LabVIEW based software for verification of the new idea of lining for mine shafts located in salt rock mass

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Abstract:

High values of salt rock mass convergence might cause serious problems with maintenance of shaft lining located in salt rock sections. The most efficient existing method of negative convergence influence prevention is periodic removal of creeping salt from shaft walls. However, the process of salt removal is problematic in terms of shaft and hoisting system typical operation. A new shaft lining idea allows removal of creeping salt by leaching without the need for stopping the shaft operation. Following paper presents a software, developed in LabVIEW environment and applied in the framework of test facility, designed for purpose of verification of theoretical assumptions of new construction of shaft lining. Developed software consists of applications for data acquisition, based on Event-Driven Queued State Machine pattern, and data processing, designed as Producer-Consumer pattern.

Keywords: shaft lining, software for mining engineering, salt mine, mine shaft, LabVIEW, data acquisition, data processing, Event-Driven Queued State Machine

1. Introduction

An idea of utilization of the salt's characteristic feature, which is high water solubility is not a new concept. Actually, evaporation of salty water was a first historic method of the salt production. This way of salt sourcing was in use for ages in numerous places all over the world, utilizing surface and underground salty waters and rock salt dissolved in water [1-3]. Borehole leaching is the most modern and efficient, as well as the most popular nowadays method of the salt production [2, 4-6]. In 20th century caverns leached in salt deposits were recognized convenient tanks for storage of carbohydrates, hydrogen and other liquid or gaseous substances. Some of this caverns are made for purpose of storing only. Brine is then just a by-product of leaching [4-5].

Convergence of salt rock sidewalls might be a reason of very strong pressure acting on the shaft lining [7-11]. Convergence rate is an indicator of a need for undertaking prevention activities to minimize its destructive influence on the lining.

Numerous solutions of shaft lining preventing the influence of the convergence were used in salt rock mass in different countries. The basic approach is very high load bearing capacity steel shaft lining [12-13]. Another approach is a high lining yielding. Such construction was applied in SW-4 shaft of Polish copper mine Polkowice-Sieroszowice, a part of KGHM Polska Miedź SA [14-15]. Concept of a hydraulic yielding support, comprising of watertight lining and water column between the lining and shaft sidewalls, was also presented [16].

Specialized research indicates a possibility of excessive load of the shaft lining occurrence as a result of rheological deformations of salt rock mass [14-15]. It is then necessary to remove the creeping salt from the shaft. The idea of the new shaft lining construction is based on use of fresh water for purpose of the creeping salt removal. As the salt is easily dissolved in fresh water, a contact of the whole area of salt rock mass with water poured behind the shaft lining should be provided.

The new construction of a shaft lining, called the tubing-aggregate lining consists of:
– preliminary sidewalls bolting,
– watertight tubing lining,
– porous material filling –coarse grained aggregate of high compressive strength,
– a system of pipes, pumps and tanks for water circuit.

The key element of the shaft lining construction is the aggregate filling, because its task is to provide contact between shaft sidewalls and lining. Moreover, it forms a porous structure, which is freely penetrated by leaching medium. It also plays a role of deformable and equalizing layer for point loads [17-18].

2. Testing facility

Research for purpose of verification of the shaft lining construction and operation presented above was conducted using specifically designed test facility, which was widely described in works [18-19]. The idea of its work, comprising data flow between its components is presented in Fig. 1. Blue line represents a water flow forced by a pump. Temperature was regulated by a heater assembled in a water tank, while the value of the water flow was measured by an indicator. A system of rock sample's loading (a pump with a cylinder) and main chamber for salt sample and aggregate are shown in the central part of the figure. Data was gathered using notebook via suitable connectors. Tests were also registered by a time-lapse camera.

