre of tunnel, or a 44 % lower truck loading per metre of tunnel anchor.

Much more far-reaching is a consideration of the quantity of CO₂ saved during the manufacture of the steel. First of all, a reduction in weight of 44 % per se means a reduction of 44 % in greenhouse gases. If B500 reinforcing steel had been used, the geology of the Stuttgart Airport Tunnel would have required SN anchors with a diameter of 25 mm. The high-strength SN anchors made of SAS 900/1050 SN required a diameter of only 18.6 mm. **Table 1** shows a comparison of the steel masses.

The raw material for the high-strength SN anchors from Annahütte comes from the Lech steel works. In the process, scrap steel is fed into its recycling circuit. When making steel from iron ore, the CO₂ footprint of the appropriate electric furnaces compared to the blast furnace route is considerably smaller: 453 kg CO₂/t steel [2] for the SAS 900/1050 SN from the electric furnace in Meitingen, including the rolling of the product in the Annahütte steelworks, compares with around 4 times the amount, 1,744 kg CO₂/t steel [3], for steel products from the blast furnace.

When a comparison is made between the high-strength SN anchor from the electric furnace and a conventional SN anchor from the blast furnace, the CO₂ reduction is even greater. In total, the savings in mass of 44 % and the savings in the manufacturing process of 75 % result in a CO₂ reduction of approximately 85 %!

**Construction Operation**

The high-strength SN anchors are installed in the same way as conventional SN anchors. A saving of 44 % in the steel mass in the airport tunnel was a gain not only for the environment. The miners and the management of the construction company also benefitted from the new development.

For the underground crew, less mass meant considerable relief during the installation process due to easier

| Table 1: Comparison of loads and masses of conventional and high-strength anchors |
|----------------------------------|----------------------------------|----------------------------------|
| **Diameter [mm]**               | **Yield load [kN]**             | **Breaking load [kN]**           |
| Conventional SN anchor B500     | 25                               | 245                              |
| High-strength SN anchor SAS 900/1050 SN | 18.6           | 245                              |
| **Mass [kg/m]**                 | **Yield load [kN]**             | **Breaking load [kN]**           |
| Conventional SN anchor B500     | 3.85                             | 270                              |
| High-strength SN anchor SAS 900/1050 SN | 2.13           | 285                              |
lifting and insertion into the borehole (Fig. 4). If they are required, small bending operations are considerably facilitated by the 58 % reduction in section modulus.

And the use of a coarse thread suitable for construction sites is another positive aspect (Fig. 5). For the site management, the continuous, hot-rolled coarse thread – well suited to the construction site – made it possible to keep standard lengths in stock and react quickly to changes in geology or logistics. In addition, the reduced steel masses and lower transport costs were interesting from an economic point of view.

Conclusion

The example of the use of high-strength steels in the Stuttgart Airport Tunnel illustrates the sustainability potential present in some areas of tunnel construction. Deutsche Bahn AG has thus not only fulfilled its mandate in its core business. Doing so has shown that a focus on environmental issues does not necessarily mean disadvantages in other areas. The airport tunnel and the contractors involved were able to show that advantages in CO₂ emissions could even go hand in hand with installation advantages. In the interests of a level playing field, it is to be hoped that tendering authorities will in future take the issue of sustainability into account at the outset in the invitations to tender.

References


Prospects for visual Inspection of Tunnels using flying Drones

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Introduction

Inspection and maintenance of tunnel networks is a challenging task due to their inaccessibility and the potential hazards they present (Fig. 1). Early detection of leaks, cracks, and corrosion changes is critical for effective structural health monitoring. It allows for early intervention, reduces the cost of remedial measures, and minimizes the risk of unexpected failure. [1]

During inspections, notes and photographs are taken and information is collected and entered into a digital database, although some information may be recorded on paper. This information is used to conduct further inspections at regular intervals or additional checks and measurements, and may also trigger immediate maintenance or rehabilitation activities. However, the information is only partially analyzed to assess the tunnel's condition, damage progression, maintenance requirements, etc., because this process is time-consuming and expensive. Conducting regular and systematic inspections can help minimize overall costs by identifying critical areas early and initiating refurbishment work while damage is still minor. Failure to conduct regular inspections increases the risk of a significant incident, which would require more extensive refurbishment work. [2]

Maintenance interventions and raw inspections inside subway and tunnel facilities can be time-consuming and logistically challenging, with difficulties accessing the tunnels, limited space, low lighting, and harsh work conditions such as humidity and dust. Inspections of tunnels are mainly conducted through visual walk-throughs based on available data, which allows for a focus on specific features and areas of concern.

Inspection and maintenance operations in tunnels can be costly and time-consuming and limited by various factors such as time constraints, physical space limitations, the intrinsic conditions of the tunnel (e.g. limited space and the presence of service pipes), traffic flow, and in the case of railway tunnels, the presence of overhead electric cables.

Currently, the inspections are performed manually, which often requires the interruption of traffic and the use of scaffolding, disrupting the quality of the infrastructure's service. The available space for these operations is often restricted to the width of emergency pavements. These on-site works must be carried out during closure periods for safety reasons, often during night shifts, and are expensive. It is subject to human error due to performing by experienced but potentially untrained staff and sometimes adverse working conditions and extensive coverage areas.

Having accurate information about the inspection location is crucial in reducing the time needed for inspections, because the efficiency of manual inspections can be reduced over the day, increasing the risk of accidents.

As passenger and freight traffic increases, there is less time available for inspection and repair, making it essential to develop special systems that can quickly identify areas needing repair. Automating these operations can improve safety and productivity in the short and long term. To operate effectively in these environments, an automatic system [3] must be able to handle localization, mapping, path planning, collision avoidance, and limited knowledge of the environment based on onboard sensor data.
narrow spaces, and the need to carry a sufficient sensor payload and external light source. The design of these vehicles must also consider safety, particularly regarding collisions involving the propellers. [6]

Effective navigation and localization are essential for platforms to move from one location to another, plan routes, or make decisions while exploring an area. A human operator can achieve this through manual or semi-autonomous control or complete autonomy. Navigation requires sensor and external environment sensor measurements to provide feedback and help avoid obstacles, build a map, plan optimal routes, and reach a goal. Localization also uses these sensor measurements to estimate the platform’s position relative to its current location or a coordinate frame origin. Currently, tunnel inspections are primarily manual, requiring long deployments at night and often involving subjective data that is time-consuming to process. However, using digital technologies can potentially make these processes more efficient. The data collected during an inspection assesses the tunnel’s condition and plans for future maintenance. [7, 8, 9]

To prioritize the most significant damages and construction costs, it is necessary to carry out inspections for the entire tunnel or tunnel network. Based on the findings, the owner or operator can establish financial plans and intervention schedules, as well as create a maintenance intervention plan for the tunnel or specific zones within the network.

Unmanned aircraft vehicles (UAVs) or flying drones are increasingly being used to produce images, videos, and simple 3D models, but high-resolution recordings of transport infrastructure using techniques such as photogrammetry, laser scanning, thermography, and multispectral analysis offer more possibilities and require more advanced sensor technology and operational planning. Laser scanning is a standard data acquisition method but does not provide colour information. Photogrammetry [6], on the other hand, provides good colour images but takes longer to process. The processing of the large amounts of data involved in recording the condition of a structure, known as the “digital twin”, can take several days of computing time even for simple structures, and the requirements increase exponentially with higher resolution. Digital methods that are as mobile as possible are used to record the condition of a construction, identify and evaluate any damage, and assess the “structural health” using realistic material parameters. Regular monitoring of the health condition of ageing infrastructure using UAVs for structural surface inspection can gather more image data at a lower labour cost. The high-quality images and well-controlled acquisition routes allow for the use of artificial intelligence algorithms to enable quantitative evaluation or measurements of structural defects. Drone inspections can also facilitate the maintenance of structural infrastructure health and reveal deterioration [2,10].

Drone inspection of tunnel surfaces remains a challenge due to the dark and confined underground environments.

### Overview

According to the German standard DIN 1076, building inspections are required for various civil engineering structures, such as tunnels, retaining walls, noise barriers, and traffic sign gantries [4, 5]. The number of tunnels has increased significantly recently, making them, particularly demanding structures to inspect. According to the data of the German Federal Ministry of Digital and Transport (BMDV), already in 2017, the number of tunnels on federal highways reached 271, and the total length of tunnels reached 269.7 km (Fig. 2). In turn, the number of tunnels owned by Deutsche Bahn AG in 2021 reached 745 (Fig. 3).

Exploring and assessing tunnels for remediation purposes present a challenging problem in underground navigation. Especially in urban settings, subway tunnels, sewer systems, and storm drains require a constant inspection to meet operational health and safety regulations. Among other things, UAVs for these inspections face challenges such as high power consumption, sensitivity to wind conditions and movement through narrow spaces, and the need to carry a sufficient sensor payload and external light source. The design of these vehicles must also consider safety, particularly regarding collisions involving the propellers. [6]

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Unmanned aircraft vehicles (UAVs) or flying drones are increasingly being used to produce images, videos, and simple 3D models, but high-resolution recordings of transport infrastructure using techniques such as photogrammetry, laser scanning, thermography, and multispectral analysis offer more possibilities and require more advanced sensor technology and operational planning. Laser scanning is a standard data acquisition method but does not provide colour information. Photogrammetry [6], on the other hand, provides good colour images but takes longer to process. The processing of the large amounts of data involved in recording the condition of a structure, known as the “digital twin”, can take several days of computing time even for simple structures, and the requirements increase exponentially with higher resolution. Digital methods that are as mobile as possible are used to record the condition of a construction, identify and evaluate any damage, and assess the “structural health” using realistic material parameters. Regular monitoring of the health condition of ageing infrastructure using UAVs for structural surface inspection can gather more image data at a lower labour cost. The high-quality images and well-controlled acquisition routes allow for the use of artificial intelligence algorithms to enable quantitative evaluation or measurements of structural defects. Drone inspections can also facilitate the maintenance of structural infrastructure health and reveal deterioration [2,10].

