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Preview bauma
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Natural disaster protection
Gripper TBM

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Leaky segmental joints can be resealed efficiently by means of an injection needle applied directly through the joint itself. You can learn more about this cost-saving “keyhole technology” in the English issue of GeoResources Journal 3-2018 or the German edition of GeoResources Zeitschrift 2-2018 as well as at the TPH Bausysteme GmbH`s booth C3.436 in Hall C3 at the bauma 2019 in Munich.

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bauma 2019 – innovative, global, digital and attractive

Klaus Stöckmann, Deputy CEO, VDMA Mining, Frankfurt, Germany

Next year it rolls around again: from April 8 to 14, 2019, the bauma will be held for the 32nd time in Munich, Germany. In the past, this leading world fair has set up record upon record. The organisers are confident that it will stay this way in 2019 so that the bauma will be able to consolidate its position as the world´s biggest trade fair of its kind.

bauma • Construction and mining machinery • Exhibition • Mining • Geotechnics • Tunnelling

Every three years the **bauma** attracts more than half a million visitors from over 200 countries as the innovative engine for the global branch for construction, building materials and mining machines. The **bauma** is the magnet for the rest of the world in similar vein to the CONEXPO or MinExpo in America. In Las Vegas it may be all very American but in Munich visitors and exhibitors can expect Bavarian-German hospitality (less with respect to the prices for staying overnight but in pure market economic terms). Apart from this, the world´s leading engineering fair represents an optimal platform for obtaining an all-embracing overview on the latest technology, targeting business deals or taking advantage of international markets. This is underlined by the 583,929 visitors from 219 countries that turned up at the last bauma in 2016, including 138,929 from the mining segment, who are obviously equally appreciative. Indeed, the bauma does not fail to impress when compared to Las Vegas – whether it´s MinExpo or CONEXPO-CON/AGG – when it comes to figures alone: 605,000 m^2 in Munich as against 78,038 m^2 or 232,257 m^2 in Las Vegas. In fact, even taken together the two US fairs are nowhere near the area occupied by **bauma**.

Innovations and Innovation Prize

However, quantity is not everything. Innovations after all, fuel success. The bauma three-year cycle is perfectly geared to the industry´s innovation needs. This is reflected among other things by the **bauma** Innovation Prize, which was invoked with significant participation on the part of the VDMA (German Mechanical Engineering Industry Federation), the bauma and leading organisations from the German construction industry in order to emphasise the fair´s role as the heartbeat of the branch. More than 100 exhibitors participated in the competition to come up with the best solutions in five categories:

- Machinery
- Components, digital systems
- Construction work, constrution method, construction process
- Science, research
- Design

The organisers are confident that an equally high number of entries for 2019 will take part. Contributions can be registered up until September 5.

During the course of the fair these developments will be presented on "Innovation Day" at the **bauma** Forum in Hall C2. Furthermore, new results stemming from joint research projects are also to be found there under the caption "Research live".

Digitalisation

Something essentially in its infancy three years back will be displayed on a grander scale in 2019: Digitalisation of machines and processes, whether on the construction site, in machinery, for machines communicating with one another, for "raw material extraction 4.0" with autonomous machines (without people present in dangerous areas) or for the sensor-supported, automated preparation of (building) raw materials.

Initiatives directed at the younger Generation

Furthermore, some of the universities involved are showing approaches to new solutions for machines and methods quite apart from canvassing for academic (engineering) new blood.

THINK BIG is also directed at the younger generation. This initiative promoted by exhibitors and the VDMA to foster technical professions in the construction and mining machinery branch attracted around 15,000 pupils to the fair in 2016, who took part in demonstrations featuring machines and simulators. 17 companies, training institutions and associations will be taking part and offering the students a real hands-on experience.

The centerpiece will be the "Workshop Live!" stage, featuring 20-minute shows each day. Actual trainees revealed what they have to learn on real machines and what they must be able to do later on in their profession.

Partner Country Canada

Then of course, the partner country Canada with its abundance of raw materials and great need for infrastructural development is bound to provide **bauma** 2019 with interesting impulses. Events relating to Canada are planned during the first two days of the exhibition at the **bauma** Forum in Hall C2.

We are looking forward to welcome you in Hall C2 at the **bauma 2019** in Munich.

Sincerely yours
Klaus Stöckmann

bauma 2019 in Munich, Germany:

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Slopes in loose Rock – Stabilisation and Erosion Protection in a single Operation

Dipl.-Ing. Eberhard Gröner and Dipl.-Ing. Armin Roduner, Geobrugg AG, Romanshorn, Switzerland

The creation and widening of infrastructures – such as roads, railway lines and buildings – frequently requires new cuttings or the steepening of existing slopes in loose rock. This article explains findings with planting vegetation and the stabilisation of such slopes and introduces novel combined systems of randomly entangled mesh made of synthetic material with mesh consisting of high-tensile steel wire, facilitating efficient installation.

Geotechnics • Loose rock • Securing slopes • Erosion protection • Efficiency • Innovation

1 Introduction

In many cases new cuttings and the steepening of existing slopes are required in loose ground and rock (**Fig. 1**) when producing and extending infrastructures such as roads, railway lines and buildings. Effective planting with vegetation is of great significance for successful and sustainable stabilisation of natural slopes and new cuttings in loose rock.

Ideally slopes should be created with a slight gradual incline so that stability is not jeopardised. If this is feasible then the effect of straightforward greening measures such as erosion control mats is usually sufficient to protect against washouts. However, they soon reach their limits of application if steeper slopes have to be secured or stability problems close to the surface or of a global nature occur (**Fig. 2**).

Geotextiles, which are used as greening aids, generally only possess minimal strength and are thus only effective for flat slopes or combined with a stabilisation scheme such as wire mesh. During the last 15 years, meshes made of high-tensile steel wire combined with soil nailing have established themselves for stabilising slopes. They are capable of sustaining major forces and transfer them effectively into the nailing thanks to their high puncturing resistance. Suitable dimensioning methods are available.

In order to extend the range of application of fibre matting or geomats made of synthetics in conjunction with dry or wet seeds as greening aids, they were combined at the factory with a high-tensile steel wire mesh in order to enhance their load-bearing capacity. They are applied to stabilise rock and loose ground slopes. A newly developed product now combines the advantages of mesh made of high-tensile steel wire for slope stabilisation and geomats for greening slopes or protecting them against erosion in conjunction with soil nailing. Quite apart from enabling still higher loads to be sustained, the system can be easily installed.

This article explains developments and experiences with erosion control mats as greening aids and wire meshes for stabilising slopes during the past fifteen years. At the same time, it introduces two new combined systems and findings during their application.

Fig. 1: Ad hoc slumping on a slope in the grounds of a sports facility
Source of images: Geobrugg AG

Fig. 2: Slumping on an embankment with a slope with appox. 25° incline and geotextile erosion protection mat without nailing

2 Supporting Greening with synthetic or natural Erosion Control Mats

An effective and functional layer of vegetation is required or must be produced for stabilising slopes in the long term [1, 2]. Newly developed loose rock slopes usually lack nutrients owing to the removal of the surface layer [3]. Through the removal of the vegetation layer there is a corresponding lack of roots capable of growth and a natural presence of seed.

Fig. 3: Erosion channels caused by the flow effect of the draining water, which remove the soil and reduce or prevent the growth of plants

Fig. 4: Exemplary slope stabilisation with high-tensile wire mesh, soil nailing and erosion control mat [5]

The aim is essentially to diminish or control external erosion. In this connection, a distinction is drawn between primary erosion with the so-called dropping effect and secondary erosion with the so-called flowing effect (**Fig. 3**). An erosion control mat should minimise the impact energy of the drops and be able to correspondingly retain soil particles in the flowing water [2].

In order to support the greening of loose rock slopes, a large number of erosion control mats and geotextiles exists [4]. Synthetic geotextiles e. g. consisting of polypropylenes, and natural geotextiles made of organic materials, e. g. jute or coconut fibres, are used. Organic natural products can be applied for flatter slopes. The advantage is that they store a portion of the water and on account of their composition release nutrients thus enabling plants to grow. In the case of steeper slopes, synthetic products offer an advantage. Their intrinsic weight is lower and alters only slightly on contact with water. Furthermore, the strength decreases at a later point of time than in the case of organic products.

3 Flexible Slope Stabilisation Systems with Wire Meshes and their Dimensioning

Flexible slope stabilisation systems made of wire mesh combined with nailing have become widespread in the meantime for securing loose ground and rock slopes and have proved themselves if applied correctly (**Fig. 4**). Owing to a lack of principles such as standards or guidelines it is often the case that only inadequate demands are posed on these safety systems and no proofs of stability conducted.

As a consequence, systems are available or installed, which are not adapted to the given local static conditions or their components are not geared to each other. This can possibly lead to malfunctioning with disastrous results on account of material collapses – as well as causing serious instabilities. Both the interplay of the system's bearing resistances as well as its individual elements including netting, mesh or attachments must be known so that the required proofs of stability can be conducted thanks to adequately dimensioned models [6, 7].

Dimensioning against instabilities close to the surface can be carried out in accordance with the Ruvolum® [8] dimensioning concept. It is generally valid and can be applied for dimensioning safety factors for instabilities close to the surface in loose rock as well as for extensively loosened rock slopes. The basis for dimensioning is provided by the bearing resistances, which are established in realistic, repeatable tests. The dimensioning concept was described at length by Rüegger in 2002 and 2004 [6, 1]. It contains the investigation of instabilities close to the surface and running parallel to the slope (**Fig. 5**) as well as local instabilities between the individual nails (**Fig. 6**). The influence of pore water overpressure, flow pressure and seismic forces can also be taken into consideration.

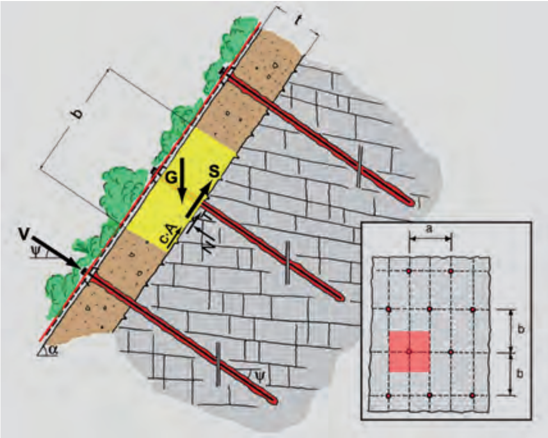

Fig. 5: Superficial instabilities running parallel to the slope

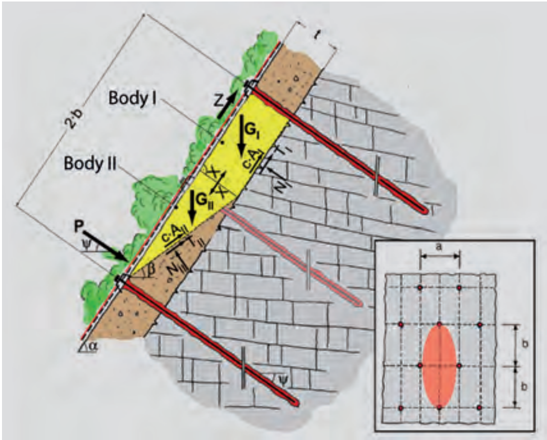

Fig. 6: Local instabilities between individual nails

4 Tests on a steep Slope to evaluate Erosion Control Mats

In 2000, initial field tests were embarked on in Switzerland to evaluate the efficacy of three different erosion control mats combined with high-tensile wire mesh on a steep slope.

The following requirements were defined by the Geobrugg AG in conjunction with the Ingenieurbüro Rüegger Flum [9]:

- Good sprayability for wet and dry seed to establish as much sowing material on the substratum as possible
- Good adaptability to the underground
- Low mass related to area, even given ingressing water
- Good adherence of the mat to the underground/low sliding potential
- Good retention properties for soil particles, organic materials and seed material
- Colour-coordinated for a natural appearance and low degree of heating

During the tests in 2000, various erosion control mats were installed on a test area in the Valais, Switzerland and a high-tensile wire mesh. The following alternatives were tried out (**Fig. 7**):

- Area I: Three-dimensional, extremely dense, three-layer erosion control mat made of black polypropylene
- Area II: Three-dimensional, corrugated erosion control mat made of black polypropylene
- Area III: Two-dimensional, flat geogrid made of black polypropylene

The test area was aligned south-west and was located on low-nutrient soil with pronounced dry-moist changes. Greening was accomplished with dry seed. The best greening success was provided by the three-dimensional corrugated mat on Area II. In the case of Area III it is presupposed that the retention properties of a two-dimensional, flat erosion control mat are too minimal for soil particles and seed material. For Area I, it is presumed that owing to the pronounced albedo, in other words the reflection of the black surfaces in the case of this dense mat caused greater heating of the slope, which led to faster drying out or rather non-germination of the seed.

In July 2003, field tests were undertaken with a three-dimensional so-called geomat or randomly entangled mesh based on the recognitions from the previous tests. The aim was to investigate the retention properties, adaptability to the underground and sprayability. Focus was concentrated on an erosion control mat consisting of extruded monofilaments, which was 18 mm thick and possessed a 600 g/m² mass relating to area. The cavity proportion amounts to more than 95 %. **Fig. 8** shows the test areas in Bischofszell, Switzerland. The described geomat was installed on the far right. The other areas are reference areas without erosion control mat or with similar products consisting of polypropylene. In order to come up with conclusions relating to the sprayability, wooden frames with an area of 1 m² were set up, which are visible on the lower edge of the photo.

The test area was landscaped with a hydroseed by the Verdyol Company of Switzerland. For hydroseed-

Fig. 7: Test areas in Switzerland for evaluating different erosion control mats on a steep slope

Fig. 8: Test areas in Switzerland for examining the efficacy of a geomat for erosion protection in 2013

Fig. 9: Test area approx. 10 weeks after the hydroseeding process and after heavy rain: otl without erosion control mat and otr with geomat

Fig. 10: Erosion control mat Tecmat [8], high-tensile steel wire mesh [6] and soil nailing

ing water is mixed with the seed, a mulch and an adhesive on an algae basis. The mulch in question was a so-called export mulch comprising straw fibres with a fibre length < 4 mm. Roughly four weeks after hydroseeding, the test area experienced heavy precipitation, leading to the slope being affected by landslides close to the surface. After a further six weeks, it was shown that all but roughly 10 % of the seed in the reference area without erosion control mat had been removed. Correspondingly low plant growth was identifiable (on the left in **Fig. 9**). In the area with the geomat, which was between 30 and 45° steep, more than 90 % of the area was covered with a layer of vegetation (on the right on **Fig. 9**). Based on these tests, in 2004 the Geobrugg AG marketed an erosion control mat under the trade name Tecmat [10] with the following characteristics (**Fig. 10**):

- Extruded monofilaments made of polypropylene with irregular loop structure
- 18 mm thick
- 600 g/m² mass related to area
- Cavity proportion > 95 %
- Colour curry green

5 Examples of Applications for stabilising Slopes combined with Erosion Control Mats

5.1 Stabilising an irregular Rock Slope in Miraflores, Panama

A very irregular rock slope in Miraflores, Panama, was secured in 2013 with the Tecco® G65/3 System and the Tecmat erosion control mat. The erosion control mat and the mesh were adapted successfully to the irregular slope. The fall of the folds indicates that part sectors do not fit properly (**Fig. 11**). The neighbouring zones are lavishly landscaped thanks to the good conditions for growth. Vegetation is starting to reveal itself in the area that was secured.

5.2 Securing a Slope in weathered Rock after a Landslide in Remscheid, Germany

Following a landslide, a slope with weathered rock in Remscheid, Germany, was secured with the Tecco® G65/3 System and the Tecmat erosion control mat in the year 2015 (**Fig. 12**). The growth conditions are good as can be seen on the opposite slope. The slope is relatively uniform. It is hard to fix the mat to the hard underground, thus resulting in slight displacements affecting the erosion control mat.

5.3 Securing an evenly profiled Slope in loose Rock at Dorndorf, Germany

In 2015 in Dorndorf, Germany, an evenly profiled slope was secured in loose rock. Deep hollows were excavated around the nail heads in order to be able to pretension the Tecco® G65/3 high-tensile wire mesh. The erosion control mat could be located in such a way that it fitted snugly with a low proportion of cavities beneath the erosion control mat on the slope (**Fig. 13**).

5.4 Conclusions

The three examples indicate that applying a combination of erosion control mat and high-tensile wire mesh can be accomplished with great success. It emerged from the irregular slopes in the first two examples that the erosion control mat did not always fit uniformly. It is equally important in the case of wet that the mat can be treated with an export mulch (fibre length < 4 mm). Owing to the slighter water absorption capacity of synthetic mats they are less susceptible to sliding under load. Depending on the conditions underground, it can be difficult to fix a mat in place. The third application example adapts well to the underground. No displacement of the mat is anticipated even when subjected to load. Nonetheless, the mat must be suitable for being injected with a sowing method.

6 Factory-devised Systems with combined Meshes made of high-tensile Steel Wire and Erosion Control Mats made of Polypropylene

Optimisation by means of a factory-devised combination of erosion control mat and high-tensile wire mesh as a joint product was the obvious approach. First of all, the erosion control mat is reinforced in structural terms. This affords the possibility of ensuring that the safety measure is more resistant to sliding. Straightforward assembly represents a further advantage as the erosion control mat and the high-tensile mesh can be installed on the slope in a single working cycle.

Initial tests with a standard product were carried out with the Deltax® G80/2 high-tensile wire mesh [11] in 2012. The mesh possesses an internal circular diameter of 80 mm with a wire diameter of 2 mm. The load-bearing capacity amounts to 53 kN/m. It is frequently used without nailing as a curtain and for steep slopes, where only smaller stones are anticipated. The erosion control mat reinforcement provides sufficient support for small stones. In some cases, applications with soil nailing take place.

As described in Chapter 5, the erosion control mat cannot accept all loads without harm for all applications. Displacements of individual membranes beneath the mesh are to be expected in the fall line, above all, when fixing is tricky. In order to be in a position to secure and green slopes affected by landslides close to the surface or with global stability problems adequately, reinforcing the Tecco G65/3 high-tensile wire mesh was tackled (**Fig. 14**). The mesh possesses an inner circular diameter of 65 mm with a wire diameter of 3 mm. The load-bearing capacity amounts to 150 kN/m with a puncturing resistance of 180 kN against the spike plate system with edge lengths of 33 cm x 20 cm [12]. **Fig. 14** shows that the choice of mulch fibres is important. Long fibres cannot penetrate the erosion control mat sufficiently.

