GEORESOURCES Journal

Journal for Resources, Mining, Tunnelling, Geotechnics and Equipment

3 | 2023

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GeoResources Verlag

ISSN | Online 2364-8430 • Print 2364-8422

www.georesources.net

Long-term Monitoring of backfilled Salt Mines – a new wireless Rock-pressure Measuring System

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Wired rock-pressure measuring systems are not rated as suitable for the long-term monitoring of abandoned salt mines as they are expensive, technically complex and lacking in functional reliability. A ZIM cooperation project was therefore set up to develop, build and successfully test in situ a wireless measuring system designed for long-term measurement applications. The first prototypes are now ready for the instrumentation process.

Mining • Post-mining • Salt • Monitoring • Long-term monitoring • Rock pressure • Measuring equipment • Innovation • Development • Safety

1 Starting Point and Project Motivation

The salt industry's abandoned mine workings pose all kinds of hazards, from mine-water infiltration, disposed-of chemicals and accumulated waste to the risk of ground movement and displacement. Effective measures therefore often have to be put in place to monitor pressure conditions so that these deformation processes can be properly assessed. This has traditionally been achieved using sensors with wire-bound data transmission of the measurement signals and energy supply. The high demands placed on the mechanical and corrosive robustness of the cable connections and on the ability of the cable ducts to withstand fluid pressure mean that wired systems of this type are both labour-intensive and expensive to install and, moreover, tend to lack the functional reliability needed for a monitoring lifetime that may extend over several decades.

A ZIM cooperation project [1], which is being promoted by coordinators AiF Projekt GmbH, was therefore set up to develop a wireless system with energy-independent rock-pressure sensors that would enable long-term monitoring of disused mine workings and tunnels. This joint research and development initiative is being supported by project partners:

- GGB Society for Geomechanics and Construction Measurement (project reference ZF4099402GR7)
- IBeWa Engineering Partnership Mining, Water and Landfill Technology, Wilsnack and Partners (project reference ZF4486501GR7)
- IAB – Institute for Applied Construction Research Weimar gGmbH (project reference ZF-4013661GR7)

The research activities focused primarily on:

- The development of a modular measurement system for determining pressure and temperature at selected measuring points over extended periods
- Assessment of the measurement performance of the pressure transducer (**Fig. 1**) based on numerical simulations and with reference to the operating conditions
- The functional verification of the measurement system as borne out by model and test-based findings
- The development of a bi-directional, wireless data transmission system between the measurement probes and the external transmitter-receiver station based on the use of adapted radio technology in dry salt formations

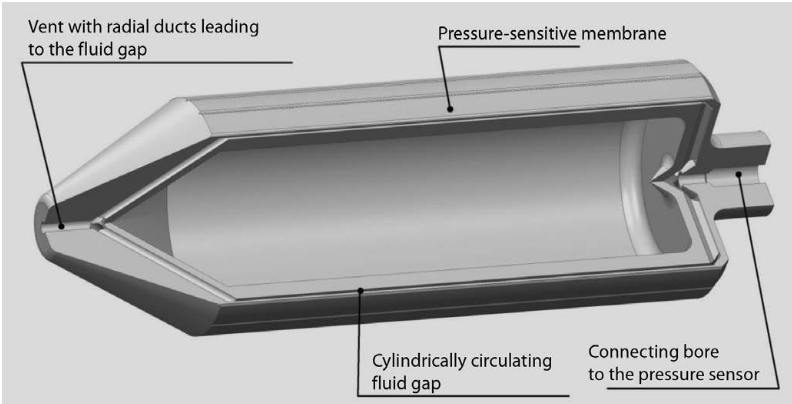

Fig. 1: Layout of the cylinder sensor head (CAD model)

From the developer's perspective the project specifications that presented the greatest challenge and posed the highest risk were:

- **Design changes to the pressure transducer:**
  - Housing diameter d: 65 mm < d < 165 mm
  - Sensor-head material: rustproof
  - Aerial material: POM
  - Mechanical stability/flexibility against mechanical loading and deformation within the rock
  - Mechanical decoupling between pressure transducer and transmitter/receiver unit
  - Maximal battery capacity for lengthy service periods t (t > 10 years)