Testing compartment was made of 12 mm thick S355 steel sheet and it was divided into open and closed part. The closed part is a sealed system equipped with a sleeve for hydraulic cylinder assembly. Cylinder's piston with a plate loads a salt sample. Pressure is transferred through the sample and aggregate to a test plate, where stress and strain is generated. Their values, measured by a strain gauge and displacement sensor, located in the measuring unit. Inflow and outflow valves allow to control direction and velocity of water flow through the testing compartment. Overflow container with capacity of 70 litres allows water to circulate in a testing compartment – pumping unit – water tank cycle [19].

The pumping unit comprises of a plastic filter, a membrane pump of maximum discharge of 11.3 l/min, a flow meter and a set of valves - suction valve, inflow valve and outflow valve. The construction of the membrane pump ensures its safe operation in salty environment (internal part of

the head is made of ethylene propylene diene monomer - EPDM and Santoprene®, while the external part of polypropylene) with maximum pressure height of 10 m. Depending on a way of connecting, the pumping unit allows water to flow from the top or from the side of testing compartment [18].
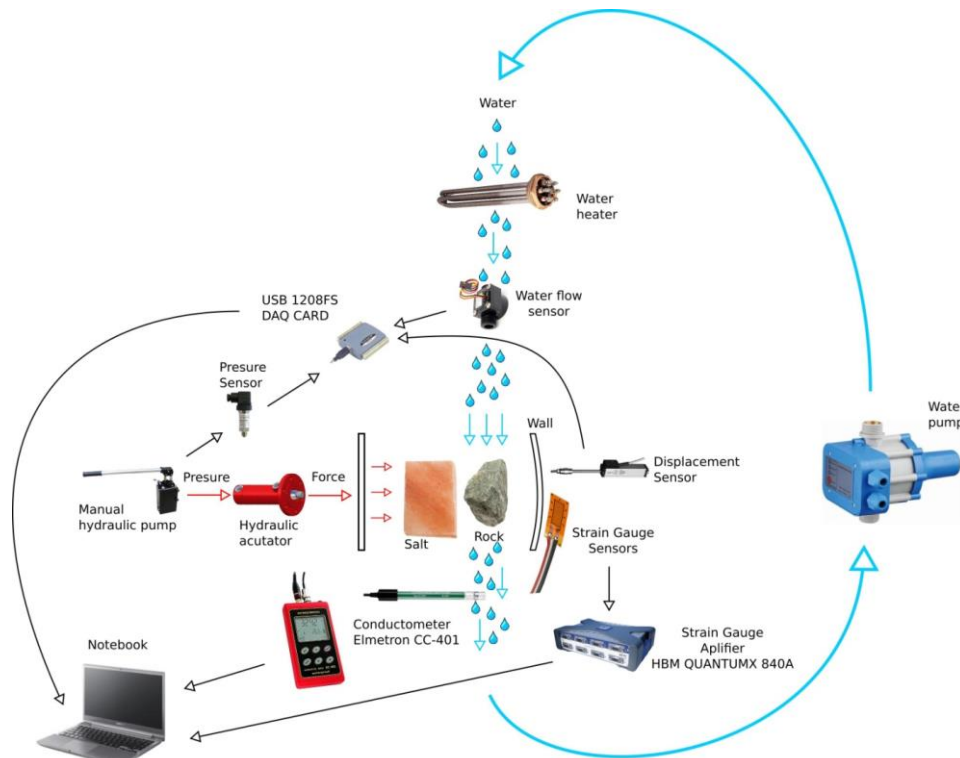

Fig. 1. Operation scheme of the test facility [18]

A hydraulic unit consists of a manual pump (max 250 bar), hydraulic pipes, a hydraulic cylinder and a hydraulic fluid pressure sensor. System was designed to provide pressure of 80 kN for maximum pump operation pressure (180 bar). Pressure sensor allows to calculate load [18].