Fig. 11: Rock slope in Miraflores, Panama, secured with mesh and erosion control mat

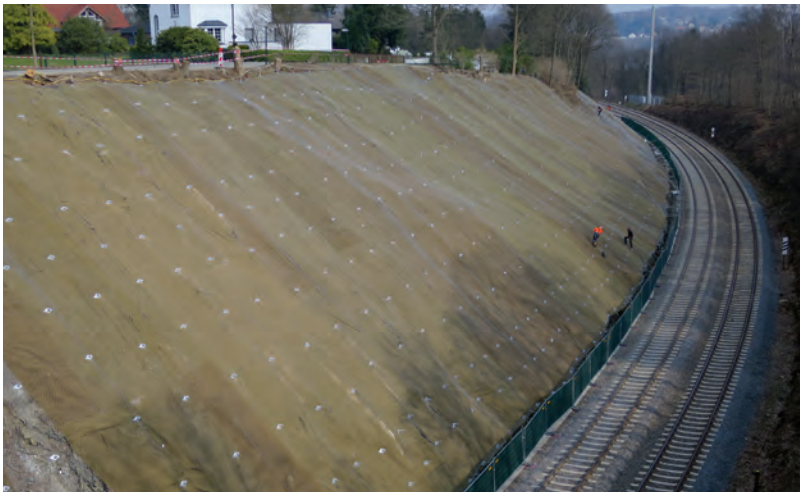

Fig. 12: Securing a cut slope after a landslide in weathered rock

Fig. 13: Uniformly profiled slope in loose rock with close-fitting erosion control mat

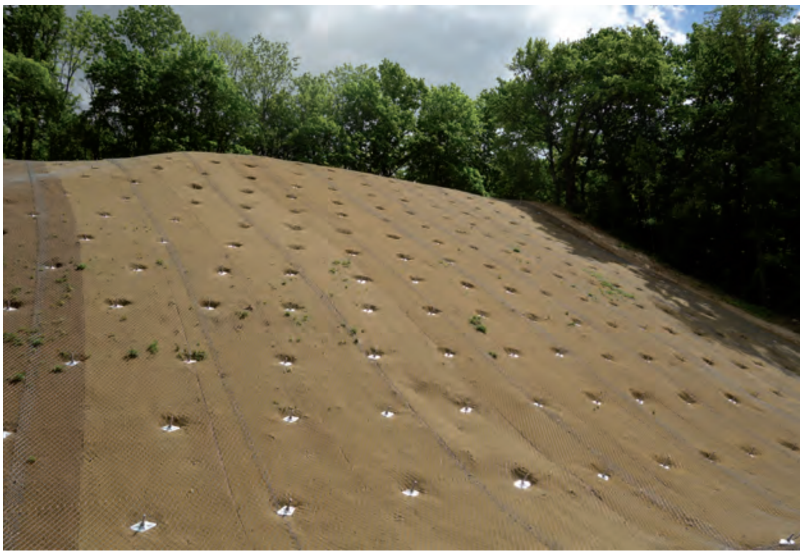

Fig. 14: Erosion and greening mesh made of high-tensile steel wire and mat consisting of three-dimensional polypropylene textile after hydroseeding

7 Conclusions and Outlook

Essentially, naturally degradable, organic erosion control mats are preferable. However, they reach their limits in the case of steep slopes. Three-dimensional geomats, e.g. made of polypropylene, offer advantages thanks to their lower weight and their good retention properties. Colour-coordinated, lighter erosion control mats heat up to a lesser extent and provide a better greening effect apart from being less conspicuous.

The structural reinforcement of geotextiles, which are used for erosion control mats, with high-tensile wire mesh extends their application range through their higher load-bearing capacity. Thanks to reinforcement with high-tensile wire mesh with a punturing resistance of 180 kN, instabilities close to the surface can be secured down to a depth of 2 m. They can be reliably dimensioned in keeping with the Ruvolum concept. Global instabilities can also be secured given commensurate dimensioning.

Furthermore, the extent to which the properties of synthetic geomats can be combined with those of organic ones was studied. An alternative is provided by the direct application and reinforcement of coconut, jute or cellular wool mats. Further developments of natural geomats based on paper represent a further possibility. One thing is certain: the greening of slopes is a very complex topic and depends on a large number of factors.

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Risk Analysis for Argentina's „Train to the Clouds" efficiently developed using innovative Methods

Geoconsult Group, Wals in Austria and Buenos Aires in Argentina

At the end of January 2018 Geoconsult and Georesearch from Wals/Salzburg in Austria have presented in Buenos Aires a risk analysis for the "Tren a las Nubes" (Train to the Clouds). They developed the analysis in very short time at low expenditure using innovative modern methods. The risk analysis provides a well-founded basis for future investments in Argentina's rail-infrastructure in the North-western region of Argentina.

Geotechnics • Infrastructure • Risk analysis • Drones • Natural disaster • Argentina

Austrian engineers are recognized worldwide as experts for the improvement and optimisation of railways in all sorts of difficult terrain not only limited to Alpine regions. At the end of January 2018 specialists from Geoconsult and Georesearch from Wals/Salzburg in Austria have presented in Buenos Aires a feasiblility study and a risk analysis for the "Tren a las Nubes" (Train to the Clouds) which has been developed concisely in very short time at low expenditure using innovative modern methods. The risk analysis provides a well-founded basis for future investments in Argentina's rail-infrastructure and is an important contribution to the economic development and improvement of living conditions in the North-western region of Argentina. Until now the assessment of risks and associated dangers of a linear infrastructure consisted in mapping the terrain on the ground by walking kilometre for kilometre along its entire length in order to develop models for risk analysis. In the past the evaluation of the approximately 570 km long Argentine section from Salta to Socompa on the Chilean border on the railway line to Antofagasta on the Pacific Ocean in the Northern Region of Chile (**Fig. 1**) would have taken at least six months of fieldwork. By the application of modern methods such as the use of drones the amount of fieldwork has been reduced to less than a month concurrent with an increased quality and distinctly lower costs for data collection. The study was sponsored by Austria Wirtschaftsservice.

Train to the Clouds

The railway line from Salta (Argentina) to Antofagasta (Chile) has been taken into operation in 1949 after a construction period of 27 years (**Figs. 2+3**). The railway line comprises:

- 29 bridges
- 21 tunnels
- 13 viaducts
- 2 switch back bends
- 2 switch backs
- 21 stations

It crosses several salt flats rises to an elevation of over 4,400 m and is in parts subject to extreme climatic conditions. The world famous tourist train "Tren a las Nubes" runs along a stretch of the line including the "Viaducto Polvorilla" the highest viaduct in South America (**Fig. 4**).

Fig. 1: Railway route of the "Tren a las Nubes" across the Andes from Argentinean Salta to Chilean Antofagasta
Source: Wikipedia

Fig. 2: Structure of the railway line taken in operation in 1949
Source of Fig. 2 to 6: Geoconsult

Fig. 3: Another bridge of the railway line

Fig. 4: Viaducto Polvorilla – a 223 m long steel framework construction with 63 m the highest viaduct in South America

Challenge of Nature

The extensive and exposed mountain ridges of the Andes represent major challenges for planning, construction, maintenance and operation of traffic infrastructure. Until now roads are the main transport routes between Argentina and Chile, which are however often in bad shape and can only be used part of the year due to the climatic conditions.

The study shows the potential along this transport corridor, which is the only railway line between Argentina and Chile still in operation. This is of major importance especially considering it against the background of existing natural resources.

Innovative Methods of Analysis

Because of the extreme topographic location the extensive analysis of natural hazards and risks is an important basis for decision making for the railway operator in order to perform adequate maintenance measures in the future. A particular challenge for the Austrian specialists has been the extension of the area to be investigated of over 10,000 km^2, the poor quality of available data and the very short period of time of less than 6 month to carry out the work.

The special challenge consisted in investigating such a huge area at high altitudes subject to extreme climatic conditions in a short period of time. A two stage process has been developed. In a first stage based on remote sensing data (satellite pictures) and local expert workshops “hot spots” where identified and associated first risk analysis performed. In a second stage the locations have been verified in situ and further explored by the use of drones (**Fig. 5**). Based on data from the existing infrastructure, identified natural hazards as well as specific logistical requirements models for time tables have been developed allowing an estimate of the annual total transport capacity. Integral interdisciplinary methods have been used in order to analyse natural hazards along the entire line based on satellite data and simultaneously assessing potential availabilities of service based on the technical condition of the railway line. By establishing step by step options for improvement and tailor made concepts for logistics and cargo handling it was possible to derive yearly transport capacities conclusively.

Fig. 5: The experts of Geoconsult during a field trip in the „Tren a las Nubes“

Fig. 6: Railway infrastructure with potential for investments

Enormous Potential for Railway Transport

The economic and geographic conditions of the region have been assessed with the conclusion that an enormous potential of goods favourable for rail transport faces a very small actual share of railway transport mostly due to structural reasons. Logistics are highly ineffective because of missing logistic hubs non coordinated cycles of loading, a poor transport infrastructure missing multimodal connections and inadequate warehousing. Consequences are uncertainties in the reliability of transport additional costs and limitations of production capacities reasons which influence the economic development of a region unfavourably.

The experts of Geoconsult and Georesearch with their partners STL-Solutions for Transport & Logistics and Planum (both from Graz, Austria) recommend a step by step improvement of the existing railway line as well as the arrangement of multimodal hubs for goods in order to stabilize the region's economy (**Fig. 6**). The investigation of the entire railway line has shown that the railway infrastructure which initially has been designed for heavy traffic is safe for operation. For an increase of current capacities a number of immediate and construction measures have been recommended.

Risk Reduction for the Railway

In order to assess the natural hazards and risks a two stage analytical method has been followed by the experts. On the basis of satellite data and a first field trip with interviews of experts in the field 94 risk areas have been identified categorized by type of risk, intensity, frequency and consequence and the resulting risks analysed. The areas have been overflown in detail by drones collecting new field data. The risk analysis has been updated with the new detailed data. Approximately 25 % of all risks have been assessed as high. Suitable technical and organisational measures have been proposed for risk mitigation.

Conclusion

The feasibility study has been presented end of January 2018 in the Austrian foreign economic centre in Buenos Aires to a delegation of members of the Argentine ministries for mining and infrastructure as well as the Argentine railways.

Geoconsult Group

The Geoconsult Group Geoconsult is a private independent engineering company offering engineering services to government departments and private companies worldwide. Services comprise structural and civil engineering, geotechnics, soil and rock mechanics, geology, hydrogeology, geo- and information sciences, surveying, mining and electrical engineering. All development stages of engineering projects starting from initial studies and concepts for investigation campaigns followed by all phases of the design process up to services during construction, control and consulting are covered. Geoconsult has branch offices in Europe, Asia and Latin America.

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Tunnelling with Gripper TBMs – Pre-detensioning Factor for Dimensioning the Shotcrete Shell

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The stress redistribution in rock acts on the load affecting temporary shotcrete supports in tunnels. This article explains numerical calculations, which were undertaken at the University of Applied Sciences, Darmstadt. They serve to analysis the rock's stress deformation behaviour when tunnelling with a Gripper TBM and to establish pre-relieving factors for dimensioning the shotcrete shell.

Tunnelling • TBM • Gripper • Shotcrete • Modelling

1 Introduction

In order to be in a position to depict the spatial stress deformation behaviour of the rock in tunnelling in two-dimensional numerical calculation models, the support core or support load method is frequently applied [1]. In a first step for the support load method the initial loads at the edge of the excavated cross-section are determined (**Fig. 1**). In a second mathematical intermediate step the elements in the area surrounding the excavation are deactivated. Then the initial forces, which were established in the primary stress state around the edge of the excavated cross-section, are applied and reduced by a pre-detensioning factor α_k. Subsequently in a third step e.g. the shotcrete shell is activated in the case of a temporary shotcrete support.

A high pre-detensioning factor α_k signifies that the support must only accept a small portion of the loads from the stress redistribution. In order to be able to establish the pre-detensioning factor α_k, complicated three-dimensional calculations are needed, or it can be derived from measurements obtained from projects carried out in a similar manner.

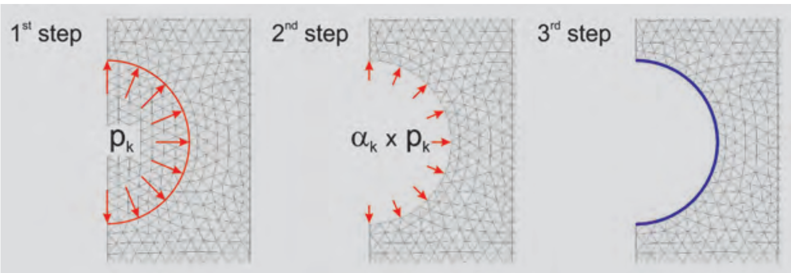
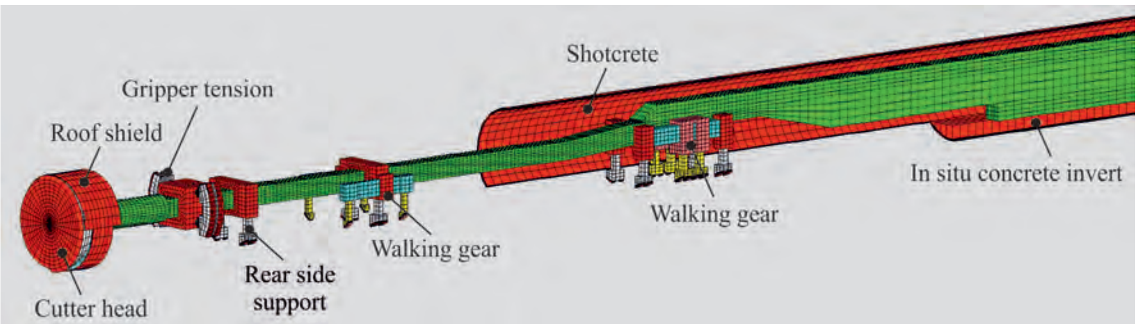


Fig. 1: Support load method using the example of a full-face excavation
Source of images: Darmstadt University of Applied Sciences

Various approaches are in existence from systematic three-dimensional numerical investigations, for estimating the pre-detensioning factor α_k with little effort. Corresponding approaches are published in [2] for mechanised drives in soft ground. Approaches obtained from extensive numerical studies are presented in [3] for mechanised drives in hard rock with a tunnel boring machine with shield (TBM-S).

In contrast, only a few results are available for mechanised tunnel drives with a Gripper TBM [4]. So far, the influence from the variation of material parameters to describe the rock or from the variation of geometrical parameters has not been further investigated for this type of machine. As a consequence, extensive parameter or sensitivity studies with a detailed three-dimensional numerical simulation model were undertaken at the Darmstadt University of Applied Science. The most important results from these studies are presented in this report.

Fig. 2: Numerical calculation model for the Gripper TBM



2 Numerical Calculation Model

The three-dimensional numerical model devised for the sensitivity studies forms the complex construction cycle of a drive with a simple pretensioned Gripper TBM. The numerical calculation model with the individual modelled areas is presented in the **Figs. 2+3**. The geometrical dimensions, the material characteristic values and the construction cycle correspond with those of the Gripper TBMs that were applied in the individual sections during the excavation of the Gotthard Base Tunnel [5, 6, 7]. [8] and [9] contain a detailed description of the three-dimensional calculation model.

3 Numerical Sensitivity Studies

In extensive numerical sensitivity studies, the theoretical stress deformation behaviour of the rock during a mechanised tunnel drive with a Gripper TBM was analysed in order to obtain the stress or rather the pre-detensioning factor α_k for the temporary shotcrete support. Taking isotropic material properties of the rock into consideration, the rock characteristic values, the overburden height $h_ü$ and the thickness of the temporary shotcrete support d_s were varied in the sensitivity studies. The individual parameters with the varied ranges are summed up in **Table 1**.

4 Calculation Results

4.1 Radial Stresses of the Rock

The radial stresses of the simulated rock, calculated for the sidewall area, are depicted exemplarily in **Fig. 4**. In this case, the radial stresses, which act on the sidewalls at the direct edge of the excavation, are shown. It can be

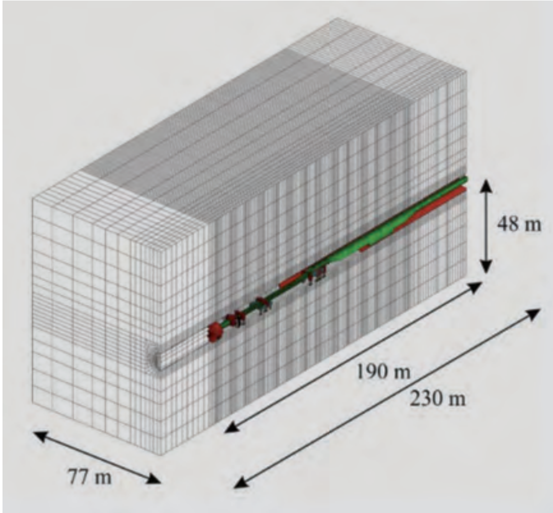


Fig. 3: Three-dimensional numerical model for Gripper TBM with presentation of the simulated ground

Table 1: Range of applied rock parameters with isotropic characteris

Parameters		Range
Specific weight of rock γ_{rock}	[kN/m³]	25
E-module of rock E_{rock}	[MN/m²]	500 bis 5,000
Poisson's ratio μ	[-]	0.2
Angle of friction of rock φ_{rock}	[°]	25 bis 40
Cohesion of rock c_{rock}	[MN/m²]	0.1 bis 2.0
Overburden height $h_ü$	[m]	100 bis 800
Thickness of shotcrete d_s	[cm]	10 bis 25

Fig. 4: Radial stresses for the side wall area depending on the distance to the working face

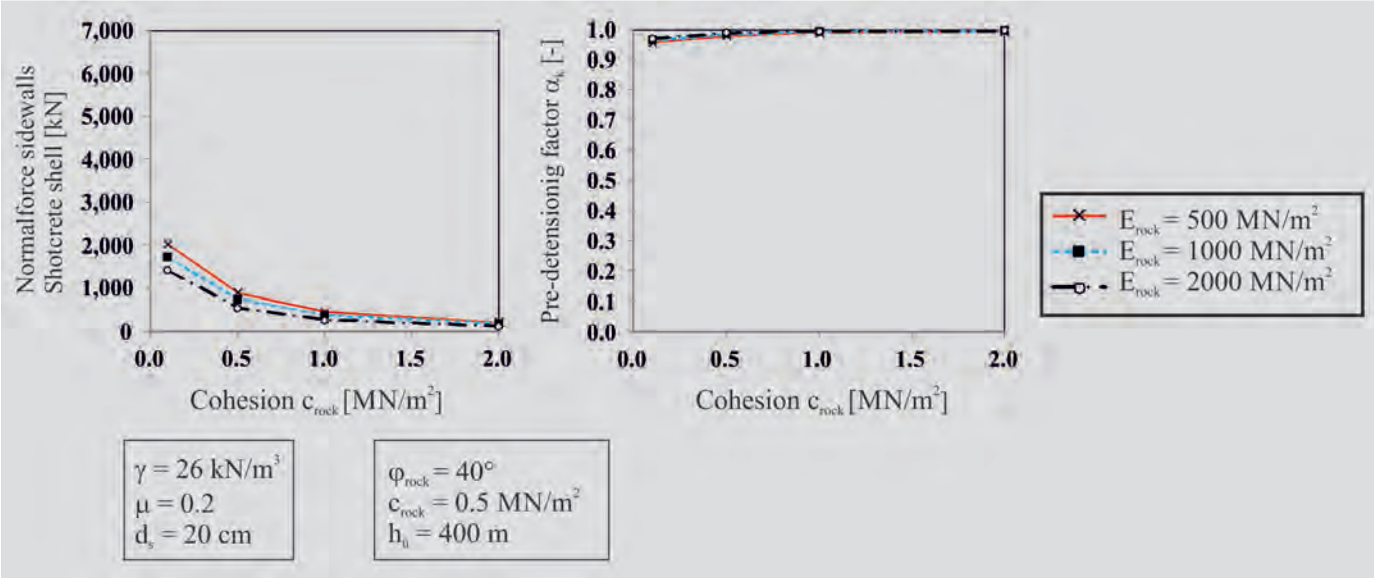


Fig. 5: Maximum normal force of the shotcrete shell at the sidewalls and pre-detensioning factor α_k depending on the cohesion of the rock c_{rock} for varied elasticity modules of the rock E_{rock} and overburden height $h_{ü}$ = 400 m

very clearly discerned here that the rock stresses at the working face area are redistributed. Directly in front of the excavation the magnitude of the radial stresses in the sidewall area increases very greatly prior to very quickly dropping to zero in the area around the cutter head. In the area of Gripper pretensioning the radial stresses increase as expected as a result of the introduction of the pretensioning forces from the Gripper. The increase in the radial stresses in this case greatly depends on the magnitude of the forces introduced by Gripper pretensioning. After Gripper pretensioning has been relocated in the course of the drive, the radial stresses drop again to reach zero in the area relieved by Gripper pretensioning. During the installation of the shotcrete support and the in situ concrete invert as expected an increase in the radial stresses occurs in the sidewalls until a constant value results. In this case, the increase depends on the shotcrete's chronological strength development. It becomes very clear when presenting the radial stresses in **Fig. 4** that the rock stresses, which act on the temporary shotcrete support, are extremely slight. When the radial stresses in the roof area are considered, a similar stress development occurs as in the sidewalls with the exception that as expected the influence of Gripper pretensioning is not perceptible.

