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Tunnelling • Mechanised driving • Hard rock • Risk • Cases of damage

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Tunnelling • Major project • Immersed tunnel • Concrete • Construction operation • Denmark

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Mining • Technology • Innovation • Roadmap • Future mining

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Mining • Salt • Mining machinery • Drill and blast • Continuous mining

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Mining • Tunnelling • Conveying technology • Monitoring • Maintenance • Digitalisation

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Energy supply • Storage • Gas • Strategy • Research • Russia • Europe
Digital transformation is not as easy as it seems. It has to start in our brains with fresh and lateral thinking. Thinking function and integration of the software development from the beginning are key success factors.

**Digitalisation • Automation • Lateral thinking • Mining • Software development • Cooperation**

**Digital Transformation**
Dr. Christoph Müller, Mobiletronics GmbH, Ladbergen, Germany

In today’s IT world, we permanently get flooded by all kinds of buzzwords and new mostly marketing related slogans. Also “Digital Transformation” or “Digitalisation” may be regarded as such temporary buzzwords.

And is “Digital Transformation” really something new? For more than 20 years we have talked about automation in mining. The world’s first fully commercial autonomous uphole drill rigs were put into operation at LKAB in Kiruna, Sweden in 1998. We have also been using computers for years, impressively visible by the conference for "Applications of Computers and Operations Research in the Mineral industries” (APCOM) which started in 1961 and recently was staged for the 39th time in Wroclaw/Poland (please see Figs. and box).

Already at the beginning of the 2000’s, the former head of automation at LKAB, Irving Widgén, coined the phrase “a mine is a moving raw material factory”. What was meant was he was considering applying as much of the factory and process automation as possible to the underground mining environment and running an underground mine like a factory. In contrast to a static factory however, a mine as the “moving raw material factory” is being built at the same time while the existing factory is operating. And the operation constantly moves into the newly built areas.

**Holistic View**

Regarding a mine as a “moving raw material factory” means that a holistic view of the entire operations is needed: Up to now we have regarded automation as an "on top" addition to an existing machine. Related to mine operations, we were used to isolated shift and task based thinking. Now we need a holistic view: I tried to express this as “Mining Process Optimisation will be the next big step change in mining after mechanisation and automation” in my keynote to the APCOM in 2005, long before the word „digitalisation” was created.

This transformation, however, is not as easy as it seems. It has to start in our brains: It is related to all levels from the geologist to the final product. We have to stop thinking in single isolated responsibilities, departments and cost accounts: Small savings on one issue may often cause an enormous amount of collateral cost somewhere else in the operations. Interdisciplinary competence is needed together with fresh and lateral thinking as well as the use of off-the-shelf and standardised technology wherever possible to enable digital transformation at reasonable cost.

“Digitalisation” also has a big impact on equipment manufacturers: Now they are facing at the same time demands on integration of the machines into overall mining processes and the trend towards e-drives. Therefore, a customer-centered functional and operational approach is needed rather than selling big amounts of standard products: Through highly modular and component-based product structures they have to find answers to increasing demands on customisation: How are the machines integrated into the IT infrastructures of their users? How can the operation time of a battery powered machine be adjusted to the individual operation cycles of a specific mine? With a fresh and free-thinking approach this need for customisation and service is a huge chance especially for smaller manufacturers who do not need to care about the history of a huge legacy portfolio.

**Our Thinking has to change**

Regardless of mine or equipment supplier: Our thinking has to change towards a top-down holistic and function-oriented view: The most expensive part in digital transformation is the development cost for soft-
due to functional errors detected during the automation phase. And logically the software was then blamed for never being ready in time!

If we start thinking function first (which in the end means software) and then design everything else around the functionality, we speed up the design, use the most recent technology and reduce cost! A good example for this kind of thinking is the StreetScooter, a small electric delivery truck for Deutsche Post, originally produced by a spin-off from the RWTH in Aachen: The developers were urged to question everything in traditional vehicle design by adopting a “think different” approach resulting in a successful product which big automobile manufacturers now envy.

Important Mining Country Poland and Katowice Fair

As this issue is also dedicated to the Katowice fair in Poland, one of Europe’s most important mining countries, I would like to direct the “think different” concept to our Polish readers as well: Coal will also be needed in the future for other purposes than energy like for the production of high quality carbonised steel. I am deeply convinced that if the operation of the mines is reviewed by open and straightforward lateral thinking openly using experience from all over the world they also can be operated efficiently and to an ultrahigh degree “digitally” and autonomously. Also the Polish equipment industry is known for manufacturing very robust and reliable equipment. If “digitalised” using modern functional design as well as on-board IT and services backing the equipment, there is a lot of potential on the world market!

Paradigm Change

All players in the industry who understand the paradigm change towards digital transformation as well as compatible thinking and who actively team up with technology suppliers and academia will be very successful in the years to come!

Yours
Christoph Müller

APCOM
APCOM means “APplications for Computers and Operations research in the Minerals industries”. This series of bi-annual conferences founded in the early 1960’s is held in varying locations around the world. Through the strict paper peer review it is the leading high-quality discussion forum for innovations in mining related to IT and mathematics with a well-balanced mix of academic and industrial participation. The next conference will be hosted in South Africa in 2021.

More Details: www.apcom.info

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Hard coal mining has become a thing of the past in Germany. But it has always fostered technology. Thus, engineering companies, which stemmed from mining, nowadays apply their knowledge to other sectors. We are confronted with mining know-how all over the world and its story is one of success.

Maik Tiedemann, the CEO of the Essen Company DMT GmbH & Co. KG maintains “He who is aware of the depths of the earth, fears neither the expanses of space nor global technological challenges, which can be confronted and resolved through engineering skills”.

The company sees itself as the leader in the engineering segment of the TÜV Nord Group (Fig. 1). Its roots stretch back to the year 1737, when the first organisation to improve safety in mining in Germany was established. Today, DMT embraces 14 companies with more than 30 subsidiaries throughout the world. Around 1,000 employees generate an annual turnover of 120 million euros involving more than 10,000 projects in over 150 countries.

**Safety of Ropes**

Lives depend on the cables that hold roofs, bridges or offshore floating cranes. The Bochum Rope Testing Centre – the DMT test lab for non-destructive and destructive testing – tests and analyses ropes and caters for their safety (Figs. 2+3). It was originally developed for mining, where hoisting ropes secured the transport of coal and material as well as manriding. Now, this know-how is used to the advantage of major structures involving suspension, tensioning and traction ropes throughout the world.

The Essen Company DMT GmbH & Co. KG demonstrates with engineering performance that methods derived from mining are extremely versatile.

**Mines • Safety • Knowledge transfer • Lateral thinking • Companies • Services**

The 135 m high “London Eye” Millennium Wheel, the biggest of its kind in Europe, can carry up to 800 passengers during a single rotation (Fig. 2). The operator has regular tests carried out on key components as a protective measure. DMT undertakes long-term fatigue tests on samples of an original “rotation rope” in its Rope Testing Centre thus contributing to the safe operation of the cult attraction.

DMT is also responsible for testing the cables of the 40.5 ha roof area – the world’s largest – of the Hajj Terminal at Jeddah International Airport, as well as what was formerly the world’s longest suspension bridge, the Brooklyn Bridge in New York. It was the first such bridge to use supporting ropes made of steel.
In addition, DMT tests the spectacular roof of the 90,000-capacity Wembley Stadium in London, which can be opened or closed within an hour. It is borne by a 135 m high arch structure, that is visible from afar. This extends for 315 m above the arena, making it the greatest clear span worldwide.

Beneath the sea, the Rope Test Centre diagnoses the “Big Hydra” ropes, which link offshore crane ships, responsible for laying pipelines at a depth of 2,000 m, with the seabed in the Gulf of Mexico.

**Measurement Technology for Excavations**

However, DMT’s actual home lies in the earth. If tunnels are driven through rock or below the seabed, even the slightest deviations can result in high costs or endanger people’s lives. The world’s longest underwater tunnel – the Channel Tunnel – was opened 25 years ago beneath the Straits of Dover between France and the UK. It is altogether 50 km long, 37 km of which lie beneath the sea. Two tubes were driven – one from the mainland and one from Britain. As Maik Tiedemann points out they would have been seriously misaligned at the breakthrough below the Channel, if the tunnellers had not had the support of the DMT precision measuring device Gyromat (Fig. 4).

Thanks to this instrument the prescribed direction for tunnelling is continuously checked to ensure you arrive exactly where you want to be. Gyromat is based on the most exact fully automatic surveying gyroscope to determine geographical north. The explosion-proof system originally devised for underground roads in mining operates with high precision with an extremely slight deviation of a maximum of 1.2 cm per km.

As a result, this international leading measurement technology is applied for many tunnel excavations: in the Gotthard Base Tunnel, the Himalayas, at the Brenner, in Hongkong, at the Cern particle accelerator in Geneva, for the megalithic temples on Malta, for waste water tunnels in the USA, hydro power plants in Lesotho and Iceland as well as in many metro projects. The Gyromat clearly harbours a monopoly on knowledge from Ruhr mining.

**Monitoring the Düte Bridge near Osnabrück**

Since 2015 the Düte Bridge on the A1 motorway in Germany has been completely renovated while still operational. Circumstances require the existing structure to be monitored and keep traffic moving on the residual portion of the bridge. DMT was commissioned to tackle this project and deployed the Online Monitoring Platform Safeguard (Fig. 5), which supplies an exact picture of the actual state of the bridge as well as important pointers on its structural integrity by means of a large number of geotechnical and geodetic sensors.

In this way, the safety of man, machine, material and the structure itself is assured. Actually, the monitoring of bridges is only one example of applying monitoring solutions on the part of DMT. Loading cranes, buildings, waste dumps, machines, boilers – essentially all objects, in which a sensor can be integrated, can be incorporated in the online platform (Fig. 6).
Conclusion

Even although hard coal mining is a thing of the past in Germany: the technical know-how acquired pertaining to safety over decades pays dividends throughout the world today. The culture-steeped force of German hard coal mining continues because its fount of knowledge is applied in many ways thus catering for innovation. DMT risk and project management exudes confidence: “If it is feasible, we’ve probably done it already”.

DMT has thus shown that transformation can be successfully brought about so that today it is in great demand as a provider in the markets of plant construction and process engineering, infrastructure and the construction sector and of course, when it comes to raw materials by dint of the engineering and consulting expertise it still possesses.

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Fig. 6: Manifold possibilities for deploying the Online Monitoring Platform Safeguard
Photo: DMT GmbH & Co. KG

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New Diaphragm Cut-off Wall for the Rosshaupten Dam
Stefan Jäger, Bauer Spezialtiefbau GmbH, Dachau, Germany

Idyllically located at the foot of the famous Neuschwanstein Castle, Forggensee in the Allgaeu region is the fifth largest lake in Bavaria, with a surface area of approximately 16 km², and is the largest reservoir in Germany in terms of surface area. The structure has been in operation since 1954 and dams the water of the Lech river from Fuessen to Tiefenbruck. Forggensee serves as flood protection along the entire Lech and for the uniform regulation of its flow. In fall and winter the lake releases water to the Lech river, which is particularly important during fish spawning time. In spring it absorbs the water from melting snow and prevents regular flooding. Additionally, the Forggensee lake today represents a popular tourist destination far beyond the local region. To prepare the Rosshaupten Dam for the future, the power plant operator Uniper Kraftwerke GmbH commissioned Bauer Spezialtiefbau GmbH with renovating the inner seal of the dam.

Parallels between the Sylvenstein Dam and the Rosshaupten Dam

About sixty years after their construction history is repeating: both the Sylvenstein Dam and the Rosshaupten Dam became operational in the 1950s and were modernised consecutively within a few years. Recently, a diaphragm cut-off wall was built as a new sealing element in the existing dams. The construction of the two dams was an outstanding technical achievement for the time, and the modernisation according to today’s standards also represents a spectacular challenge, in which the latest diaphragm wall equipment was used in order to solve the difficult construction tasks. Both sites are similarly constructed – in both the Sylvenstein Dam and the Rosshaupten Dam on Forggensee (Figs. 1 + 2) the retaining structure is an earthfill dam approx. 40 m high with a supporting body made of gravel and boulders and a centrally located sealing core made of material with a high cohesive content, such as loam and clay. As part of the modernisation, the consultants and designers decided to renew the internal seal with a diaphragm wall that is 1 m thick and approx. 70 m deep. Both diaphragm walls needed to be constructed from an extremely narrow dam crest. Additionally, they needed to be embedded not only in the earthfill dam body but also into the dam base-foundation level and executed in a two-phase process.

Two-phase Method

During execution of the two-phase method, the trench is excavated with the supporting effect of a slurry made of bentonite and water (Fig. 3). Then the slurry-stabilized trench is filled with the diaphragm wall building material from bottom to top in the contractor method. In the process, the stabilizing slurry is displaced upward and pumped away. In terms of elements, this results in a new internal seal made of so-called clay concrete or soil concrete often also called plastic concrete. The new sealing element should ideally have a similar rigidity as the existing sealing core. The plastic concrete itself consists of sand and gravel with a very small maximum grain size of only 8 mm. A distinctive characteristic of the plastic concrete was the high percentage of clay, with approx. 350 kg/m³, and the far lower cement content of only approx. 80 kg/m³. With this recipe, the cut-off wall construction material takes on the desired characteristics: a low permeability value for water and a low E (deformation)-modulus, which also determines the rather low compressive strength of the plastic concrete of only approx. 1 MN/m².
Cut-off Wall Construction

The walls for both the Sylvenstein Dam and the Rosshaupten Dam were executed in single-trench elements (Fig. 4). At 3.2 m, the length of each single trench corresponds with the width of the diaphragm walling grab and the trench cutter. To connect the individual trenches to a wall, the pilgrim-step method was applied, which is often used in specialist foundation engineering. First two primary panels with a gap of less than 3.2 m between them are excavated and concreted. As soon as the plastic concrete of the primary trenches has stiffened, the gap is closed with a secondary panel. In the process the secondary panel cuts into the adjacent primary panel and connects them to a continuous wall with two closed joints. A trench cutter is ideal to execute these secant or overcut joints extremely well. The teeth of the cutter wheels cut the flanks of the young primary trenches cleanly and roughen them. The fresh plastic concrete of the secondary trench is applied to the rough surface and interlocks to form a joint that is almost completely impermeable to water. The size of the overcut of the trenches depends on multiple factors: A large overlap provides more reliability, because the overlapping of the trenches is still sufficient even if there are deviations in the joint. However, a smaller overlap is much more economical to execute and reduces the construction time due to the more rapid progress. At the same time, a smaller overlap requires that all panels be excavated vertically with high precision. This means that even during the trench excavation it is necessary to monitor precisely how much the diaphragm walling grab or the trench cutter deviate from the plummet. To do this, two independent methods for surveying the trench during the excavation are used, which monitor each other.