Drone inspection of tunnel surfaces remains a challenge due to the dark and confined underground environments.

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**Fig. 2:** Number and length of tunnels on federal trunk roads under the construction responsibility of the German federal government

Source: https://bmdv.bund.de/SharedDocs/DE/Artikel/StB/tunnel-zahlen-daten-fakten.html

**Fig. 3:** Number of tunnels owned by Deutsche Bahn AG from 2012 to 2021

environment (Fig. 4), which can interfere with drone navigation and precision and the lack of GPS signals. Researchers are working on developing stable navigation and data acquisition methods for these harsh conditions. Some alternatives include using railcars or ground robots equipped with cameras. However, these can be expensive and have limited adaptability, making it challenging to cover a complex underground infrastructure network, including inclined tunnels, cross passages, and shafts. The maneuverability of UAVs allows for access through vertical direct access shafts, and their ability to move in 3D spaces makes them relatively less affected by obstacles. [11, 12]

**Sensors**

The integration of laser scanners into UAVs has dramatically enhanced the accuracy required in surveying technology and system integration. The simultaneous weight optimization of these devices has also made using laser scans with drones very appealing for infrastructure and industry applications. According to ISO 5725-1, accuracy consists of trueness (the closeness of measurement results to the actual value) and precision (the repeatability or reproducibility of the measurement). Drones with coordinated components weighing up to 15 kg can currently achieve an accuracy of about 10 mm for trueness and an accuracy of approximately 5 mm for precision. LiDAR sensors, which can measure at rates of over 500,000 per second, can be used in higher weight classes and provide even higher quality results and analyses. Laser scanning methods can be used to record the condition of road surfaces and tunnel surfaces, and digital acquisition using terrestrial and airborne laser scans, photogrammetry, and combined evaluations can create highly accurate plans, and 3D models. The use of industrial drones with various sensors, including LiDAR, inertial measurement units, GPS, radar, distance measurement devices, cameras, motion detectors, pressure gauges, and others, allows for the collection of environmental and spatial data. Photogrammetry and LiDAR can be combined to produce even more precise, photo-realistic replicas of objects. UAVs equipped with imaging and laser sensors benefit structural health inspections due to their aerial mobility, low cost, and efficiency. They can inspect structures in hard-to-reach areas, identify the damage, and monitor structures over time. [4]

**Piloting and Underground Navigation**

Using UAVs for tunnel inspections can be challenging due to several technical issues, such as the lack of GPS or GNSS signal in confined, cluttered spaces, the inherent weight constraints of UAVs, and the limited energy autonomy of these devices, which makes it difficult to accurately locate and control the UAV. The success of the UAV-based inspection task also depends on the UAV flight parameters, the payload choice, and the parameter configuration of the sensors and instruments carried by the UAV. [13]

UAV-based inspection applications typically use either manual or automatic flight navigation. The operator manually controls the UAV during the inspection process in manual flight navigation (Fig. 4). Conducting tunnel inspections using UAVs necessitates particular piloting abilities and ongoing attentiveness from the operator. The operator supervises the UAV during the inspection and may intervene if any unexpected events occur. In contrast, in automatic flight navigation, the UAV follows a pre-determined trajectory that has been programmed and uploaded into the UAV. It is essential to note the difference between automatic and autonomous flight navigation [13]. While automatic flight navigation is designed to minimize human intervention, autonomous flight navigation does not allow any human intervention during the flight and can independently cope with unforeseen and unpredictable situations. Currently, UAV regulations in many countries do not allow autonomous flight navigation in open airspace due to safety concerns, but this may change as the technology becomes more mature and secure [10].
Advantages of Using Drones for Tunnel Inspections

Using unmanned aerial vehicles (UAVs) for tunnel inspections offers several advantages over traditional inspection methods [13]. One of the main benefits is increased safety, as the UAV operator can control the drone remotely from a safe location. A specialized inspector can monitor the video feed or access the collected images and videos later on a device. UAVs also offer increased accessibility, as they can easily reach hard-to-reach places that may be difficult or impossible to access using traditional methods (Fig. 5). In addition, UAVs are typically more cost-effective than renting heavy machinery and can also save on costs associated with traffic control, such as lane closures during highway bridge or tunnel inspections. Finally, UAVs can significantly reduce inspection time due to their high mobility.

Case Study – Inspecting Dubai’s Metro using the Elios 2

The Dubai Metro is a significant public transportation network in Dubai that consists of 47 stations, 9 of which are underground and connected by tunnels that extend over 14 km. In the past, the tunnels were inspected manually by inspectors walking through them or using a moving platform. However, this process was hazardous and required temporary scaffolding to inspect higher areas. To improve the safety and efficiency of tunnel inspections, the Roads & Transport Authority (RTA) in Dubai decided to trial the use of drones for this purpose. The Elios 2 drone (Infobox), made by Flyability [14], was selected for the task due to its ability to operate safely and reliably without GPS in environments with no GPS signal, such as the underground tunnels of the Dubai Metro [15].

Conclusion

A tunnel inspection using an UAV (unmanned aerial vehicle) can provide a detailed and comprehensive view of the tunnel’s condition. Some potential conclusions that could be drawn from a tunnel inspection using a UAV include the identification of any structural defects or damage, blockages or obstructions, and the overall condition of the tunnel walls, ceiling, and floor. Additionally, a UAV inspection can identify areas that may require further investigation or maintenance and provide valuable information for developing a maintenance or repair plan.

References

[2] Schneider, O.; Prokopová, A.; Modetta, F.; Petschen, V. (March 2019): Tunnelinspektion mit künstlicher Intel-

Flyability [14] is a Swiss company building solutions for the inspection and exploration of indoor, inaccessible, and confined spaces. Allowing drones to be used safely inside buildings, enables industrial companies and inspection professionals to reduce downtime, inspection costs, and risks to workers. With hundreds of customers in over 50 countries in Power Generation, Oil & Gas, Chemicals, Maritime, Infrastructures & Utilities, and Public Safety, Flyability has pioneered and continues to lead the innovation in the commercial indoor drone space. The Elios offers several benefits for tunnel inspections, including a significant reduction in on-site working time, the ability to scan objects in 360 degrees, and the ability to carry out inspection, mapping, and survey tasks with a single tool. It also has high-resolution imaging, frontal illumination, sideward flashing, and non-line-of-sight communication.

Collision resilience: The Flyability Elios is a specialized drone designed for confined spaces. It has a protective frame made of carbon fibre that surrounds the drone and can withstand collisions up to 1.5 m/s. With a spherical cage protecting propellers from impacts, Elios remains stable through lightning-fast corrections on the propellers’ speed and direction of rotation. The entire payload is mounted on a retractable structure that protects it from damage in case of frontal shocks. Reinventing collision resilience, Elios allows to capture every corner and inch of the most complex and confined assets, from a safe location.

Accessibility: With an overall dimension just below 40 cm, Elios fits into standard manholes and can enter any space where an inspection is needed. It can safely and easily be flown into assets without any human access needed; at no point do workers need to enter the space during the inspection. Robust transmission: Its transmission system is also robust and can maintain a connection to the drone through walls and obstacles. The Elios is often used for inspections in challenging locations, such as underground tunnels, as it can access difficult areas safely and efficiently, eliminating the need for temporary scaffolding to perform remote inspections beyond the line of sight, through walls and past obstacles with Elios. Its wireless transmission system overcomes the needs of indoor configurations and is compatible with the Range Extender for the most complex setups.

GPS-free stabilization: Elios features 7 stability sensors specifically designed for indoor allowing it to hover in space, easily navigate through unstructured spaces and take razor-sharp close-up images in GPS-denied environments, in dark and troubled airflows, and beyond the line of sight.

Distance lock: With the distance lock, Elios remains at a set distance, ranging from 30 cm to 200 cm autonomously.

Full HD live streaming: Situational awareness and perform live inspections in First-Person View (FPV) thanks to the increased details of the Full HD live streaming built into Elios.

Thermal & 4K close-up inspection: Elios has a payload in the front cage opening, fitted with a thermal and a 4K camera side by side. 12MP still and video recording gives stunning detailed images with 0.18 mm/pix resolution to spot the tiniest cracks.

10K lumens: The Elios features the most powerful and intelligent lighting system ever built on a commercial drone. Carrying 10,000 lumens of light, adjustable to the needs, Elios provides the right amount of lighting to see the big picture or the tiniest crack.

Dustproof lighting: Dustproof lighting allows First-Person View aircraft navigation to traverse dust spaces without losing sight of the objective. Splash and dust-resistant design, equivalent to at least IP44. LIDAR Payload: IP68.