3. Electrical system

Testing facility was equipped with an electrical system, which was needed to supply devices such as pump and heater. To provide proper level of safety of the operator and the test facility itself, additional electrical components became necessary. Fig. 2 presents the electrical diagram [18].
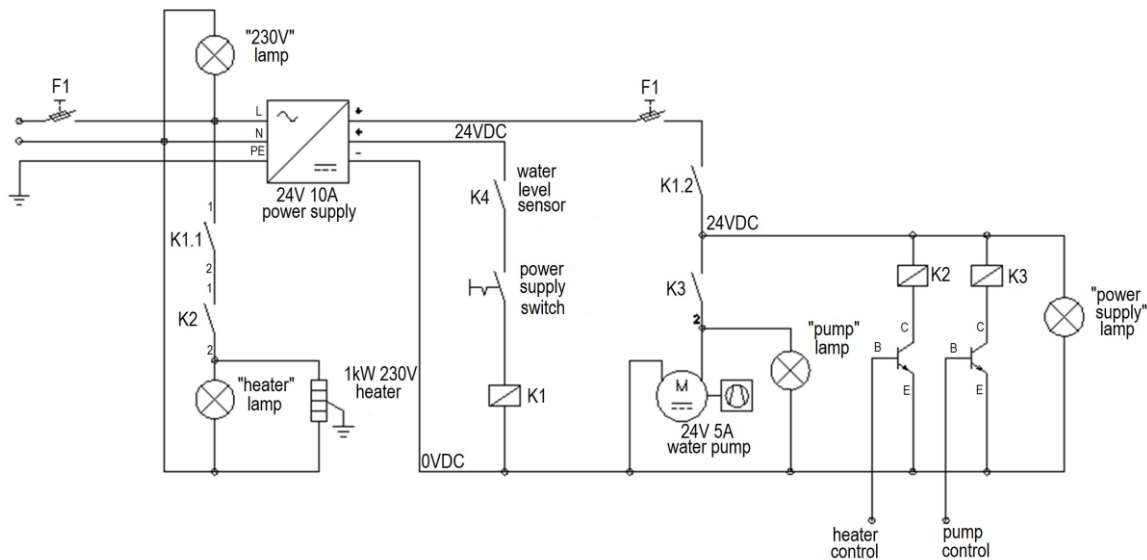

Fig. 2. Electrical diagram

Electrical system comprises of following components:
– fuses protecting from short circuits,
– 24V pump and sensors power supply,
– level control relays for pump and heater,
– indicator lamps,
– water pump,
– 240V 1kW water heater,
– Darlington circuit ULN2003 for coils control with USB 1208FS-Plus card.

4. Data acquisition and processing

Within the formwork of the research programme it became necessary to design an application for control of the testing facility and data acquisition. Because of the complexity of the issue and requirement for communication with HBM, National Instruments and Elmentron measuring devices, LabVIEW environment was chosen to develop needed software.

Requirements defined for the dedicated software were communication with measuring devices, data acquisition and control of water pump and heater work.

4.1. Measuring devices

Testing facility was equipped with following measurement devices:
– HBM Quantum MX840 – an eight-channel measuring amplifier allowing data acquisition from seven load cells connected in half bridge circuit and temperature sensor PT100 with Ethernet interface.
– Measurement Computing USB-1208FS-PLUS – eight-channel measuring card, recording data from displacement, pressure, water flow sensors and controlling water pump and heater work with USB 2.0 interface.
– Elmetron CC401 – conductivity meter allowing to measure water salinity with RS232 interface.

4.2. Data acquisition application

Analysis of requirements for the data acquisition application indicated Event-Driven Queued State Machine as a suitable pattern for this purpose.

It is one of the most complicated and the best functioning behavioural software design patterns. It combines architectures of state machine, queued system and event system. This design pattern captures events of application user, like start of measurement, queues events/states and handles them in one state machine process in order in which they were added to a queue. Event-Driven Queued State Machine allows to properly capture and handle all user's event, even if other processes are in progress [20].

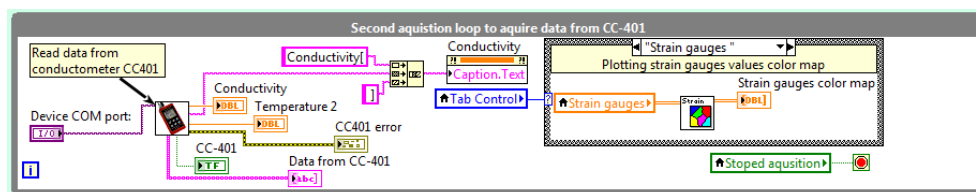Fig. 3, 4 and 5 show diagrams of sample features implemented in the application.