4.2 Stress of the temporary Shotcrete Support

The major portion of the evaluations of the sensitivity studies is processed in the **Figs. 5+6+8+9**. The stress resultant required for dimensioning the temporary shotcrete support/shell is represented by the maximum normal force in the sidewall area. The calculated bending moment obtained from the parameter studies plays no part in dimensioning owing to its meagre size so that it is no longer depicted. The pre-detensioning factor α_k is also applied in **Figs. 5+8+9** in addition to the absolute maximum value of the normal force.

In **Fig. 5** the dependence of the normal force in the sidewalls and the pre-detensioning factor α_k from the cohesion of the rock c_{rock} is presented for varied elasticity modules of the rock E_{rock}. It is evident that the influence of the elasticity module on the normal force in the sidewalls veers towards zero as the cohesion of the rock increases. When considering the pre-detensioning factor, it also becomes clear that the elasticity module of the rock exerts no relevant influence on the temporary shotcrete support. The reason for this is that the elastic portion of the deformations occurred prior to the relatively late installation of the temporary shotcrete support so that no stress redistributions can result from it. On the other hand, it is revealed that the cohesion of the rock exerts an influence on the load transference of the temporary shotcrete support. In this connection, it should be noted that the influence is only a slight one given a pre-detensioning factor of 0.96 to 1.0.

In **Fig. 6** the maximum normal force of the temporary shotcrete shell in the sidewalls is visualised dependent on the cohesion of the rock c_{rock} for various angles of friction of the rock φ_{rock} and overburden heights. No values could be depicted given an angle of friction of the rock φ_{rock} of 25° combined with rock cohesion c_{rock} of 0.1 MN/m² and an overburden height $h_{ü}$ of 400 or 800 m, as in this case, the simulated rock collaborated numerically. This signifies that in the case of this characteristic value combination the unsupported area is no longer sufficiently stable and that a temporary support e.g. by means of a system of anchors or support arches would be required here in the unsupported area within the scope of the drive. When observing the diagrams in **Fig. 6** the influence of the rock's shear strengths is revealed on the one hand, and the influence of the

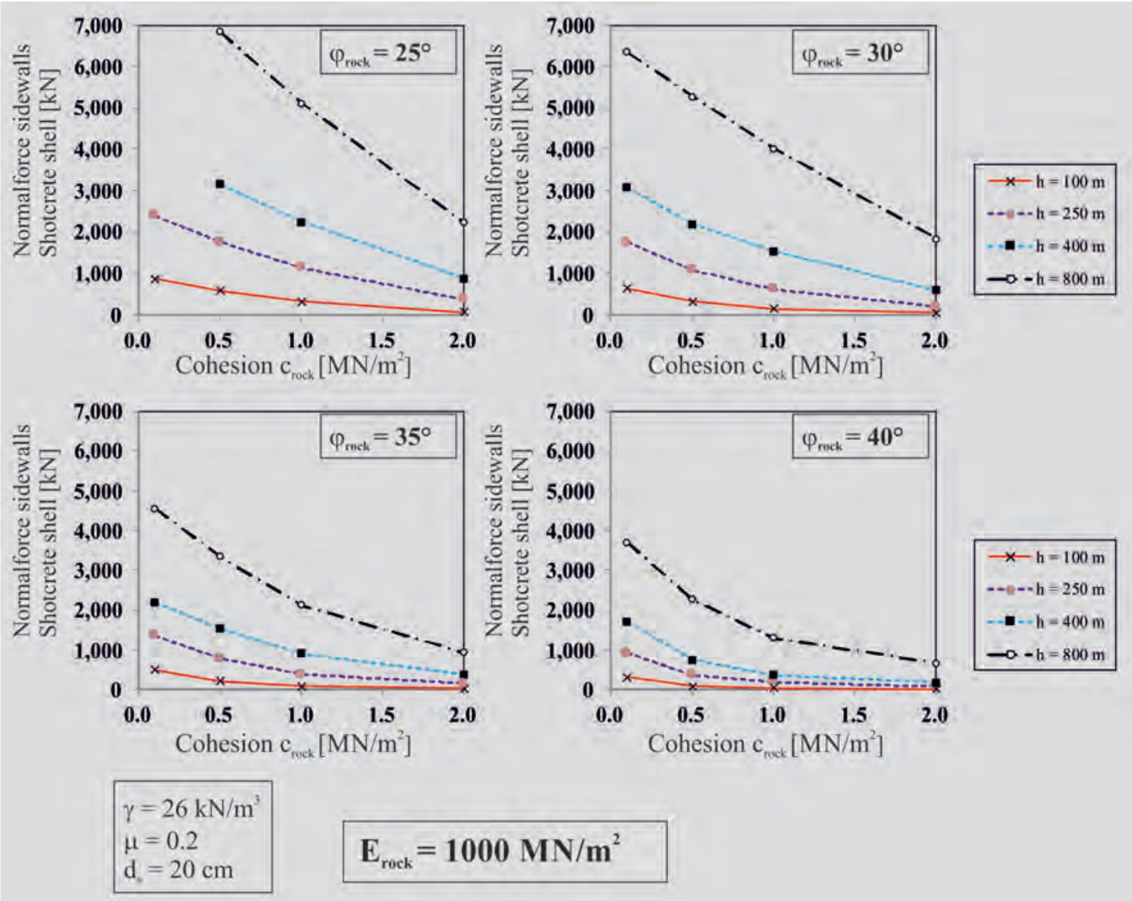


Fig. 6: Maximum normal force of the shotcrete shell at the sidewalls dependent on the cohesion of the rock c_{rock} for varied angles of friction of the rock φ_{rock} and overburden heights $h_ü$

overburden height on the size of the maximum normal force in the sidewall area on the other. In the case of rock with low shear strengths as expected greater normal forces result for the shotcrete shell than in the case of rock with higher shear strengths. The reason for this is that the stresses in the case of rock with low shear strengths redistribute more effectively, i.e. that the stresses in direct proximity to the excavated cross-section cannot be sustained and the rock plasticises (**Fig. 7**). Thus, a larger arch is created in the rock. The rock pressure, which results beneath the arch, must be correspondingly shored up by the temporary shotcrete support. The normal forces in the shotcrete shell increase as the overburden height becomes greater as is evident in **Fig. 6**. In addition, a larger arch is formed as the overburden height increases.

The influence of the rock's shear strengths and overburden height on the load imposed on the temporary shotcrete support is put into perspective when observing **Fig. 8**. Here the pre-detensioning factor for the influencing variables presented in **Fig. 6** is visualised. The pre-detensioning factor lies between 0.92 and 1.0 for the presented variants. When comparing the overburden heights, it is evident that the curve progressions are practically identical and that the overburden height exerts no effect on the size of the pre-detensioning factor. For the rock's angle of friction a slighter influence on the size of the pre-detensioning factor is discernible. The greatest influence on the size of the pre-detensioning factor results from the cohesion of the rock.

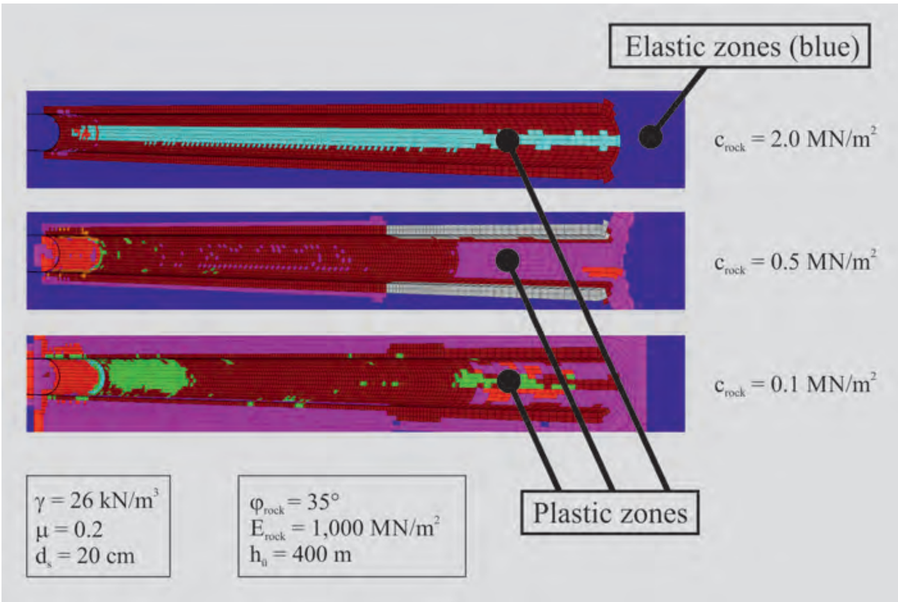


Fig. 7: Formation of the plastic zones in the rock dependent on the cohesion of the rock

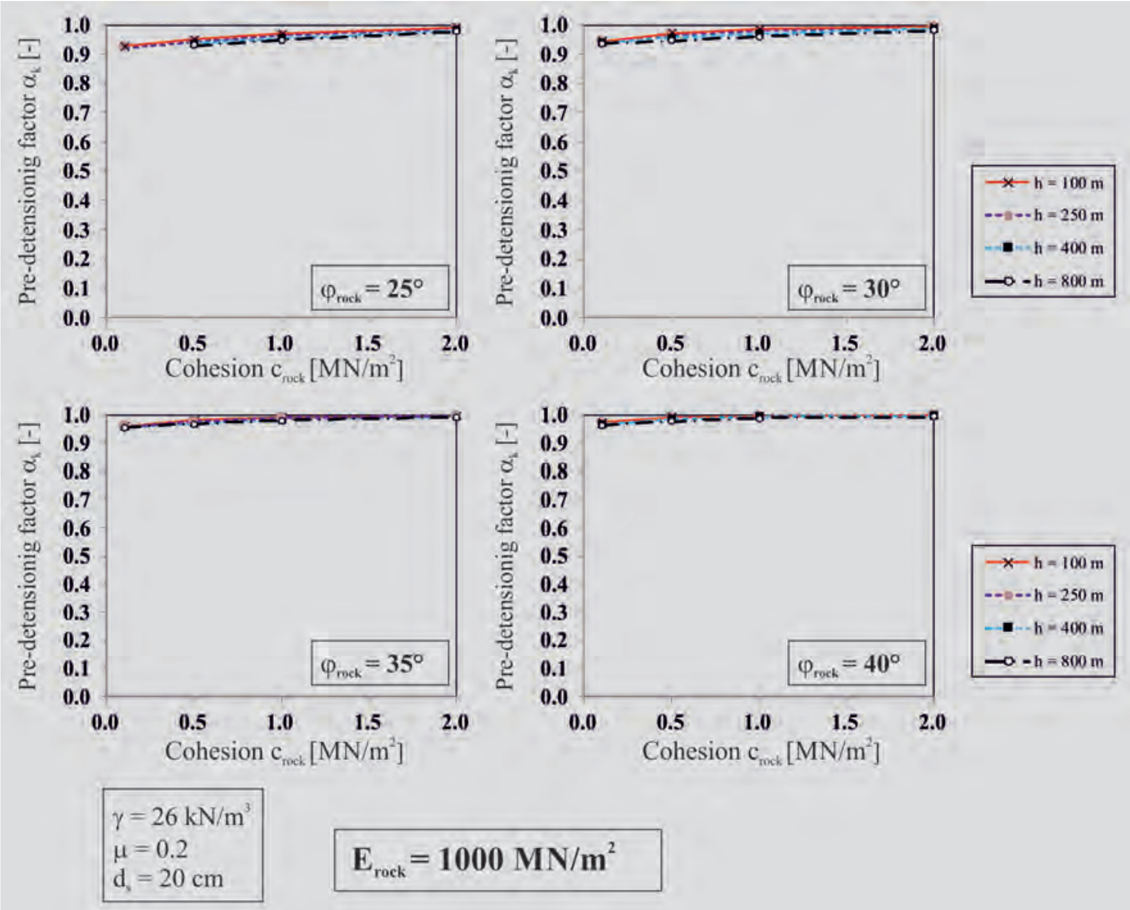
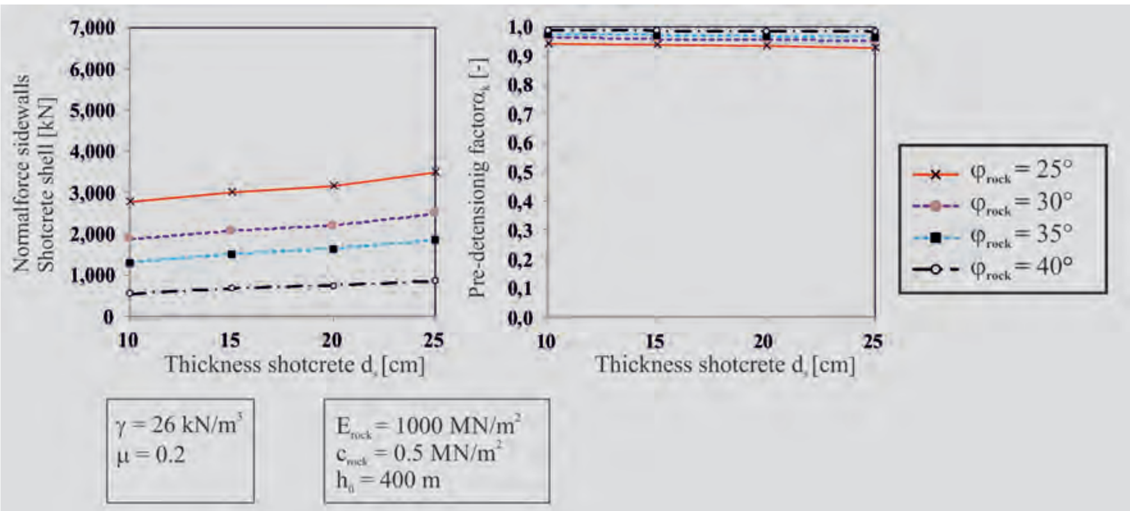


Fig. 8: Pre-relieving factor α_k dependent on the cohesion of the rock for varied angles of friction of the rock φ_{rock} and overburden heights $h_ü$

In **Fig. 9** the results are visible, which are yielded for the variation of the thickness of the shotcrete shell d_s in relation to the rock's angle of friction. The shotcrete shell's thickness has only a very slight influence or rather is of secondary importance regarding the size of the maximum normal force in the sidewalls. As the thickness of the shotcrete shell increases, the normal forces in the shotcrete shell are augmented slightly, due to the fact that the stresses from the rock grow as the stiffness of the shotcrete shell increases. It is also evident at this point that the greater influence on the size of the maximum normal forces in the shotcrete shell is derived from the rock's shear strength.

Fig. 9: Maximum normal force of the shotcrete shell at the sidewalls and pre-detensioning factor α_k dependent on the thickness of the shotcrete d_s for varied angles of friction of the rock φ_{rock} and an overburden height $h_ü$ of 400 m



The pre-detensioning factor for comparing the thickness of the shotcrete shell lies between 0.93 and 0.98.

5 Evaluation of the Results and Outlook

The results yielded by the calculations indicate very clearly that from the varied parameters elasticity module, angle of friction, cohesion, overburden height and thickness, the characteristic values of the shear strengths of the rock exercise the greatest influence on the size of the maximum normal force in the sidewall area. This recognition is placed in perspective when observing the size of the pre-detensioning factor that the values for the pre-detensioning factor, which is needed for undertaking two-dimensional numerical calculations for applying the support load or support core method, lies between 0.93 and 1.0. This signifies that only a very slight load occurs for the shotcrete support for the considered range of characteristic values in **Table 1** and the shotcrete support only bears a maximum of roughly 7 % of the load stemming from the rock. More distinctive differences are revealed when comparing the pre-tensioning factors of drives with TBM-S (approach in keeping with [3]) and Gripper TBMs (**Table 2**).

When higher characteristic values of the rock are involved the load affecting the shotcrete support in the case of a drive with a Gripper TBM is so low that the outcome is a practically load-free case. This becomes evident in the studies by the fact that the shotcrete shell cannot be meaningfully dimensioned for isotropic elastoplastic non-time-related material behaviour of the simulated rock.

A further need for research is indicated here. Firstly, it is imperative to examine how the rock's stress deformation behaviour reacts given a simulated joint structure of the rock and secondly which effects result through simulated time-dependent material behaviour of the rock. At present, further investigations are being carried out towards this end at the University of Applied Sciences in Darmstadt.