Oblique lighting: To reveal textures and identify defects, inspectors use a lighting technique that creates shadows in asperities. Reproducing this technique with our new oblique lighting systems, looking for pitting, cracks or build-up becomes as natural as doing it with a flashlight.

Planning & reporting: The Cockpit software has been designed to be able to prepare inspection reports on the fly. Once the inspection is completed, simply connect Elios to your computer using the USB port fitted on the drone to import all of the work results into Software Inspector. From there, it would be able to further investigate captured data, document findings, and create reports. Inspector provides real-time data and allows for autonomous flight with accurate positioning.
tunnelling/ideas Workshop

[Image 259x618 to 556x777]
[Image 375x92 to 460x211]
[Image 375x392 to 460x511]
[Image 375x242 to 460x361]

Zuber, Dukowitz and Palomba: Prospects for visual Inspection of Tunnels using flying Drones

Fig. 5: Tunnel inspection using an UAV in hard-to-reach places
Source: Flyability

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[1] Zuber, Dukowitz and Palomba: Prospects for visual Inspection of Tunnels using flying Drones


Strabag’s Circular Construction & Technology Centre (C3) at Bremen’s former oil port in Germany shall establish a regional circular economy that preserves resources and avoids carbon emissions. A comprehensive sustainability concept for soil remediation, construction and operation forms the basis for the pilot project.

**Geotechnics • Sustainability • CO₂ reduction • Climate • Remediation • Circular economy • Research • Development**

The Strabag Group has launched a pioneering flagship project as part of its sustainability strategy with a symbolic groundbreaking ceremony on 4 November 2022. The remediation and construction work for the Circular Construction & Technology Centre (C3) at Bremen’s former oil port started. As a pilot project, the competence centre for urban mining and construction waste processing will lay the foundation for the resource-saving, low-carbon construction of the future. The recycled building materials developed and obtained here will make a significant contribution to establishing closed material cycles in the construction industry in the Bremen region. Over the next two years, however, Strabag Environmental Technology must first sustainably clean up the site of the former refinery tank farm, which was heavily contaminated with mineral oil. The step-by-step construction of the buildings and of the plant technology will begin in 2024; the facilities for recycling construction waste are also scheduled to go into operation that same year.

**Resource-saving, sustainable Remediation**

The redevelopment concept for the 13-hectare site foresees a complete relocation and encapsulation of the existing soil stockpiles at the site. Prior to this, the contaminated sites are surveyed and any recyclable building materials that can be used later as a base layer, for example, in the construction of the site, are identified. The site is cleared of explosive ordnance, and measurements to determine the concentration of hazardous substances in the soil are carried out before the soil is excavated and separated according to its mechanical properties and further processed, if necessary. Only waste that cannot remain on site for environmental and groundwater protection reasons is disposed of. The next step is to relocate the existing stockpiles, which largely eliminates the need for truck transport and the associated carbon emissions.

**Climate-neutral and energy-autonomous Operation**

The Centre is being built using sustainable methods of construction and with climate-friendly building materials such as wood and recycled concrete. The facility will be operated in an energy self-sufficient and climate neutral capacity. Power is to be generated by photovoltaics, with heat coming from a heat pump in combination with ground-level geothermal energy. A rainwater collection system will allow the construction waste processing and the sanitary facilities to be operated without additional water consumption.

**Technology and Research**

About 130 people from various Strabag Group entities will be employed at the centre for urban mining and construction waste processing. Debris materials are to be separated and recycled as secondary raw materials down to the finest, high-quality particle sizes for use as equivalent substitutes for primary raw materials, e.g. in asphalt and concrete production. For the continuous further development of the technical processes, Strabag will expand the centre into a technology and research facility with a start-up campus for construction waste recycling and other environmental technology business fields. Collaborating with universities, testing laboratories and specialist institutes, the facility will research and develop new recycling options for the circular economy of tomorrow. The project in Bremen is the Strabag Group’s first competence centre for sustainable circularity. The Group plans to establish additional Circular Construction Centres at other European locations in the future.
Postal Logistics Hub as a Coal Mine Restructuring Project – Ukrainian-German Ideas for the Post-mining Era

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General Background

The coal industry, not only in the EU and around the world is being downsized due to the gradual abandonment of coal operations. This is primarily due to the EU policy of reducing coal-fired generation levels that has been set for 2050, along with the transition to renewable energy sources. These guidelines are in line with the EU Directive No. 2010/787/EU on the need to close uncompetitive coal mines by 1st January 2019.

The last half century has seen major changes in the coal industries of Europe, the United States of America and China. The main factors behind these changes are mechanisation, government policy and competition from other types of fuel in the electricity markets. The economies of Asia, Eastern Europe and Africa are now facing the same factors of change, with significant job cuts already being imposed in China and likely to occur in other Asian countries as well.

In 2015, there were 128 coal mines operating in 12 EU Member States with a total annual production capacity of 498 million tonnes. Poland had the largest number of coal mines (35), followed by Spain (26), Germany and Bulgaria (12 each). Germany was the largest producer (184 million tonnes a year), followed by Poland (135 million tonnes), Greece and the Czech Republic (46 million tonnes each). The current situation is as follows [1]:

- Only 2 hard coal producers remaining in Europe:
  - Poland with 55.0 Mt in 2021 and 54.4 Mt in 2020
  - Czech Republic with 2.2 Mt in 2021 and 2.1 Mt in 2020

- 9 lignite producers:
  - Bulgaria with 28.3 Mt in 2021 and 22.3 Mt in 2020
  - Czech Republic with 29.3 Mt in 2021 and 29.5 Mt in 2020
  - Germany with 126.3 Mt in 2021 and 107.4 Mt in 2020
  - Greece with 12.1 Mt in 2021 and 13.9 Mt in 2020
  - Hungary with 5.0 Mt in 2021 and 6.1 Mt in 2020
  - Poland with 52.4 Mt in 2021 and 46.0 Mt in 2020

German Background

The last coal mine in Germany was finally closed in 2018. Prior to this the closure programme had been carefully regulated. The beginning of the mid-1950s had seen an oil boom explode on to the energy market. By 1959 this had led to bankruptcies and closures in the mining sector. During this period the number of mines fell from 128 in 1958 to seven in 2005 and then to just two by 2018. The Ruhrkohle company (later RAG) was founded in Essen on the 27th November 1968. This umbrella organisation was to be responsible for minework-
ers’ social insurance matters and for the general running of the mines. It was a joint-stock company that included 23 coal associations with approximately 120 mines. The basis for the creation of Ruhrkohle was the law on the adaptation and rehabilitation of the German coal regions. On 7th February 2007 an agreement was signed between the German Government, the coal-mining states of North Rhine-Westphalia (also often referred to simply as the Ruhr), and the Saar, the RAG company, the industrial union of the coal mining and chemicals industry (represented by the IG BCE industrial union) and the energy sector that laid down plans for the closure Germany’s coal mines. The law on financing coal enterprises was adopted in December of that year. RAG was thereby committed to a socially-acceptable phasing out of coal mining by the end of 2018. After this RAG would be responsible for the overall impacts of the coal mining industry for a further 30 years. RAG currently has responsibility for the repair and restoration of mine ventilation shafts and for the rehabilitation of former coke-chemical enterprises that once belonged to the concern. It is also liable for the so-called ‘perpetual obligations’, which mainly comprise the management of the water resources and drainage systems as part of the mine water management programme, but also includes polder measures and the control of water quality in rivers such as the Rhine and the Ruhr. These controls are especially important for the former coalfield areas where water has long been at risk of pollution from industrial processes.

After the mines were closed the key question was how to properly manage and develop business concepts for the former mining enterprises and their operating sites. RAG Montan Immobilien GmbH was specifically created to resolve this issue. The company’s main remit was to develop and implement projects aimed at the rehabilitation and economic restitution of these former mining facilities.

One successful example of such an after-use concept is IKEA’s European distribution centre on the old Ewald colliery site in Herten (Ruhr), which received the German “Landscape 2007” award. As well as accommodating leisure and recreation facilities this site is now host to a wide range of businesses, including trade, logistics, services, technology, gastronomy, crafts and culture (Fig. 1). The 53 hectares of the former colliery location also serves as a hub for various enterprises and is home to the largest landscape park in Europe.

The transformation of the coalfield regions meant huge changes for Germany in general, and for North Rhine-Westphalia in particular. The mining workforce declined from 607,000 in 1957 to just 7,480 in 2016 (Fig. 2), while during the same period annual production fell from 151 million tonnes (183 mines), up to 3.9 million tonnes (two collieries). Some six universities, 15 colleges and 60 research centres have been founded in North Rhine-Westphalia since 1961, while suitable re-use concepts have also been developed for the abandoned mining sites. While coal was the reason for the creation of settlements in the Ruhr Area since 1850, this urban agglomeration – with its population of more than five million citizens – has undergone a significant change of image based on environmental technologies, new mobility, digital communications, cyber security, logistics and health care [2].