Measurement Technologies

Inclinometers are installed both in the grab and in the trench cutter, which indicate initial reference points about the verticality deviation of the excavation tools. In addition, the CIS and GIS systems, which were developed by Bauer, are used. These abbreviations stand for the “Cutter Indication System” as a control system for the cutter and the “Grab Inclination System” as a system for determining the position of the grab. Both systems utilise a state-of-the-art implementation of a principle that experienced diaphragm wall builders have been using for a long time to detect severe deviations: The inclination of the wire ropes to which the grab or cutter are attached provide information about their exact position in the trench. For CIS and GIS, a tachymeter records the position of the aboveground section of the wire ropes three-dimensionally in space (Fig. 5). Similar to a vector, the aboveground direction is extrapolated downward in order to calculate the subsurface position of the tool in the trench. Therefore, at regular intervals the excavation with the grab or the cutter is interrupted, and the current position of the excavation tool is determined and compared with the specified target position. If it is determined that the trench is showing a tendency to deviate, it is possible to react immediately before the
deviation becomes too great. If the grab deviates too much during the excavation, the trench cutter takes over the excavation of the trench a little earlier. As a result of the continuous operation method of the cutter and its effective steering flaps, the course of the trench can usually be corrected much more quickly than would be possible with the grab.

This principle clarifies the division of application of the two diaphragm wall devices. The top 40 m of the dam from the crown to the contact area of the dam was excavated using a Bauer DHG hydraulically operated diaphragm walling grab. The Bauer MC 64 duty-cycle crane, which had already proven itself on the Sylvenstein Dam site, was used as a base machine (Fig. 6). The diaphragm walling grab was optimally suited for excavating the trench in the dam body because the high closing forces of the hydraulic grab loosened the cohesive material of the sealing core very well. The switching of the two pieces of equipment went according to plan as soon as the trench had been sunk to the foundation surface of the dam.

**Subsoil**

The solid rock on which the Rosshaupten Dam was built is made up of alternating claystone and marlstone layers, permeated by bands of sandstone and also coal in some places. The distinct stratification of the rock below the dam is characteristic. The molasses layers often alternate at an interval of a few centimeters and there is rarely a layer that is several decimeters thick. Tectonic deformations have folded the layers of sedimentation stone almost vertically, frequently resulting in the formation of crevices. The undecomposed bedrock on the Rosshaupten Dam exhibits compressive strengths of between 8 and 85 MN/m². Compressive strengths of approx. 35 MN/m² have been measured in most solid cores from exploration drilling. Via the measurement system installed in the dam and at the foot of the dam, experts ultimately arrived at the assessment that individual crevices in the rock became more and more aquiferous over the years, and that a downward current of the dam would be possible as a result – a scenario that has already come to pass in places. The experts and designers therefore proposed a deep diaphragm wall as an additional internal seal. Using a current model it was determined that the new cut-off wall had to be constructed up to 30 m into the rock below the dam so that the hydraulic gradient remained within a range that was not harmful to the structure.

**Using the Trench Cutter**

With the help of a trench cutter, a cut-off wall can be produced over larger stretches in rock economically and with high quality (Fig. 7). The special challenges in Rosshaupten were multifaceted: half of the diaphragm
cut-off wall totaling 13,000 m² in size had to be embedded in the rock, and at the same time only a very narrow dam crest was available as a working area. During the construction of the diaphragm wall on the Sylvenstein Dam in 2012, the latest trench cutter at the time was used to produce the diaphragm wall in the middle of the dam crest. During the construction project on the Rosshaupten Dam the main challenge was even greater, because the diaphragm wall is not in the middle of the narrow dam crest, but instead is shifted toward the upstream face. The reason for this is the contact area of the dam, because there is a wedge-shaped drainage layer in the downstream half of the dam between rock and sealing core. A diaphragm wall planned in the cross section of the sealing core would have met or cut into the drainage layer over almost the entire length of the dam. To prevent this, the axis of the diaphragm wall was shifted by about 3 m toward the upstream face. This resulted in the available working surface on the dam crest being substantially reduced so that the diaphragm wall rigs could not be positioned to ride over the trench. There was only an approx. 6 m wide strip next to the diaphragm wall as a work surface for the grab, cutter and auxiliary tools – far too narrow for a trench cutter with a standard operating position. However, thanks to the latest generation of Bauer trench cutters, the cut-off wall was produced in the desired position, without widening the crown of the dam: the base machine, a Bauer MC 96 (Fig. 8) duty-cycle crane with the Bauer HDS-T hose drum system, was equipped with a turning device so that the BC 40 trench cutter could be rotated on its own axis. This made it possible to align the cutter parallel to the undercarriage even when the upper carriage of the duty-cycle crane was only partially pivoted. The diaphragm wall could only be executed for the project in Rosshaupten in this special rig position (Fig. 9).

**Conclusion**

The work on the diaphragm wall was done in 24-hour operation. Even during the winter months, work was not interrupted and it was possible to proceed according to schedule. The specialist foundation engineering work was completed in spring 2019.

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How the Gabion Construction Method developed

Man has learned to make use of available resources as the natural landscape has become transformed into a cultural one. In order to develop steep sloping plots of land for agricultural purposes in an optimal manner, they were terraced with drystone dikes (Fig. 1). It was soon discovered that this enabled erosion and working the land to be mastered. Furthermore, these walls were also available for storing heat thus improving the microclimate. In addition, useful small forms of life could find space to live in the nooks and crannies of the walls, resulting in a functioning eco-system. Today, in our increasingly more technological world, we describe such impacts as “win-win situations”, which need to be created artificially through a great deal of effort. In the course of many years, the art of making drystone dikes has been perfectioned. The stones have to resist the elements to be able to withstand constant frost-thaw cycles. In addition, a functioning drainage system must be installed so that no water pressure acts on the rear side of the wall. In the Alps, initial findings have been made in conjunction with erosion protection measures. The available stones could be set in a wire basket structure without having to be specially processed. However, the mass of stones is only guaranteed to hold together for as long as the wire structure wards off corrosion. The duration of this disintegration process depends on the surrounding conditions and first and foremost, on the properties of the wire material (Fig. 2).

In Switzerland in the 1970s, welded wire lattice mats with a more effective corrosion-resistant coating made of Galfan – an alloy consisting of 95% zinc and 5% aluminium – was developed. Preformed welded eyelets enabled the lattice mats to be formed into cubic, closed blocks, which provided structures that looked really aesthetic. As people became more environmentally conscious, such gabion retaining walls increasingly replaced traditional concrete retaining structures. Furthermore, they proved to an economic alternative (Fig. 3).

Need for Sets of Rules

As the number of gabion structures increased, major differences in quality became evident. Even some relatively low structures revealed large self-deformations while being produced (Fig. 4). As a result, some of them had to be removed immediately after being set up. Others delighted the client and the observer by fitting in aesthetically with the existing landscape. This resulted in the question being raised of how satisfactory structures can be produced in the long term. Public authorities in their role as clients realised the necessity for sets of standards. As a consequence, a code of practice containing basic...
requirements was worked out and subsequently revised after a number of years [1, 2]. Thanks to the initiative of the federal Land (state) of Bavaria additional specifications were drawn up dealing with stones used for filling and wire materials [3 to 5].

**Further Development of the Gabion System**

At the beginning of the new millennium, the Hoy Geokunststoffe GmbH, Kesselsdorf contemplated possible improvements in the quality of materials and manner of construction of their gabion systems. In this connection, it was intended to first of all, improve the corrosion-resistant coating to such a degree that concrete conclusions could be drawn about damage to the coating during installation due to the use of hard stones for filling purposes in some cases. Furthermore, all the individual steps for producing the structure had to be described in such a way in order to provide a “standard construction method” comparable with a concrete structure.

Test series were embarked on to improve the properties of the wire coating. The idea was to discover whether better protection can be provided against damage caused by stones, when they are installed, as well as higher resistance to thawing salt if other metallic additives were used in the coating. The coating used up till that point in time comprising 95% zinc and 5% aluminium was exactly at the so-called eutectic — in other words, the mix ratio of the alloy, at which it starts to smelt at the lowest temperature and the lowest amount of energy. Thanks to extensive series of tests, a coating ratio with a higher proportion of aluminium and improved ductile behaviour for processing the wires were come up with. As a result, the service life of structures is substantially increased in comparison with a conventional coating of the same thickness. In addition, it could be shown that the mechanical strength of the welded connection was just as good as with a conventional covering. As the eutectic no longer applies owing to the higher share of aluminium in the alloy, a higher smelting temperature is needed, something leading to a more homogeneous covering. Surprisingly, it was shown that this coating reacted substantially better to the effects of installation and salt. As a consequence, this promising coating was patented and is currently being marketed under the brand name “Bezinal 2000” [6].

**National Technical Approval**

Against this background, talks were held in 2006 with the official approval body, Deutsches Institut für Bautechnik (DIBt) in Berlin, to apply for a National Technical Approval. This approach to establish new construction methods has proved itself in the past, for example, for soil nailing. Numerous questions arose during the talks, which in part, only appeared solvable with the Federal Institute for Materials Research and Testing (BAM), Berlin, and other test institutes. In late 2008, the Hoy Geokunststoffe GmbH tabled an official application for approval. For this purpose, a list of questions or rather a specification sheet was drafted:

- Essentially the structure must be “calculable” like every retaining structure in the building industry. In other words, serviceability and load-bearing capacity must be assured on a permanent basis in accordance with Eurocode 7 [7 to 9].
- How great is the strain on the wire structure and how must the wire structure be designed (wire strength, wire properties, grid size, setup of the wires)?
- How can the corrosion-resistant coating’s sustainability be assured even following possible damage during installation and in a particular installation environment?
- Which demands must be posed on the stones?
- Which parameters does interaction between the stones and wire structure depend on? Harder stones for example, cater for a more stable structure and are more sustainable, however, they affect the corrosion-resistant coating more than softer ones.
- Stones should preferably be packed as densely as possible to restrict deformations. Consequently, a so-called “low-void” filling is called for. Criteria are necessary for a low-void filling.
▶ How can this absence of voids be secured on the construction site?
▶ How do individually filled baskets affect the behaviour of the complete structure?
▶ Must baskets be bonded mechanically or are stacking and frictional contact sufficient?

Furthermore, as is normally the case with construction systems, it has to be proved that the system components which have been examined and evaluated, are applied in the quality corresponding with the initial inspection. This has to be assured by depositing the precise chemical and physical basic materials (formula) and through ongoing quality control.

When discussing these in part, very complex issues, it soon became clear that the best way to obtain approval within a reasonable period of time is to adopt a step-by-step approach. As a result, the application was restricted to gravity walls made of monolithic bonded eyelet gabions up to 6 m in height.

Tests to obtain Approval

As a first step, 6 m high test walls were produced in 2010 using various hard stones with competent monitoring by the BAM and then demolished (Figs. 5 + 6). In order to make sure that the filling was as free of voids as possible, the layers of the individual baskets were compacted in three tiers. Following demolition, wire samples were taken from places particularly impacted and examined. Thereby, the newly developed coating withstood the compaction of the individual tiers that were installed in a highly ductile manner without any negative installation damage. Based on further investigations and research results, BAM drafted a sustainability concept, by means of which it is possible to secure a service life of at least 50 years for the wire coating [10, 11]. As it is known that after the coating is used up, further corrosion of the basic material progresses very slowly, durability of at least 100 years can be reckoned with. The prior condition for this assumption is that all wire lattices are installed in an environment lacking permanent ground moisture. As a consequence, it is generally advisable to provide the rear side of the structure with a functioning drainage system.

According to the code of practice [7] verification against an individual element failing (inner stability) must be provided amongst other things (Fig. 7). As at present, sufficient knowledge is not available to come up with computational evidence, this can only be resolved by means of large-scale load tests. Towards this end, first of all three basic tests were carried out supported by the technical expertise of the TU of Munich [12 to 14]. A cubic individual basket with a 1 m edge length was installed within the scope of a trial and filled while being monitored (Figs. 8 + 9). The gabion was installed in a rigid concrete box. It was open at the front, so that only an even deformation at the air-side was possible akin to an actual structure. Earth pressure, which in reality acts on the rear side of the gabion owing to backfilling, was simulated by installing a quadratic air cushion with a side length of 1 m behind the test gabion. In the gabion structure, the lowest layer of gabions is always affected by the greatest compressive stress as a result of the baskets stacked above. This situation was to be reflected by the tests. Thus, first of all, assuming a weight of a filled basket of 19 kN/m³, the pressure load was increased during the tests in each case by 19 kN to reach a load of 171 kN. This maximum load corresponds to a structural height of altogether 10 m. While carrying out the tests, the external deformations were documented by means of numerous sensors with the internal wire forces recorded by strain gauges. The tests revealed that given controlled, low-void filling by compacting the individual tiers at peak load, vertical settlements of 7 to 8 mm and horizontal deformations of 13 to 14 mm were not exceeded.