Table 2: Pre-detensioning factors α_k for TBM-S (determined after [3]) and a Gripper TBM for two variants of parameters A and B

Parameter		Variant A	Variant B
Specific weight of rock γ_{rock}	[kN/m³]	26	26
E-module of rock E_{rock}	[MN/m²]	1,000	1,000
Poisson's ratio μ	[-]	0,2	0,2
Angle of frictionof rock φ_{rock}	[°]	35	30
Cohesion of rock c_{rock}	[MN/m²]	1.0	0.5
Cutter head diameter	[m]	9.5	9.5
Overburden height $h_ü$	[m]	400	100
Thickness of segment/shotcrete	[cm]	20	20
Pre-detensioning factor α_k for TBM-S	[-]	**0.81**	**0.72**
Pre-detensioning factor α_k for gripper TBM	[-]	**0.98**	**0.97**

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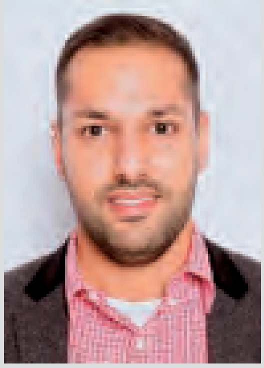

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Innovative Plug-in Crosscut Elements

Elkuch Group, Herzogenbuchsee, Switzerland

Precast elements called Plug-in Crosscut Element (PCE) have been developed to reduce the installation time inside the tunnel significantly.

Tunnelling • Crosscut • Precast element • Installation • Time saving

The Idea

The idea of crosscut precast elements was born in order to take account of the challenging installation environments in long railway tunnels. Elkuch Group and Biprotec GmbH could bring the concept to market maturity – supported by members of the Swiss Center of Applied Underground Technologies (SCAUT).

Fig. 1: Transportation of precast elements (PCE) using a rail car
Source: Elkuch Group

The Production

The concrete elements are manufactured in a workshop outside the tunnel. The mold is aligned with the crosscut's geometry to reduce tolerances. Once the reinforcement has been placed, all necessary interfaces as bolts, threaded sleeves and RFID tags are precisely positioned. After concrete pouring and stripping, all additional components as fans, aeration tubes, doors and control cabinets are installed and pre-tested.

The Installation of the PCEs

When the tunnel is ready the fully functional and verified PCEs are transported on a rail car (**Fig. 1**) or a flatbed trailer in front of the crosscuts. A manipulator moves the PCE into its final position. Compared to the conventional method of installation for a crosspassage door the PCE (installation time approximately 90 minutes) reduces the installation time considerably.

Elkuch Group

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Follo Line in Norway – A new Dimension in Hard Rock Tunnelling

Herrenknecht AG, Schwanau, Germany

The Follo Line Project in Oslo is a revolution for tunnel-rich Norway. Previously, tunnels have mostly been built the traditional way with explosives. For the largest infrastructure project in the land of the fjords, tunnel boring machines are now being used. Since late 2016, four Double Shield TBMs from Herrenknecht have been simultaneously biting their way through the toughest hard rock for a new railway line: a first worldwide.

Tunnelling • TBM • Major projects • Hard rock • Infrastructure • Railway • Norway

Agnethe Hoff Finnøy works on the Follo Line, the largest infrastructure project in the tunnel-rich land of the fjords. Her site office is bare, the only wall decoration a photo. In it she stands smiling between the cutterhead of a tunnel boring machine (TBM) and the rock of Oslo. Every day the thirty-year-old geologist for Norwegian railway company Bane NOR drives into the mountain to check and document the status of the advance (**Fig. 1**). "My friends ask me with amazement how such a TBM operates. When I tell them the machine presses against the rock, rotates and the rock breaks, they can hardly imagine that it actually works," says the geologist and laughs. Then she passes the visitor an almond-shaped, palm-sized chunk of stone: "Gneiss, a particularly hard rock." The chunk is heavy in the hand (**Fig. 2**). "The TBMs crack the hard rock into chips like this," says Hoff Finnøy and smiles: "It works wonderfully!" This finding is relatively new in Norway.

"Probably no state has more tunnels than Norway. For every inhabitant, statistically there are 1.3 m," says Anne Kathrine Kalager, Bane NOR's project manager for the main tunnelling section on the Follo Line Project. Previously, tunnels in Scandinavia have mostly been built with the traditional drill & blast method. Only in a few hydropower projects smaller tunnel boring machines were used. The best way to deal with the indigenous rock is by means of explosives, because tunnel boring machines would have a tough time with it – for a long time that was the prevailing opinion. The Follo Line Project brings movement into this tradition. Using mechanized tunnelling technology, the unique large-scale project is creating the longest railway tunnel in Norway and eliminating a bottleneck in the transport network of the future. The new twin tube will run 20 km from the municipality of Ski to the south of Oslo right into the center of the metropolis – with an open section at both ends, 22 km in total. Four million cubic meters of rock have to make way – almost double

Fig. 1: Agnethe Hoff Finnøy, geologist on the Follo Line Project for Bane NOR
Source of the figures: Herrenknecht AG

Fig. 2: Hard rock
With a compressive strength of up to 300 MPa, the gneiss in Oslo is one of the hardest rocks ever successfully excavated with mechanized tunnelling technology. The demands on the disc cutters are correspondingly challenging.

Fig. 3: Anne Kathrine Kalager, project manager for Bane NOR
"We must always keep looking for the best methods – and in this project TBMs have decisive advantages."

Fig. 4: Central jobsite

Thanks to the high advance rates of the Double Shield technology, all tunnelling work can be managed and carried out from one central jobsite.

Fig. 5: Oslo is booming

The Norwegian metropolitan area will grow significantly in the coming years, especially in the south. The Follo Line will reduce travel times for commuters to the city center by half and thus significantly expand Oslo's direct catchment area.

Fig. 6: Fernando Vara, project director for construction joint venture Acciona-Ghella

"Ten rings of concrete segments are good when the geology is difficult. But 14 or 15 rings are normal."

the volume of the Cheops pyramid. In future commuters will save eleven minutes on the short route, half of the current travel time.

Decisive Advantages of the TBM Solution

"If we want to stay fit for the future we can't just say: we'll do it the way we've always done it," says project manager Kalager (**Fig. 3**). "We must always keep looking for the best methods – and as it turns out, in this project TBMs have decisive advantages." To carry out the project as quickly as with mechanized tunnelling, for drill & blast a total of seven jobsites would have been needed in the metropolitan area, some of them difficult for trucks to access. "So drill & blast tunnelling would have meant a huge burden on the traffic and the many residents living near the jobsites."

By contrast, the TBM solution gets by with only one central point of attack (**Fig. 4**). Two 900 m long access tunnels connect the large Åsland jobsite on the surface with two underground caverns. From there, two machines each bore south and north initially served as assembly site for the four TBMs and are now used as logistical nodes for the drive. The large jobsite is linked directly to the E 6 highway. There are no nearby residents to be disturbed by the years of construction work. "All these advantages were decisive for the TBM solution," explains Anne Kathrine Kalager.

When the project is completed, the tunnel portal will be located just a few hundred meters from the main railway station. Kalager lets her gaze wander to the harbor and the spectacular opera with its glass facade and bright Carrara marble, building cranes, new residential blocks and modern office buildings right on the water: Oslo is booming (**Fig. 5**). "In recent years, we Norwegians have learned to think more and more about the future," says Kalager. For example, every second new car in Oslo is electrically powered, and throughout Norway the electricity for this comes almost entirely from emission-free hydropower. The country does not touch its treasure from the North Sea oil of about 160,000 € per inhabitant, it invests the gigantic sum of 832 billion € in a state fund to secure prosperity for future generations. "Half the Norwegian population lives within a radius of 100 km around the capital," emphasizes Kalager. "Thus the Follo Line also strengthens the social foundation for the future. Meanwhile it has become sexy to commute to the office by train. Instead of getting stuck in congestion, you can work or relax."

Breakthrough by the End of 2018

For the trains to whizz through the mountain at up to 250 km/h from 2021, the breakthrough of the two tubes must be achieved by the end of 2018. For this reason Fernando Vara reaches for his smartphone every morning at 6.30 a.m. "So in the first minute after waking up I can see if the day is going to be stressful," says the Spaniard with a grin. The 47-year-old is the project director of the construction joint venture, which is made up of the companies Acciona from Spain and

Ghella from Italy (**Fig. 6**). Early in the morning, Vara first checks the WhatsApp group, where the night shift reports the progress of the previous day. The Double Shield machines manufactured by Herrenknecht can simultaneously bore and line the freshly bored tunnel with rings made of 1.8 m wide reinforced concrete segments. So that usually means an advance of 27 m/d and machine.

In the extreme hard rock with up to 300 MPa compressive strength, such advance rates can only be achieved with particularly strong and robust machines. On each of the four Herrenknecht TBMs, 13 engines with 475 horsepower each drive the 265 t cutterhead (**Fig. 7**). Strong vibrations, dust and deafening noise are the consequences, that takes its toll on people and technology. Sometimes Vara reads in WhatsApp that a machine has not progressed well during his nightly rest. For example, if the fissures in the rock in front of the cutterhead are full of groundwater, which frequently happens in the southern sections. Then, in the daily morning maintenance shift, a liquid cement mass is injected into the fissures to displace the water. To prevent an unnecessary waste of time producing the required holes, extra-strong drilling rigs are installed on all TBMs. But even with events like this, project director Vara can continue managing the jobsite calmly, because the project is on schedule. “This is also thanks to Herrenknecht,” says the engineer, who has spent his entire working life to date on Acciona tunnel projects. “I’ve worked with Herrenknecht throughout my career. So I can say that the company is good at sticking to schedules.”

Ahead of Schedule

The factory acceptance for the first TBM in March 2016 took place eleven months after the order was received. There were only 19 months between the signing of the contract and the fourth and last machine beginning operations in Oslo in November 2016. At times some thirty Herrenknecht service experts were on site at once actively supporting assembly of the machines. “So we were four months ahead of the official schedule with the TBM launch,” says Vara, who is responsible for the daily work of around 500 people on the large-scale jobsite. Being under time pressure, potentially excessively overworking the machines and thus risking major damage with long downtimes would be a nerve-racking undertaking, he emphasizes. “But thanks to the head start in the schedule we can now work with great concentration and yet also relatively relaxed. We are making even better progress than expected.”

Quality and Reliability Matter

The advance stands and falls with the quality of the excavation tools. The cutter discs made of special steel, 19 in in diameter and each weighing up to 372 kg are pressed against the extremely abrasive rock with up to 32 t of pressure on 70 concentric tracks. The wear is enormous. During the entire project, about 6,000 disc

Fig. 7: TBM for the Follo Line Project
All 4 Double Shield machines for the Follo Line Project were manufactured by Herrenknecht at the headquarters in Schwanau (Germany) and commissioned together with the customers.

Fig. 8: Luis Paliza Cuartero, project engineer Herrenknecht
“In close cooperation with our customers we feel our way ever closer to the optimal parameters for the disc cutters.”

cutters have to be changed on each machine. “Even the tiniest improvement to the discs counts. Because changing means downtime,” explains Vara: “If optimal cutter management allows us to complete just one more tunnel ring per day and machine, this ultimately adds up to put us two to three months ahead of the planned project time.”

Engineer Luis Paliza Cuartero is responsible for Herrenknecht’s cutter management in Oslo (**Fig. 8**). He ensures that the removed, worn disc cutters are loaded onto trucks and transported to the Herrenknecht plant 1,500 km away in Schwanau. There they are completely overhauled for reinstallation (**Fig. 9**). “In close cooperation with our customers we feel our way ever closer to the optimal parameters for the disc cutters,” explains the Argentinean. “We improve details on the bearing and try out the effects of different lubricants and seals.”

Up to 50 refurbishment experts at the Herrenknecht headquarters work on the professional rebuilding of the disc cutters so there are always enough fresh excavation tools available in Åsland and the contracting joint ven-

Fig. 9: Regular maintenance and repair
of the machines and their components are a prerequisite for consistently high advance rates in the complex Norwegian hard rock.

Fig. 10: Refurbishment at the Herrenknecht headquarters
Up to 50 cutter experts in Schwanau handle the professional refurbishing of the disc cutters. In total an estimated 24,000 disc cutter changes are necessary for the 4 TBMs.

Fig. 11: Francesco Giampietro, TBM manager Ghella
"I've never had to deal with such hard rock before. You can only handle that with teamwork."

ture can take care of other tasks (**Fig. 10**). "This process works like clockwork," reports Francesco Giampietro happily (**Fig. 11**). As a long-time TBM manager with Ghella, with a total of 140 employees he is responsible for ensuring the four 150 m long power packs are tunnelling at all times if possible.

Specialists on Sites

"Hard rock and four machines at the same time: that means we all have to work together very closely and trustfully to be successful," emphasizes Giampietro. On average, seven Herrenknecht specialists are on site every day to assist the TBM manager and his people with incidental maintenance and repairs, but also to support the advance. "I've worked with other TBM manufacturers in the past, but never experienced such knowledge and close cooperation as with Herrenknecht. The colleagues are excellent partners and team players, whose experience we benefit from every day."

Precisely because the extremely hard and abrasive rock means sometimes physical limits are reached, "logistics are extremely important," Giampietro emphasizes. "Not only the machines have to run with precision, but also the supply of first-class tools and spare parts – for four machines at once."

Herrenknecht engineer Luis Paliza Cuartero supports this mammoth task with his service colleagues on site. On behalf of the contracting joint venture he has an eye on ensuring that the strictly timed maintenance plans are adhered to, the hoses of the hydraulic circuits are in good condition, the electrical components are not soiled, engines and pumps are lubricated at the specified intervals: "It's in everyone's interest that the machines are kept in the best possible condition over the entire distance of the drive. That's why we are so attentive, sometimes suggest sensible preventive maintenance to the customer on the basis of experience and are always at his side."

Special Solutions for lean Jobsite Logistics

So-called multi-service vehicles (MSVs) (**Fig. 12 +13**) ensure a demand-oriented supply of disc cutters, spare parts and in particular reinforced concrete segments for the tunnel lining. With four trailers coupled to each

Follo Line Project Data

- **Machines:** S-980/S-931/S-982/S-983
- **Machine type:** 4 Double Shield TBMs (»Magda Flatestad«, »Anna from Kloppa«, »Queen Ellisiv«, »Queen Eufemia«)
- **Shield diameter:** 9,900 mm
- **Drive power:** 4,550 kW
- **Tunnel length:** 9.5 km
- **Geology:** hard rock, gneiss
- **Customer:** joint venture Acciona-Ghella
- **Client:** Bane NOR (state railway company), Norway

Fig. 12: Multi-service vehicles (MSV)

The multi-service vehicles specially designed for the project in Oslo can also cope with the narrow curve radii of the caverns and load 2 complete sets of segment rings.

Fig. 13: Coordinated design of machines and MSVs

Thanks to the quick unloading station in the back-up area, the MSV can unload at maximum speed and drive out of the tunnel again.

Fig. 14: Consistently high advance rate

of 14-15 rings per day achieved – Thanks to regular maintenance and excellent teamwork

other, these special vehicles designed and built by Herrenknecht subsidiary TMS can load up to 125 t and thus tow the concrete segments for 2 complete segment rings to the TBM in one trip. The rubber-tired vehicles can be used very flexibly on the jobsite. Inclines and declines of up to 10 % and the tightest curve radii of 15 m are not a problem – the basis for ensuring the continuous advance stops as seldom as possible.

"But what are the machines without the people?" asks Anne Kathrine Kalager, the Bane NOR project manager. She has her office on the jobsite, she wants to feel the pulse of the project every day, carry out inspections and talk with those involved. "Because I am constantly on site I can say: we are very satisfied with the cooperation of everyone involved. The Herrenknecht colleagues are only meant to be on site as supervisors. But I also see them giving a hand as well. That convinces me that Herrenknecht and the Acciona-Ghella joint venture jointly take responsibility for the performance (Fig. 14), and with this team we will achieve the goals we have set ourselves."

Herrenknecht AG

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In Norway, where the whole industry had long been focused on drill & blast while smaller TBMs only have performed in water projects, many assessments and analyses were needed before the decision for the TBM as the best solution was made, recalls Kalager. She expects the Follo Line to send a signal for further projects in Norway. "In future TBMs will be a realistic alternative in large projects, even in our extreme hard rock."

Subsurface Transportation and New Energy Carrier Vehicles

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The need for New Energy Carrier vehicles is on the very top of today's political agendas. The reduction of CO emission goes hand in hand with new risks in subsurface transportation. The search for solutions to manage these risks is the topic of the research project SUVEREN, funded by the German Federal Ministry of Education and Research.

Energy • Transportation • Emission • Underground • Safety • Research

The need for New Energy Carrier (NEC) vehicles in order to reduce CO emission from internal combustion engines is on the very top of today's political agendas all over Europe and the world. The importance of the topic is highlighted in the Executive Summary [1] to the policy study carried out as part of the EAFO project (European Alternative Fuel Observation) for the European Commission Directorate General Mobility & Transport with the following words: "*... The transport sector is expected to deliver a 60 % reduction in greenhouse gas (GHG) emissions in the EU by 2050.*"

New Risks

From an operational safety point of view, the introduction of new energy carriers goes hand in hand with inducing completely new risks – including some "known unknowns" and perhaps "unknown unknowns", too – that may occur as a result of an incident involving new energy carrier vehicles. Further, due to lack of experience, these new risks are accompanied by higher uncertainties regarding consequences and probability. However, new risks in many cases are linked with either gaseous energy carriers, in case of which the relative density compared to the air is one of the relevant parameters, or with the thermal runaway behavior of lithium-ion-batteries (**Fig. 1**), the most represented battery type in Battery Electric Vehicles (BEVs). The latter may lead to unexpected ignition or re-ignition after the batteries having been extinguished, and on top of that, large amounts of smoke may be produced even before fire is visible outside the battery or the car they are built in. The reasons for temperature rise may be manifold, including (but not limited to) exposure to high temperature environment, defects inside the cell, a surge in the charging or discharging current, said Francesco Colella et alia in "Electric Vehicle Fires" at the 7th International Symposium on Tunnel Safety and Security, Montreal, Canada, 2016 [2]. Gas leakages are the other important factor in terms of new risk in underground transportation facilities. While Compressed Natural Gas (CNG) will accumulate below ceilings due to the fact that its density is lower than the density of air, Liquefied Petroleum Gases (LPG) may flow into sewer systems or just to the bottom of the infrastructure. Either way, the concentration of gases may build between flammability or explosion limits depending on the leakage rate and the ventilation conditions. Distributing in sewer systems, they may form a special risk to first responders as it is difficult to define a green (safe) zone for their operation if reliable sensors installed in right places are lacking.