### Polish Transformation Plans

Many countries are facing similar challenges to those Germany has experienced during the transformation of recent years. Poland, for instance, intends to cease coal production by the year 2049. Wujek colliery in Kato-
The following state-owned enterprises are still in operation:

- **DTEK Group** (PJSC DTEK Pavlogradvugillia, DTEK Dobropillyavugillia LLC, etc.)
- **PJSC ‘Krasnodonvugillia’** (part of the Metinvest Group)
- **PJSC Shakhtoupravlinnia Pokrovskie**
- **Others**

In 2019 the public-sector enterprises (33 collieries) produced about 3.565 million tonnes of coal and the private-sector companies (14 mines) some 27.425 million tonnes [4]. The low profitability of the state-sector coal mining enterprises is a key reason for their restructuring.

The sustainable energy transition to a low-carbon economy that is taking place in the world’s developed countries is having a huge impact on the restructuring of the mining sector, which essentially means a reduction in coal production and usage and the application of measures for the systemic transformation of coal-mining regions. According to the ‘Energy Strategy of Ukraine to 2035’ and the ‘Plan for the Transformation of the Coal Regions of Ukraine’ all unprofitable state-owned mining enterprises will be closed by 2030 [5, 6], which means decommissioning some 27 state mines. Ukraine continues to provide subsidies to the state mining sector through 2022. A report on direct subsidies to the coal sector in 2018-2019 shows that of all the contracting parties of the energy community Ukraine remains the largest provider of state aid to the mining industry. Some 275.44 million euros of direct subsidies were paid out in 2018, this almost doubling to 476.08 million euros in 2019. This contrasts with coal-industry outgoings of over UAH 31 billion (about 1.1 billion euros).

Plans for a massive downsizing of the coal industry have to take account of the complex post-mining problems of the coal companies and coalfield areas since such a transition does not just mean the liquidation of mines but also entails a strategy for regional development in which mineworkers, their families and communities will have new opportunities for a decent life and ongoing development. The transformation of the coal regions is therefore one of the key challenges facing Ukraine in the medium term. There are two main reasons underlying the urgent need for these changes. The first of these is the European policy of abandoning the coal-fired generation of heat and electricity in order to reduce emissions of greenhouse gases and pollutants so as to prevent further climate and environmental changes, and the obligations that fall to Ukraine in this respect.

The dependence that most mining towns have on subsidised coal mining enterprises (which are locally based) has a negative effect on the area’s economy. Business activity, local infrastructure and local budgetary income now depend on the provision of budget subsidies to coal industry companies located in the region. However, subsidies from enterprises have not preserved the infrastructure of the cities and could not prevent the

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1 Russian military aggression against Ukraine may affect the rate of closure of coal mines and slow down the reduction of coal use for a certain period, but the general trend will continue in the medium term.
socio-economic degradation of the coalfield communities.

In 2021 the Ministry of Energy of Ukraine prepared a project for restructuring the state-owned coal mining sector and the Ministry of Community and Territorial Development drew up a plan for the transformation of the coal regions. The new concept for reforming the industry proposes uniting those mines designated as ‘promising’ into a new integrated structure based on the state-owned ‘Centrenergo’ company, which already manages several power plants. It is expected that such a merger will help increase the country’s energy independence and make investment in state-sector generation more attractive, thereby facilitating its privatisation at some point in the future. A preliminary audit has found that six or seven of the 33 state-owned mines can be designated as ‘promising’. The others are set to be phased out over time, though some may be put up for privatisation.

The transformation of the regions will be carried out gradually in stages and simultaneously with the liquidation of coal mining enterprises (3 to 4 mines a year) and the provision of economic and social support from the state. This will affect more than 38 thousand miners and will have an impact on over 100 thousand family members and 51 mining towns with a total population of around 500,000 people in the Volyn, Donetsk, Luhansk and Lviv regions. There will be no single rigid scheme for this transformation process. Decisions will be based on the results of the analysis of each specific enterprise and region, taking into account a broad public dialogue, the opinion of territorial communities, mining unions, etc. Public consultations will also form part of the planning for a just transition process.

The ‘just transition’ formula means that coal industry specialists will be given opportunities to take up alternative employment after the closure or reorganisation of the coal enterprises. Social support, educational development and retraining programmes will therefore have to be provided for each region. The specific direction taken will depend on the economic development plan for the region in question.

It should be noted that Ukraine’s coal industry has already experienced major changes in funding during the 1996 to 2005 period. This affected some 100 mines and was carried out as part of the economic restructuring programme, though was not properly thought through. The systematic approach taken at that time meant that the mine closure scheme created various environmental and social problems. The mistakes made by Ukraine’s restructuring policy of the 1990s have to be taken into account alongside the best domestic and global achievements of the past decades so as to produce modern post-mining concepts and programmes capable of delivering fully holistic solutions [7, 8, 9].

**Conservation Project for Novovolynska Mine No. 10 with the Creation of a postal Logistics Hub**

The Lviv-Volyn coal basin is located in the western part of the country. It covers an area of about 10,000 km² and continues into Polish territory. The presence of carbonaceous deposits on the territory of the future Lviv-Volyn coal basin was substantiated in the theoretical works of the Polish geologist J. Samsonovich in the early 1930s. In 1938, under his leadership, research was carried out with the help of exploratory wells drilled by a Silesian company (‘Community of Mining and Metalurgical Interests’). This operation proved the existence of workable coal seams at Halychany, Stoyanov, Buzko, Kizlov, Tartakov and Zavvyshnyany. In 1949 the ‘Zahidshakhtobud’ Trust was set up and work started on the construction of the first coal mines in the area. A major regional fuel and energy complex was developed on this basis and would play a key role in solving the energy problems of the Western Ukraine. These coal reserves were then exploited for more than half a century, leading to the depletion of the most profitable deposits. All the collieries still operating in this area (12 coal companies) are scheduled for comprehensive closure in the coming years [10, 11, 12].

The only exception to this is Novovolynska No. 10 mine (‘the object of incomplete construction’), which has been under construction at the State’s expense for more than 30 years and is now nearing completion. However financing has not been available for several years and the funds provided are only allocated for maintenance purposes. No investment is being made in the construction work and the mine requires conservation for an indefinite period. Given the energy crisis created by the state of martial law it would be expedient, in the opinion of the authors, to complete the construction of the mine as quickly as possible so as to have access to additional sources of steam coal (the mine has been designed for an annual production capacity of 0.9 million tonnes). However, as far as a final decision on the conservation of the object is concerned, it would be well worth considering the alternatives of using the territory of the mine, surface complex and underground structures.
The mine (Fig. 3) is located 10 km from the city of Novovolynsk in the Volyn region. The mining concession borders on the Zahidny Bug River to the north and on the technical boundary of the Novovolynska No. 1 mine to the south.

The area occupied by the mine measures 8,000 m by 4,400 m, giving an overall take of some 35 km². There are four coal seams with balance reserves of some 40 million tonnes. Working depths range from 390 to 620 m. The seams are generally horizontal with gently undulating bedding and have a lateral dip of between 5 and 70° (eastern part of the mine field). The seam thickness is generally between 0.97 and 0.65 m.

The mine workings are accessed by two centrally located twin shafts that are set some 90 m apart from each other (Fig. 4). The main shaft is 6 m in diameter and is equipped with two coal skips and a single dirt loading skip. This shaft is used for winding coal and dirt and acts as the mine’s upcast shaft. It measures 635.5 m in depth. The auxiliary shaft, which is 7 m in diameter, is equipped with two single-cage winding systems and is used for manwinding and for transporting materials and equipment. This downcast shaft is 642.2 m in depth, the actual shaft mouth standing 202 m above sea level. The deposits are developed via two mine horizons and the shaft insets serving each horizon are arranged around the shaft columns. The upper horizon is 355 m below sea level (557 m below the shaft mouth) and the lower horizon is 425 m below sea level (627 m below the shaft mouth). The vertical distance between horizons is 70 m. The mine uses a centralised suction ventilation system based on a VCD-31.5 fan unit. The fan is connected to the skip shaft by an air channel. The volume of air supplied to the mine is put at 140 m³/s. More than 14,000 m of workings have already been driven.

The authors’ proposals for changing the functional purpose of the object relate to the ‘Logistics Hub 10.0’ project, consisting of a high-performance network sorting node for new logistics centres operated by the Ukrposhta joint-stock company. The plan also envisages the opening of a re-training centre for coal industry employees, this to be managed by the regional employment offices. Ukraine’s international postal network suffers from having only one sorting centre in the city of Kyiv, this being connected to most of the regional sorting stations. This situation restricts the reliability of the mail delivery process and increases transit and sorting times. This degrades the quality of the service and increases overall costs while reducing the level of service provided. Ukraine’s status as a candidate for membership of the European Union, along with the active flow of goods across the country’s western border, calls for the creation of a second logistics centre in the western part of the nation. Moreover, given that paper correspondence (which the old postal network was mainly geared up for) has been overtaken, in specific weight terms, by commodity flows, there is a growing need for setting up a logistics hub for household goods. It is worth noting that the e-commerce market in Ukraine has significant potential and its projected growth in the pre-war period reached 23% a year. If JSC Ukrposhta is to compete on an equal footing with the Nova Poshta post and freight company (currently the market leader) when it comes to delivering goods on the e-commerce market it now urgently needs to establish a western logistics hub. The transformation of the company’s logistics in accordance with the developed model will enable JSC Ukrposhta to:

▶ Effectively deliver predicted shipment volumes – 65 million items in 2022 (pre-war forecast), 129 mil-
for the long-term storage of goods in the underground mine workings with their constant temperature levels as well as for the storage of goods (equipment) for dual purposes. The plan is not only to use the existing mine facilities, which will be equipped accordingly, but also to construct a number of hangar-type warehouses on the site (Fig. 5).