In order to safeguard these positive results statistically, further large-scale tests were executed at the Uni-
Nimmesgern and Schmauser: 
Eyelet Gabion System with National Technical Approval

All analyses were checked by DIBt and verification of serviceability issued in accordance with § 17 of University of Applied Sciences (FH) in Münster (Fig. 10) [15]. A test cycle on the basis of the verification concept of Eurocode 7 (Geotechnics) was agreed on [7], namely in order to prove the service limit state (SLS) of a compressive stress of at least 160 kN and for verifying the ultimate limit state (ULS) for a compressive stress of at least 240 kN (Fig. 11). A horizontal deformation of 2% related to the nominal height of the test gabion equaling 1 m was accepted for the serviceability limit state (SLS) as the abort criterion and the break of a gabion element for the ultimate limit state (ULS). In each case, four tests with centric load and eccentric load (resultant 1. core range) were undertaken (Fig. 12 otl + otr). All the tests were able to be conducted as planned up to the maximum load of the applied hydraulic cylinder of 250 kN. This pressure load corresponds to a superimposed load of 15.6 m in height given a gabion specific weight of 16 kN/m³, in other words signifying a total wall height of 16.6 m. Altogether, only unexpectedly small deformations (Table 1) resulted from these high stresses. The maximum values of the settlement for the head plate and the horizontal displacement of the front side of the gabion are shown in Table 1 for the load stages 7 m in height, 11 m in height (proof of service limit state SLS) and the maximum load stage 16.6 m in height (proof of ultimate limit state ULS). All the results indicate that the wire structure could be optimally geared to the stone filling and the method of installation.

**Summary**

All analyses were checked by DIBt and verification of serviceability issued in accordance with § 17 of
Fig. 12: Centric load position (otl) and first core dimension load position (otr) [15]

Table 1: Determined maximum deformations V in a vertical direction and H in a horizontal one given centric and eccentric load positions for different load or wall levels [15]

<table>
<thead>
<tr>
<th>Test</th>
<th>Load position</th>
<th>Filling</th>
<th>Maximum deformations V / H (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Load 96 kN / Height 7 m</td>
</tr>
<tr>
<td>G1</td>
<td>centric</td>
<td>dumping method</td>
<td>8.5 / 25</td>
</tr>
<tr>
<td>G2</td>
<td>eccentric</td>
<td>dumping method</td>
<td>50 / 3.0</td>
</tr>
<tr>
<td>G3</td>
<td>manual stowing</td>
<td></td>
<td>70 / 3.0</td>
</tr>
<tr>
<td>G4</td>
<td>manual stowing</td>
<td></td>
<td>78 / 2.8</td>
</tr>
<tr>
<td>G5</td>
<td>dumping method</td>
<td></td>
<td>107 / 8.0</td>
</tr>
<tr>
<td>G6</td>
<td>manual stowing</td>
<td></td>
<td>11.6 / 7.0</td>
</tr>
<tr>
<td>G7</td>
<td>dumping method</td>
<td></td>
<td>11.0 / 8.1</td>
</tr>
<tr>
<td>G8</td>
<td>manual stowing</td>
<td></td>
<td>9.0 / 9.2</td>
</tr>
</tbody>
</table>

The Model Building Regulation (Musterbauordnung (MBO)) [16]. In December 2017, a National Technical Approval and building permit were awarded [17, 18]. As a result, gravity walls with “Quicky Forte 2000” eyelet gabions up to 6 m in height can be regarded as a “standard construction method”. The approval describes the characteristics and composition of the gabion baskets, the stones used for filling, the determining of the reference value of the specific weight, production including drainage and backfilling, transport, storage and labelling. Furthermore, the components of the certificate of compliance and the planning, dimensioning, execution of the structure and its monitoring are dealt with. Fig. 13 displays a standard cross-section. An important design detail is the arrangement of a drainage system directly at the rear side of the structure. By preventing permanent moisture, it was possible to ensure practically atmospheric conditions and the sustainability of the corrosion-resistant coating. The dimensions of the individual baskets and verification for the foundation are determined by a static calculation for every local construction scheme [7]. A ground expertise and the establishment of the specific weight of the stones foreseen for filling purposes and the compaction work form the basis for this calculation (Fig. 14). In similar vein to the procedure adopted for other construction materials, a monitoring and certification authority for gabion baskets ensures that the structural parts used at a local construction site correspond with the properties described in the approval. The certification authority supervises the producer’s regular in-house monitoring and executes external monitoring. Control measures implemented by the construction supervision (Chapter 3.2.5 of the Approval) ensure that the approval [17] is implemented on-site. In this way, the client obtains a documentation of the quality of construction thanks to the certificate of compliance in addition to a structure without defects.

The construction system comprehensively described in the National Technical Approval (Allgemeine bauaufsichtliche Zulassung (abZ)) consists of a modular system, with which an undulation of up to 6 m in height can be permanently secured using monolithically bonded eyelet gabions (Fig. 15). For this purpose, the Hoy Geokunststoffe GmbH’s gabion system with its boundary conditions documented specifically in the approval can be regarded as a standard construction method involving gabions, although the construction method is not generally regulated.

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Fig. 14: Model gabions for ascertaining the reference specific weight

Fig. 15: Executed retaining structure
In a globalised world, the standardisation of products is essential to make sure that they perform as expected. This article describes how standardisation in the European Union helps to achieve a certain quality standard and what users must be aware of to compare different geohazard products.

Why CE Marking and what does this mean?

CE marking with the symbol CE has existed in its present form since 1985. The letters “CE” stand for the French phrase “Conformité Européene” which literally means “European Conformity”. CE marking is a certification mark that indicates conformity with health, safety and environmental protection standards for products sold within the European Economic Area (EEA). The CE marking is the manufacturer’s declaration that the product meets the requirements of the applicable EC directives. The added value of CE marking is that all EU countries must allow construction products bearing the CE mark to be sold. This means that public authorities cannot ask for any additional marks or certificates or any further testing. It is, however, important to know the basics of a CE marking.

Responsibility for CE Marking

The responsibility for the CE marking lies with whoever puts the product on the market in the EU, i.e. an EU-based manufacturer, the importer or distributor of a product made outside the EU, or an EU-based office of a non-EU manufacturer.

CE Marking for Construction Products and how it acquired

Under the wing of the European Commission the European Committee for Standardisation (CEN) takes care of all European Standards and supports the EU Legislation.

The Construction Products Regulation No. 305/2011 (CPR) of the European Parliament and of the European Council is a regulation dating from March 9, 2011 that lays down harmonised conditions for the marketing of construction products. The EU regulation is designed to simplify and clarify the existing framework for placing construction products on the market. The CPR helps authorities and consumers to receive high quality and safe products and to compare different products.

By testing the products either to a harmonised European standard or a European Assessment Document (EAD), it is ensured that the basis for comparing product performance is the same. The test results display all relevant parameters in a detailed manner. Customers can ask the producers to provide them with the details to enable products and their performance to be compared.

If no harmonised standard exists for a specific product, then a European Assessment Document (EAD) can be issued. This is the documentation of the methods and criteria accepted in the European Organisation for Technical Assessment (EOTA) as being applicable for the assessment of the performance of a construction product in relation to its essential characteristics.

Based on an EAD, the Technical Assessment Body (TAB) performs the tests on the product and issues a European Technical Assessment (ETA). As soon as the European Commission approves and lists the ETA, the notified body issues the CE marking. Finally, the Declaration of Performance (DoP) must be drawn up by the manufacturer, who then assumes responsibility for the conformity of the product with the declared performance. It is a key part of the Construction Products Regulation. It provides information on the performance of a product.

Natural Hazard Prevention

The new Standardisation for Rockfall, Debris Flow, shallow Landslides and Slope Stabilisation

In the field of geohazard products, the following three main EAD are to be found, which cover different special applications:

- EAD 230025-00-0106 “Flexible facing systems for slope stabilization and rock protection”
- EAD 340020-00-0106 “Flexible kits for retaining debris flows and shallow landslides/open hill debris flows”
- EAD 340059-00-0106 “Falling rock protection kits”

All EADs can be found on the official website of EOTA: https://eota.eu/en-GB/content/eads/56/
What are the Details of an EAD?

Let us take the EAD “Flexible facing systems for slope stabilization and rock protection” as an example. In this EAD, several tests are described for flexible facing which have been used worldwide for decades. They are available in two different qualities, mild steel wire and high tensile steel wire. For both qualities of steel in combination with soil nailing / rock bolting three key characteristics for the products exist:

- Puncturing at the nail head plate (shearing-off resistance at the upslope edge of the spike plate)
- Slope parallel load transfer into the nail with interaction of the soil (tensile strength)
- Deformation/elongation of the mesh under load in per cent

Tables 1 + 2 show the groups and classes for categorising the performance of the flexible facings.

What does this mean for Users?

This means that by using these tables, it is possible to clearly define in the tender documents the bearing resistances for a flexible facing needed for a specific project in the tender documents. Different products can be compared easily.

The main advantage is that based on these tables, it would be possible to clearly define the three characteristics for a flexible facing which are needed for a specific project in the tender documents. Thus, different products can be compared on a unique level. Of course, the basis of the tender specifications must be the design in accordance with the expected failure scenario.

It is important to know that it is possible to obtain a CE-Marking without having performed all the tests. For example, often only the tensile strength of a mesh has been tested but all other parameters are missing. However, if these parameters are unknown, it is impossible to dimension an economic and safe solution.

### Table 1: Informative: groups of meshes/nets regarding tensile strength and shearing-off resistance

<table>
<thead>
<tr>
<th>Group</th>
<th>Shearing-off resistance $P_s$ at the upper surface of spike plates</th>
<th>Slope parallel tensile strength $Z_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$P_s &gt; 135$</td>
<td>$Z_s &gt; 50$</td>
</tr>
<tr>
<td>2</td>
<td>$80 &lt; P_s \leq 135$</td>
<td>$29 &lt; Z_s \leq 50$</td>
</tr>
<tr>
<td>3</td>
<td>$50 &lt; P_s \leq 80$</td>
<td>$19 &lt; Z_s \leq 29$</td>
</tr>
<tr>
<td>4</td>
<td>$25 &lt; P_s \leq 50$</td>
<td>$4 &lt; Z_s \leq 19$</td>
</tr>
<tr>
<td>5</td>
<td>$0 &lt; P_s \leq 25$</td>
<td>$0 &lt; Z_s \leq 4$</td>
</tr>
</tbody>
</table>

### Table 2: Informative: groups of meshes/nets regarding relative elongation in longitudinal tensile strength test

<table>
<thead>
<tr>
<th>Class</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$\leq 6$</td>
</tr>
<tr>
<td>B</td>
<td>6 to 10</td>
</tr>
<tr>
<td>C</td>
<td>10 to 14</td>
</tr>
<tr>
<td>D</td>
<td>$&gt; 14$</td>
</tr>
</tbody>
</table>

To avoid failures in installations and liability risks, it is important to make sure that the parameters in the DoP (Declaration of Performance) or ETA are in accordance with the corresponding design of the project. Thus, if investors, designers and contractors want to be sure of obtaining the right product with the expected performance, the test results must be checked in detail.

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Swiss Tunnel Congress STC 2019
Dipl.-Ing. Roland Herr, International Freelance Journalist, Wetzlar (Germany)/Bangkok (Thailand)

Read about the Swiss Tunnel Congress STC 2019, the development of tunnelling in Switzerland and the importance of the young members for the Swiss Tunnelling Society.

Tunnelling • Switzerland • Conference • Youth development

“The future for tunnelling in Switzerland shines brighter than two years ago”, stated Stefan Maurhofer, President of the Swiss Tunnelling Society (STS), in Lucerne, Switzerland (Fig. 1). The annually Swiss Tunnel Congress (STC) with Colloquium, organised by the Swiss Tunnelling Society since 2002, is the most important event for tunnelling specialists in Switzerland (Fig. 2). Stefan Maurhofer took his time to talk to international journalist Roland Herr about the conference, the development of tunnelling in Switzerland and the importance of the Swiss young members for the society (Fig. 3).

“The first week of June in Lucerne is the highlight and meeting point, every tunnelling specialist in Switzerland keeps free in his diary long time in advance,” stated Stefan Maurhofer not without pride. Also this year, the 18th Swiss Tunnel Congress was organised in the KKL (Culture and Congress Center Lucerne), in the first four years as “Alp Transit Conference”, with Colloquium on the day before and the offer to visit job sites on the day after, from 4th to 6th June 2019. About 380 participants joined the seven highly qualified presentations of the Colloquium and about 700 participants took the chance to join the 14 presentations of the Congress and to stroll over the exhibition (Fig. 4). For the colloquium, the numbers are rising and for the Congress, there is a very good average reached now, explained an obviously satisfied Maurhofer. Nine different countries (13 to 15 %) were represented in 2019, but most of the participants are from Switzerland speaking German (75 to 80 %) with also French and Italian, which is common due to the multilingual country. For that reason, there is a translation from German into English, French, Italian and vice versa during the whole conference and also the proceedings are in four languages.

From the start, the Swiss Tunnel Congress was a very international orientated event and that makes this conference so interesting. With the international advisory board, the STS is reaching a strong selection of the international projects which are proposed to present at the STC. That is the successful recipe, how to realise a good mixture of international and Swiss papers, making this conference so unique in Europe.

To mention only some of the presentations would be not fair for the other very interesting topics. For that reason, just download the proceedings [1].

Prospering Tunnelling in Switzerland

With the Megaprojects Gotthard and Lötschberg Base Tunnel, the projects of the New Railway Link through the Alps (NRLA, in German: NEAT), tunnelling in Switzerland experienced a huge demand. After completion, the tunnelling industry in Switzerland, unfortu-

Fig. 1: The STC is organised every year in June in Lucerne, Switzerland
Source of the photos: Roland Herr

Fig. 2: Conference opening by Stefan Maurhofer

Fig. 3: Stefan Maurhofer talking about the STC, tunnelling and the young members

Fig. 4: The STC – is a highlight and meeting point for tunnelling specialists

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Swiss Tunnel Congress STC 2019
nately, went a bit down. Only one year ago, at the STC 2018, the figures for tunnelling in Switzerland were more than not amusing. But a light at the end of the tunnel could be seen due to discussions in the Swiss Parliament, how to finance the improvement of the infrastructure in Switzerland. And now, the decisions are made. The Swiss government will spend 6.4 billion CHF (about 6.45 billion USD) for the railway system and for rail tunnels until 2025 and another 11.9 billion CHF (about 12.0 billion USD) until 2035. This is a huge volume just to invest in the modernisation of the railway system and the construction of new railways. Also for the road construction, 14.8 billion CHF (about 14.92 billion USD) is planned to be invested until 2030. With these huge investments in the next 10 to 15 years, a lot of projects are in the design phase actually. There are tunnels to modernise as well as to build new, like the 4th Tube Stadelhofen in Zurich, the Brüttener Tunnel in Winterthur or the new second tube of the Gotthard Road Tunnel. Especially the Swiss Federal Railway (SBB) is expanding the system in the next 10 to 15 years.