Fig. 1: Battery charging station in a parking lot
Source: Shutterstock 315689351

Fig. 2: Concepts of escape routes – e. g. parking areas
Source: Shutterstock 75010960

Escape Routes – Impact on the User

When it comes to underground safety regarding toxic gases, fire and explosions, ventilation and escape route design play an important role to achieve a safety level satisfying to our community (**Fig. 2**). The European Directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network [3] covers emergency exits as well as safety installations in accordance with the self-rescue principle in case of fire. Ventilation and distances to overcome to reach safe areas are the key elements in escape route design for tunnels and maybe other underground transportation facilities (**Fig. 3**). Especially when it comes to complex urban underground facilities, there's a growing importance of quality and reliability of data to serve the purpose of having real control over ventilation, and maybe dynamic escape route signalization, too. The choice of sensors including the right locations to acquire relevant data requires a holistic understanding of risk phenomena, physical properties, human behavior and how all these factors correlate with each other. Today, we are well aware of relevant measurements in terms of incident detection and ventilation control for internal combustion engine (ICE) vehicles in case of fires. But there is less experience with BEVs or Hybrids or gas as an energy carrier. So what kind of sensors do we need to detect toxic gases vented from the cells? What perhaps is the correlation of venting gas volumes and the state of charge of the cells? How do we deal with pressure vessel scenarios comprising gas release, controlled through an overpressure vent or uncontrolled through a crack resulting from a mechanical damage, gas release with or without fire? These are very difficult scenarios from the safety perspective of an user of an underground urban transportation facility or parking area. But they are relevant to guarantee safe escape routes during all phases of operation.

Impact on the Structure

Apart from the very important aspect of user safety, there are two kinds of new impacts on the structure compared to the standard fire scenarios we know from experience. The first one is the heat of a jet-flame potentially harming the structure through a very concentrated thermal load on a small area of a surface. Even if there are fire protection measures foreseen and tested according to standards, the thermal load of a jet-flame may be different in terms of impact on the structure and following weaken structural integrity of buildings. What remains is an uncertainty regarding the risk assessment and the decision whether or not it is safe to enter a building for first responders. An underground jet-flame scenario could also influence tactical aspects of first responders, as normally they want to protect infrastructure, but they don't want to extinguish a gas fire. Perhaps there is a need for adaptation of their equipment.

Chemical attacks through acid resulting from battery combustion are a second new phenomenon harmful on health and safety of humans and structural integrity on the long term. Hydrogen fluoride (HF), e. g. as a result of a battery fire, forms a weak acid in dilute aqueous solution. And although hydrofluoric acid is regarded as a weak acid, it is very corrosive, even attacking glass when hydrated [4]. That makes it very challenging and difficult to measure HF in an experimental setup of a battery car fire test, as HF in the concentration expected in such a test would attack sensors through corrosion. So today, HF concentration from a battery fire is not known or proven by measurements from fire tests (**Fig. 4**). Consequently it is rather difficult to draw conclusions and to make a sound suggestion to improve safety.

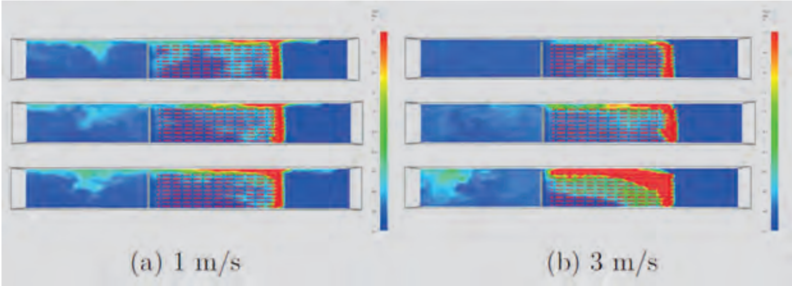

Fig. 3: Impact of ventilation in a tunnel
Source: Fogtec

SUVEREN – Search for Solutions

Together with the Bundesanstalt für Materialforschung und -prüfung (BAM) and Studiengesellschaft für Tunnel und Verkehrsanlagen e. V. (STUVA), Fogtec Brandschutz GmbH & Co. KG will develop and investigate in the frame of the SUVEREN research project (FKZ: 13N14393, 2017 bis 2020), both new technologies and new concepts to improve the safety level of underground transportation facilities – taking into account risks and boundary conditions emerging from New Energy Carrier vehicles.

Fig. 4: Fire test in a tunnel
Source: Fogtec

New technologies comprise hardware for fixed fire suppression systems as well as simulation and detection tools adapted to the special needs and risks brought by batteries, CNG, hydrogen pressure vessels or biofuels into tunnels of today's and tomorrow's transportation facilities. The new concepts will on the one hand side lead to new guidelines for tunnel safety design, and on the other hand side result in training courses for a target group including owners, operators and designers of underground transportation facilities like – both urban and rural – tunnels, car parks, or subsurface storage spaces.

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SUVEREN – Safety of City Underground Structures due to the use of New Energy Carriers

Together with Bundesanstalt für Materialforschung und -prüfung BAM, STUVA e. V. the following aspects will be examined:

- Safe use of New Energy Carriers in underground urban space
- Case studies
- Technologies to mitigate damages
- Development and validation of models
- Safety concepts for underground urban spaces
- Standards, regulations and trainings

More information about SUVEREN:
www.suveren-nec.info

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studied engineering for ship operating engineering at the University of Rostock. After several stations as a project engineer with a focus on research and development and later on as the managing director at the nautical Institute for Safety Engineering on ships he became an expert for fire protection certified by TÜV Rheinland. Since 2013 Rajko Rothe is managing director of the Institute for Applied Fire Safety Research (IFAB GmbH) located in Berlin, Germany.

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Chromite Ore Mining in Kazakhstan – Experiences with fibre-reinforced Shotcrete

Dipl.-Ing. Olaf Schmidt, project manager, deputy general director, TOO Schachtbau Kasachstan, Chromtau, Kasakhstan
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In the Donskoy Mine GOK in Chromtau, Kazakhstan, the TOO Schachtbau Kasachstan, a joint subsidiary of the German companies Schachtbau Nordhausen GmbH and Thyssen Schachtbau GmbH is driving a roadway in tricky geology with a small cross-section by means of NATM. Apart from the application of suitable engineering, the innovative shotcrete with polymer fibre reinforcement and consistent quality assurance in particular contributes towards ensuring that requirements are fulfilled.

Mining • Chromite ore • Supporting • NATM • Shotcrete • Fibre concrete • Kazakhstan

1 Introduction

In 2009, the operator of the "10th Anniversary of the Independence of Kazakhstan" chromite ore mine in Chromtau, the AO TNK Kazchrome, was seeking an improved support system for horizontal headings in the 2nd construction section (**Fig. 1**). The geological general conditions at a depth of 880 m are so complicated that the existing support system is no longer capable of withstanding the rock pressure that is created. On behalf of Kazchrome, the German mining companies Schachtbau Nordhausen GmbH, Nordhausen, and Thyssen Schachtbau GmbH, Mülheim a. d. R., devised a concept based on existing rock characteristic values, which ideally suits requirements. After a series of consultations and expert discussions, a contract was drawn up to set up a connecting heading on the –480 m level at a depth of 880 m in October 2012. The contract was agreed on between the AO TNK Kazchrome and the TOO Schachtbau Kasachstan, Almaty, Kazakhstan, a joint subsidiary of the two German mining companies [1].

In February 2011, the AO TNK Kazchrome company issued an invitation to attend a round table in Chromtau, for which competent representatives of many Russian and Kazak mining institutes turned up. Representatives of the two mentioned mining companies also attended from Europe. Those involved were briefed in advance on the parameters of the future heading as first and foremost knowledge on the geology represents an essential prerequisite for preparing the groundwork for mining in a proper fashion. The aim of the round table was to evolve technology designed to ensure the production of a heading guaranteeing a high rate of advance given extremely difficult conditions.

2 Geology of the Roadway

Kasakhstan's chromite ore reserves are located on the southern fringe of the Urals. In contrast to other deposits, which for instance like in South Africa – run for hundreds of kilometres as massive bands of the magmatic stratification, the Kasak reserves are present in lenticular shape. The surrounding rocks are gabbro amphibolites and serpentinised perododites. Work on producing the heading takes place in fine grained rocks, which possess complicated fissure systems owing to their specific genesis. Numerous fissures bear testimony to prior intensive fault tectonics and a major stress potential in the rock. The original rock structure has been greatly disturbed resulting in fragmentation.

It is very problematic for ensuring that the technology is optimally harmonised if e.g. five to ten different fissure systems are encountered at the working face, which are devoid of any clear orientation. The extreme pressure and temperature conditions during metamorphous accompanied by the simultaneous transformation of basic minerals have caused seritisation and chloritisation. The outcome is the rock stability has

Fig. 1: Chromite ore mine Donskoy GOK, Chromtau, Kazakhstan – distance between service shaft (otl) and ventilation shaft (otr) approx. 4.5 km
Source: TOO Schachtbau Kasachstan

been substantially reduced. In these zones the rock is ground and worn down to such an extent that overbreaks are scarcely to be avoided. If water is present in these fault-riddled areas this creates an additional set of problems. The rock mass then disintegrates rapidly and convergences result. To master this situation, the rock requires to be precisely assessed during every round of advance, utmost flexibility as well as the application of innovative driving technologies and modern support systems. The conventional support system used by the client involving steel arches with stowing by hand, which had already been installed in parts of the –480 m level, revealed its inability to cope with the geological situation.

3 Support Technology based on the NATM

A support concept with anchors and shotcrete in accordance with the New Austrian Tunnelling Method (NATM) was selected – a novelty for the Kazak mining industry. The geological situation that was described posed special challenges on the driving technology, which had to be taken into consideration during the selection process:

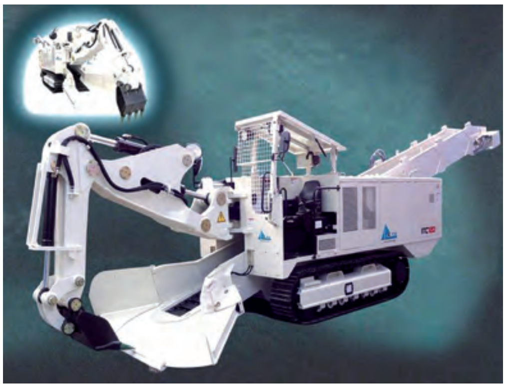
- Only a minimum amount of ingressing water was permitted in conjunction with the applied machines and equipment. Water leads to further weakening of the rock given the prevailing rock conditions. The natural underground water already presents substantial difficulties so that an additional influx of water as a result of the applied technology should be avoided at all costs. Thus, when drilling takes place an air-water mix is used for flushing rather than water alone. However, it is not possible to avoid water entirely for industrial safety reasons as the dusts that occur during drilling are extremely hazardous to health.
- The blasting process was aimed at tackling the rock very gently as it had a tendency towards spalling. The application of detonating cord in the hole area enables the exact contour to be separated in a gentle manner. The aim of gentle blasting is to avoid spalls and reduce the rock masses and amount of supports. Owing to the highly fissured rock, however, lower efficiency results from the use of blasting. Nonetheless, by adjusting and optimising the blasting pattern to the local circumstances and the available explosives, it was possible to attain a highly satisfactory result.
- The support system must on the one hand, guarantee the safety of the workforce at the face during the driving phase and on the other, assure the stability of the roadway over a lengthy operating period as the main haulage tunnel (capital underground workings). A fibre-reinforced shotcrete shell was chosen as the bearing support system, rounded off by radial anchors. The shotcrete is placed by means of a manipulator in order to make sure that no member of staff must work in unsecured areas during the supporting phase.

3.1 Machines and Equipment

The previously mentioned parameters were taken into account when selecting the machine park. At the same time, an average rate of advance of at least 90 m per month with a length of advance of 2 m in so-called excavation class 5 was secured with the selected engineering in conjunction with the necessary support technology. The premise during the selecting of the equipment was the required relatively small roadway cross-section of 13.7 m^2 in supported state. The client defined this cross-section in his technical remit in order to ensure that the excavated muck was kept to a minimum. A further challenge was posed by the extremely short period of six months between commissioning and the start of tunnelling, as most manufacturers have considerably longer delivery times for mining equipment for excavations with small profiles. Taken on a worldwide basis, the combination of highly specialised driving equipment and such small roadway cross-sections occurs relatively seldom. Ultimately, the equipment described as follows was provided after taking all specifications into consideration.

Fig. 2: Drilling rig Atlas Copco Rocket Boomer 282
Source: www.atlascopco.com (www.epiroc.com)

Fig. 3: Tunnel header/loader ITC Terex Schaeff 120 F4
Source: www.itcsa.com



3.1.1 Drilling Rig

A two-arm drilling rig – Type Atlas Copco Rocket Boomer 282 with telescopic booms and drill hammers of Type COP 1838 HD+ is deployed (**Fig. 2**). Consequently, both the blast holes and the outer contour holes for gentle blasting as well as the radial anchors in the relatively small cross-section can be drilled. The installed air-water flushing system ensures that no excess water infiltrates the rock during the drilling process.

3.1.2 Loading Equipment

The ITC Terex Schaeff 120 F4 header/loader was chosen for loading (**Fig. 3**). It not only carries out loading as such into the vehicles provided by the client, it is also the technical unit for setting up the lattice arches.

3.1.3 Haulage

The client provides locomotives and mine cars as well as transportation for the loaded muck according to contract (**Fig. 4**). A 3-way points system (Type Maschinenbau Mark) was commissioned to safeguard supplying empty cars and the removal of full ones on the single-track route (**Fig. 5**). The points system located on the driving track is advanced in stages commensurate with tunnelling. In keeping with the quantity to be loaded, a train comprising five to seven cars is filled. The cars are switched on the 3-way set of points in such a way that it is always possible for one car to be loaded by the header/loader. The header/loader and drilling rig travel over the central track of the points, as they have to be interchanged after the corresponding working steps.

Fig. 4: Locomotives and mine cars deployed at the Donskoy GOK mine for transporting loaded muck
Source: TOO Schachtbau Kasachstan

Fig. 5: 3-way points system Maschinenbau Mark
Source: www.maschinenbau-mark.de

3.1.4 Concrete Production

The production of the shotcrete represents a particular challenge given the prevailing circumstances, such as availability and quality of the aggregates. In order to be able to fulfil the required strengths of a quality class C 25/30 fibre-reinforced shotcrete, the shotcrete is produced in a hall on the surface autonomously. Towards this end, a concrete mixing plant – Type Hartmann 1125/750 S – was assembled (**Fig. 6**). It was set up in a hall on account of the extreme climatic conditions with very hot summers and very cold winters. It has to be ensure in terms of process technology that the temperature of the aggregates stays between +5 and +25 °C. The hall is accordingly completely thermally insulated and sealed. The client installed electric hot air heaters for the winter period, by means of which the mixing water can also be heated in order to make sure the boundary conditions for the fresh concrete are complied with.

Fig. 6: Concrete mixing plant Type HA MP 1125/750 SM, Hartmann
Source: www.hartmann-betonmischanlagen.de

The production of concrete underground is not possible owing to a lack of space. The application of the dry shotcrete method is not permitted owing to the restricted ventilation conditions on the –480 m level.

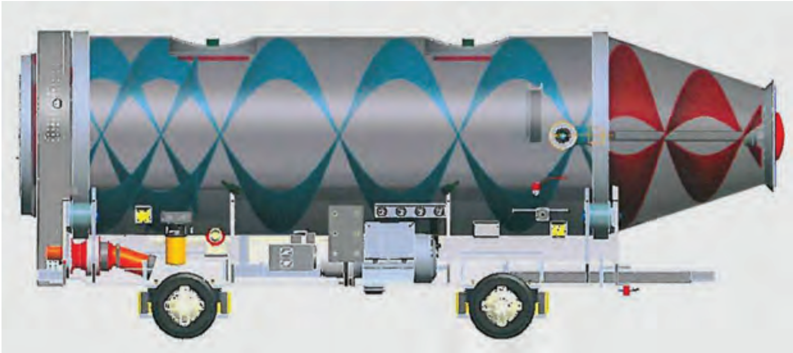


Fig. 7: Concrete remixer Type BM4 Karl-H. Mühlhäuser GmbH & Co. KG
Source: www.tunnelling-equipment.com

Fig. 8: Shotcrete manipulator Type Meyco Oruga
Source: www.epircoc.com

Fig. 9: Concrete pump Putzmeister P 715 SE on rail car
Source: www.moertelmaschinen.de

3.1.5 Concrete Transport

Concrete remixers of Type BNM 4 made by Karl-H. Mühlhäuser GmbH & Co. KG (**Fig. 7**) are deployed in order to carry the mixed and chemically retarded shotcrete to its point of installation (delay of up to 4 hours). The trackbound and electro-hydraulically driven remixers have a capacity of 4.0 m³. However, they are only filled with roughly 3.1 m³ thanks to better processability and owing to the improved mix. Depending on the excavation class, two to three units per round of advance are needed.

3.1.6 Placing the Shotcrete

An electro-hydraulic manipulator – Model Meyco Oruga made by Atlas Copco – is used to apply the concrete on the spot (**Fig. 8**). A Sika Schweiz AG's synchronised chemical pump – Model Aliva 402.2 synchro – adds accelerator directly at the spraying nozzle. A concrete pump – Type 715 SE made by Putzmeister – caters for transporting the concrete from the remixer to the manipulator (**Fig. 9**). The pump was set on an autonomously built and developed rail car in order to transfer the concrete from the remixer outlet to the pump receptacle.

Initially work had to be undertaken using an Atlas Copco, Meyco Altera concrete pump. However, this was then replaced by a Putzmeister 71 SE concrete pump enabling the throughput rate to be increased from 6 to a maximum of 18 m³/h. As a result, the time needed to install the shotcrete shell in a comparable section was reduced to a third.

Thanks to the shotcrete technology applied by SBK, shotcrete shells of 3 to 25 cm thickness can be accomplished. Shotcrete processing by the manipulator is undertaken for industrial safety reasons quite apart from the improved spraying rate. Thus, in the event of poor rock, in this way an initial securing layer can be placed safely without any member of the workforce having to venture into the unsupported area. After deployment the "spraying train" is driven to correspondingly equipped washing areas so that wear-intensive residual concrete can be removed from all the technology. This cleaning work has turned out to be extremely important and essential in practice and is thus carried out with appropriate care.

The same technology is applied to backfill any overbreak that might occur as a result of the geology in spite of the excavation class being individually adapted to the rock.

3.1.7 Further technological Steps

As this article deals with the shotcrete technology at length, other technological steps are accorded short shrift at this point. After installing the initial support in the cleared round of advance, the steel lattice arches are positioned with the aid of the manipulator. They back up the static bearing function during the first 28 days until the concrete has reached its final strength. Once the round of advance has been provided with the technologically appropriate amount of concrete, the radial anchors are subsequently drilled and placed by means of the drilling rig.