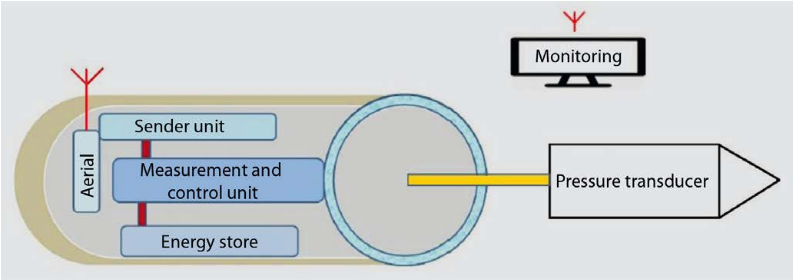

Fig. 2: Modular layout of the measurement system – main components

- **Interface specifications for sensor at measuring point:**
  - Bedding in the rock/fill material (sensor and aerial housing in stowing material)
  - Minimum influence on transmission of measurand
  - No significant change to transmission performance in the measurement environment
- **Electronics:**
  - Sufficiently large flash storage in the sensor for saving measurement data during short-term inaccessibility of the transmitter/receiver station
  - Bidirectional communication between sensor and receiver station for individual adaptation of the measurement regime and data transmission process
  - Facility for end customers to change the measurement parameters of the wireless sensor

2 Development Focus

2.1 Concept for modular Measurement System

According to the terms of reference the rock-pressure measurement system was to be modularly designed in order to enable long-term monitoring of ground pressure levels. Based on the functional and process-related specifications, together with the interface requirements, it was decided that the monitoring system should have the following modular layout (**Fig. 2**):

- Pressure transducer
- Measurement converter (physical-electric)
- Repeater for the electric measurement signal
- Converter (analogue-digital)
- Transmitter/receiver
- Control unit
- Energy store

Figure 3 shows the different installation options available for the measurement system in the proposed application and their interaction.

2.2 Construction and Design of the Sensor Head

The development of the sensor head as a pressure transducer represented the focal point of the project work. This development work involved the following subtasks:

- Formulation of constructional designs for the sensor head under consideration of the operating conditions, particularly the space requirement, the measurement technology and the influence factors (e. g. pressure, temperature and corrosive attack)
- Assessment of the proposed designs in terms of functional fulfilment (FE calculations)
- CAD design and preparation of drawings for the prototype construction

The operating principle of rock pressure measurement is based on the mechanical effect of forces and pressures on fluid-filled hollow bodies with defined membrane areas as the pressure-sensitive solid-state contours. It is assumed that the pressure build-up, as a consequence of strata movements in general, is a very slowly developing flow process within the salt rock formations. The hermetically sealed interior of the pressure transducer is connected to a sensor. The application of a force on the pressure-sensitive membrane surfaces causes the pressure of the quasi-incompressible fluid to rise within the sensor head. The pressure sensor converts the physical quantity 'pressure' into an electrical quantity and delivers it to the electronic analyser for further processing.

As the project was being developed a cylinder-shaped design was eventually considered to be the most favoured solution for the sensor head (**Fig. 1**). This shape, which offered advantages in terms of instrumentation and strength of grip with the rock and fill material, was further improved during the development process by using numerical simulation models.

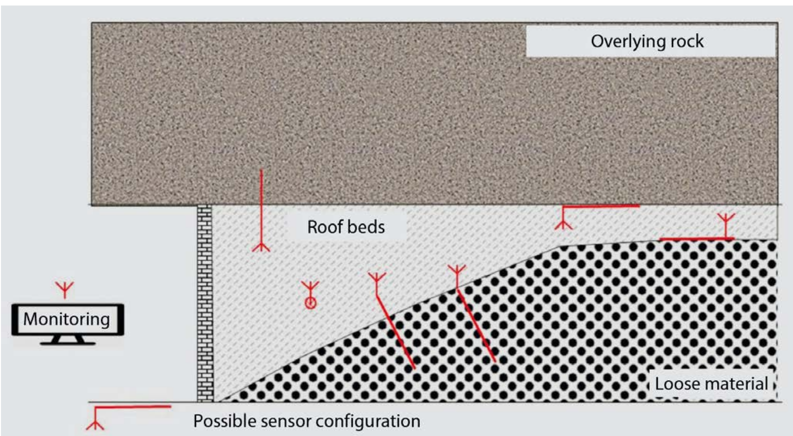

Fig. 3: Depiction showing different situations where the measurement system can be installed below ground

2.3 Simulation of Deformation to the Sensor Head under Load

Numerical calculations were carried out using the finite and discrete element method (FEM and DEM). The aim of this exercise was to assess the capacity of the sensor head construction to withstand the anticipated loads and the measurement characteristics that would result from this. The calculation findings were incorporated into the design improvements.

The load simulation that came closest to matching real conditions incorporated the interactions between the distortion of the metallic sensor head, the formation of a characteristic pressure field in the embedding material surrounding the sensor head and the fluidic properties of the fluid contained within the sensor. A particular aspect of the simulation exercise was its ability to couple load application and load distribution by way of:

- Solid-body deformation
- Fluidic pressure formation
- Pressure formation in the loose material

Because of the mutual dependencies that exist between the physical quantities it was decided to carry out a modelling and simulation exercise with coupling of the force, pressure and deformation processes.