A methodology has also been drawn up to monitor and ensure the stability of the underground workings and to lay down parameters for reinforcing the existing arch supports and rockbolting systems. The total cost of the project has been estimated at around 100 million euros and the payback period is put at some 8 years.

**Conclusion**

The preservation of Novovolynska Mine No. 10 and the implementation of the project to create a logistics postal hub on its territory reveals a new, cost-effective potential for re-purposing the company’s surface and underground facilities. At the same time, making use of the underground space will safeguard the functioning of the mine workings and ensure that, in case of critical need, the mine can quickly be put into operation as a working installation.

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Postal Logistics Hub as a Coal Mine Restructuring Project – Ukrainian-German Ideas for the Post-mining Era


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**Motivation for Recovery of Nitrogen Oxides in the Mining Sector**

The extraction of copper from mineral ores is accompanied by the emission of large quantities of nitrogen oxides NOx. These are still often released into the atmosphere, but increased environmental sensitivity and legal requirements have now led to a rethink in the industry. The realisation that these exhaust gases can be turned into valuable raw materials if they are intelligently recovered is accelerating this reorientation and making companies look for innovative, sustainable ways.

A green technology based on natural materials to recover nitrogen oxide emissions is now being tested for use in copper extraction in Chile’s Atacama Desert. Nitrogen oxides are to be used for other valuable materials.

**Recovery Method**

Krajete GmbH specialises in the development of sustainable solutions for gas extraction and purification and optimises natural processes for use in industry. The company succeeded in developing a zeolite-based way to remove NOx from emission gases. Together with the German Audi AG, this technology has been optimised for use on internal combustion engines in recent years. The process is so flexible to use that it can be adapted to other – even large-scale industrial – requirements with little effort and also has potential for copper mining

**Change in reusable Materials**

But that’s not all. Krajete specialises in converting problematic emissions into valuable raw materials. The process therefore not only allows NOx to be filtered out of gas emissions, but even the recovery and concentration of these raw materials, which can then serve as a starting point for other valuable materials such as nitric acid. The principle of the Krajete technology is the physical binding of NOx to a specially prepared zeolite matrix. From this, the gases filtered out can then be recovered cheaply and easily in concentrated form. And the best thing about it, is that the zeolite survives this process completely undamaged and can be used again. It is a sustainable principle that turns waste gases into valuable materials.

**Practical Testing in Mining planned**

The simplicity and sustainability of the process also convinced the mining company’s technology scouts. They looked at a significant number of companies for solutions for sustainable recovery of the NOx emitted during copper extraction – and finally found what they were looking for at Krajete GmbH and its company motto “On behalf of Nature”.

If the process proves successful in this setting, gigantic plants are already being discussed for NOx recovery in copper production. But there is still a long way to go and the immediate plan is to test the Krajete process in the laboratory with real exhaust gases from copper production. After that, a test facility is to go into operation and be tested. Successful operation of the plant has great potential for environmental and resource protection and can be lucrative for mining companies.

**Dr. Alexander Krajete**

is the founder and managing director of Krajete GmbH in Pasching, Austria. His company develops nature-inspired solutions for the purification of gases and high-performance gas fermentation. Processes proven in nature are the basis for efficient and economical industrial processes.

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Conventional and mechanised Shaft sinking – System Comparisons and innovative Developments
Dipl.-Ing. Thomas Ahlbrecht, Redpath Deilmann GmbH, Dortmund, Germany

1 Introduction

For more than 100 years conventional sinking using the drill-and-blast system has been by far the most commonly employed method for constructing mine shafts. This technique is very flexible and can be used under all kinds of geological conditions.

By the 1970s and 1980s shaft construction had already become a highly mechanised operation. As most mine shafts were being sunk for the coal industry the equipment used for drilling and loading out the debris was generally powered by compressed air because of the need for explosion protection. The current technology of the time included compressed-air grabs, which were suspended on winches, and hand-held hammer drills, these later being superseded by drill carriages. This type of equipment could never have complied with today’s regulations and requirements in respect of workplace noise and dust, for example. Moreover, the performance levels of the time were well below those of current electrohydraulic units. These are some of the reasons why work is still under way to develop and improve the technology available for conventional shaft sinking operations (Fig. 1).

Mechanised shaft sinking has significant advantages as far as workplace safety is concerned and it also delivers higher daily rates of advance. However, the equipment required entails a higher level of investment and consumes a large amount of energy, while the assembly and dismantling times are also fairly significant – which means that a minimum sinking depth is needed to make the operation worthwhile. Nevertheless, conventional sinking with drilling and firing can still be justified at more shallow depths when the in-situ rock is very hard and when other relevant conditions are present. Weighing up the pros and cons of the two available methods and examining the innovative developments currently available can help when it comes to selecting the most suitable and effective technology.

2 Mechanised Sinking

Shaft construction companies have been working in partnership with various mining equipment manufacturers for decades to develop new technologies for the mechanised sinking of mine shafts from the solid. These efforts have been under way in North America, Europe, South Africa, Australia and Russia. The equipment in question has mainly been designed for soft to medium-hard rock. The results of the development work were not always successful. Removing the sinking debris is one of the greatest challenges facing mechanised shaft sinking operations. One possible solution for this dilemma was to deploy shaft boring machines operating in combination with a pilot borehole that allowed the sinking de-
bris to fall into the mine roadway below. However the pilot hole method cannot be used when the shaft is being constructed as part of a new mine project.

There are at present essentially two methods available for debris clearance in mechanised shaft sinkings, the second of these generally being the preferred system:

- Hydraulic clearance using a drilling head operating under water
- Pneumatic clearance with the cuttings being removed by suction.

2.1 Shaft Boring Roadheader (SBR)

Recent years have seen the introduction of a selective-cut shaft sinking machine with a cutting drum designed for soft and medium-hard rock conditions. This Shaft Boring Roadheader (SBR), which was developed by Herrenknecht AG, has been designed as a combined sinking machine and working deck system, there being no space in the shaft for an additional working platform. The first generation of SBRs was deployed in shaft sinkings in Canada for the BHP-owned Jansen mine. A second ‘improved’ generation was then developed in association with Herrenknecht and Redpath Deilmann (RD) (Fig. 2).

2.1.1 SBR in Action at Nezhinsky in Belarus

The Nezhinsky potash mine in Belarus commissioned two 8 m-diameter shafts to be sunk to a depth of 750 and 700 m respectively. The first 165 m of each shaft were to be constructed using the freeze method and each was to be lined with watertight tubbing supports to a depth of about 320 m [1]. The permanent shaft head frames were installed for the sinking phase in order to reduce the conversion and rebuild times needed after the shafts had been completed. Both shafts were sunk in parallel and an average daily sinking performance of 3 m was contractually agreed upon [2].

The two machines destined for Belarus were assembled and tested at the Herrenknecht workshops in Schwanau. Over a period of some four weeks all types of material were used to test out the suction technology in order to determine the system’s limitations.

The SBR operators were initially supplied by Herrenknecht and in the subsequent period training was provided by Redpath Deilmann. This approach was also used for machine maintenance. Redpath Deilmann and Herrenknecht took joint responsibility for the sinking performance of 3 m a day.

2.1.1.1 Sinking Equipment

The second-generation SBR weighs around 400 t and stands 11 decks and about 50 m in height (Fig. 2). The selective-cutting boom and system weight mean that the machine cannot be braced within the shaft but must be permanently suspended on ropes and winches. The SBR has an installed drive power of 2,400 kW and features a boom-type cutting head (Fig. 3).
The cuttings are removed pneumatically from the shaft floor using blowers with a 900 kW power rating. An in-board cyclone is used to separate the cuttings from the conveying air and the solid material is then hoisted to the surface in muck buckets [2].

The cutting drum, which is operated by a 600 kW hydraulic drive unit, has a diameter of 1.2 m and measures 1.5 m in width (Fig. 4). The cutting arm has a telescoping length of 1.2 m and can cut cavity diameters of up to 12 m. The machine is designed for the economic cutting of rock with a strength factor of up to 100 MPa. The cutting action can be automated and cross pattern or pizza pattern cuts can be made to a depth of 200 mm.

2.1.1.2 Site Equipment

Each shaft was equipped with two drum-type winding machines for logistics operations. One machine was used solely for dirt winding and one for manwinding and concrete transport. The SBR was manoeuvred using four winches each with a tractive power of 50 t. The four suspension ropes were each triple reeved, making a total of 12 ropes available for the deployment of the SBR in the shaft (Fig. 5).

As already mentioned, the permanent shaft head frames were also used for the shaft construction work. The steelwork was pre-assembled on site within about three months and the frames were then erected in just four weeks (Figs. 6 and 7).

2.1.1.3 Sinking

The sinking through the freeze shaft section passed without incident and advance rates of 0.2 to 0.33 m/h were achieved. A hydraulic support ring, which has been patented by Redpath Deilmann, was used for the first time and this system proved highly effective (Fig. 8). The concrete was set in parallel with the cutting process (Fig. 9). The concrete was installed some 12 to 15 m up from the sinking floor and was placed using 5 m-high formwork. The even wall surface created by the cutting process allowed the use of a part-mechanised formwork system.