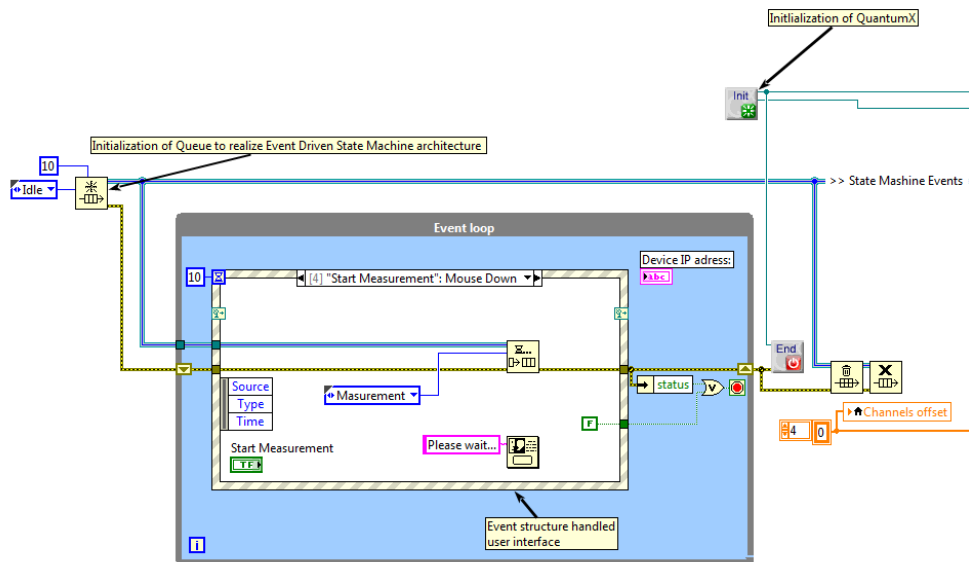**Fig. 3.** CC401 Conductivity meter operation

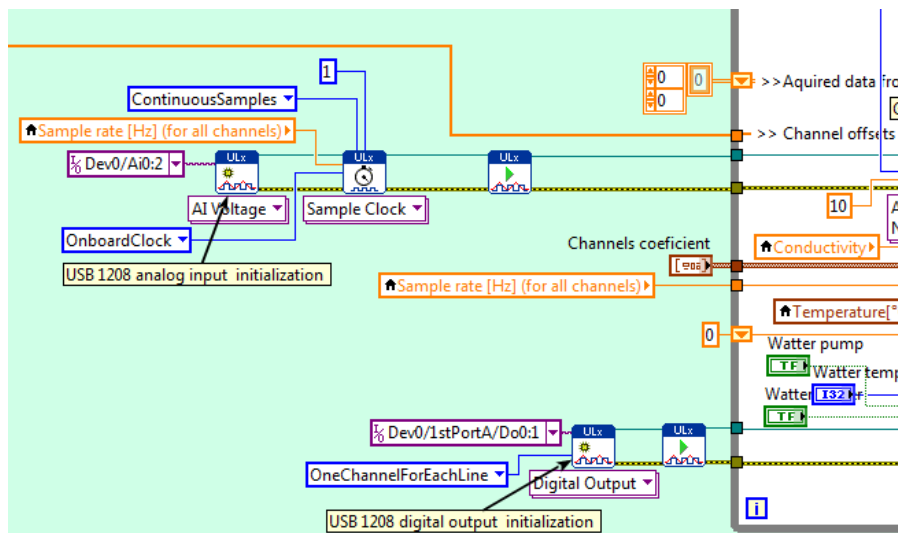**Fig. 4.** Event case structure capturing user's events

Fig. 5. USB 1208FS-Plus measuring card configuration

Graphical user interface (GUI) was divided into two main parts:
- Top right section of the window consists of four buttons:
  - ZERO – zeroing the measuring system; functionality implemented for displacement sensors to always begin the measurement from 0mm,
  - START – measuring session start,
  - STOP – measuring session finish and automatic data record,
  - EXIT – exit from data acquisition app.
- Top left section of the window (buttons/tabs of TabControl) responsible for switching between main functionalities:
  - application main window,
  - stress diagrams,
  - detailed diagrams,
  - configuration panel.