4 Shotcrete Support

The applied shotcrete is a sand-gravel mix with grain sizes of 0 to 8 mm, which is placed on the surface being processed at high pressure. Shotcrete represents an important and necessary instrument for modern, underground operations owing to its special features such as e.g. the installation process for developing roadways as well as the application of special materials and equipment. The application of shotcrete permits underground structures to be set up practically at random, wherever they may be needed. The geological conditions furthermore scarcely restrict the diversity of application of shotcrete structures.

The production of shotcrete does not differ in the method from that of normal concrete. The quality and consistency of the concrete can be regulated at any time by adjusting the water-cement ratio and adding various aggregates.

It is already evident during the offer processing and planning stages that the production and installation of a qualitatively high-grade shotcrete represents the technological solution's key to success. Consequently, particularly great importance was placed on corresponding equipment and the exact coordination of all working steps. Starting with the concrete mixing plant by way of selecting the remixer for transportation from the surface to the point of application (**Fig. 10**) right up to the placing technology itself, all possibilities for guaranteeing the utmost quality were exhausted.

In the area around Chromtau there are difficulties in procuring the aggregates gravel and sand as well as cement and the necessary chemical additives to assure a sustained high quality. The presence of suitable sands and gravels at the producer´s quarry, which comply exactly with specifications, does not actually signify that they will arrive at the construction site possessing the same quality. In some cases, the material is highly contaminated, which e.g. is due to poorly cleaned loading areas on the trucks prior to loading. Order and cleanliness in producing and processing shotcrete represent an important prerequisite for the success of shotcrete technology. Owing to the high demands set by the project parameters, this is essential to an extent that is otherwise unusual in mining. Even now after four years of driving it is still necessary to check the specifications laid down for the suppliers on a permanent and comprehensive basis.

The TOO Schachtbau Kasachstan executes self-monitoring in accordance with German guidelines and regulations to ensure that the shotcrete is subject to permanent control. Towards this end, a special test lab was set up and complete verification of the high quality is maintained in conjunction with external test laboratories.

Fig. 10: Concrete remixer being loaded with fibre reinforced concrete
Source: TOO Schachtbau Kasachstan

4.1 Checking Quality of the Shotcrete

Quality assurance is to be guaranteed for all part-processes of driving the heading in keeping with the specifications prevalent in daily practice in the parent companies Schachtbau Nordhausen GmbH and Thyssen Schachtbau GmbH. As a consequence, the following test run documentation was produced for checking the quality of the shotcrete support:

- Testing the initial materials
  - Grading curves sand, gravel
  - Lab test cement
  - Production documentation concrete chemistry
  - Chemical composition of the mixing water
- Fresh concrete test
  - Slump
  - Concrete temperature
- Ready-mixed concrete
  - Cube compressive strength
  - Cylinder strength
  - In situ tests

Samples (cubes) are taken for checking the strength of the freshly produced concrete when the raw material for each round of advance (support arch) was produced. The fresh concrete is left in a form for a day, which is covered with a wet cloth to avoid any moisture being lost. Subsequently the stripped cubes are first of all stored for six days in the water (water temperature 20±3 °C) and then in air (air temperature also 20±3 °C) until 28 days old. Once they have reached their final strength, the cubes are sent to an independent laboratory for the compressive strength check.

Core samples are taken directly from the sprayed wall after 28 days to check the solid concrete underground (**Fig. 11**). The samples are processed in-house and prepared for testing in the lab. These cylinder samples are also subsequently sent to an independent laboratory for the compressive strength to be controlled.

Fig. 11: Concrete core with 100 mm diameter and 100 mm in height prepared for concrete test – taken from shotcrete shell produced underground
Source: TOO Schachtbau Kasachstan

All tests are executed in keeping with the specifications of the corresponding guidelines DIN EN 12350 [2], DIN EN 12390 [3], DIN EN 12504 [4] as well as the EFNARC Guideline for Shotcrete [5]. Modern laboratory technology and calibrated and regularly tested measurement technology are available for undertaking all examinations.

All data collected within the scope of in-house and third-party monitoring are digitally processed and specified as well as being entered into special journals. Furthermore, a corresponding documentation is kept of the tests carried out with the freshly produced and solid concrete.

4.1.1 Testing the fresh Concrete on the Surface in the Mixing Plant (Shaft Hall)

The fresh concrete in the mixing plant on the surface is tested for the following parameters:

- Adherence to the concrete mix
- Checking the dosage of chemical additives
  - Retarder (MasterRoc HCA20)
  - Plasticiser (Master Glenium)
- Amount of reinforcing fibres used
- 4.8 kg/m^3 polymer fibres
- up to 35 kg/m^3 steel fibres
- Checking the concrete density
- Moisture of the aggregates sand and gravel
- Grain size distribution of aggregates sand and gravel
- Cement control (periodically per supplied batch)
- Water-cement ratio
- Temperature of the fresh concrete
- Temperature of the surrounding air in the mixing plant hall
- Slump of fresh concrete
- Taking samples (cubes) for controlling the concrete strength

4.1.2 Testing the Characteristics of the solid Concrete Underground

The following parameters are checked underground prior to or during the processing of the shotcrete:

- Dosage of chemical additives
- Accelerator (MasterRoc SA 167) – speeds up the setting and hydration process
- Temperature of the supplied concrete
- Temperature of the surrounding air on the spot
- Slump of the supplied concrete

After processing the following tests are carried out underground in the early stage of hardening:

- Proctor penetrometer
  - In this case the force required to drive a nail into the shotcrete to a depth of 15 mm is measured; this method can be applied for determining the initial strength in the early stage of the setting process up to a limit value of approx. 1.2 N/mm^2.
- Driving nails with the Hilti DX 450-SCT appliance:
  - Standardised nails are driven into the concrete by means of a propellant cartridge and a previously defined force; when the nails are removed the applied force is measured; the nail impaction method can be applied in the case of an initial concrete strength of up to approx. 2 N/mm^2; the ratio of the tensile force to the penetration depth represents the corresponding parameter to be checked.

Should the shotcrete strength be in excess of 10 N/mm^2, it is normally necessary to extract cylinder samples from the concrete mass.

The thickness of the placed shotcrete depends in keeping with the technology largely on the choice of the corresponding excavation class, which is established based on the prevailing rock conditions. If insufficient material for extracting core samples is available in the roadway (in excavation class 4 the shotcrete thickness e.g. only amounts to 5 cm), sprayed samples are produced in correspondingly prepared boxes. Core samples are then taken at an appropriate time from the hardened shotcrete.

Testing the effective fibre content can take place in two different ways. For the first method, a standardised sample is shattered by mechanical means so that the individual fibres can be counted. The second method consists of demixing a previously defined amount of fresh concrete. The fibre content is then controlled by extrapolation and comparison with the desired quantity.

4.1.3 Importance of the Tests

The large number of tests and their frequency indicate the high value attached to quality control. This important part-process for roadway driving is carried out with the same precision and conscientiousness from the first blast to the final round of advance. Only in this way is it possible to ensure lasting high quality.

4.2 Improving the Shotcrete Technology during the Driving Phase

A major demand on the part of the client relates to the monthly performance target. A roadway driving rate of 100 m per month in excavation class 4 (length of advance 2.50 m) has to be ensured technologically. There are good findings with the application of steel fibres, which replace classical reinforcing matting, from practice and assessing previous projects. It is not possible to save any substantial amount regarding the material but saving time at least is assured. This steel fibre technology had not been applied in Kazak mining until the project began. Thus, the procurement of suitable steel fibres was initially a logistical problem. Ultimately, fibres from Belarus, obtained via the distributor Kaspiy Plus, were utilised. These fibres are distinguished by very high form stability. With a length of 30 mm and a diameter of 0.75 mm, the fibres possess a very rigid form and are less elastic when confronted with mechanical constraints.

However, the desired form stability in particular unfortunately causes a great deal of wear on machines and equipment. The steel fibres get entangled in the concrete hoses and caught in the machines so that the latter become clogged. Material wear affecting the concrete pump, the hoses, the concrete belt conveyors and all pieces of equipment coming into contact with concrete also rose drastically during the period of application. Apart from the costs for necessary repairs, the outage times during concreting operations have a huge impact. As a result, an intensive search for alternatives commenced.

Slowly it dawned that it might well be better to use polymer fibres for producing the shotcrete (**Fig. 12**). The client had to be assured that the quality of the placed shotcrete would not suffer through switching to polymer fibre reinforcement.

4.2.1 Comparing the Shotcrete Alternatives

4.2.1.1 Steel Fibre Shotcrete

For the project, steel fibre reinforced shotcrete is applied for driving the Donskoy GOK roadway:

- Minimum concrete strength:
  - Cylinder compressive strength 25 N/mm²
  - Cube compressive strength 30 N/mm²
- Fibre dosage: steel fibre/concrete 35 kg/m³

Concrete production is carried out on the surface in the described hall. The steel fibres are added to the concrete mixer immediately after the actual mixing process. The mixing time with the added steel fibres amounts to a further one to two minutes. The ready concrete is carried by belt conveyor to the concrete remixer. This is transported to the –480 m level via the shaft cage and carried to the working face via a locomotive. A concrete pump and manipulator are used to place the shotcrete on the sidewalls. The accelerator is added to the concrete directly at the spraying nozzle. Tests on concrete cubes provided compressive strengths of at least 33.0 N/mm². The average values amounted to 36 N/mm², peak values of up to 46.0 N/mm² were measured. The required minimum cube compressive strength of 30 N/mm² was thus substantially exceeded.

4.2.1.2 Polymer Fibre reinforced Concrete

As in the case of steel fibre reinforced shotcrete a concrete mix of C 25/30 with a cement proportion of 450 kg/m³ of concrete was applied. The processing during mixing is exactly identical.

Various makes can be used as fibre reinforcement. In on-site tests two different types of polymer fibres from two manufacturers were applied – the one was “Concrix A-50 mm” and the other “BASF MasterRoc FIB SP 540”. The dosage in each case was 4.8 kg/m³ of concrete.

In similar fashion to steel fibre reinforced shotcrete, the compressive strength tests on the concrete cube must register strengths of at least 30.0 N/mm² and at least 25.0 N/mm² on the cylinder. The compressive strength tests were undertaken and documented by an accredited test lab in Aktobe.

The outcome was that it could be proved that from a static point of view it is possible to apply polymer reinforced shotcrete without diminishing the long-term bearing capacity. The compressive strength tests produced results equivalent to the test samples with steel fibre reinforcement.

On the basis of these results and findings, agreement was reached with the client to switch from steel to polymer fibre reinforced shotcrete (**Fig. 13**). Long-term

Fig. 12: Geometry of the fibres – made of steel above and polymer below
Source: TOO Schachtbau Kasachstan

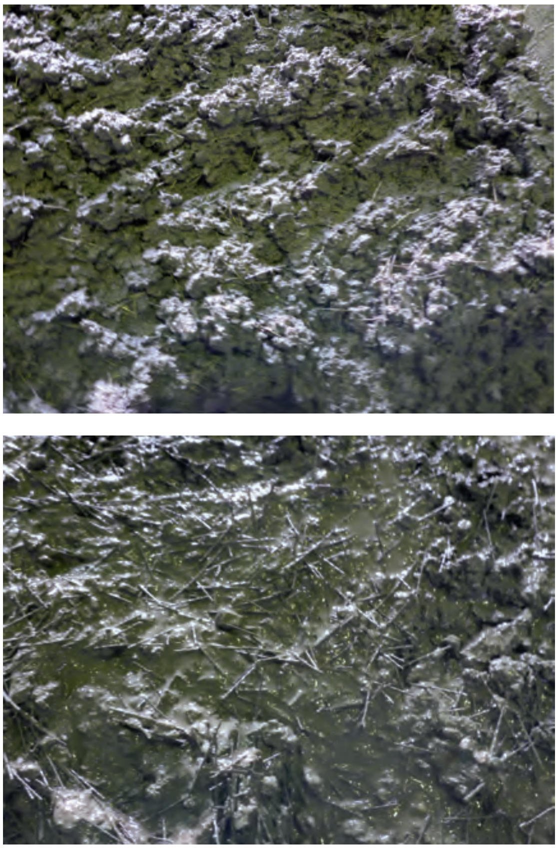


Fig. 13: Sprayed on concrete shell – with steel fibres above – and polymer fibres below
Source: TOO Schachtbau Kasachstan

observation completely backed up all recognitions and expectations.

4.2.1.3 Advantages of Polymer Fibres

The advantages of applying polymer fibres are obvious taking the example of the TOO Schachtbau Kasachstan roadway driven in Chromtau. Outstanding processing characteristics combine with an above-average decreased maintenance requirement for machines, lines and equipment. Thanks to the substantially lower aggressivity of the polymer fibres, cables, hoses and ducts are capable of being used a great deal longer. In this way, it is possible to cut down the expensive and time-consuming repair and service breaks for the concrete pump and manipulator.

Furthermore, by reducing the volume of rebound it was possible to optimise fibre and concrete consumption. The build-up of the complete layer thickness can effectively be accomplished in a shorter period of time.

The static properties of the shotcrete shell and the entire support system are not influenced negatively in any aspect. The results of the tests carried out by the manufacturers under lab conditions could be completely confirmed in practice. Thanks to homogenous distribution of the fibres in the concrete owing to their lower weight, it was even possible to observe a tendency to increase the final strength.

The significantly reduced risk of injury resulting from protruding fibres in the ready, placed concrete must also not be forgotten. Whereas previously a number of accidents or mishaps caused by injuries through fibres had occurred (e. g. punctures in working gloves or grazes), this risk was practically eliminated after switching to polymer fibres.

So far it has not been possible to come up with any definitive conclusions with regard to the long-term stability of the support system. However, it can be safely said that a long service life can be anticipated thanks to the resistance of the fibres to corrosion and alkali. The reduction or rather elimination of creeping currents also signifies a massive gain for industrial safety and health protection. Since the polymer fibres have been used there has been no damage of any kind to service cables or power circuits caused by protruding fibres.

Seen from the economic viewpoint it must be stressed that the absolute material costs for the polymer fibres per tonne are admittedly higher but thanks to the lower dead weight of these fibres compared to steel fibres, a greater amount of material is incorporated per kg of concrete. This is of significance for the static absorption capacity of flexural tensile forces in the shotcrete. The dosage of polymer fibres per cubic metre of shotcrete can be reduced to a seventh or a tenth in comparison to steel fibres. Thus, by applying polymer fibres, the same static bearing capacity is attained as with steel fibres possessing a lower fibre dosage.

For the current Donskoy GOK roadway driving project initially concrete mixes with a steel fibre proportion of 35 kg/m^3 of concrete were applied. After the switch a polymer fibre proportion of only 4.8 kg/m^3 of concrete for an equivalent mix was required. As the material costs for polymer fibres are some ten times higher than for the steel fibres, the final costs for producing 1.0 m^3 of shotcrete are practically identical for both types of fibre.

5 Conclusion

If one considers industrial safety and health protection for the workforce when coming into contact with the fibres prior to and during the mixing process as well as at the completed shotcrete shells, in contrast to steel fibres the polymer fibres do not present any potential injury hazards to workers. The application of polymer fibre reinforced shotcrete is neutral in terms of cost compared to a material with steel fibres.

In technical and static terms both alternatives are equivalent. Similarly, the application of polymer fibre reinforced shotcrete exerts no negative influence on the stability of the roadway support. The polymer fibres furthermore possess the advantage that they are resistant to corrosion. The considerably lower wear on machines, which the polymer resp. plastic fibres in the shotcrete exert on the characteristics of the support given an identical effect, represents a substantial advantage.

Polymer fibre reinforced shotcrete is innovative and state of the art in technological terms. In the case of the roadway project in Chromtau in conjunction with the client, it was possible to achieve an improvement in the results of the project that was optimal for both contractual partners by applying modern, future-oriented technologies (**Fig. 14**). It was possible to accomplish an internationally novel method in keeping with the latest state of the art with the client in Kazakhstan under sophisticated conditions.

Fig. 14: Completely developed roadway including capital track and water channel (otr, covered)
Source: TOO Schachtbau Kasachstan

6 Review and Outlook

In recent months, rates of advance of up to 150 m per month were accomplished on several occasions. The sole restricting factor was the capacity for removing the piles of muck rather than the driving technology itself.

The TOO Schachtbau Kasachstan has undertaken the driving operations in Chromtau continuously since August 2013 (**Fig. 15**). The entire workforce of the joint subsidiary of the Schachtbau Nordhausen GmbH and the Thyssen Schachtbau GmbH currently amounts to 80 members of staff, 15 of whom are from Germany.

The client TNK Kazchrome based in Aktobe is one of the world's leading chromite ore producers. Altogether, the company employs a workforce in excess of 18,000. By 2020, the company intends increasing its annual output from the two mines located in Chromtau "Molodeshnaya" and "10th Anniversary of the Independence of Kazakhstan" from 3.7 to 6.0 million t.

All in all, there is still a great potential for possible orders for the TOO Schachtbau Kasachstan. The client is planning a total length for the roadway network of 15 km on the –480 m level (depth 880 m). Currently, further horizontal headings are also foreseen on the –560 m level (depth 1,060 m) located beneath. In the long term, it is planned to develop the "10th Anniversary of the Independence of Kazakhstan" mine down to a depth of 1,560 m.

In conjunction with international partners such as the TOO Schachtbau Kasachstan and by applying progressive, state of the art technologies in Kazakhstan, the manifold and ambitious targets of the client Kazchrome (ERG) will be achieved within the predicted timespans.

7 References

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Fig. 15: After roughly four years of driving operations at –480 m level at a depth of 880 m, the breakthrough to the ventilation shaft took place in October 2016
Source: TOO Schachtbau Kasachstan

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Photovoltaics in the Mining Sector – a Win-Win Situation for the Electrification of Sub-Saharan Africa?

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Access to an affordable and reliable power supply is essential for the economic development of Sub-Saharan Africa (SSA). Deployment of photovoltaics represents a perfect solution, but the enormous potential still remains untapped. Mining, which is so energy-intensive and ambivalent in ecological terms, can supply remote regions as an anchor customer for electrification. Mine operators can anticipate a low-cost, reliable and sustainable energy supply as well as high social acceptance. At the same time, the rural population benefits from access to electricity and from the opportunity for strengthening socio-economic development.