Below the 165 m level the sinking and strata management operations became more difficult as a result of serious breakouts in the shaft wall (Fig. 10). The formwork system had to be shortened and deployed as close to the sinking floor as possible (Fig. 11) [2]. This meant con-
2.1.1.4 Current situation on site

After work was halted in the summer of 2021 both shafts (Fig. 13) were swamped by rainwater owing to the fact that the hoisting equipment had been dismantled.

Then it was all about chasing the metres in order to achieve advance rates well in excess of 3 m/d. In fact the sinking team did manage as much as 7 m/d, with the best monthly performances achieving 144 and 138 m of completed shaft (Fig. 12).

In summary it can be said that the second-generation SBR machine proved very effective and reliable – even when working in extremely poor geology. Advance rates of 3.0 to 4.5 m/d were possible under favourable strata conditions, while the machine achieved 2.5 to 3.0 m/d in the more difficult sections. The SBR performed well when it came to positioning the tubbing supports, although following the removal of the machine the shaft fittings had to be installed using a separate working platform.

Working conditions on the machines very much resembled a factory-like environment. This had a very positive impact on the on-site accident figures: a total of 3,225 tubbing segments were installed and only one finger injury was reported throughout the entire shaft sinking operation in Belarus.

2.1.2 SBR in Action at Woodsmith Mine in the UK

Woodsmith Mine is a new greenfield mining project for polyhalite extraction. The site is located in the north east of England near the North Sea coast and within the North York Moors National Park, where the fragile ecosystem imposes strict environmental standards (Fig. 16). The project commenced back in 2017 and has suffered significant delays. Redpath Deilmann has been in action on site since the autumn of 2021.

The two main shafts being sunk to access the deposits will each be 1,600 m in depth and will have a final...
diameter of 7.25 m. Both shafts will be lined with concrete over a length of 1,200 m. Tubbing supports will be used between the 750 m and the 1,150 m levels as exploratory surveys have indicated that this zone is highly water bearing and may exhibit pressures of up to 50 bar. The bottom landings that will provide access to the underground workings will be set up at a depth of 1,540 m. Both shafts will be sunk from a foreshaft 43 m in depth and 35 m in diameter (Fig. 17).

Because the site lies in a nature conservation area much of the winding equipment is installed below ground level and the mineral skips will be unloaded at a depth of about 300 m. Conservation requirements also mean that no mine buildings over 13 m in height are permitted in the area, while those that are visible at ground level must be designed to look like farmhouses. The raw mineral will not be raised to the surface at the shaft site and no ore processing facilities are to be constructed at the mine.

A 37 km-long tunnel with an excavated diameter of 6 m is therefore being driven to connect the shaft construction site to the port facilities to the north on the North Sea coast (Fig. 18). More than 20 km of tunnel have already been completed, this work being undertaken by just one Herrenknecht TBM.

A third shaft – the MTS shaft (material transfer system) – is to be constructed by drilling and blasting. This 9 m-diameter shaft will be 360 m in depth and will be lined with concrete. The foreshaft has already been excavated by a Herrenknecht VSM (vertical shaft sinking machine).

The two deep-level shafts are being constructed by Herrenknecht SBR machines, though these differ somewhat in design from those deployed in Belarus. Figs. 19 to 21 give some impression of the spatial conditions in the launch shaft during the different assembly stages. Figs. 20 and 21 show the pre-assembled SBR modules being lowered into the foreshaft.

The first machine started cutting in August 2022 and daily advance rates of around 2.5 m are now being achieved on an occasional basis. The second machine is due to commence operations in the first quarter of 2023 and both SBRs will then be operating simultaneously.
Conventional and mechanised Shaft sinking – System Comparisons and innovative Developments

Conventional Shaft sinking is employed in those cases where mechanised sinking would be too expensive or simply impossible. Constructing a shaft by drilling and blasting currently delivers an advance rate of about 2 m/d. This daily performance is in need of improvement. Conventional sinking by drilling shotholes and blasting has obviously been tested and employed longer than any other method – yet there is still room for further improvement and development.

2.2 Shaft Boring Cutterhead (SBC)

The Herrenknecht company is also working in partnership with Redpath Deilmann to develop machines with a full-section boring head for hard rock conditions. This will extend the options available for shaft boring in hard and very hard rock (Fig. 22). These SBC machines (Shaft Boring Cutterhead) are to be capable of cutting into rock with a compressive strength of as much as 250 MPa. The system is being designed for shafts of up to 2,000 m in depth and with a diameter range of between 7 and 10 m. The ultimate aim is to increase the daily advance rate to 6 m/d or more so as to reduce the construction time required for deeper shafts. As with the SBR, these machines will feature a pneumatic mucking system.

After much preliminary work and extensive pilot testing a 1:3-scale experimental rig began trial operations at the Herrenknecht workshops in September 2022 (Figs. 23 and 24). This installation is being used to test the cutting action and the floor-level clearance efficiency. Initial results indicate that the technology is headed in the right direction.
Working sequences that have to be repeated thousands of times need to be partially or fully automated.

### 3.1 New Shaft Excavator with Attachments

Loading the blasting debris and transporting it away constitutes the most time-consuming of all the operations that make up the drilling and blasting cycle and this area has the greatest potential for developing the technology further. Efforts here therefore need to focus on reducing the loading and transport times.

The RDS100 electrohydraulic shaft excavator, which does not operate on the shaft floor itself but rather is mounted on the working deck, was developed for precisely this purpose. This system is currently being trialled in a test shaft in Dortmund (Fig. 25). The excavator is shown in detail in the diagram in Fig. 26. All the control cylinders are fitted with sensor units that monitor the position of the machine in the shaft.

The shaft excavator can be fitted with a range of attachments that allow it to perform a variety of tasks (Fig. 1):
Summary and Outlook

Work is currently ongoing along a broad front in order to progress the development of new shaft sinking machines and equipment, the ultimate aim being to achieve effective and accident-free access to underground deposits. This is also being done in a way that is consistent with changing levels of commitment and risk preparedness on the part of the personnel involved.

Clients and contracting entities have an important role to play here. They have to endorse new technologies in the hope of achieving greater efficiency and improved safety levels, even when the new machines have still not demonstrated their suitability or can only do so after they have been deployed in the field. It is on this basis that we shall continue to achieve the kind of success in workplace safety levels and sinking advance rates that was recorded during project operations in Belarus.

References

This article is based on a paper presented at the 23rd Colloquium on Drilling and Blasting that was held in Clausthal-Zellerfeld on 1st and 2nd February 2023.


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Extracting Raw Materials from abandoned mine-waste Heaps in the Free State of Saxony – the ReMiningPlus Project for the environment-friendly Recovery of Recyclates from a Tailings Facility

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Dr Arite Werner, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Germany

1 Motivation

The resource potential of mining residues has been on the agenda of several development programmes in years gone by and is based on the resource management strategies laid down by European bodies, the Federal Government and the Free State of Saxony too [1, 2, 3]. Here the focus has increasingly shifted to the development of new sources for the supply of critical materials that are highly import dependent and extremely prone to supply chain risks.

One of these development programmes was ‘r³ – Strategic metals and minerals – innovative technologies for resource efficiency’, which was funded by the Federal Ministry of Education and Research (BMBF). This commenced in 2012 and was aimed at providing secure supplies of strategically relevant metals and minerals for the German economy. The relevant thematic clusters, which covered topics such as recycling, substitution and conservation, urban mining and evaluation and transfer, included a large number of projects, one of which was ‘SMSB – recovery of strategic metals and minerals from mining waste dumps in the Free State of Saxony’ (Fig. 1).

The aim of this project was to record the twenty largest mining waste dumps in the State of Saxony and to collate them in a Waste Tip Cadaster of Saxony. The ReMining-Plus project would then develop a facility for the recovery of recyclable materials from an actual tailings dump site.

2 Types of Heaps of old Mining

In mining a heap is an artificially created hill that contains either the extracted material itself or the barren discard, which is considered worthless. A mining waste site is therefore always the result of mining activity associated with the extraction of raw materials [4]. However, as these material piles may be assigned different names in the relevant technical literature the SMSB project set out to define the following three types of waste heap within the r³ waste heap cluster (Fig. 2):

- **Mining heaps**: Mining heaps are created by the accumulation of barren rock material that has to be removed from the ground by mining activity in order to access and extract the actual ore body. This waste product contains little or no reusable material and therefore is of no relevance from a raw materials point of view. These tips mostly comprise coarse stone and may at times contain several million tonnes of material, which makes them the largest bodies of their kind in terms of volume.
3.1 Research Work leading to a Review of Waste Dumps with a significant Recyclate Potential

As a result of an intensive research effort (literature, historical knowledge and archives) we now have access to a detailed survey of mining waste dumps that exhibit the greatest potential for re-mining and reprocessing. This overview contains information on the type of dump, its location, surface area and volume, the mining residues contained therein, the geological classification, the processing technology used, the stored materials and the mineral content.