In the meantime, other developments like the underground logistics system cargo sous terrain (CST) are becoming more interesting. The digital complete logistics system will connect Switzerland’s key hubs from 2030 onwards. CST takes the strain off the road and railway networks, plans to reduce environmental impact and to ensure the prompt delivery of goods for everyone. Not to forget the latest expansion plans of CERN (the European Council for Nuclear Research, in French Conseil Européen pour la Recherche Nucléaire-CERN) in Geneva, a huge project with tunnels in the underground space of Switzerland and France. By the way, this project was one of the most interesting presentations of the Congress (Fig. 5).

Lack of Engineers

But there is another problem, not only the Swiss Tunnelling Society has to fight against: the lack of talented young engineers. Stefan Maurhofer described the problem: “During the Megaprojects Gotthard and Lötschberg Base Tunnel, a lot of foreign specialists and engineers were working in Switzerland, on the contractors’ as well as on the engineers’ side. For that reason, after completing the projects and returning to their home countries, we don’t have an „overload“ of Swiss engineers. The knowledge is really profound, but if you try to get a good tunneller, it is a very hard job to find one. And also, some Swiss companies are going abroad, especially engineering and consulting companies. Also for that reason, we are supporting the STS Young Members Group in Switzerland.”

Swiss Tunnelling Society Young Members

When the Swiss Tunnelling Society young members (STSym) group was founded, there were discussions between both sides, young members and STS, how to support the STSym. The young members are embedded in the society, they have nothing to do with financing, administration, etc. They are able to focus on their tasks, events, and work, supported by the STS. The only rule is, that every young member has to be an STS member.

Additional, the president of the STSym, Jasmin Amberg, is joining all board meetings and for that reason, there is a very good exchange of all information between the Swiss Tunnelling Society and the young members. “We tell the young members, what we want to know from
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International Relations

For the Swiss Tunnelling Society and its members, the international contact into the worldwide tunnelling industry is very important, especially the collaboration with DACH (Germany-D, Austria-A, and Switzerland-CH) and BEFIPS (Belgium-B, Spain-E, France-F, Italy-I, Portugal-P and Switzerland-S). “These two organisations are very, very important for us. For example, and that shows the relevance of a congress like our STC, we organised this year in Lucerne the first joint meeting of the DACH and BEFIPS presidents ever, to agree on some strategies and how to work together. Also ITA – the International Tunnelling and Underground Space Association – is very important for Switzerland, for the STS. Here we focus on the working groups to improve, to join and to steer some developments in the right direction. We are not so much interested in the markets, our focus is on the technology and how to improve tunnelling, underground works and the use of underground space. And if we don’t reach out something worldwide in ITA, perhaps we may achieve it in Europe,” explained Stefan Maurhofer. “With a view on the ITA, it will be very important, what will happen in the next few years especially with the new Chinese Presidency. If this is really also a conclusion of China, technology-wise to start into a technical development discussion, this is absolutely interesting for us in Europe, because in China is a lot going on. This is, in ITA, I would say the challenge and the chance at the same time.”


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1 Introduction

The subsoil harbours a very high risk for executing construction during the production of tunnel structures. Experience shows that risks and cases of damage are associated with extremely high outlay and very high costs particularly in mechanised tunnelling. When excavating the Gotthard Base Tunnel for example, rock pressures and the resultant major convergences in the Bodio contract section on March 3, 2006, resulted in the tunnel boring machine (TBM) jamming. Driving could be resumed after ten days once the roof had been raised in the vicinity of the cutterhead [1].

Hazard scenarios in hard rock are numerous and extend from crumbling blocks of rock by way of extreme water ingressions right up to gas emissions. Diverse interactions of geological factors frequently first become evident should negative incidents occur during the execution of tunnelling projects. Complex geological factors, as e. g. the inhomogeneity of the rock, setbacks caused by variably hard rocks and the effects of high primary stresses must thus always be taken into consideration. Owing to the inhomogeneity/anisotropy of the rock, in such cases adjustments must be undertaken locally to cater for safety, cost and operational factors.

At the Darmstadt University of Applied Sciences, tunnelling projects, where cases of damage resulted during the course of construction, were analysed. Projects involving mechanised tunnelling were lent particular scrutiny. [2] to [4] already contain relevant results pertaining to mechanised tunnel drives in soft ground and hard rock. In the interim, further projects have been analysed and evaluated. This report presents new results with the emphasis on mechanised tunnel drives.

2 Types of Machine

Altogether 31 tunnelling projects, which resulted in damage occurring during driving, were assessed. The following three types of machine were deployed in the projects:

- Open tunnel boring machine (Gripper-TBM) in 16 projects
- Tunnel boring machine with shield (TBM-S) in 10 projects
- Double shield machine (DSM) in 5 projects

With 52 %, in other words roughly half of the projects, the Gripper-TBM type of machine accounted for the bulk of them (Fig. 1). Compared with a drive involving a TBM-S or a DSM, in the case of which the cavity is secured immediately by the segmental support, with regard to the gripper-TBM the rock is first systematically supported in the back-up area thanks to the application of a shotcrete lining. As far as the drives in the Gotthard Base Tunnel were concerned, this area e. g. was some 46.5 m behind the working face [5].

The types of machine differ in hard rock firstly regarding the kind of support as well as the way in which the required driving forces are introduced into the rock. In the case of the Gripper-TBM they are transferred as the name indicates through gripper tensioning (Fig. 2). In the case of the TBM-S excavation the hydraulic thrust cylinders rest on the segmental lining thus producing the necessary contact pressure on the working face. As far as the DSM is concerned, which facilitates a continuous drive, in other words, the segmental lining is installed in tandem with the removal of the working face, the two systems of gripper tensioning and hydra-
lic thrust jacks are deployed. Corresponding typical damage scenarios occur owing to the differences between the types of machine.

3 Risk Groups

To be in a position to assess the cases of damage or categorise the damage scenarios, risk groups (RG) were defined (Table 1). Classification is based on the geological boundary conditions and similarities in the damage situations. Table 2 presents the relevant typical damage scenarios for the individual risk groups.

4 Results

Tables 3 and 4 indicate separately the frequencies of the individual risk groups in accordance with the number of projects and proportionally for all projects in keeping with the type of machine. It must be observed here that different risk groups can relate to an individual project. Relating to all the projects a similar order of magnitude was produced for the greatest frequencies for risk groups 1 to 3 (Fig. 3). Most of the damage resulted from high overburden levels, high rock pressures, high convergences, high water ingresses, high water pressures and isolated water temperatures as well as strongly fissured and friable rock.

Table 1: Definition of risk groups (RG) in hard Rock

<table>
<thead>
<tr>
<th>RG</th>
<th>Definition of Risk Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>high overburden heights, high rock pressures, high convergences</td>
</tr>
<tr>
<td>2</td>
<td>high water ingresses, high water pressures and high water temperatures</td>
</tr>
<tr>
<td>3</td>
<td>heavily fissured and crumbling rock</td>
</tr>
<tr>
<td>4</td>
<td>high abrasiveness of the rock</td>
</tr>
<tr>
<td>5</td>
<td>cavity-like apertures with and without fill</td>
</tr>
<tr>
<td>6</td>
<td>gas deposits and other hazardous substances</td>
</tr>
</tbody>
</table>

Table 2: Damage scenarios of the individual risk groups (RG)

<table>
<thead>
<tr>
<th>RG</th>
<th>Damage Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>deformation of the cross-section, spalling, rock bursts, jamming of TBM, delay in driving</td>
</tr>
<tr>
<td>2</td>
<td>water ingresses in the tunnel cross-section, collapses owing to water, jamming of the TBM, settlements, high temperatures, delay in driving</td>
</tr>
<tr>
<td>3</td>
<td>collapses, crumbling, working face instabilities, jamming of the TBM, delay in driving</td>
</tr>
<tr>
<td>4</td>
<td>increased bit wear, damage to the bits, increased down times through replacing bits</td>
</tr>
<tr>
<td>5</td>
<td>fault zones with soft ground, friable rock or squeezing soft material, TBM drive probably impossible, working face instabilities, delay in driving</td>
</tr>
<tr>
<td>6</td>
<td>risk of poisoning, risk of suffocating, risk of explosion, delay in driving</td>
</tr>
</tbody>
</table>

Table 3: Frequency of the risk group (RG) for tunnelling sites in hard rock and mechanised driving [No. of projects]

<table>
<thead>
<tr>
<th>RG</th>
<th>Total</th>
<th>Gripper-TBM</th>
<th>TBM-S</th>
<th>DSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>11</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>9</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>8</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4: Frequency of the risk groups (RG) for tunnelling sites in hard rock and mechanised driving [%]

<table>
<thead>
<tr>
<th>RG</th>
<th>Total [% related to 31 projects]</th>
<th>Gripper-TBM [% related to 16 projects]</th>
<th>TBM-S [% related to 10 projects]</th>
<th>DSM [% related to 5 projects]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52</td>
<td>69</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>56</td>
<td>40</td>
<td>40</td>
</tr>
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<td>3</td>
<td>52</td>
<td>50</td>
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<td>4</td>
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<tr>
<td>6</td>
<td>10</td>
<td>13</td>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>
Significant differences were revealed when it came to considering the individual types of machine. In the case of the Gripper-TBM, risk group 1 represented the group with the highest frequency (69%) (Fig. 4). Gripper-TBMs are mainly applied in stable or slightly disturbed rock, i.e. some 80 to 90 % of the tunnel length should be largely stable as a reference value. As the shotcrete lining in the case of the Gripper-TBM in standard mode should be installed as late as possible in the back-up area and not with immediate effect, high rock pressures and high convergences represent a grave risk. Risk groups 2 to 6 for the Gripper-TBM reveal very similar frequencies after all projects have been scrutinised.

In the case of the TBM-S, a different picture is revealed. The group with the greatest frequency is risk group 3 (strongly fissured and crumbling rock) (Fig. 5). This concurs with the main deployment area of the TBM-S, which generally finds application in crumbling to friable rock. In comparison to the frequencies for the Gripper-TBM, a different emphasis in the frequency of the individual risk groups is clearly discernible.

The risk frequencies for type of machine DSM (Fig. 6) resemble those for the Gripper-TBM. Like the Gripper-TBM, risk group 1 is the most common. It is followed by risk groups 2 and 3 with risk groups 4 to 6 occupying the final third. However, it should be observed at this point that only five projects were available for analysis.

A further significant aspect for these cases of damage, apart from analysing the damage itself, are the measures, which were resorted to for reducing the damage or speed up the subsequent drive. Table 5 shows the measures undertaken in the individual projects. It can generally be observed that first of all, the measures for supporting the tunnel were increased, i.e. the linings were installed immediately in the case of the Gripper-TBM. Secondly, far-reaching exploratory drilling was accomplished to discover the geological conditions so that suitable additional measures could be undertaken. Similarly, technical modifications were made to the machines, e.g. by producing a greater overcut. In extreme cases, the TBM had to be extricated using complex measures.

5 Summary

It is impossible to ensure that a tunnel drive is executed perfectly. Even extensive and qualitatively high-grade geotechnical advance explorations cannot guarantee that cases of damage can be precluded. A residual risk always remains. Nonetheless, the severity of risks in cases of damage is diminished the more extensive and qualitatively high-grade the geotechnical advance exploration actually is. At the same time of course, the need to keep the costs of exploration prior to the construction phase as low as possible still remains.

Analysis of the investigated cases of damage reveals that the geological boundary conditions are a main contributing factor for the severity of the cases of damage.
It becomes evident that at some places the geology was completely different from that suggested by geotechnical exploration. In fact, this signified in the case of some of the analysed tunnel drives that the planned and deployed type of machine was not the optimal solution.

This article merely provides an overview of extensive investigations and analyses. These investigations and analyses are completely documented at length in [2] and [6].

6 References


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Fehmarnbelt Fixed Link –
The Special Tunnel Element
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1 Introduction

The Fehmarn Belt Fixed Link project will connect the Danish island of Lolland with the German island of Fehmarn crossing the Fehmarn Belt in the Baltic Sea (Fig. 1). The Fehmarn Belt Fixed Link ("The Link") will be an immersed tunnel of record-breaking dimensions with a length of 18 km located at a depth of more than 40 m below sea level. The tunnel will accommodate a 4-lane motorway including emergency lane and a 2-track railway in 4 traffic tubes.

The 7 billion Euros (price level: 2015), coast-to-coast project will be built, operated and financed by the Danish state in accordance with the treaty between Germany and Denmark signed in September 2008. The Owner Femern A/S is a Danish state-owned company responsible for the planning, construction and operation of the Link. The concept design for the immersed tunnel was developed by the consultant Joint Venture Ramboll-Arup-TEC JV, which has been the main consultant for Femern A/S since 2009.

The data presented in this paper are derived from the concept design but changes must be expected when the Design & Build contractors develop the detailed design. However, the basic design principles including alignment, size and the position of the special elements are strict requirements in the contracts and will form the basis for the future detailing of the design.

Apart from the coast-to-coast project “The Link” which is described in this paper, major hinterland works are planned in both countries, Germany and Denmark, including new motorways, twin-track railways and new bridge or tunnel connections to replace the existing bridges across Fehmarnsund in Germany and Storstrøm in Denmark.

2 Reason for Choosing a Tunnel?

From 2009 to 2010, concept designs for four main solutions for crossing the Fehmarnbelt were developed. The concept designs for the immersed and the bored tunnel were prepared by the consulting group Ramboll-Arup-TEC JV whereas the design for a cable-stayed and a suspension bridge was developed by a consulting group including COWI A/S, Kongens Lyngby, Denmark and Obermeyer Planen + Beraten GmbH, Munich, Germany.

Femern A/S carried out a thorough comparison between the different designs and selected the immersed tunnel as the preferred solution in 2011.