Energy • Mining • Photovoltaics • Africa

Electricity Shortfall in Sub-Saharan Africa

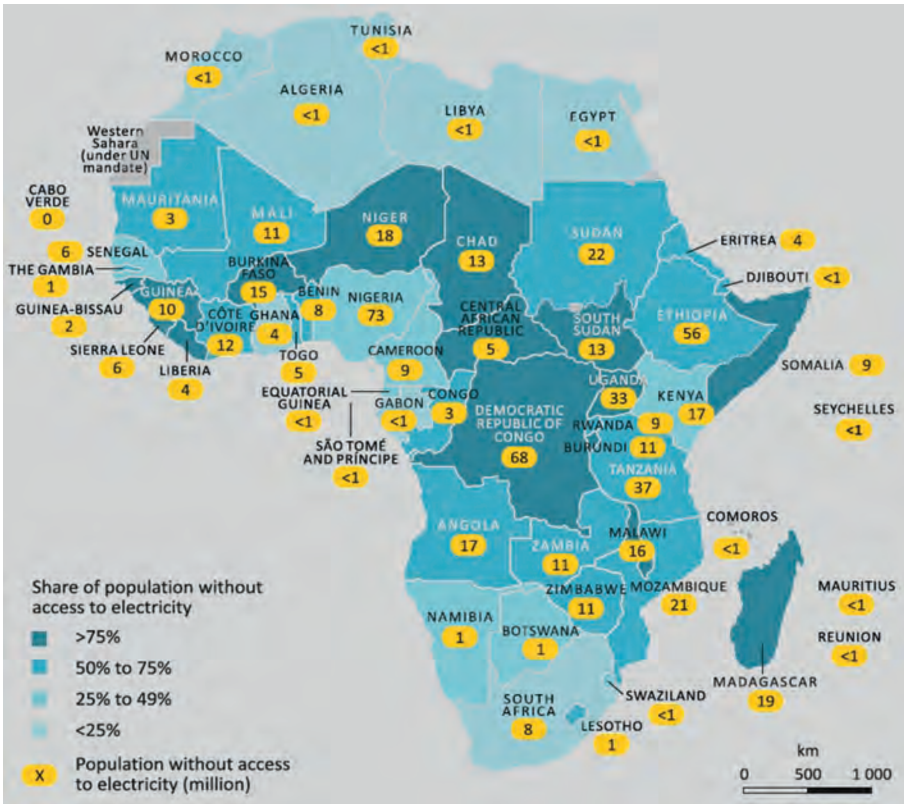
Sub-Saharan Africa (SSA) in geographical terms refers to the part of the African continent located to the south of the Sahara Desert. It includes 49 of Africa's 54 countries with a total population in excess of one billion people. Although SSA accounts for around 14 % of the world's population and indeed 18 % of its landmass, it contributes only some 2 % to the world's gross domestic product (GDP) [1]. Despite diverse national and regional conflicts, terror, famine, flight and poverty, nonetheless the region has registered some positive developments as reflected for example in the reduction of the poverty rate from 55.1 % in 1990 to 42.3 % in 2013 or in the relatively strong increase of the GDP averaging 5.3 % annually between 2000 and 2016 [2]. Although the collapse in prices for raw materials has strongly affected the resource-rich countries of SSA in particular, expectations for future growth are still most ambitious especially with regard to the catch-up potential [3].

Today, the rate of electrification in Sub-Saharan Africa amounts on average to only 42 % involving fluctuations beween urban areas of about 71 % to only 22 % in rural ones. In some countries such as Burkina Faso, Niger, Chad or the Democratic Republic of the Congo the average figure is in fact, considerably lower as is indicated in **Fig. 1** [4]. Thus, a large proportion of potential demand is supressed. Still more than the half of the population (approx. 590 million people) has still no access to electricity.

Even in countries with comparatively high rates of electrification and grid coverage such as South Africa, Ghana or Nigeria, electricity prices are high, with instable grids and necessary investments in the electricity infrastructure being neglected [5]. The average electricity consumption per capita in the household segment accordingly amounts to only 488 kilowatt hours (kWh) per annum which only constitutes to around 5 % of the comparative values for the USA [6].

In spite of a certain amount of progress, electrification on a large scale remains far behind the required levels. This is due to the fact that utilities in Africa suffer from a chronic lack of financing representing a major obstacle for investments in the energy sector. Further-

Fig. 1: Population without electricity and electrification rates in Africa
Source: IEA Energy Access Outlook 2017



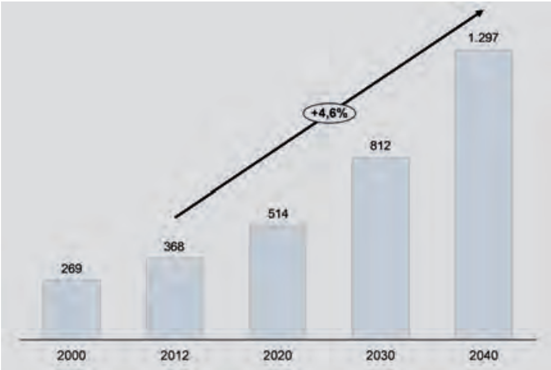


Fig. 2: Development of electricity demand (TWh) in SSA according to IEA New Policies Scenario
Source: IEA Africa Energy Outlook 2014

more, population growth outstrips attempts at electrification. Thus, for instance, the on-grid generation capacity amounts to only around 122 gigawatts (GW) today, with most of this total installed in South Africa, which is relatively far advanced [7]. The generation mix in this case is dominated by coal-fired production (mainly in South Africa), oil and gas (primarily Nigeria) as well as hydropower (on the Nile and Congo).

No Growth without Electricity

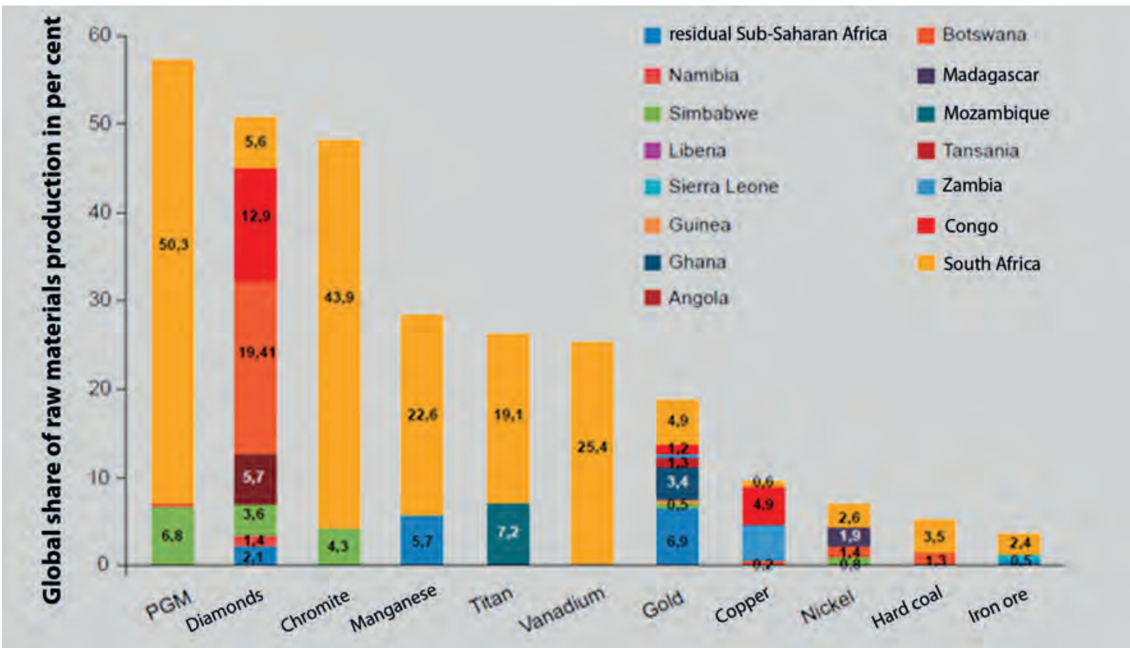
The region's energy needs are correspondingly high and are continuing to expand as a result of economic as well as population growth. The International Energy Agency (IEA) estimates that electricity demand in SSA will rise at an average of 4.6 % per year by 2040 (**Fig. 2**) to reach approx. 1,300 terawatt hours (TWh) by 2040 signifying a threefold increase [8]. The increasing demand is primarily due to the growth of an African middleclass and in turn, an increase in consumption in the private sector, urbanisation as well as an increasing number of infrastructure projects.

Satisfying the demand for electricity represents an enormous challenge for African countries and is crucial for ongoing economic development. The in part, high political and security risks as well as a lack of legal boundary conditions are compelling reasons that there is a lack of sufficient foreign funding and in turn private investments in electrification of Sub-Saharan Africa. As population growth exceeds the development of the energy infrastructure by far, the number of people in SSA without access to electricity according to the latest IEA projections will still remain at today's level in 2030 [9]. This prediction contrasts sharply with the vast conventional and renewable resources found on the African continent: the technical potential is estimated at 10,000 GW photovoltaics (PV), 109 GW wind power, 356 GW hydropower and 400 GW natural gas [10]. The economic prospects for photovoltaics in SSA in particular are better than they have ever been due to falling technological costs as well as outstanding solar irradiation values.

High Electricity Demand for Mining

According to assessments by the African Development Bank (AfDB) admittedly the transformation process from an economic structure strongly based on agriculture and natural resources to an economy with higher-quality manufacturing industries has begun. However, there is still a great deal of dependence on the raw materials sector [11]. The market share of SSA in raw materials production worldwide, as shown in **Fig. 3**, for instance, is roughly 57 % for metals belonging to the

Fig. 3: Global share of raw materials production of the sub-Saharan African countries in 2015
Source: Hartlieb-Wallthor, P.; Marbler, H.: Rohstoffe Subsahara, Düsseldorf, (2017)



platinum group, 50 % for diamonds, 48 % for chromite and 20 % in the case of gold [12]. The role played by mining in individual countries such as Zambia, Mozambique or the Democratic Republic of the Congo is correspondingly significant albeit also ambivalent. On the one hand, the mining sector represents an important element of the economic structure and contributes over-proportionally to the GDP, state revenues, exports and employment. On the other hand, its expansion since the 2000s has also led to diverse social and ecological conflicts relating to working conditions, environmental pollution, territorial control as well as the exploitation of water and land resources [13].

Mining is energy-intensive – depending on the source between 1.25 and approx. 11 % of the world energy demand as well as no less than 400 TWh of electricity consumption alone is accounted for by mining [14]. For mining enterprises energy costs – after capital costs and the factor labour – represent the biggest cost factor involving some 15 % of the total costs. Regardless of the deposits being exploited the energy costs shares for mines not connected to the grid can increase to 20 or even 40 % [15]. The following applies for certain reserves: the lower the extraction rate per ton of rock, the higher is the energy requirement. Whereas extraction rates for coal, rock or industrial minerals are comparatively high, they are particularly very low for metals [16].

For extraction and primary preparation of raw materials, apart from the fuel costs for heavy-duty working vehicles, electricity costs for the operation of the mine, transport facilities as well as the crushers and grinders are, above all, relevant. For an average-sized mine in SSA, electricity costs account for around 32 % of the energy costs [17]. The mining operation in this case depends on a 24/7 electricity supply. In underground mining, which is particularly dependent on electricity, such as for example, gold or platinum mining in South Africa, 60 % of the electricity needed for ongoing operations is accounted for by compressed air, air-conditioning, drainage, ventilation and hoisting systems [18]. Owing to a trend towards greater depths of reserves and diminishing ore grades, mining will get even more energy-intensiv in years to come. It is predicted that the greatest increases in electricity consumption in SSA will result from mining copper, platinum, chrome and gold [19].

Electricity Supply for Mines is expensive and instable

In the case of on-grid mines, traditionally power is obtained in SSA via state monopolists such as e. g. Eskom (South Africa), BPS (Botswana) or SNEL (Democratic Republic of Congo). In recent years, mining companies in many countries of the region were frequently exposed to electricity bottlenecks on account of growing demand from private households, a lack of water and instable grids quite apart from increasing and volatile prices. In the case of shortfalls – even in advanced countries such as South Africa – mine operators were faced with the choice of either cutting back on production, something that is critical for certain mining processes, or resorting to expensive self-supply.

Furthermore, as easily accessible reserves have increasingly been exploited and the demand for raw materials continues to grow unrestrictedly throughout the world, the opening up of new resources has been shifted to remote desert or rain forest regions involving in some cases low extraction rates and in turn, high energy demand. Just as it applies to private households, a remote location is associated with corresponding problems for obtaining energy due to a lack of grid accessibility as well as restricted access to the transport infrastructure (roads, railway, pipelines, water). In addition, modern mines in SSA furthermore are often operational only for a short period of time so that there is no need to create a sustainable infrastructure. As a consequence, it is not economically viable to build conventional power plants or transmission grids. This applies especially for mining precious metals, for which the absolute electricity demand is considerably lower than for iron ores despite relative higher energy intensity.

Thus, diesel generators are the first choice for providing electricity. They are easily available, can be cheaply acquired and are technically mature. However, diesel supply is expensive and prices are highly volatile in many regions. Only around 40 % of the price for diesel is influenced by the price of crude oil. For mines set up in

Table 1: Examples of photovoltaic projects in mining in SSA

Mine	Operator	Technologies	Developer	Year
Thabazimbi chromite mine (South Africa)	Cronimet Mining	▸ Diesel (1.6 MVA) ▸ PV (1 MWp)	Cronimet Mining Power Solutions	2013
New Luika gold mine (Tanzania)	Shanta Gold	▸ HFO (7,5 MW) ▸ PV (0,7 MWp)	REDAVIA	2017
Essakane gold mine (Burkina Faso)	IAMGOLD	▸ HFO (57 MW) ▸ PV (12,5 MWp)	EREN Renewable Energy	2018
Otjikoto gold mine (Namibia)	B2GOLD	▸ HFO (25 MW) ▸ PV (7 MWp)	Barloworld (Caterpillar)	2018
Bisha copper and zinc mine (Eritrea)	Nevsun	▸ Diesel (22 MW) ▸ PV (7,5 MWp)	Aggreko	2018

remote areas, apart from the fuel costs themselves, the transport costs involved when carried by tank trucks and the risk of losses and theft as well as state levies or dependence on subventions mount up [20]. In addition, there are logistical risks resulting from bottlenecks at the refineries, political conflicts or a lack of security.

Photovoltaics for lowering Costs and raising Acceptance

The mining industry in SSA has clearly been subjected to pressure owing to the collapse of prices for raw materials, so that reducing operating costs becomes increasingly essential. Energy efficiency potentials that are easy to tap have often been achieved although an adjustment of mining operations to a fluctuating electricity supply is scarcely possible. At the same time, state or regional stakeholder groups assert their claims to financial involvement, environmental protection and social responsibility. Thus, with regard to energy supply, two challenges face mine operators involved in global competition: securing a competitive and reliable energy supply as well as the social licence to operate.

Mining companies can improve their cost position and their ecological footprint, through integrating photovoltaics in their energy mix. Numerous exemplary projects already exist in SSA (**Table 1**).

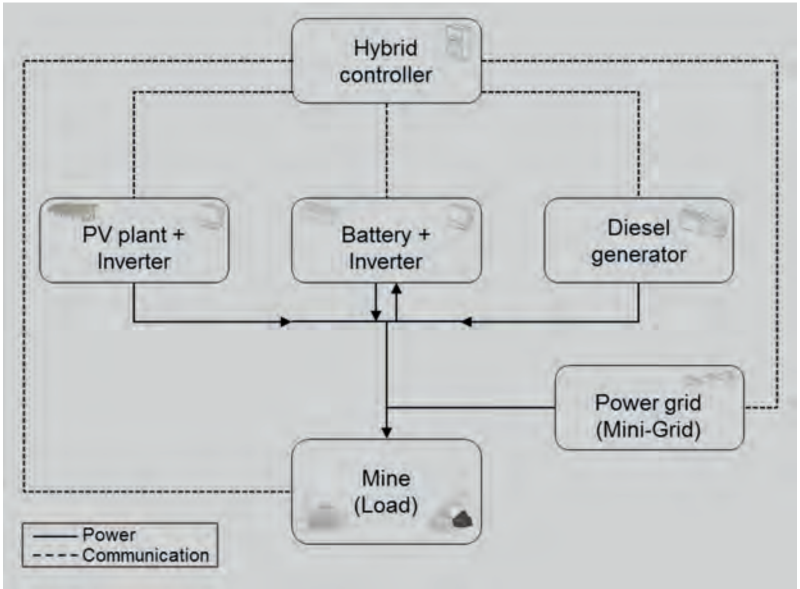
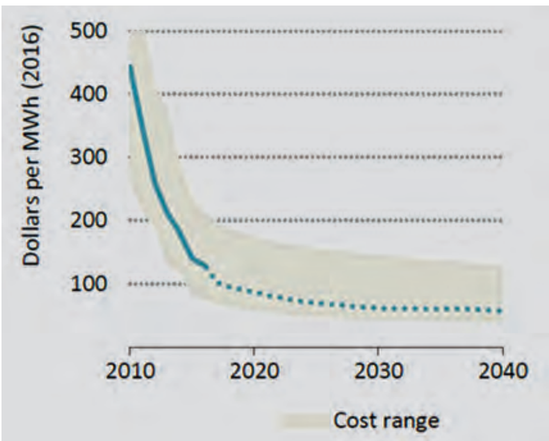


Fig. 4: Diagram of a PV-diesel hybrid system at a mine with mini-grid
Source: based on Rycroft, M.: Renewable and hybrid energy systems for the mining industry (2015)

Fig. 5: Development of the average electricity generation costs for PV "utility-scale" projects up to 2040
Source: IEA World Energy Outlook 2017



Economically dependent on Diesel and PV Costs as well as the Mine's Lifetime

In practice, photovoltaics in its pure form is only applied "behind the meter", meaning operated behind the metering point or by long-term contracts (power purchase agreements, PPA). However, in remote, off-grid regions, it is usually installed as an element of what is known as a hybrid system. Such hybrid power plants combine various types of generation forms. Typically, this can be a combination of generators driven by diesel or heavy fuel oil (HFO) in conjunction with one or several renewable energy sources such as photovoltaics. Frequently a battery component is involved in the case of off-grid systems so that the use of diesel is further reduced and to optimise the utilisation depending on the load profile. Batteries also help to balance out the fluctuating generation provided by PV (**Fig. 4**).

The economics of a PV-diesel hybrid system is primarily assured by the amount of diesel that can be saved by the application of photovoltaics. The determining factors of influence for the corresponding feasibility calculation are in this respect the diesel costs, the levelized cost of energy (LCOE) of the photovoltaics (possibly including batteries) and the mine's remaining lifetime. In the case of an on-grid mine additional revenues can where appropriate be accrued by feeding surplus or stored electricity into the grid.

A diesel generator consumes approx. 270 l/MWh and has an efficiency of ca. 32 %. In other words, 68 % of the energy input is lost in the form of heat. Thus, in the case of diesel costs amounting to around 1 US$/l today the costs for a mine procuring electricity already amount to around 0.3 US$/kWh. A comparatively small gold mine with a 6 MW generator capacity therefore continuously requires 39,000 l of diesel per day. The diesel costs correspondingly amount to 39,000 US$ per day or 14 million US$ per annum [21].