3.2 Investigation of selected Dump Sites

Investigations were carried out at four dump sites that were selected on the basis of the following criteria:

- Processing dump tailings: Mineral processing dumps contain the residue material from mineral processing operations, which may involve flotation or various mechanical procedures such as magnetic separation. Heaps that are created from flotation residues are referred to as tailings dumps as the suspension from the flotation process is directly flushed onto the storage facility. The material in these tailings dumps mainly comprises sand and fine sand. As this residue is generally the result of primary ore extraction operations its recyclates content is usually higher than that of material in mining heaps. The recyclates content of the material will depend on the effectiveness of the mineral preparation process. The more effective the preparation process the lower the recyclates content of the residual materials. As the technologies used in previous years were never fully capable of extracting the valuable material from the ores the resource potential of these tailings dumps is fairly high. The Free State of Saxony is now home to old mineral processing sites from the GDR days that contain large bodies of mineral tailings that are similar in size to mining heaps. These legacy tailings constitute the State’s greatest potential source of recyclate material.

- Smelter dumps: Smelter dumps or slag heaps contain the waste material left over from the smelting of metal and ore concentrates and are always located near to former smelting works. They may also present a significant recyclate potential, depending on the effectiveness of the smelting process, though in Saxony their contribution will be of secondary importance. In the Freiberg area in particular this slag was often used as building material, which is why the slag heaps throughout the State of Saxony are fairly small in size [6, 7].

3.3 Exemplary detailed Investigation with innovative Modelling

The two waste dumps with the greatest recyclate potential were then selected for a detailed investigation. One of the sites in question was the David Schacht tailings dump in Freiberg. The investigation then called for a further nine exploratory drillings to be made to the base of the facility. Some 100 samples (each representing a core interval of 2 m) were taken from the total of ten drill cores and these were subjected to a detailed analysis in order to establish their chemical and mineralogical composition. The complex nature of this investigation programme is briefly outlined below.

The material had to be dried prior to analysis. As the David Schacht site contained sulphide material it was necessary to use a freeze drying process in order to prevent the sulphides being oxidised to sulphates. The analysis programme comprised a number of different methods, including:

- Mineralogical analysis (X-ray powder diffraction, mineral liberation analysis (MLA))
- Chemical analysis (WD-XRF spectroscopy (wavelength dispersive X-ray fluorescence spectroscopy) and elementary analysis (C, N, S) of sample powders along with ICP-MS after sample fusion)
- Particle size distribution (laser granulometry)
- Sample preparation (de-agglomeration, sample division)

The comprehensive analysis programme served to identify the resource potential of the two waste dumps selected for the exercise. Moreover, it was hoped that the project would help develop the most efficient and economic processing methods for strategic metals. Further tests in connection with chemical and biological leaching were also carried out in order to identify an effective process for dissolving the metal ions. The resulting concentrates were then further investigated in downstream metallurgical processes. The analysis findings were subsequently combined with a digital terrain model and historical maps so that a 3D model could be generated of the structure of the waste dump. This included using drones to overfly and survey the site. Additional data relating to
particle size distribution, mineral dispersion and liberation and the distribution of concentration were also used to create the model. The 3D model of the David Schacht waste facility depicted in Fig. 3 shows how zinc sulphide is distributed through the body of the dump.

The main aim of the modelling exercise was to visualise and quantify the suitability of individual target minerals for processing. Using the measured particle properties and their interpolation throughout the entire body of the waste dump it was possible to make a realistic assessment of the quantities of remaining recyclables (and contaminants) that could actually be extracted using the currently available technologies. This also provided a visual of how the extractable minerals were distributed through the dump and how they could be factored into suitable extraction concepts. The method is based on characteristic physical and chemical properties that are relevant in terms of the processing opportunities available. It provides a more realistic picture of the actual recoverability factor than previous methods. The latter usually focus on the volume and recycle content of the waste dumps and from this calculate a theoretical recycle potential that is based on a homogeneous composition. However technical limitations mean that this can never be fully achieved in reality. The new form of interpolated model allows the process-relevant properties to be input concurrently and in a weighted manner. This shows the extent to which the mineral-rich particles are available for the processing technology in question. The potential of the waste facilities can be realistically evaluated by this new type of model and this then allows conclusions to be drawn as to the economic and technological feasibility of the process.

3.4 Preparation of a Cadaster of the relevant Mining Waste Dumps in Saxony

The findings obtained from the SMSB project were used to generate a cadaster of the 20 most relevant mining waste dumps in the Free State of Saxony. This information was then combined that obtained from other r³ projects. From this a consolidated (r³) resource cadaster was produced that covered some 460 dump sites (as at January 2018). The knowledge that was acquired during the project phase as regards the methods for characterising, investigating and processing the waste dumps was compiled and published in a collective method-handbook [8].

3.5 Knowledge-sharing for a German Cadaster of Mining Waste Resources

After the project ended the data from the r³ resource cadaster were handed over to the BGR (Institute for Geosciences and Natural Resources) to be used as a basis for creating a central nationwide cadaster of mining waste resources. The waste-dump cadaster was supplemented with other available data on metal-bearing mineral residues from former mining activities, including uranium waste facilities and mining heaps under mining authority control. This nationwide data gathering process called for an exhaustive research effort. The Fraunhofer Institute for Environmental, Safety and Energy Technology and the Helmholtz Institute Freiberg for Resource Technology (HZDR-HIF) have been working on behalf of the BGR to develop a waste-dump cadaster [9]. This has involved consultations with the relevant authorities at both federal and local level. Providing reference data on mining waste dumps also meant analysing all kinds of cartographical material (from federal, national and local sources). This research involved sifting through archive material. All this highlights the complexity of the task at hand, and the challenges associated with it, as the data collected in this way were of quite variable quality and quantity. Moreover, the geodata had to be presented using a standardised description and a uniform data format had to be selected for this purpose. The collected data were stored as GIS data, processed in accordance with the INSPIRE Directive [10] and saved to a database. The data research and processing work resulted in a total of 2,377 waste storage sites of this kind being identified throughout Germany, each reference being filed along with further technical information [8].

4 The ReMiningPlus Project for maximising the Resource Potential using new Technologies

4.1 Background

One particular technology that has established itself in recent decades is the bioleaching technique, which is based on the biological conversion of an insoluble metal compound into a water-soluble form. In the context of the bioleaching of metallic sulphides the activity of aerobic, acidophilic Fe(II)-oxidising bacteria leads to the oxidation of metallic sulphides into metallic ions and sulphate. Sulphur oxidisers may also be involved in this reaction [11].

In ancient times and through the Middle Ages it was also recognised that metals could be released from mining waste heaps as a result of an exposure to air and precipitation. This process was also described by Georgius Agricola in his pioneering work de re metallica [12].
Table 1: Key data for the David Schacht and Hammerberg flotation ponds in the central Freiberg mining area [25]

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Formation</th>
<th>Sequence</th>
<th>Ores</th>
<th>Vein type</th>
</tr>
</thead>
<tbody>
<tr>
<td>First mineralisation cycle</td>
<td>gravelly-blende lead ore formation (eb formation)</td>
<td>gravelly (pyritic) sequence</td>
<td>pyrite, arsenopyrite, marcasite, galenite, traces of native gold</td>
<td>quartz</td>
</tr>
<tr>
<td></td>
<td>Zn-Sn-Cu sequence</td>
<td>sphalerite, chalcopyrite</td>
<td>Ag-bearing pitchblende</td>
<td>Ag-bearing quartz</td>
</tr>
<tr>
<td></td>
<td>Pb sequence</td>
<td>galenite (Ag-bearing)</td>
<td>quartz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>noble brown spar formation (eb formation)</td>
<td>sulphide sequence</td>
<td>Ag-bearing sphalerite, galenite, pyrite, marcasite</td>
<td>brown spar</td>
</tr>
<tr>
<td></td>
<td>Ag sequence</td>
<td>silver ores and native silver</td>
<td>carbon spar</td>
<td></td>
</tr>
<tr>
<td>Second mineralisation cycle</td>
<td>eba formation, only secondary</td>
<td>iron-baryte sequence</td>
<td>quartz (variety agate, amethyst), baryte</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fluorobaryte lead ore formation (eba formation)</td>
<td>hard vein (baryte-quartz sequence)</td>
<td>chalcopyrite, pyrite, limited silver ores</td>
<td></td>
</tr>
<tr>
<td></td>
<td>soft vein (main fluorite and calcareous baryte sequence)</td>
<td>chlorite, pyrite, limited silver ores</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bi-Co-Ni-Ag formation</td>
<td>arsenic sequence (rare)</td>
<td>native arsenic, native bismuth</td>
<td>quartz, fluorite baryte</td>
</tr>
<tr>
<td></td>
<td>(noble destinies, at lode intersections)</td>
<td>silver-sulphide sequence</td>
<td>silver ores, silver native</td>
<td>carbon spar, quartz</td>
</tr>
</tbody>
</table>

(Fig. 4). This is the first known reference to a procedure that we know as ‘heap leaching,’ which is now used around the world for treating mining waste material and for processing copper ores with a low metal content.

The fact that microorganisms are the main participants in the release mechanisms was only recognised in the twentieth century [13, 14, 15]. After evidence had been provided in a number of cases as to the significance of microorganisms for copper mobilisation from copper-bearing ores the first patent for such a process was taken out in 1958 by the Kennecott Copper Corporation mining company. This led to the setting-up of the first commercial heap leaching operation in the early 1960s [16]. Heap leaching plants are now state of the art for lean ores with a low primary metal content.

There have been very few industrial-scale projects of this kind for reprocessing mining waste materials and tailings. One such operation was set up in 2000 at Kasese in Uganda, where quantities of pyrite concentrate with a significant cobalt concentrate of 1.7 % were successfully extracted from a mining waste heap and leached in aerated stirred-tank reactors [17].