Application main window, presented in Fig. 6, comprises of:
- main graph in the central part of the screen with current data courses,
- indicators in the bottom left section presenting values of measured quantities, such as pressure, displacement, temperature, water flow and salinity in an easy and convenient way,
- temperature regulator and water pump control in the right bottom section.
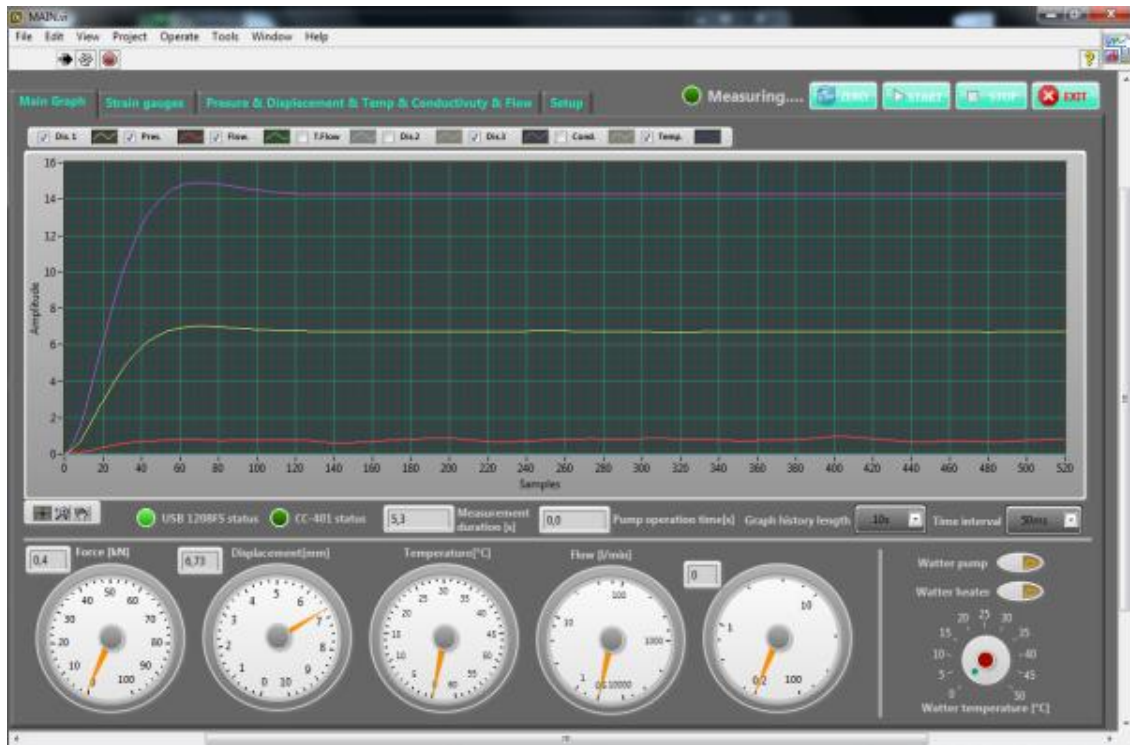
Fig. 6. Application main window