The results of the DEM-based calculation, as carried out on bedding material subjected to varying levels of pressure, were incorporated into the deformation calculation as a pressure field. The deformation of the sensor head was then calculated using a transient calculation method. A calculation result for the assumed loads and material properties in this simulation stage is shown in **Fig. 4**.

The resistance to the expected load conditions is very much dependent on the bedding characteristics and on the spatial distribution of the pressure field in the bedding medium. When the bedding is in an inhomogeneous external pressure field that is under load, for example, pressure differences will arise in the volume of the annular gap as a function of the load ratio λ. These will in turn result in a movement of the fluid leading to a state of equilibrium of the internal pressure. This means that the deformation of the pressure-sensitive surfaces, along with the changes in fluid pressure and material tension, are dependent on the behaviour of the bedding material. In the case of loose material the external pressure acting on the pressure transducer builds up as a function of the load ratio λ. This is expected to result in much greater deformation at the cylinder head.

Fig. 5: View of sensor head after 3D printing

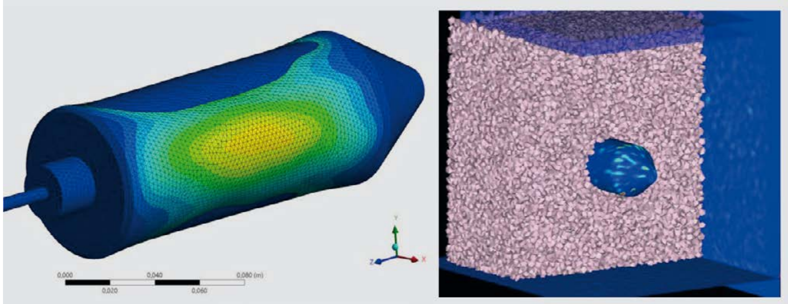

Fig. 4: Deformation of the cylinder barrel on taking on external load (pressure field) from the bedding material (depiction of deformation greatly exaggerated)

The simulation exercises showed that for the practical long-term operation of the sensor head in a monitored salt dome an all-round uniform and positive bedding is essential in order to ensure a reliable and durable measurement function. The simulation exercises were carried out under the additional assumption that during the process no detachments (air gap) from the pressure-sensitive cylinder surface were able to occur around the cylinder barrel. This meant that in terms of the loading condition the bedding was able to behave similarly to a fluidic bedding material.

2.4 Construction of the functional Model

A number of different constructive proposals were developed for the sensor head, these then being improved in several stages in order to meet the complex functional requirements imposed by the surrounding conditions. This implementation phase involved the use of both conventional (forming and connecting) as well as additive (3D printing based on the SLM technique (SLM: selective laser melting) production methods. **Fig. 5** shows the cylindrical sensor head blank produced by metal 3D printing. **Fig. 6** then shows part of the measurement system with the sensor head and pressure sensor together with the analysis and transmission unit for the wire-bound in-situ tests. **Fig. 7** presents an overview of the general sensor layout for the wireless data transfer process.

The calibration of the pressure measurement system, which was done to metrology standard, was carried out in