The BMBF-funded development programme ‘WIR! – change through innovation in the region’ also includes support for the consortium project ‘recomine – resource-oriented environmental technologies for the 21st century’. This initiative will seek to transform the Ore Mountains of Saxony into a model region for the future-oriented treatment of waste material from the mining industry. The ReMiningPlus project, which commenced in 2021, will run for three years and is specifically aimed at achieving this goal. The David Schacht tailings dump near the town of Freiberg, which is described in more detail in the section below, was chosen as the project site. Prior to this decision a significant amount of work had already been done (e.g. Ecometals 2014-2018 [18], SMSB 2013-2016, [19]; ReMining 2017-2021, [20]) to investigate the resource potential of the site and to develop modules for processing its contents.

4.2 Project Site: the David Schacht Tailings Dump

4.2.1 The Freiberg Mining Area

Mining has been practised in the Freiberg area since the 12th century and this continued right up until the final third of the 20th century. This industry was essentially based on the area’s polymetal Ag-Pb-Zn vein deposits, with silver, lead and zinc being mined right up until all operations finally ceased in 1969 [21, 22].

The Freiberg deposits are located in the northeastern part of the Ore Mountains. The area around Freiberg is composed of grey orthogneiss and is known as the Freiberg gneiss dome, this consisting of a medium to coarse crystalline biotite double-feldspar gneiss. The starting materials for this gneiss were the magmatic rocks of granodioritic composition that intruded during the Upper Proterozoic period. Metamorphosis, and with it tectonic superimposition, then took place in conjunction with the Hercynian orogenesis in the Lower Carboniferous and the alpidic orogenesis in the Cretaceous period [23].

Some 1,100 ore veins have been documented over the entire area of the Freiberg deposits. These can be...
allocated to two tectonically and chronologically different shear-fissure systems that owe their origins to the tectonic inventory of the Hercynian orogenesis (1st mineralisation cycle, 1st fault system) and the alpidic orogenesis (2nd mineralisation cycle, 2nd fault system) [24]. The most important formations, ores and minerals are given in Table 1.

### 4.2.2 Waste Dumps within the David Schacht Complex

Ore mining over the years has left a large number of legacy waste dumps, one of these being at the David Schacht ore processing site. The David Schacht Complex itself comprises a series of mining waste dumps that can be divided into three separate zones, namely a coarse mining waste heap (with the David Schacht surface facilities) and two tailings dumps – the David Schacht tailings facility in the north and the Hammerberg tailings site in the south (Fig. 5). The tailings storage sites are the result of the final stage of the mining operations that lasted from 1937 to 1969, when low-metal ores were processed using flotation methods and the processing residues (tailings) stored on site (Table 2). Between 1951 and 1964 some 50,000 to 70,000 m³ of flotation tailings were flushed into the storage pond at the David Schacht site every year when the plant was operating normally. When the maximum storage capacity was reached in 1964 a new tailings dump was established (the Hammerberg site) in order to maintain the flow of material from the flotation plant. The Hammerberg facility started up in 1964 and remained in operation until 1969.

### 4.2.3 The David Schacht Tailings Site

The David Schacht tailings facility is described in greater detail below. The site was in operation from 1951 to 1964. According to [23] the tailings dump known as ‘Am Davidschacht’ was set up in the northern extension of the David Schacht coarse mining waste heap (Fig. 6). The eastern dam was composed of large-size mining discard. Tipping this material created a natural slope angle of 40°, which was very steep and therefore deemed to be of limited stability. The western slope was formed by a pioneer dam constructed from coarse mining waste material, though this only extended over the basal section of the facility. Every four metres in height after this, as the tailings were discharged into the dump, a berm of rinsing sand was constructed so that in its final state the structure comprised three berms 3 to 4 m in width. These raised banks had an average slope angle of 30 to 35°. A reclarification and rainfall collection basin was set up in front of the eastern embankment in an existing valley area. The base of the storage pond originally lay at least 385 m above sea level and when rinsing ceased the authorised height was initially about 415 m above sea level (reached in 1963).

The main constituents were fine-grained flotation tailings with quartz, feldspar and sheet silicates, with the sulphides pyrite, arsenopyrite, sphalerite and galena as minor constituents [27].

As the flotation plant only ever achieved metal yields from the ore of 60 to 80% during the time the settling pond was in operation the rinsing sands now contain 0.5 to 1.5% zinc and 0.3 to 1.0% lead, along with arsenic and cadmium [28]. Moreover, due to the indium content of up to 3,800 ppm in the sphalerite of the Freiberg deposits the tailings material also contains between 5
and 70 ppm of indium. The indium takes the place of zinc and according to Table 2 the David Schacht tailings dump is thought to contain about 31 t of indium [29].

No specific surface sealing measures were put in place at the tailings dump after the rinsing operation finally came to an end. Some landscaping work was done and the site was simply covered over with materials of different origins (construction waste, excavated earth and coal industry residues). Recultivation measures, which were carried out after mining operations ceased, proved to be less successful because of the very low pH values involved. Nevertheless, the plateau of the waste heap has grown over again with vegetation due to the ongoing process of natural succession and the extreme conditions present at the site (enhanced levels of heavy metals and low pH values) have caused unique biotope types to develop and rare species to settle there.

4.2.4 Project Concept

The project concept is shown in simplified form in Fig. 7. The tailing sands from the David Schacht site are taken up and concentrated using a new flotation agent before being leached out by iron- and sulphur-oxidising microorganisms. The leaching solution is separated from the leaching residue and both products are then reprocessed. The existing modules from the previous projects were to be assembled together and added-to for this purpose. The bioleaching module and the recyclate module are shown in Figs. 8 and 9 respectively. For the ReMiningPlus project the existing plant has been retrofitted with an environmental module in order to complete the materials cycle. The environmental module is connected downstream of the materials module within the process chain and is used for the final elimination of pollutants from the process solution. What is special about this set-up is that it is all housed inside shipping containers. This pilot installation is therefore semi-mobile and can be used to carry out similar tasks at other sites (Fig. 10).

Both solid residue and liquid material flows are produced throughout the process. From a cycle management and resource efficiency point of view the primary objective is to generate as little waste as possible, and ideally none whatsoever, but rather to demonstrate recycling solutions for both the solid and the liquid waste material. The process water from the environmental module, for example, is to be re-used for the bioleaching process, in other words it will be returned back to the start of the process chain. The residue from the bioleaching process is also to be analysed to determine whether it can be used in the building materials industry. One of the special features of the ReMiningPlus project is its holistic approach to metal recovery, contaminant immobilisation and environmental remediation at the David Schacht dump site – something that is very much in keeping with international efforts to develop a controlled tailings management process.

Special software is used to replicate the technology in model form and to evaluate it with the test data. The aim is to carry out model calculations with comparable material and to assess the economic viability of using geobiotechnological methods for the re-processing of a mining residue.

The project was accompanied by a public outreach programme aimed at increasing raw materials awareness.
Information on raw materials, for example, should be made available to the public in an easy-to-understand language by way of environment-oriented educational events that focus on sustainable development. The aim of all this is to improve people’s awareness of natural resources and to draw attention to the potential of innovative methods for extracting indigenous raw materials from disused mining waste dumps. The idea of organising environment educational events focused around ‘mining and raw materials’ has been developed by trialling new proposals face-to-face using online surveys and interviews. Two info panels detailing the results of the project work are also to be set up at the project site. The processing plant can serve as a demonstration unit for promoting a greater understanding of raw materials production processes. This can be supplemented by an app or website designed to provide information on mining-relevant themes.

5 Outlook

Raw materials and their production is a subject that not only holds considerable potential for conflict but also brings with it a great deal of emotion, especially when it comes to the impact of raw materials mining [30]. What has also become apparent in recent years is that our society needs to move towards an ideology-free awareness of natural resources that is based not on fear and anxiety but on knowledge and proper information.

The NIMBY effect (‘not in my backyard’) also applies here. While people clearly accept that mining as an industry is essential for maintaining prosperity, they do not want to see it happening too close to their own ‘backyard’ [31]. Germany’s dependence on imports of raw materials and the dreadful working and environmental conditions that exist in third countries have only gradually become public knowledge. Supply chain verification has now become a legal requirement. And as Germany does not have significant reserves of strategic primary resources of its own it would be well worth while investigating whether the legacy residues from earlier mining activities have the potential to supply our needs – and not only now but in the years ahead.

6 Acknowledgements

I would like to express my thanks to project-partner staff members and my own colleagues at G.E.O.S Ingenieurgesellschaft for their help and support:

- Dr Arite Werner and Philipp Büttner – Helmholtz Institute Freiberg for Resource Technology
- Sabine Meißner – SAXONIA Standortentwicklungs- und -verwaltungs mbH
- Ronja Puschmann and Eva Pretzsch – GEOPARK Sachsens Mitte e. V.
- Jörg Döring – Kaden & Döring OHG
- Dr Frank Haubrich and Sebastian Braune – G.E.O.S Ingenieurgesellschaft mbH.

The project ‘Facility for the recovery of recyclates from sulphide tailings dumps and their sustainable remediation (ReMiningPlus)’ is being funded by the Federal Ministry of Education and Research (BMBF). WIR! – Change through innovation in the region.

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