Configuration panel shown in Fig. 7 allows to:
- configure USB 1208FS-Plus measuring card (entering sensors constants, setting sampling frequency),
- read real values from sensors,
- read measuring channels offset after zeroing the system,
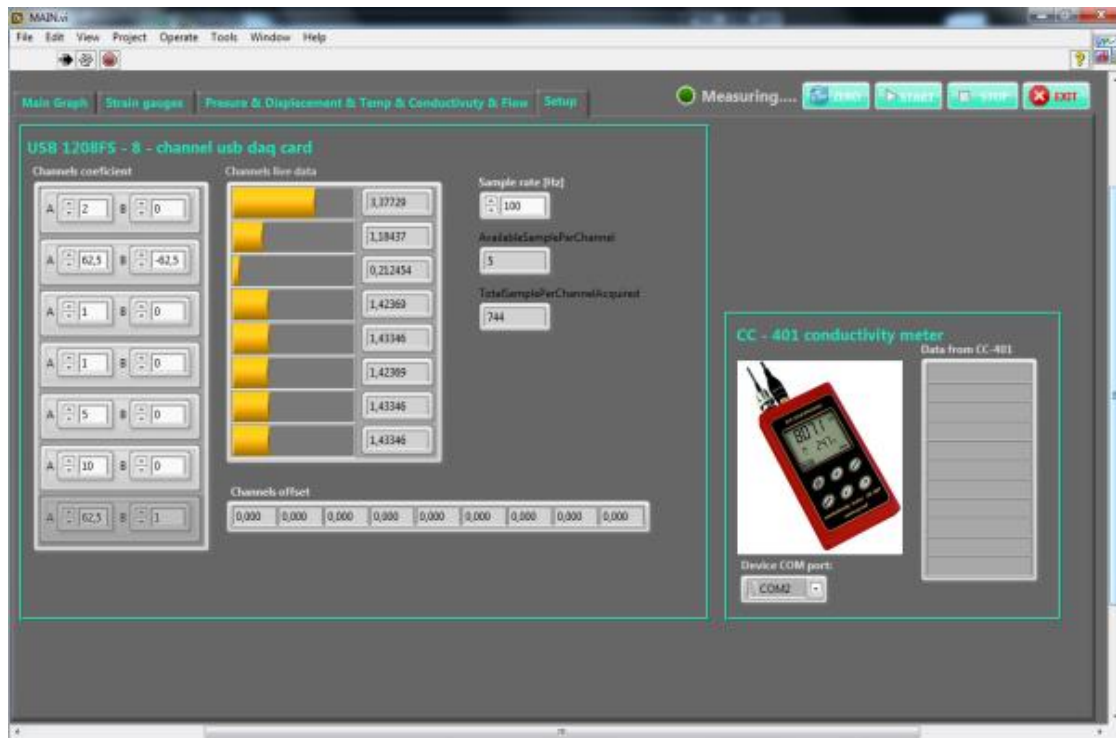- set communication port and preview data of CC-401 conductivity meter.

Fig. 7. Configuration panel

4.3. Data processing application

The main reason of development of dedicated data processing application was lack of suitable solutions available on the market. Requirements for the application were as follows:
- analysis of huge amount of data,
- comparing and summarizing of measurements' results, which are rarely synchronized in time, because of non-repetitive characteristics of the experiment process,
- ability to generate identical sets of diagrams for different entry data,
- data recording during its processing, including verbal notes,
- ability of duplicate analysis.

After an analysis of software available on the market, a decision was made to develop dedicated application. Simplicity of implementation and previous experience (data acquisition application development) LabVIEW environment was chosen for purpose of development of data processing application meeting the demands.

Functional requirements to implement were as follows:
- data loading from external files,
- data resampling (sampling frequency adjustment due to low processes characteristics),
- ability to select pieces of data,
- ability to merge pieces or full data from different measurements and comparing them,
- generation of separate diagrams and ability to designate approximate curve characteristics of presented data,
- ability to generate diagrams of measuring signal sequences and X/Y diagrams to present relationships between different quantities,
- ability for curve development and adding them to existing data according to measurements not included in the measuring system, like measurement of sample's contact area.

Basing on the analysis of listed requirements, architecture based on the Producer-Consumer design pattern was selected. This pattern perfectly fits an application which transfers data between a number of threads.