In contrast, the LCOE of photovoltaics have fallen rapidly in recent years and can actually compete with fossil electricity generation in many parts of the world. The LCOE for utility-scale systems have fallen by 68 % between 2010 and 2017 thanks in particular to technological advances, cost savings due to mass production as well as increasing competitive pressure (**Fig. 5**). Thus, for many SSA countries, PV represents the generation technology that is the most cost-favourable, most environmentally acceptable and the quickest to implement [22].

The remaining lifetime of a mine can represent an obstacle to applying PV, but the described price development ensures that a positive business case can exist given a residual life cycle of 5 to 7 years. The energy costs can be reduced by 10 to 20 % by using a hybrid system. The operator Cronimet Mining Power Solutions cites diesel savings of 30 % or 450,000 l per annum with a break-even point after only about four years for a South African chrome mine [23]. However, it is not possible to provide a generally valid statement relating to economic viability. For this purpose, the mine's exact load profile as well as the technical and commercial options must be examined for each individual use case.

Today, providing a complete supply solely comprising renewable energies may still be uneconomic owing to the still comparatively high battery prices, additional costs for special power inverters and the control unit of the hybrid system. On the other hand, substituting photovoltaics for diesel fuel is not. Thus, the application of photovoltaics is especially attractive in the off-grid sector. As far as on-grid mines are concerned the application of photovoltaics represents a long-term hedge against rising and volatile diesel-electricity procurement and CO_2 costs. In addition, there is less dependence on state electricity monopolists.

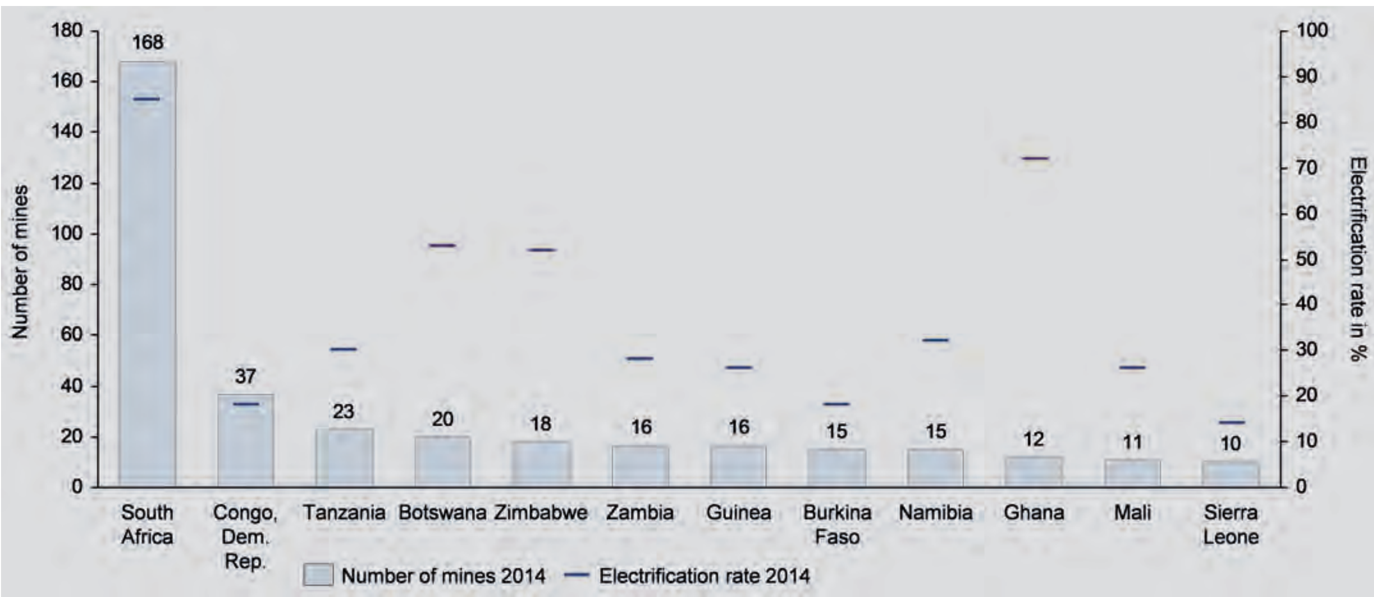
Mines as Anchor Customers for the Electrification of SSA?

Whereas the development of central generation capacities and grids currently represents the most cost effective method for urban dwellers in SSA, rural areas far away from the existing grid infrastructure have to depend on other solutions such as local mini-grids or off-grid applications, which are normally still driven by diesel fuel. The cost development of photovoltaics as well as innovative marketing methods have in the interim helped establish a number of photovoltaic micro-applications on the domestic sector. Backed by international donation and government programmes, it was possible to advance the electrification of rural regions in recent years although it still remains inadequate.

At the same time according to the World Bank, an estimated 15.9 billion US$ has been spent in the SSA mining sector on investment for generating energy and operative energy costs, without actually strengthening the public power infrastructure [24]. In the process, the mining industry would able to act as an anchor customer for environmentally friendly and affordable electrification with the application of photovoltaics thanks to its high and uniform power requirements. Furthermore, it would have been possible to foster socio-economic development above all, in rural regions. The secured power demand offers a specialised private operator (independent power producer, IPP) a predictable source of revenue thus reducing investment risks. In this way, surrounding villages can be more easily electrified. On account of its resources the private operator is also able to maintain and service the system and the grid successfully in the long term, something which regularly constitutes an obstacle for PV-hybrid systems in rural SSA owing to a lack of qualified staff.

Particularly in countries with a very low rate of electrification such as the Democratic Republic of Congo, Tanzania, Zambia, Guinea, Burkina Faso, Mali or Sierra Leone there is an appreciable number of existing or planned mines, which represent a good starting point for this approach of electrification (**Fig. 6**). In this case, the solution space for measures in addition to pre-financing includes supplying surplus power via mini-grids to the surrounding rural population and leaving the infrastructure intact once the mine's lifetime is over. Usually, a photovoltaic system possesses a technical service life of more than 20 years so that in many cases the mine's life cycle is exceeded by at least ten years so that

Fig. 6: Mine projects and electrification rate in selected countries in 2014
Source: World Bank Africa - PowerMining Projects Database 2014 & IEA Energy access database 2014



the system is available to the local population for at least another ten years.

In addition, the installation of mini-grids and renewable energy plants in remote rural regions also leads to local economic stimulation as accessing electricity encourages commercial activities. Constructing and operating the hybrid system as well as the mini-grid helps establish new qualified places of work apart from having a knock-on effect for other economic sectors. As a result, additionally a positive contribution towards combating rural poverty is made. In this connection, photovoltaics represents a crucial element for a low carbon development strategy in SSA and also contributes towards improved local air and water quality and in turn, to a higher quality of life in general.

Outlook

Mining will continue to play a crucial role in the economic development of SSA for the foreseeable future. Up till now, the rural population has benefitted from this only to a limited extent. Furthermore, the mining industry finds itself in rather a quandary at present with diminishing margins and uncompetitive power supply uncompetitive in terms of price. The deployment of photovoltaics in mining offers a chance to combine positive economic effects with public benefits. The market for such hybrid power plants finds itself in an early stage of development. The major portion of its potential has still to be exploited. Among other things, this is accounted for by a relatively conservative mining branch, for which a reliable power supply is admittedly critical, although energy production is not among its core activities. Further challenges are posed by arrangements to finance a project with a single power consumer as well as operation under in some cases extreme climatic conditions in desert and rain forest regions in some cases. The regulatory framework in individual countries is also in need of improvement.

For the future, the market research company Navigant predicts that the percentage of renewable energies amounting to only 0.1 % (without hydropower) today will increase to 5 to 8 % of the mining industry's worldwide energy consumption by 2022 [25]. The American Rocky Mountain Institute for its part even promotes that renewables will rise to constitute a 15 % share of power requirements in 2025 [26]. In this way, mine operators are giving themselves the chance to secure the 'social licence to operate' quite apart from improving their operative cost position. Rural areas in SSA can be electrified more easily thanks to these anchor customers. Furthermore, African governments will only achieve their climate targets by including the mining industry given its major importance. This is all the more crucial as SSA is particularly affected by the consequences of climate change.

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Mathematical Modelling of Water Hammer Effect in shut-off and regulating Valves and Pipes with anti-corrosive Coating

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Motivation

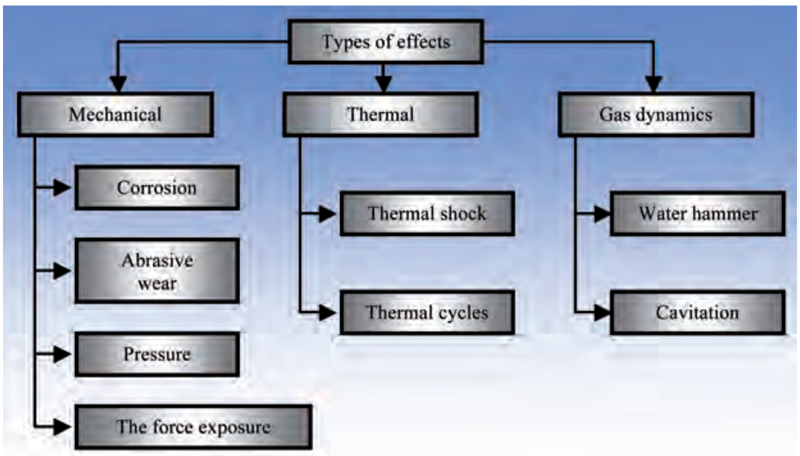
New technologies for extraction and processing oil and gas as well as mineral processing place even higher requirements on the design and materials used for the equipment. In today's oil and gas and processing manufacturing, a significant part of the industrial equipment operates under high mechanical loads, pressures and temperatures. Furthermore, it is adversely affected by a variety of corrosive environments. Nevertheless, its operability and technical safety have to be guaranteed.

Equipment for extracting and processing oil and gas as well as mineral processing is subject to great operational strain. Special coatings are intended to protect the components – especially valves and pipes – against wear and chemical loads. This article deals with the modelling of pressure surges, which largely contribute to damaging such coatings.

Energy • Oil and gas • Mineral processing • Valves • Coating • Water hammer • Model

Fig. 1: Loss of the coating on the ball and the seat of the ball valve

Fig. 2: Types of effects on elements of the shut-off and regulating equipment



Special coatings with improved corrosion resistance against abrasion and chemical aggression due to corrosive environments [1] are used to protect products, in particular valves and pipes, for various purposes. However, in practice, these coatings sometimes fail before the end of its estimated service life which can lead to severe mechanical damage (**Fig. 1**).

Analysis

Analysis of the majority of valves used in oil and gas mining and processing industries indicates that the valves are usually subjected to the effects listed in **Fig. 2** during operation.

Drops in pressure and temperature are the most significant among the destructive effects. As shown in **Fig. 3**, during operation there are pronounced pressure changes, far exceeding the working pressure, certainly indicating the occurrence of the water hammer effect in the system. In most cases, the basic cause of the water hammer effect in the piping system, is when the shut-off valve is triggered, thus instantly interrupting the flow, creating a shock wave in the system, which in turn leads to a tension-compression stress that damages the protective coating of various working valves elements [2].

As is known, the water hammer value depends on a number of design and technological parameters [3]:

- Liquid flow rate and its viscosity
- Flow portion sizes
- etc.

A numerical experiment was conducted to determine these quantities, on a real design ball valve with a pro-

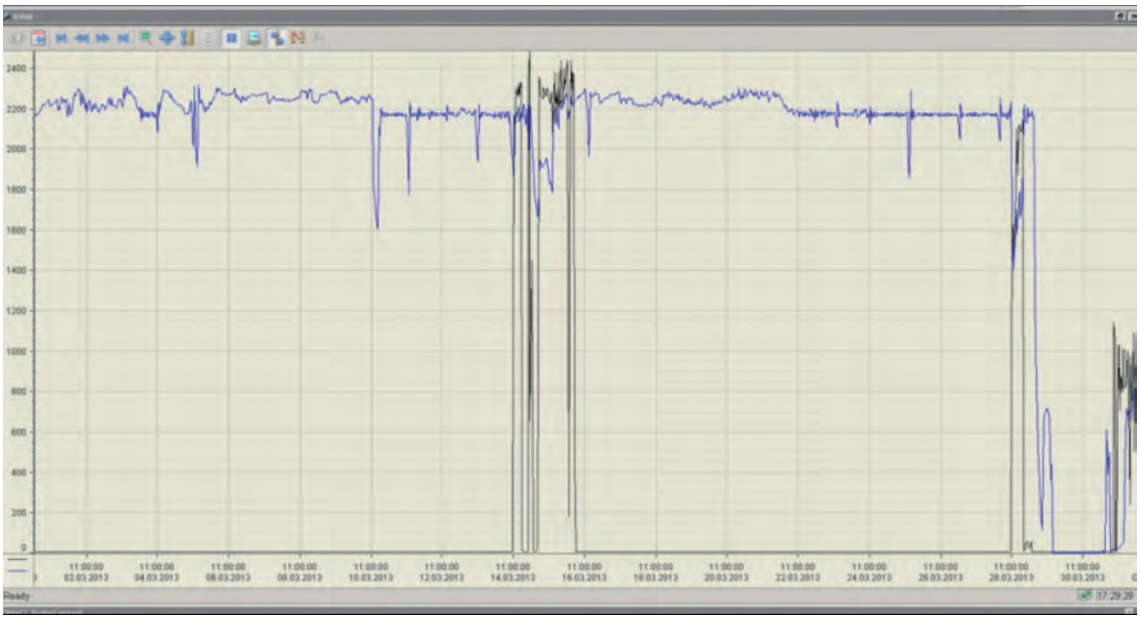


Fig. 3: Schedule pressure drop in the system shut-off and regulating equipment for the month

tective coating, using the following design and technological parameters:

- The diameter of the flow part DN 80
- Pressure 4 MPa
- Exploitation temperature 250 °C

For modelling the water hammer effect, the flow part has been allocated (**Fig. 4**). In Newtonian fluid it is defined as the working environment. For the calculation, a model was applied. The basic equation of this model is the Navier-Stokes equation (1) in its integral form, with arbitrary volume limited by the following boundary conditions [4]:

$$\frac{\partial}{\partial t}\int_V U dV + \oint_{\partial V}\left[(v-w)U - G\right]dS = \int_V R dV \quad \text{..................} \quad (1)$$

$$U = \begin{bmatrix} \rho \\ \rho v \\ \rho E \\ \rho\varphi \\ 0 \end{bmatrix}, G = \begin{bmatrix} 0 \\ \tau \\ \tau v + k\nabla\theta \\ d_\varphi \nabla\varphi \\ d_\psi \nabla\psi \end{bmatrix}, R = \begin{bmatrix} 0 \\ f^B \\ f^B v + q^B \\ S_\varphi \\ 0 \end{bmatrix} \quad \text{..................} \quad (2)$$

The τ-tensor shear stresses are:

$$\tau = -pI + 2\mu e + \lambda \nabla v I \quad \text{..................} \quad (3)$$

The e-strain tensor is given in (4):

$$e = \frac{1}{2}\left[\nabla v + (\nabla v)^T\right] \quad \text{..................} \quad (4)$$

where:

v	velocity vector
w	movement vector depending on the grid speed
p	pressure
ρ	density

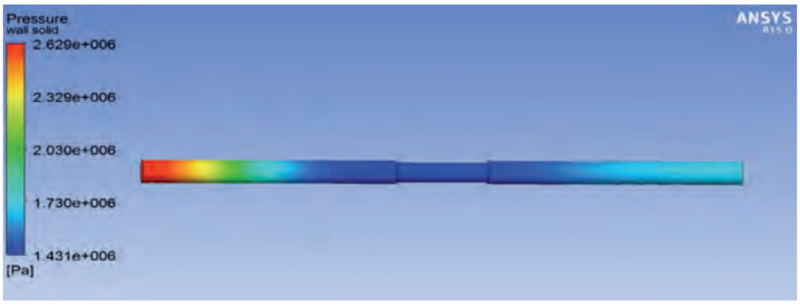


Fig. 4: Flow model of ball valve (the pressure distribution at the reflected wave)

E	specific energy, $E = (½\, v^2 + e)$
e	internal energy
θ	temperature
μ	Poisson's ratio
λ	viscosity
f^B	the power of the volume (body) fluid
k	thermal conductivity
q^B	specific heat release rate
φ	component regulatory convection-diffusion equations, can include turbulent kinetic energy and turbulent dissipation – ε (if used K–ε model) and φ_i - mass ratio [4]
S_φ and d_φ	diffusion coefficients

Especially for the conservation of mass, momentum and energy of the system, additional diffusion equations may be included to simulate gravity and electromagnetic interactions.

Results of FEM simulations for a valve with 80 mm diameter show that for different flow speeds, the peak values of pressure during hydraulic shock can significantly exceed the working pressure (**Fig. 5**). Time of wave travel in the valve is about 1.5 x 10^{-3} seconds. To assess the reliability and strength of the coating, a joint analysis of Fluid Structural Iteration is necessary. On

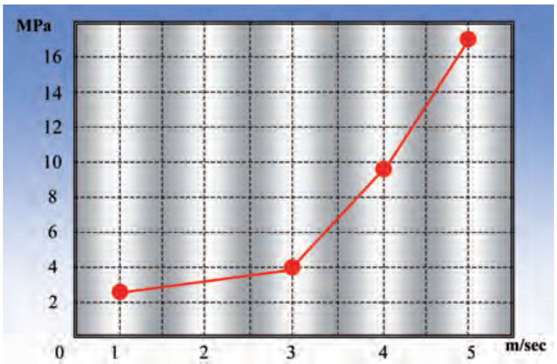


Fig. 5: The dependence of the maximum pressure on the flow velocity

the basis of this analysis the water hammer effect on the strength of the coating can be evaluated.

The process of calculation used the following assumptions:

- Absolutely rigid walls of pipes and valves excluding their deformation
- Newtonian fluids
- Excluding the effect of temperature on the properties of the fluid

Conclusion

Thus, the solution couples field hydro gas dynamics analyses with thermal-stress problem taking into account contact interaction and will solve the problem of premature failure of valves with protective coatings by selecting the optimum geometrical and physical and mechanical parameters of coatings.

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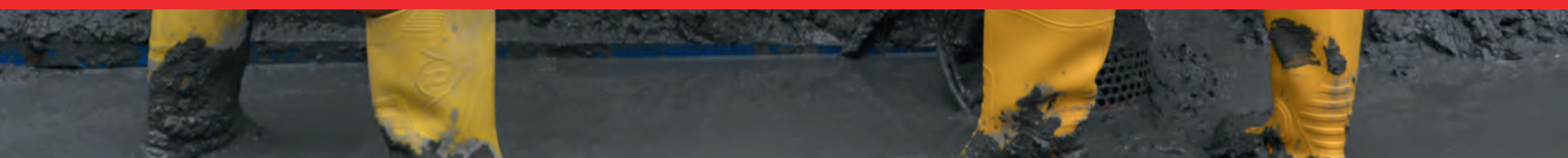

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