The Fehmarnbelt Tunnel possesses record-breaking dimensions. The length of the immersed tunnel is around 18 km. This article focuses on the challenges facing concrete tunnel element production and immersion.

Tunnelling • Major project • Immersed tunnel • Concrete • Construction operation • Denmark

It was a surprise to many that the immersed tunnel solution was able to compete with the bridge solutions consequently replacing the cable-stayed bridge as the preferred option for The Link. There were several reasons of why the tunnel solution turned out to be more competitive. A few of them are mentioned below:

▶ The industrialised production method that had proved its worth in the Øresund Tunnel project (a 4 km immersed tunnel between the Danish islands Amager and Peberholm) resulted in cost savings as well as an improvement in the quality of the concrete works
▶ The ventilation concept that was switched from the transverse system traditionally used for long tunnels to a longitudinal concept and a permanent firefighting system introduced in the road tubes
▶ The introduction of the special elements to facilitate the operation and maintenance of the long tunnel, to create a safe working environment for the personnel and to increase the availability of The Link
Immersion Tunnel in General

An immersed tunnel is made using large concrete elements (with typical lengths of 100 to 175 m) designed to float when closed at both ends with a bulkhead. The individual tunnel elements are towed to the tunnel location and placed successively in a pre-dug trench. The elements are lowered by filling a temporary ballast tank inside the element with seawater. The water ballast will later be replaced by permanent ballast concrete. The elements are provided with a large circumferential rubber seal on the primary end – the Gina gasket. This will form a watertight connection with the preceding element when the small waterfilled compartment between the new and the preceding element is emptied and the full water pressure on the secondary end of the element compresses the Gina gasket. The elements are then backfilled and a protection layer of stone is installed above the tunnel roof.

3 The Immersed Tunnel Concept based on the Øresund Production Method

The total length of the coast-to-coast project is about 25 km including connections to the existing road network and railway system. The immersed tunnel part has a length of 17.6 km and the total tunnel length – including the cut & cover sections – is approximately 18.2 km. In total, the tunnel comprises 89 concrete elements:

- 79 standard elements (STE), each 217 m long
- 10 special elements (SPE), each 39 m long

The special elements will be installed at regular intervals (approximately every 1.8 km) in between the standard elements as shown in Fig. 2.

The tunnel elements (Fig. 3) will be produced in a large factory. The total quantity of structural concrete is around 2.5 million m³ and the ballast concrete will amount to approximately 400,000 m³. The reinforcement quantities are estimated at around 400,000 t.

The development of the concept design included detailed analyses of possible construction methods and space requirements. The Øresund production method was selected as a basic overall principle for the design and the extensive background documentation from the execution of this project – completed in the late nineties – constituted an invaluable source of data for the design process.

In the Øresund project the unique cast and launch method was introduced for the first time. It has since been further developed and used for several other large immersed tunnel projects such as the Hong Kong-Zhuhai-Macau Link. The method is shown schematically in Fig. 4. The method includes an industrialised production line at ground level typically close to the tunnel site. Each discrete tunnel segment is cast by full section casting on a fixed casting bed and after a short curing period the segment is pushed free of the casting bed for match casting of the next segment. The method requires an advanced retractable formwork system. The whole production process is accomplished as line production in a large factory building providing controlled and safe climatic conditions during casting and curing as well as good indoor conditions for the construction workers. Once a complete tunnel element has been cast the entire element is pushed free of the casting bed by hydraulic jacks for match casting of the next segment. The method requires an advanced retractable formwork system. The whole production process is accomplished as line production in a large factory building providing controlled and safe climatic conditions during casting and curing as well as good indoor conditions for the construction workers. Once a complete tunnel element has been cast the entire element is pushed into a shallow part of the launching basin that is then cut off from the fabrication area by a sliding gate. In the shallow part of the launching basin the element is prepared for transportation and equipped with watertight bulkheads. The deep basin is cut off from the sea by a floating gate which is used to open and close the basins. The shallow basin which is surrounded by high dikes is pumped full of seawater until the element...
is afloat after which the element is towed to the deep part of the launching basin. The water level is lowered so that it corresponds to the outside sea level, permitting the floating gate to be opened. The element can then be transported to the tunnel site and immersed into its final position. While tunnel elements are being prepared for immersion in the deep basin, the casting of the following elements continues in parallel.

For the Øresund project, two production lines were established to produce in total 20 tunnel elements each around 175 m long. In order to meet the planned opening date for The Link in 2028, a total of 5 production lines are foreseen for the standard elements as well as one additional production line for the 10 special elements. All the tunnel elements will be constructed in a huge site area close to Rødbyhavn as shown in Fig. 5.

4 Tunnel Element Production

A large temporary harbour is required to accommodate the vast amounts of construction materials required for the element production – i.e. cement, aggregates, additives and reinforcement – as well as the sand and stone materials required for the backfilling and the protective layer above the tunnel. The harbour will be combined with the launch basins for the tunnel elements as shown in Fig. 5. The harbour will also provide a protected area for storage of tunnel elements waiting to be immersed.

To facilitate an industrialised production method with a moveable formwork system, the tunnel segments should be as uniform as possible. However, the mechanical, electrical and control systems for the tunnel require space and some of the units such as e.g. transformers, firefighting systems and low point sumps require ample room and easy access to function properly. For a very long immersed tunnel, it is a challenge to create the necessary space in an optimal manner. For The Link, the key to an economic solution was to minimise the tunnel cross-section in general and at the same time create as many uniform tunnel elements as possible. The chosen solution to ensure sufficient plant room space and access requirements was to create the special elements, making it possible to optimise the standard elements and producing them to be geometrically identical thus facilitating an efficient casting process.

The layout of the production facility reflects the industrial methods and is divided into specific areas for specific activities e.g.:

▶ Prefabrication area for reinforcement cages
▶ Casting hall
▶ Curing hall
▶ Fit-out area
▶ Shallow and deep basins

Each production line comprises six skidding beams that will support the tunnel segments during skidding from the casting area, over the sliding gate, to the final fit-out area in the shallow upper basin. The skidding beams are large concrete beams provided with a number of bearings equipped with supporting jacks under each of the segment walls. The bearings are provided with low-friction pads to facilitate the skidding operation of the segments which will be performed with several pushing jacks.
4.1 Standard Tunnel Element (STE)

The STEs are all straight and geometrically similar – they consist of 9 segments of approximately 24 m in length (Fig. 6 and Table 1).

The individual segments are cast in one pour of around 3,300 m³, i.e. without any construction joints. The casting will be done continuously across the production lines and will require a robust and reliable production and delivery system for the concrete. There is no reinforcement connection between the individual segments but they are connected with flexible joints. A temporary post-tensioning system is provided to facilitate transport and immersion of the elements and after the element is placed and fully backfilled, the post-tensioning cables will be cut to allow movement in the segment joints. The segment joints are anticipated to open up to 5 mm due to the yearly temperature variations and are provided with a rubber/metal injectable waterstop to accommodate the calculated movements.

The requirements for the concrete mix are very strict. An elaborate quality control system is to be established at the site and a comprehensive test programme is foreseen. The good concrete quality and control together with the optimal in-door casting conditions for the STEs will ensure a watertight concrete element and consequently no external watertight membrane is anticipated. The STEs will weigh more than 75,000 t excluding the ballast concrete.

4.2 Special Tunnel Element (SPE)

Each of the 10 special tunnel elements is 39 m long, 47 m wide and around 13 m high (Fig. 7 and Table 1). The SPE contains two levels: the road/rail deck level and below an installations deck level.

The installations level offers space for all necessary facilities and the mechanical and electrical tunnel operating systems, such as sumps, pump rooms, power supply and other ancillary equipment. The SPEs are supplied with fresh air from the central gallery between the road tubes. The SPEs are wider than the STEs designed for lay-bys for maintenance vehicles coming from Denmark. In addition, the SPEs provide other advantages, such as:

- Room for transformers which can be replaced from road level
- Access to mechanical and electrical equipment without interfering with traffic
- An underpass for personnel on foot accessing the central gallery between the road tubes and the rail tubes

The SPEs will be cast on a special production line (No. 6). The line is covered with a building similar to the production halls for the STEs and the concrete is produced on the same batching plants. However, the production of such large concrete elements poses some challenges and the casting cannot be done in the same optimal manner as for the STEs. Consequently, to ensure a watertight high-quality element suitable for technical installations, the contract requirements are strict in regard to design, workmanship and temperature control during the casting and curing process. Construction joints cannot be avoided in the special elements, but the number must be minimised in the sea-facing part of the structure and will be located in areas with low tensile stresses. As an extra precaution, the special element will be provided with a full external watertight membrane.

5 Immersion

5.1 Fit-out and Float-out

When the elements are leaving the curing area they will be pushed to the shallow basin for fit-out, including installation of the Gina gasket, fire protection boards, bulkheads, access shafts, ballast tanks and piping as well as post-tensioning cables and various equipment needed for the marine operation.

The float-out procedure includes filling the basin with water and winching the standard element to the deeper part of the basin. When the elements are leaving the deep basin, the immersion pontoon at the front and the rear of the element will be installed as shown in Fig. 8. The elements will then be transported to the immersion location by tugboats. The elements will typically be transported with a freeboard of 30 to 40 cm.

<table>
<thead>
<tr>
<th>Element type</th>
<th>STE</th>
<th>SPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>79</td>
<td>10</td>
</tr>
<tr>
<td>Length (m)</td>
<td>217</td>
<td>39</td>
</tr>
<tr>
<td>Width (m)</td>
<td>42</td>
<td>47</td>
</tr>
<tr>
<td>Height (m)</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Weight (t)</td>
<td>75,000</td>
<td>27,000</td>
</tr>
<tr>
<td>Number of segments</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Length of a segment (m)</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Concrete volume of a segment (m³)</td>
<td>3,300</td>
<td></td>
</tr>
<tr>
<td>Connection of segments</td>
<td>flexible joint</td>
<td></td>
</tr>
</tbody>
</table>
For the special elements, the immersion pontoons will be installed inside the basin so that the tall elements can be lifted before they are transported out of the basins and the harbour as shown in Fig. 9. The elements will be winched to the deep basin and transported to the immersion location. The same set of immersion pontoons are foreseen to be used for both type of elements.

5.2 Preparation of the Trench and Immersion Process

The trench is in a separate contract and the excavated soil – in total around 15 million m³ – is used for land reclamation on Lolland and to a lesser degree on Fehmarn.

Prior to the immersion of an element the tunnel contractor will clean the trench with a Trailing Suction Hopper Dredger or similar machine to ensure that loose sediments are removed before the foundation layer is installed. The foundation bed will be prepared as an approximately 80 cm gravel layer and placed in the trench with high accuracy using special equipment.

When the element arrives at the immersion location, the immersion pontoons will be connected to anchor wires attached to pre-installed marine anchors and to the preceding element (Fig. 10).

The element will be positioned directly above the prepared foundation bed while being supported by the immersion pontoons. The tunnel elements are provided with a water ballast system consisting of multiple tanks and associated piping. In the special element, the available space and rooms in the basement will also be used for ballast water storage.

The immersion sequence will start by reducing the freeboard as seawater will be pumped into the ballast tanks. When the element has sufficient negative buoyancy, the element is lowered through the waterline and kept below the waterline during the remaining ballasting operation. Before the immersion process starts the survey, systems are checked and the element and the preceding one inspected – generally using a remotely operated underwater vehicle (ROV). However, a diving crew will be on stand-by during the entire immersion process.

The tunnel element will be gradually lowered, and the hoist loads and element position will be monitored carefully from the command control centre placed on one of the pontoons.

The lowering process will continue until the element is just above the gravel bed and the pin at the primary end of the element is connected to the catcher at the secondary end of the previously installed element. The position is adjusted within the necessary tolerances and the element is lowered down onto the gravel bed while being pulled against the preceding element so that the Gina gasket can touch and close the full cross-section perimeter. Once the final position is accepted, the immersion joint is emptied by means of remotely operated...
valves in the bulkhead of the preceding element and the water from the emptying operation is fed to the ballast water tanks inside the preceding element. By emptying the immersion joint, the hydrostatic pressure will push the element against the preceding element with a resulting horizontal load of more than 10,000 t. The joint will close tight and the Gina gasket will be fully compressed.

5.3 Foundation of Special Element

The joint between the standard and special elements will require particular attention due to the height difference between the elements. As shown in Fig. 11 there will be a gap underneath the standard element preceding the special element.

Once both the SPE and STE have been installed, the gap underneath the standard element will be filled with a suitable bedding material such as: pumped-in sand, grout bags, or something similar. The filling operation will be tackled from the outside of the elements from a vessel or a barge or possibly through a piping system installed underneath the STE. This is a delicate operation and detailed geotechnical information and calculations are required to determine the achievable slopes and the specific need for foundation support for the cantilevered part of the STE.

5.4 Backfilling and Protection Layer

The elements will be backfilled continuously with sand dredged from the sourcing area at Kriegers Flak. After backfilling, a thin filter layer of gravel is placed via a fall-pipe on the roof of the element to protect it during placing of the armour layer consisting of stones of up to 1,000 kg.

After finalisation of the filter layer, a 1 m armour layer of quarry stone is installed by side stone dumping or a similar method. This operation will complete the outside construction works for the tunnel element. Parallel to the outside completion works, the comprehensive inside works including exchange of the water ballast with concrete, finalisation of the immersion joints, cutting of the post-tensioning cables etc. will continue.

6 Status of the Project

The project received the German Plan Approval (“Planfeststellung”) in December 2018 following a 5-year approval process. However, as expected objections were filed against the Approval and the court case against APV-SH (Amt für Planfeststellung Verkehr in Schleswig-Holstein) has now been initiated at the Federal Court in Leipzig to establish whether the complaints will have suspensory effects.

In 2015, permission to start the project in Denmark was given once the Construction Act was passed in Parliament so that Femern A/S signed conditional contracts with the preferred bidders for the four major civil works contracts in May 2016.