Fig. 6: Functional model components for wired in-situ tests

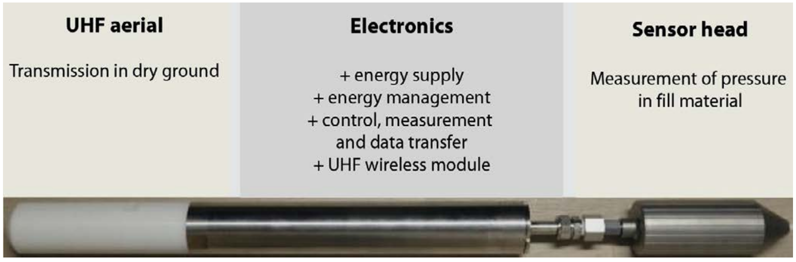

Fig. 7: General view of pressure transducer with wireless data transmission

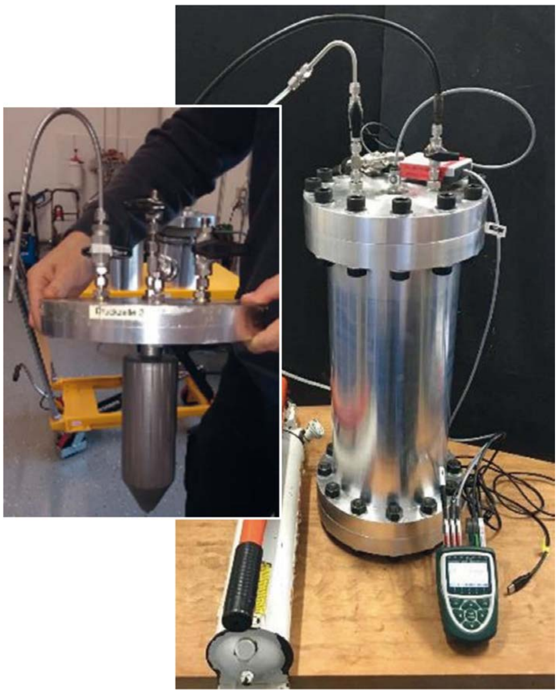

Fig. 8: Test set-up for calibration in the pressure autoclave

Fig. 9: Installation site of rock-pressure sensor for test arrangement 1

Fig. 10: View of site chosen for test 2 at Teutschenthal mine

an autoclave (**Fig. 8**) for the entire measurement range to 100 bar (10 MPa). The results were stored in calibration protocols for every type of sensor system and are readily available for individual measurement applications.

3 Testing Measurement and long-term Performance under practical Conditions

The functional model test was carried out after consultation with interested parties and project managers at two installation sites in the Teutschenthal mine (GTS Grube Teutschenthal Sicherungs GmbH & Co. KG, Germany):

- **Test setup 1 – Installation in a recess within a local excavated chamber**
  Test setup 1 was aimed at testing the measurement system under real-life conditions and establishing its measurement performance. The functional model of the pressure transducer was installed in an existing recess inside a local excavated chamber within a native salt formation at Teutschenthal mine (**Fig. 9**). In this case the pressure transducer was embedded in a layer of salt grit (**Fig. 9 right**) and pressure was applied in a controlled manner via a ram. In order to assess the measurement performance a number of tests were carried out with a view to correlating the applied pressure with the pressure recorded by the embedded sensor.
- **Test setup 2 – Installation in a borehole in the sidewall**
  The second test arrangement sought to investigate the long-term performance of the measuring system at another installation site at Teutschenthal mine (**Fig. 10**). For this purpose the pressure transducer was located in a dipping borehole drilled into one of the sidewalls. Frictional contact with the surrounding rock was achieved using an MgO-based bedding material (concrete). The layout chosen for the test matched the kind of installation conditions generally found in a mining environment. All the system subfunctions associated with measurement logging and transmission were executed under consideration of the in-situ conditions and constraints. As well as assessing the data gathering process the test also sought to check out the wireless data transmission system. This focused on bidirectional communication with the installed sensor. The control of the readout and the transfer of the logged data into specially provided database management systems, such as GKSpro® developed by GGB (Society for Geomechanics and Construction Measurement), was achieved using Bluetooth technology.

4 Conclusions

The joint project in question involved the development of a system for the long-term monitoring of pressure levels in disused mine workings and tunnels using wireless technology for the transmission of the measurement data. The project also included building and testing a functional model. One significant result of the research work involved the development of a new type of measurement probe that could fulfil all the main functional conditions specified for the monitoring system.

The geometric dimensions, operating characteristics and measuring performance meet the requirements of the remit. The constructional design as a fully-enclosed, hydraulically sealed system is effective at detecting and recording pressures in accordance with structural metrology standards.

The strength-related characteristics of the sensor head were developed using the finite element method in a multiphysics simulation with coupled calculations, this focusing on:

- Solid-body deformation
- Fluidic pressure formation
- Pressure formation in the loose material

The resistance to the expected loads is very much dependent on the bedding at the measurement point and on the all-round form-fitting and force-fit contact between the pressure-sensitive surfaces and the strata. The energy management solution proposed for the monitoring system is currently designed for an operating life of at least ten years.

5 Summary and Outlook

A ZIM cooperation project [1], which is being promoted by coordinators AiF Projekt GmbH, has been set up to develop a system for the long-term monitoring of pressure levels in disused mine workings and tunnels using an innovative measurement probe with wireless transmission of the measurement data.

The newly developed measuring system was tested under in-situ conditions and has been rated suitable for various measurement tasks in dry salt formations. System application will always involve some degree of adaptation to match the local conditions and conform to the task at hand. The first prototypes are already going through a planned instrumentation process at the BGE (German federal company for radioactive waste disposal).

6 Reference

[1] Federal Ministry for Economic Affairs and Climate Action (BMWK): Another ZIM project success story – Wireless monitoring of disused mine workings. Cooperation project no. 223. As at June 2022.

7 Project funding

This project is being funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) following a decision of the German Bundestag.

ZIM Zentrales Innovationsprogramm Mittelstand

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

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