The contracts were won by the two international contractor consortia:

- Femern Link Contractors (FLC) including i.a. Vinci Construction Grand Projets S.A.S., Per Aarsleff Holding A/S, Wayss & Freytag Ingenieurbau AG, Max Bögl Stiftung & Co. KG, CFE SA.
- Fehmarn Belt Contractors (FBC) including i.a. Boskalis International B.V. and Van Oord Dredging and Marine Contractors B.V.

The contracts have lain partly dormant since 2016, but having received German Approval the Danish political parties supporting the project announced on March 26, 2019 that the construction work is to start on the Danish side. The execution of the harbour and the production facility will therefore be initiated this year – starting as soon as the necessary work planning has been finalised.
The Mine of the Future: The 5S Innovation Model for the Minerals Industry
Prof. Dr.-Ing Antonio Nieto, PhD, School of Mining Engineering, University of the Witwatersrand, Johannesburg, South Africa

1 Introduction

Nowadays, more than ever, production-driven industries, such as mining, are easily impacted by technology shifts that can result in a rapid loss of competitiveness. Thus, the continuous development of technology and applied innovation is essential in any industry, including the mining industry, in order to stay relevant and competitive during following decades. For the mining industry to survive, innovating today is crucial for maintaining high levels of growth, productivity, and sustainability.

2 Global Technology Challenges

In 2017, the U.S. National Academy of Engineering (NAE) [1] published the results of a study aimed at identifying future global technology challenges. The NAE study identified several major technology challenges and classified them into fourteen grand themes as shown in Fig. 1. The engineering challenges shown in the NAE report served as an initial guide for defining potential challenges the mining industry will face during the years to come, such as the engineering and development of technologies related to energy, water, health, and safety, thus helping to confirm the innovation model introduced in this article.

Even though the NAE report clearly identified key engineering challenges of the future, the report failed to recognize an additional very important challenge our society will certainly face during the decades ahead, namely the sustainable supply of raw materials, such as minerals. Without minerals, no new technology can be developed – neither today, nor in the future.

Minerals are intensively used in the industries considered in the NAE report, such as the construction, equipment, power, and communication industries, and in many high-tech industries, such as robotics, aerospace, electronics, etc. Thus, minerals are practically used in every strategic sector mentioned in the NAE report.

Fig. 2 shows an alternative classification of technology challenges. The grand pillar challenges are arranged in five clusters, or technology drivers, which today’s industry will have to face and prepare for during the decades ahead.

Industry is currently experiencing a tremendous technology transformation. With the rapid advancement of technology, any industry can fall victim to sudden disruptive technology shifts, potentially rendering any company obsolete in just a few years. To survive during the twenty-first century, the mining industry needs to take innovation seriously and consider it an integral element of any mining company’s business plan.

It is thus imperative for the mining industry to have a clear idea of the technology that will be needed in the future and to prepare today with a clear innovation strategy. Innovation strategies need to be implemented in every aspect and at every level of a company’s growth plan.
As witnessed during recent decades, well-established companies such as Kodak from the photo industry, Blackberry from the communications industry and Blockbuster from the media industry, all very quickly lost their market relevance by failing to recognize the dynamics of new emerging technologies. The lack of a modern and clear innovation strategy and the lack of a technology roadmap within their corporate business models contributed to their sudden loss of technological relevance and eventual business collapse.

Developing an innovation strategy and technology roadmap for the mining industry is not an easy exercise. Mining operations vary significantly in terms of the methods used, and the mineral commodity being extracted, facing very different operational challenges that require different technologies. Thus, there is the motivation to develop a basic mining innovation model – introduced here – that hopefully can help as an initial innovation strategy reference model.

### 3 The Concept of applied Innovation

The standard definition of innovation is “the use of better solutions that meet new requirements,” which is a definition that can be extended under the context of applied innovation within a corporation as “the result of activities or functions of translating an idea or invention to enhance a product or service that creates value.”

Innovation activities or functions can be many; however, within the context of designing an innovation model for the mining industry, the innovation formula considered is based on a simple concept: the formation, transfer, and enhancement of information or knowledge (k). The first function of knowledge is the creation and transfer of information from one individual to another, as well as from one generation to the next, which is the creation and preservation of information through time (t). The second function is the enhancement of the gained knowledge, which is the augmentation or improvement of existing information or the status quo. The third function is applying the enhanced knowledge to improve a system (s), service (v), or product (p).

A simplified knowledge-based innovation equation follows [2]:

\[
([\text{Creation (k)} + \text{Transfer (k)}] + \text{Enhancement (k)} + \text{Application (k)}) \times t = \text{Innovation (s,v,p)} \]

### 4 The Mining Innovation Model

This article intends to introduce a clear and comprehensive mining innovation model that can be applied to any type of minerals industry, regardless of the mining method used or commodity being extracted.

The model is designed to clearly indicate what those key technologies are that need to be considered today based on five ultimate operational conditions – innovation drivers – that will be critical in the mining industry of the future. As seen in Fig. 3, the five operational conditions / operation drivers are:

- (1) achieving maximum safety
- (2) simplifying systems
- (3) using smart-intelligent solutions
- (4) designing stealth operations
- (5) following a sustainable strategy

These five innovation drivers are thus common denominators to any mining industry regardless of their operational nature today and in the future.

The five innovation drivers have been carefully defined as the result of several years of teaching, research,
and consulting for the mining industry and are carefully selected to be applicable to any type of mining operation: metal or nonmetal, underground or surface, and soft-rock or hard-rock mining.

It is thus envisioned that the innovation model introduced in this article can serve as an initial guideline for the mining industry to identify those technologies that need to be addressed today to ultimately achieve the five operational conditions to operate the “mine of the future” effectively.

5 Ultimate Mining operational Conditions / Innovation Drivers for the Mine of the Future

5.1 Safe

The first operational condition that any industry, including mining, needs to achieve is total safety. The innovation model introduced here proposes the use of technology to achieve total safety. This is accomplished by creating innovation policies that assist the process of achieving an ultimate safety operational condition. The mine of the future will focus on a very strict zero accident/incident policy. Fatalities will be an extremely rare event due mainly to virtual-reality and augmented-reality training, to the use of remote-operated equipment, and advanced smart-automation technology, as described in section 5.3.

The mine of the future will not just aim to reduce the number of accidents and incidents through advanced technology, it will also invest in the use of non-invasive biosensor technology to monitor the health and safety of every worker continuously to maintain and even improve the health of every employee. The mine of the future will commit to improve the well-being of its employees:

▶ Using smart sensors and artificial intelligence to continuously assess personnel health and stress levels
▶ When necessary, promote healthier diets, exercise routines, meditation
▶ Even suggest a well-deserved break from their job routines

The following are examples of technology related to creating a total safe operational condition:

▶ Virtual-reality (VR) applications in training and maintenance
▶ Augmented-reality (AR) applications in training and maintenance
▶ Real-time ground control sensors
▶ Through-the-ground communications
▶ Rapid borehole drilling
▶ Real-time tracking and monitoring
▶ Smart automated systems
▶ Remote-operated systems
▶ Real-time underground mapping and tracking
▶ Fatigue detection technology
▶ Vibration monitoring in human-operated vehicles
▶ Biosensor applications in real-time health monitoring

5.2 Simple

Simplicity is the second operational condition to achieve in the mine of the future. The innovation model proposes a simplification strategy when considering the development and adoption of new technology: the model promotes “innovation by simplification” versus innovation by complexity. Thus, simplification is a key driver when designing the mine of the future – looking for simplification at every level within the mining system.

One key technology in the simplification process is the adoption of a modular system strategy. Modular operations in mining, in terms of production capacity, are an important technology-driven strategy that can prepare any mining operation to quickly adapt to sudden market shifts that very often push a mining operation to either reduce or increase production capacity without incurring significant capital and operational costs. Hence, modular systems are an excellent operational approach for adapting production as the mining system matures during stages of development as well as during the extraction of the mineral resource.

Indeed, technology innovation is a great strategy that can bring solutions to complex problems; however, if care is not observed, new solutions can result in even more complex systems eventually resulting in even more complex problems. Complexity will inevitably bring more systems and subsystems, and in turn, more uncertainty, and more risk, which will eventually result in higher costs. Innovation by simplification is key to avoiding unintended complexity when solving problems or improving products or systems.

Some of the most common operational management systems used by the industry today deal with identification of production constraints, variation minimization, and simplification [3]. The following are some examples of innovation methods and technology related to creating a simplified operational condition:

▶ Total quality control and total quality management
▶ Total productive maintenance
▶ Theory of constraints
▶ Lean production
▶ Six Sigma
▶ Modular mining systems

5.3 Smart

After safety and simplification, the third ultimate operational condition in the mine of the future is maximum productivity. In this case, it is productivity to the highest level possible by using smart and autonomous technology.
Today, technology transformation is advancing so rapidly that it is difficult for any industry to anticipate potential loss of competitiveness because of the adoption of new technologies, always with the looming possibility of suddenly falling victim to technology disruption. Worldwide, the industry is indeed facing a tremendous technology transformation: The Fourth Industrial Revolution (IR4).

IR4 consists of several advanced technology trends such as automation, big data analytics, artificial intelligence, machine learning, virtual and augmented reality, 3-D printing, and several other technologies [4]. IR4 is a reality, is happening and will radically transform how the industry thinks and operates. A transformation so radical requires in one generation a completely new set of skills and competencies that do not exist today.

There are several IR4 advanced technologies that will indeed transform industry forever. Two of them, however, are worth mentioning to achieve a smart operational condition in the mine of the future: smart automation and smart data analytics.

Smart automation, based heavily in real-time sensorial technology, advanced robotics, and of course, artificial intelligence, is the next evolutionary step in automation. Future automated equipment will move beyond operating autonomously but will also do so by adapting to variable conditions, and even collaborating with other smart autonomous equipment or systems. This new collaborative autonomous technology will result in incredible smart and efficient systems that will require minimum human intervention. In mining, this is probably good news; currently, mining faces new operational challenges in extracting minerals under very difficult scenarios, most of the time under hazardous conditions for humans.

Smart data analytics is the next step in the development of data analysis algorithms that will not just sort, organize, and filter data, but will also analyze data in different forms, bring conclusions, and provide answers and solutions to, sometimes, unseen problems. Smart data analytics will find potential problems intelligently before they occur and provide possible solutions.

The following are examples of technologies used to create a smart operational condition:

- Embedded sensors
- Internet of things
- Big data analytics
- Machine learning
- Artificial intelligence
- Block-chain technology
- Real-time data networks
- Battery-based equipment technology

5.4 Stealth

Stealth mining is the fourth operational condition in the mine of the future. During the lifespan of a mining operation, large footprints are created [5]. By executing an effective innovation strategy, mining footprints can be significantly reduced. Innovative mining methods and new mining equipment will assist in attaining a minimal footprint or "stealth" operational condition. Footprint minimization will inevitably steer mining operations toward the use of underground versus surface mining methods. Most likely, the mine of the future will be underground and heavily automated or remotely teleoperated.

Compared to the high production rates typically seen in surface mining operations, the key to high production rates in an underground environment will be achieving the three conditions mentioned earlier – safety, simplification, and smart technology – as well as developing and applying new underground mining and processing strategies. Promoting minimal material handling in the recovery and processing of the mineral is such a strategy.

The evolution of the mine of the future into becoming an underground stealth operation consists of three technology phases. The first phase is the total automation of transporting the ore material from the underground stope to a processing plant located on the surface. The second phase is to handle the blasting, processing, and recovery of the ore material all underground. The third phase is using advanced in situ recovery methods that will leach the mineral content directly from the host rock without the need to use traditional blasting and processing methods.

Advanced underground cave mining is also a promising approach to mine at large capacity rates. New caving monitoring technology is being developed today that will help track the caving flow in real time as the material is being extracted [6].

Surface mining will not completely disappear in the future. It will still be used by the minerals industry for a number of years. However, surface mining methods of the future will need to evolve drastically from digging massive open pits into digging temporary open trenches, mined by fully autonomous equipment. Open trenches, once mined, will be immediately filled in and fully reclaimed to avoid massive mining footprints that otherwise can last for several decades if standard open-pit mining methods are used.

The following are examples of innovation methods and technology used to create a stealth operational condition:

- In-line recovery methods
- In-mine recovery methods
- In situ recovery methods
- Sequential opencast-and-fill mining
- Advanced cave mining: real-time underground monitoring
- Modular mining systems

5.5 Sustainable

Sustainability is the fifth condition in the mine of the future. Sustainability in mining can be defined as that
Mining

ultimate operational condition where a mining system is self-sustained in terms of the resources it needs to operate. The mine of the future will use only renewable energy and will reduce water use to a bare minimum, deploying highly advanced recycling systems and continuous sensorial systems with zero discharge.

A sustainability condition in mining also promotes social and economic development in the region where the mining unit is operating. Mining sustainability must promote economic development during and after operation and must fully embrace the total preservation and enhancement of the local ecosystem. A sustainable condition in the mine of the future also considers the first condition described in this model – total safety.

In this case, the model promotes sustainability through innovation, which promotes sustainability through the application of technology to assist with resource-use optimization and in turn, regional economic development, maintaining and improving local ecosystems.

The following examples of methods and technology relate to creating a sustainable operational condition:

- Use of renewable energy resources
- Recyclable water systems
- Waterless systems
- Advanced energy-efficient systems
- Fully embracing social responsibility
- Socioeconomic development
- Business-model community participation

6 Conclusions

Nowadays, innovation is a key survival strategy to maintain high levels of growth, productivity, and sustainability in any industry. To stay relevant and survive the new paradigm of extremely rapid technological evolution and even technological disruption, defining a technology innovation model today is crucial for the mining industry of the future. The proposed mining innovation model is designed based on key operational conditions that are expected to be critical in any mining operation of the future. The innovation model is specifically devised for the mining industry and is also designed to be consistent and independent of any type of mining method or commodity being extracted, such as metal versus nonmetal mining, underground versus surface mining, and soft-rock versus hard-rock mining.

The model defines five key operational conditions that are the innovation drivers: (1) achieving maximum safety, (2) simplifying systems, (3) using smart-intelligent systems, (4) designing stealth operations, and (5) following a sustainable strategy.

The innovation model introduced in this article can serve as an initial guideline for the mining industry to identify those technologies that will need to be addressed today to ultimately achieve the five operational conditions needed to effectively operate “the mine of the future.”

7 References


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The changing Salt Mining

Eric Gourley, Sandvik Mining and Rock Technology, Stockholm, Sweden

After 120 years of drill-and-blast extraction, one of Western Europe’s largest salt mines transitioned to continuous mining. The shift to a quieter method under urban areas has extended mine life by many years.

The Franken shaft’s blue headframe rises high above the surface facilities at Südwestdeutsche Salzwerke AG’s Heilbronn salt mine (Fig. 1). The industrial area is just three kilometres north of the centre of Heilbronn, a city of 125,000 people about 50 kilometres north of Stuttgart.

The Heilbronn mine is one of Europe’s first industrial salt operations. Drills struck the first rock salt in 1881. Mining began on December 4, 1885 – the St. Barbara’s Day holiday celebrated by miners in countries around the world – and the operation has been a key producer of rock salt and evaporated salt for business, industrial and pharmaceutical customers, winter road maintenance and household use ever since.

Seasonal Fluctuations in Demand are a Challenge

The mine can extract and hoist more than 4.5 million tonnes of raw salt each year. David Saage, department head of the rock salt unit, who has worked at the Heilbronn mine for 10 years, says weather-driven market volatility poses a challenge (Fig. 2).

“We are dependent on winter business,” he says. “In a green winter, when there is no snow, the sales go down. When the snow comes, market demand increases and to maintain a continuous process with so much volatility is a challenge. When we get a white winter, we have higher volumes of de-icing salts, where we need a certain amount of flexibility in the equipment fleet.”

For 120 years, Heilbronn’s salt deposit was extracted exclusively using conventional drill and blast methods. Many of the hundreds of kilometres of tunnels comprising the Heilbronn mine today run directly beneath the city’s residential areas. In 2005, the mine looked to move away from drill and blast to a quieter mining method.

Implementation of mechanical Cutting

Heilbronn decided to implement mechanical cutting, introducing its first Sandvik MB770 continuous miner in May 2006 (Fig. 3). The machine’s performance was proven in coal but it had never been used in a salt mine. The introduction of continuous mining also required adjustments to the mine’s haulage and infrastructure. The mine commissioned a second Sandvik MB770 in December 2008 and a third in 2011.
Not only has continuous mining eliminated the downtime previously required for blast gas clearance, it has also minimised the need for crushing the extracted rock salt. Each continuous miner can excavate more than 100,000 tonnes per month.

Heilbronn relies on three continuous miners to cut away rock salt. A continuous miner trams to the working face and a Sandvik TH540 dumper truck reverses into position under the continuous miner’s conveyor system. The continuous miner fills the dumper, which hauls the salt to the feed conveyor (Figs. 4 + 5).

**Machine Operator convinced of the Concept**

Operator Marvin Traub (Fig. 6), who has run continuous miners at Heilbronn for seven years, appreciates the automatic cutting sequence of the Sandvik MB770. “You only occasionally have to cut by hand,” he says. “The machine always cuts one metre. And the machine always drives a metre forward. We’ve set it to three cuts, so that the machine does 33 cm per cut. After one metre, you tram it forward one metre, and then you put the automatic mode on and it starts from the beginning again.”

Traub also drives the Sandvik TH540 from time to time, and favours it over the mine’s 30-tonne trucks. “You drive straight on, not like with the other trucks,” he says. “With them, you’re side on, similar to an underground loader. Here, we drive facing forwards. Only when reversing do you need to use the camera and mirrors. The Sandvik TH540 is a great match for the Sandvik MB770.”

Heilbronn still operates three of its four Sandvik continuous miners and recently purchased a fifth. The mine’s first Sandvik MB770 is now on display in a visitors’ museum in Bad Friedrichshall. From May 2006 to March 2016, the unit mined around 8 million tonnes of rock salt, traveling more than 110,000 m.

**Use of conventional Methods for Peak Demand**

Heilbronn still utilises drill and blast in some parts of the mine that are not directly below urban areas to

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**Continuous Miner Sandvik MB770**

Sandvik MB770 is designed for a variety of continuous mining tasks in non-coal and non-gassy operations up to 5.3 m (17.4 ft) in height. This high-performance robust machine combines special design features for cutting, loading and face ventilation. A slow speed revolution cutter head guarantees less dust and fewer vibrations. The automated, programmable cutting cycle guarantees accurate cutting while the visualisation and data logging system further increases the performance.
compensate for seasonal peaks in salt demand (Fig. 7). Seven-metre blast holes are drilled and each blast produces more than 1,000 tonnes of rock salt. Sandvik loaders transport the blasted rock salt to the crusher, which crushes the salt so that it can be transported by conveyor. Heilbronn operates four Sandvik loaders, LH621, LH517, LH514 and LH307.

**Conclusion**

“The most important criteria for suppliers is reliability in terms of the availability of the machines, the economics and the long service life of a machine,” says Saage. “The availability of the machines is the top priority. Machinery that isn’t running is superfluous. The Sandvik equipment has proven to be very reliable at Heilbronn.”

**Südwestdeutsche Salzwerke AG**

Founded in 1883, Südwestdeutsche Salzwerke AG is one of Europe’s key salt producers. The company produces rock salt and evaporated salt for business, industrial and pharmaceutical customers, winter road maintenance and household use, including Germany’s famous Bad Reichenhaller brand. Südwestdeutsche Salzwerke AG employs around 1,000 people across four locations in Baden-Württemberg and Bavaria. The city of Heilbronn and the state of Baden-Württemberg each own a 49 percent stake in the company.

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**HUESKER’s reinforcement, containment, dewatering and filtration solutions offer opportunities to reduce construction time, reduce construction and operational risk and provide Geosynthetic solutions which contribute to the economic, social and environmental sustainability of mining projects and operations.**

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Heavy Industry 4.0: proactive Maintenance of Conveyor Belt Systems through digital Sensor Technology

Jonas Kothy, Livewelt GmbH & Co. KG, Dresden, Germany

Max Gertz is facing a trap – although he doesn’t know it yet. The product manager from Rema Tip Top is in India, standing in front of a customer’s conveyor belt system, the only tool available to him is his Belt Thickness Monitoring System, BTM for short, an in-house development of the German company’s service department. The trap: a primed conveyor belt. The trapper: the system operator, pretending to know less than he actually does. The objective: testing the capabilities of a system for the proactive maintenance of conveyor belt systems developed by Rema Tip Top, pooled under the names of Rema MCube and Rema CCube. M stands for monitor, maintain and manage and C stands for command, control and communicate.

The idea behind it is simple, the technical realisation a bit more complicated. It is – in equal measure – about a comprehensive evaluation of a conveyor belt system and a view into the future. What is the current condition of the conveyor belt and how will it presumably develop over the days, weeks or months ahead?

New Challenges, new Opportunities: Digitalisation in heavy industry

Strong keywords are sited in the context of digitalisation of the mining industry:

- Economic and ecological sustainability
- Maximisation of profitability
- Reduction of downtimes

The fourth industrial revolution has reached this line of business and the development may hit many market players in a disruptive way rather than have a gradual effect. After all, Industry 4.0 will result in the same opportunities and risks for the mining industry as it will for many other lines of business. In the future, a conveyor belt will be required to be both durable and comprehensively digitalised. A mine must be both profitable and autonomous. A production sequence must not only be satisfying with human understanding; it has to be the optimal solution on the basis of objective technical criteria. State-of-the-art sensor technology enables the collection of an increasing amount of detailed data, the evaluation of which is a big data analysis presenting new challenges to companies.

Thomas Moser is the person at Rema Tip Top responsible for meeting these challenges on equal terms. “What we want to prevent in any case are unplanned downtimes,” is how Moser describes his approach. “We are guided by the principle: prevent the uncontrollable and control the unpreventable.”

At the bauma the Rema Tip Top AG presented a new monitoring system for conveyor belt systems. This article hones in its manner of functioning and capabilities – and a special try-out in India.

Mining • Tunnelling • Conveying technology • Monitoring • Maintenance • Digitalisation

bauma 2019: Rema Tip Top presents the mobile Belt Thickness Monitoring System

Less than ten kilometres as the crow flies from company headquarters in Poing, the Messe München opens its doors every three years for the bauma, the world’s leading trade fair for construction machinery and the mining industry. At the latest bauma, in April 2019, Moser presented the new prototype of the BTM module (Fig. 1).

Fig. 1: Proud fathers of success: Thomas Moser and Max Gertz presenting the BTM module at the bauma 2019
Basically, the system consists of three components: the core element is the ultrasonic sensor array for measuring the thickness, complemented by an RFID receiver unit for localising the damage by means of RFID tags built into the conveyor belt, and the corresponding control unit (Fig. 2 and Table 1). The prototype presented at bauma is a mobile variant and pools all these functions in a black, oblong box, equipped with ten ultrasonic sensors. There are extensible elements between the sensors by means of which the module can be adjusted to a width of up to 3.2 m, akin to an accordion (Fig. 3).

The product is placed transversely to the direction of conveyance underneath the conveyor belt so that the entire belt is forced to run once over the testing station after one revolution. The conveyor belt does not have to be stopped for the scan to take place. The measuring station has zero contact with the belt which ensures continuous and safe productivity while measuring. During the revolution, the sensors measure the distance between sensor and conveyor belt constantly down to the milimetre, from which – based on the calibration measurement – the thickness of the conveyor belt can be derived. The sensors generate hundreds of readings per second, thus providing a precise graphic representation of the conveyor belt even after only a single revolution.

The collected data are transmitted from the control unit to the provided software and evaluated (Fig. 4). The options for evaluation primarily depend on the type of sensors used, the core element for the BTM module deployed for measuring the thickness. To analyse the data, the user enters known parameters such as belt length and velocity and defines critical areas of belt thickness, for instance, a minimum thickness of 13 mm and an initial thickness of 22.7 mm. These critical areas of thickness depend on the belt material and the goods to be conveyed. An optimally defined minimum belt thickness offers sufficient protection against longitudinal rips without the belt having to be classified as a reject prematurely.

From these data, the software calculates a graphic representation of the results that displays the different readings along the entire conveyor belt by means of a

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**Table 1: Technical data of Belt Thickness Monitoring (BTM)**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>110 / 240 VAC 50/60Hz, 15 A, constant current source</td>
</tr>
<tr>
<td>Environment temperature range</td>
<td>–40 to +70 °C</td>
</tr>
<tr>
<td>Operating humidity</td>
<td>20 to 90% relative humidity, non-condensing</td>
</tr>
<tr>
<td>Ethernet connectivity</td>
<td>Cat 5 Copper (RJ-45) jack (10 /100 MHz ) WiFi-connection – 802.11 a/b/g/n</td>
</tr>
<tr>
<td>Operating system and computational power</td>
<td>Operating system: Microsoft Windows 8.1 including all critical security updates</td>
</tr>
<tr>
<td></td>
<td>Processor: Intel Celeron, CPU 1037U, 1.80 GHz, (2 CPU)</td>
</tr>
<tr>
<td></td>
<td>RAM: 4096 MB</td>
</tr>
<tr>
<td></td>
<td>Hard disk: 500 GB disk capacity</td>
</tr>
<tr>
<td>Monitor</td>
<td>17-inch touchscreen monitor</td>
</tr>
<tr>
<td>Ultrasonic sensitivity</td>
<td>0.34 mm precision</td>
</tr>
<tr>
<td>System casing and sensor casing protective class</td>
<td>IP 65 – no dust intrusion, complete touch guard. Water jets directed against the casing through a nozzle (6.3 mm) must not have any harmful effects.</td>
</tr>
<tr>
<td>System casing mounting bracket</td>
<td>4 x mounting brackets on the backside of the casing (13 mm)</td>
</tr>
<tr>
<td>Ultrasonic sensor casing mounting bracket</td>
<td>2 x universal ball joint brackets for simple setup and adjustment</td>
</tr>
<tr>
<td>RFID tag receiving unit</td>
<td>UHF Alien RFID receiving unit, POE, TCP/IP and RS-232 with casing and cable seals</td>
</tr>
<tr>
<td>RFID tag</td>
<td>UHF RFID tag c/w with unequivocal address</td>
</tr>
</tbody>
</table>

---

**Fig. 2:** MCube in operation: a permanently installed monitoring module on a running system

**Fig. 3:** A whole bunch of measuring points: an ultrasonic sensor of the BTM module

**Fig. 4:** Everything in the box: the central control unit of the system
colour code (Fig. 5). In this way, potential risk spots for longitudinal rips in the belt can be identified at a glance since they are marked in red in the overview. The position of the selected area in the conveyor belt revolution is displayed through the RFID tag. In the measurement example shown here, severe wear can be detected in the area between 462 and 472 m, the thinnest spot measured with a belt thickness of only 14.06 mm – just 1.06 mm above the defined minimum thickness.

One of the strong points of the system is the bundling of several measurement time points: when several measurements are conducted over a certain period of time, these data can shed light on the presumable wear during the next time intervals. This enables an estimation of at what point in time the belt will fall below the minimum thickness, which means at what point in time the risk of longitudinal rips in the belt will substantially increase.

In addition to inspecting the longitudinal course of belt measurement, the cross-sectional analysis yields valuable insights for optimising the belt revolution as well. The measurement shown here (Fig. 5) reveals a clear trend: on the left side of the conveyor belt, which is at the top margin of the software representation, much higher belt wear can be detected than on the right side. This could be attributed to unbalanced loading of the
Mining

sors connected in an intelligent way (e.g. Fig. 6). No standard product is going to prevail; the emphasis is really on customised composition and integration of the right modules from a wide-ranging technology kit.” The added value for the customer is crucial thus requiring an optimal information flow – regardless of which type of sensor supplies the data.

**BTM Field Test in India**

Back to India and to Max Gertz, who keeps on standing in front of the trap – yet unaware of what he is facing. The conveyor belt to be tested has a length of 840 m, at a velocity of 2.7 m/s one belt revolution takes 38 minutes – and this is precisely the time Gertz needs to collect all necessary data by means of the BTM module. The evaluation by means of the software quickly reveals to the trained eye: the conveyor belt consists of an old and a new section, the junctions are highlighted in dark green in the colour code since they are a bit thicker than the rest of the belt. In addition, this conveyor system shows unbalanced loading which made individual belt spots potentially vulnerable to rips. The customer is impressed, although he already had this information in broad outline, albeit collected laboriously by hand and not during a measurement that lasted about 38 min. Max Gertz and his BTM module can clearly cope with this little trap, this 840-metre long challenge made of rubber. With the help of the BTM module, the customer has received more information than he already had about this particular conveyor belt and can now take detailed measures to prevent damage to the belt. Thomas Moser would possibly couch it like this: “The uncontrollable has been prevented and the unpreventable controlled”.

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**Ultrasound, Radar, Drone: the right Technology Mix is crucial**

Besides ultrasonic thickness measurement there are other options for the acquisition of relevant data with the objective of enhancing profitability: employing radar sensors enables precise measurement down to the millimetre of volume, velocity and belt misalignment, albeit it is more expensive than ultrasonic measurement. Drones can be equipped with various types of sensors and monitor large systems from the air; however, they need a trained drone pilot monitoring the operation. This is why Moser does not see a single technology dominating in the foreseeable future: “It’s always the right mix of different technologies and different sensors connected in an intelligent way (e.g. Fig. 6). No standard product is going to prevail; the emphasis is really on customised composition and integration of the right modules from a wide-ranging technology kit.” The added value for the customer is crucial thus requiring an optimal information flow – regardless of which type of sensor supplies the data.

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**Fig. 6: Example of technology mix – schematic drawing**

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The Potential for Development of Underwater Natural Gas Storage in Europe

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Introduction

The gas supply reliability to the European market is one of the most important factors of economic growth. Seasonally adjusted demand for natural gas has long been regulated by underground gas storage (UGS) facilities. However, UGS facilities are not located in all European gas-consuming countries, which arouses grave misgivings about energy supply in emergencies. The construction of UGS facilities is possible only in certain geological structures, which are found in few countries in Europe. An alternative method is necessary to storing natural gas independent of the geologic aspects of a country. The analysis of gas storage methods revealed that one of the most effective ways is underwater natural gas storage in impermeable spheres of soft material.

Topical Status and Development Problems of Underground Gas Storage in Europe

UGS facilities operations make it possible to even out seasonal or short-term falls in demand. In general, UGS facilities are divided into two main groups depending on the purpose of the gas storage. The first group is base load facilities (seasonal storage facilities), the second – peak load facilities (peak shavers). Base load UGS facilities are intended for cyclic storage operation with relatively small deviations of UGS daily performance from monthly average value (increase or decrease in the range from 10 to 15%). Peak load UGS facilities are meant for cyclic storage operation with significant changes (peaks) of more than 10 to 15% of the daily production/injection rate for several days from monthly average value.

UGS facilities are mainly built in depleted deposits, in aquifers, in salt bed caverns, in caverns of firm rock or in exhausted mines. In recent years, UGS facilities created in salt caverns are becoming widespread in the construction of new gas storage facilities. If emergency gas recovery is possible to cover peak loads, UGS facilities in salt caverns possess several advantages.

There are 144 UGSs with a total capacity of 97 billion m³ in Europe. The UGS capacity has increased by 14 billion m³ over the past three years in Europe and the demand for new gas storage is growing. It is important to note that UGS capacities are unevenly distributed throughout Europe. Eastern Europe has a significantly less advanced capacity for gas storage than elsewhere. Among the EU gas consuming countries, no natural gas is stored in Greece, Albania, Bosnia and Herzegovina, Finland, Lithuania and Estonia. There is only one UGS facility in Latvia for the Baltic States. Of the non-EU countries, only Turkey and Serbia have gas storages. There are no UGS facilities offering commercial possibilities in Norway in spite of the high level of gas production and its important role in European gas supply [1].

In emergency or exceptional situations, a headline indicator of the UGS effectiveness is a technical feasibility of maximum daily production rates for gas wells. Gas production volume depends both on UGS capacities, but as well as their type. For instance, the maximum daily gas production of the UGS facility in the Netherlands is twice that of in Hungary with approximately the same capacities. About 2 billion m³ of gas per day is the total production volume of UGS facilities in the EU. The core of the problem lies in the fact that about 60% of this volume is accounted for by three countries – Germany, Italy and France. However, it is not possible to estimate the efficiency of using gas reserves from a UGS facility in an emergency from one gas production volume [1].

In order to better assess the situation with gas storage in Europe, it is necessary to compare the daily production volume of UGS facilities with the average daily consumption of natural gas in European countries. Calculations revealed that the average daily demand of natural gas is higher than the possibility of its supply from the UGS facilities in ten countries, i.e. the production/consumption ratio is less than one. This category in-
The potential for development of underwater natural gas storage in Europe

Incl: mainly countries of Eastern Europe – Romania, Poland, Bulgaria, Croatia, and Turkey – together with the United Kingdom, Ireland, Spain, and Portugal. It is necessary to include Switzerland too, where there is no UGS facility. The daily production volume of the UGS facilities in other countries exceeds or corresponds to roughly the average daily consumption of natural gas. In emergency or exceptional situations, natural gas surplus provided by UGS facilities in those countries where the maximum production volume exceeds the domestic demand can be transported to neighboring countries. This has led the EU to invest in the development of a gas pipeline network between countries in order to increase the reliability of their gas supply [1].

The UGS facilities network should cover the territory of Europe evenly to solve the problem of natural gas supply reliability. In this case, the emergency pipelines between the countries would not be required. However, this cannot be achieved primarily due to geological reasons: geological structures that allow the construction of base load UGS facilities in depleted deposits and aquifers are not present everywhere and there are only a few regions to accommodate peak load UGS facilities in salt bed caverns. It should also be noted that the investment in the construction of peak load UGS facility is significantly higher than that in the building of base load UGS facility. It is necessary to find alternative methods of natural gas storage, preferably in peak mode.

Alternative Methods for Storing Natural Gas

The alternative methods of natural gas storage typically include underground storage in exhausted mines (for instance, coal mines) or storage in artificial caverns inside firm rock. There are examples of such gas storages, but these are scarce.

The Skallen lined rock cavern (LRC) storage facility was put into operation near the main gas pipeline in the city of Halmstad area on Sweden’s west coast. The geological requirements for the construction of LRC storage facilities are related to the rock mass quality. The cavern was formed in granite at a depth of 115 m, gas-tightness is provided by a steel liner. The geometrical volume is 40,000 m³, it is only half the size of commercial caverns. The project demonstrated that LRC storage facilities are not only expensive to construct and maintain but also the pressure and volume are limited. Oversize caverns can cause rock deformation and gas leaking. Such gas storages can serve a small number of consumers, which makes them economically unattractive.

Another example is underground storage in exhausted mines. At the present time, two of the four gas storages in exhausted mines are in operation:

- The Burggraf Bernsdorf UGS facility (the potassium salt mine, Eastern Germany)
- The Leiden UGS facility (Leiden Coal Mine, Colorado, USA)

The Burggraf Bernsdorf UGS facility is analogous to a storage in salt caverns operated for about 40 years, with a maximum permissible working pressure of more than 3.6 MPa (the highest pressure for such UGS facilities). The main factors for maintaining such operating pressure are:

- Sealing of gas storage using special concrete plugs
- The properties of surrounding rocks (rock and potassium salt)
- Hydraulic and mechanical sealing systems

The operating experience of such gas storages showed that gas losses and leakages during storage can only be prevented by covering the mine walls with sealing materials and constructing large concrete bulkheads in the mine shaft. A pressure in exhausted mines above the geostatic (and sometimes hydrostatic) one will cause a rock formation to fracture. In addition, a part of the stored methane is absorbed by coal in the coal mines. For all these reasons, the gas storage volume does not exceed several tens of millions m³.

Liquefied natural gas (LNG) terminals on the seacoast are considered as an alternative way for storing compressed gas. On arrival at the terminal, LNG tankers unload the cargo into the terminal storage tanks. LNG can be stored in the tanks for up to a month and pumped out for sending to customers after regasification. However, maintaining the liquefaction temperature, LNG regasification and gas compression are very energy-intensive processes, which significantly increase the cost of gas. In addition, it is impossible to provide a sharp increase in the volume of pipeline-supplied gas (as in the case of a peak load UGS facility), because there are peak-power limitations of the units.

High-pressure compressed gas tankers have also been proposed. These tankers are kept at pressures around 25 MPa or 250 bar. So, one vessel with a length of 300 m, a width of 50 m and with a draft of 10 m could contain up to 15 million m³ of natural gas [2, 3]. The high-pressure tankers should operate in European seas, in places, where LNG terminals are already operating. Hence, it follows that the tankers are not needed as long-term storage facilities. As noted by developers, the tankers are intended to ensure stable gas deliveries from offshore platforms – their use as gas storages is not foreseen.

Another alternative technology for storing natural gas is currently being developed in Japan. This is gas hydrate technology [4]. Natural gas at 5 to 10 MPa is converted into gas hydrate (a crystalline solid form of water and gas); its concentration increases to 160 m³ of gas per 1 m³ of gas hydrate. Then the gas hydrate is cooled down to a temperature of between 5 and 20°C and the pressure is reduced to atmospheric level. As a result of the effects of gas hydrate self-preservation [5],...
the solid monolithic hydrate can be stored indefinitely, if the temperature remains within the required range. Thus, the gas hydrate can be kept in an industrial refrigerator. In order to extract the gas, it is sufficient to raise the temperature of the hydrate above 0 °C. Besides the fact that this technology is only beginning its development, the storage of gas could require high energy costs for the operation of refrigerators in regions of Europe with a warm climate. Apparently, the gas hydrate technology is applicable for gasification of remote Arctic locations, where a negative temperature (Celsius) prevails most of the year [6].

Such exotic methods for storing natural gas as earth-based gas-holders and above-ground balloons make no sense because of risks to the public and the environment. What remains as a basis for storing natural gas by alternative methods, if opportunities of underground storage are limited by geology and storage facilities located above ground are dangerous for people’s lives or too expensive? The answer is water.

Underwater Gas Storage - the unused Reserve

There are tens of thousands of large lakes and artificial storages part from vast marine resources in Europe. Furthermore, a large part of the coastline and deep-water areas is located in countries where the construction of UGS facilities is impossible or impractical due to geological problems: Norway, Sweden, Finland, Switzerland and Eastern Europe. If gas storage facilities could be underwater, it would result in a significant improvement in the security of energy supply in Europe. Moreover, if it is possible to create underwater storage facilities on an industrial scale (more than 100 million m³) and locate them near submarine gas pipelines (for instance, North Stream), the need for building additional pipeline routings can be reduced considerably.

In the mid-2000s, the idea of such a peak/base load underwater gas storage facility originated in Russia, where serious energy supply problems were revealed in the Leningrad Region, particularly in the city of Petrozavodsk [7, 8]. The city is located on the western shore of Lake Onega, the second-largest freshwater lake in Europe. For geological reasons, UGS facilities cannot be built in the area, therefore various alternatives for storing natural gas had been considered. In this instance, the option of underwater gas storage was declared the most effective one according to target parameters.

The project included the building of 1,670 spheres possessing gas barrier properties at the bottom of Lake Ladoga or Lake Onega. The spheres made of fibre-reinforced materials could withstand high pressures up to 7.5 MPa as in a main gas pipeline. The gas storage volume would cover 500 million m³. The design diameter of the spheres was 20 m, each sphere could contain a gas volume from 4,200 m³ at 0.1 MPa to 300,000 m³ at 7.5 MPa. The spheres were to have been held in place by nylon ropes on metal piles, which were to be embedded in a concrete foundation to a depth of 20 m below the ground surface (Fig. 1). Natural gas was supposed to be supplied from the Volkhov compressor station. The station was to be located on the southern shore of Lake Ladoga. The water depth at the gas storage construction area would have been 30 to 50 m. The top of the spheres was assumed to be at a depth of less than 10 m. The planned size of the underwater gas storage facility was 800 x 840 m or 672,000 m².

A rubberized nylon fabric with a cord thickness of 3 mm was chosen as the material for the spheres. The wall of the sphere was supposed to be multi-layered. Calculations have shown that the sphere rupture at 10 MPa (25 % overdesign) can be prevented using 42 layers of the fabric. Consequently, the wall thicknesses would have been 12 to13 cm.

The selected fabric is neutral with respect to water, so environmental pollution problems would not have occurred. Indeed, it was essential to ensure the security of the underwater gas storage facility against accidents or sabotage. In this regard, it was suggested that swim restrictions would have to be imposed and a protected environmental zone established. Since the wall of the sphere was to have been multi-layered, the upper layer would be most exposed to the negative effects of environmental changes. It was recommended that this layer be replaced at certain intervals.

The cost of building the gas storage was estimated at $ 100 million, taking into account all materials and provided services [9]. It was expected that the underwater gas storage facility would be operated in both base-load and peak-load modes. Such gas storages are very rare in the world.
However, the gas supply problems were solved in the Leningrad Region thanks to the construction of the transnational Yamal-Europe gas pipeline and the underwater storage project was not implemented. Because of the project cancellation, it was not possible to carry out the necessary research work on important topics such as optimal material selection and gas control system design. The research results would have served to reduce the construction and maintenance costs of gas storage.

**Conclusions**

There is thus a strong case for creating underwater gas storage facilities in the EU. Such natural gas storage facilities are durable, easy to manage, do not lead to alienation of land, sometimes even serve as a breeding ground for wild fauna and help regulate the spring flow of rivers. The number and size of the spheres for underwater gas storage could be changed arbitrarily, which makes it possible to construct storage facilities even for small villages and enterprises, which are frequently far from the European UGS facilities. This method for storing natural gas could solve the gas supply problems in those European countries where the production/consumption ratio is less than one. Gas storage spheres could be located at depths greater than 5 m in seas, rivers, lakes and reservoirs. In addition to their intended use for storing gas purposes, these spheres can also be used to regulate the river flow. During spring floods, which can be a significant threat to lives and property, gas spheres could rise to the water surface, thus increasing the reservoir capacity. However, the construction of underwater gas storage facilities in Europe would require technological research work concerning in particular:

- Gas control system design
- Optimal material selection
- Fastening system engineering
- Definition of storage locations

**References**


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