Producer thread is handled by user interface in case of the developed application. It reacts on buttons and other controls, which might be used by application's user. Sample functionalities of Producer thread are:

− loading data from a file,
− selection of piece of data from the loaded file and its transfer to Consumer thread,
− closing an application.

Producer thread architecture was shown in Fig. 8. As it can be seen, its key element, connecting threads of Producer and Consumer is a queue (marked with 1). Consumer dequeues data (2) and transfers it to further processing (3) under the thread, where it is added (4) to a cluster array. Cluster consists of a set of measuring data loaded from a file as a multidimensional array, sampling frequency data and verbal notes, written by user during data loading.
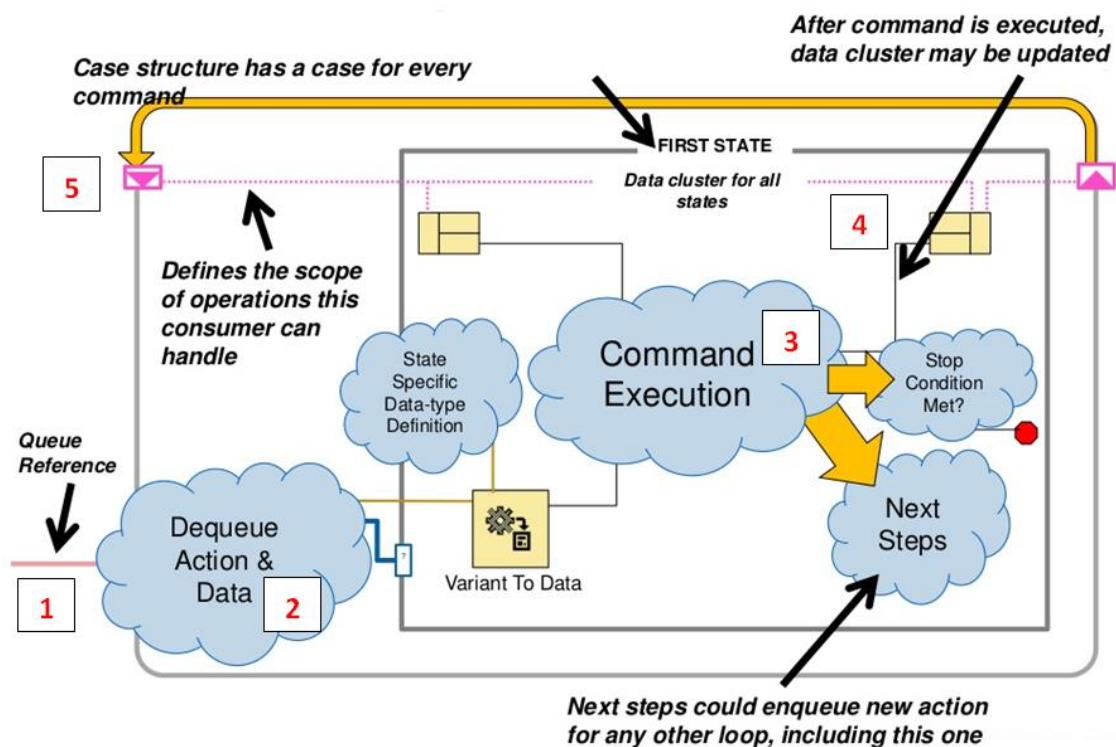
Fig. 8. Diagram of the Consumer thread

Data availability in subsequent iterations of thread main loop is possible thanks to shift register (5). Sample functionalities of Consumer thread are:

− dataset creation,
− data displaying on graphs,
− designating approximation curves using selected data.

User interface was divided for few subsections. Fig. 9 presents a screen of loaded measuring data preview. A top window presents summary graphs of dataset. Bottom windows contains a selected curve and its approximation (bottom left; in the figure displacement course in time and its linear approximation is shown) and X/Y graph (bottom right), which can be freely modified by a user by selecting a dataset for graph generation (in the figure a displacement course in displacement function is presented).
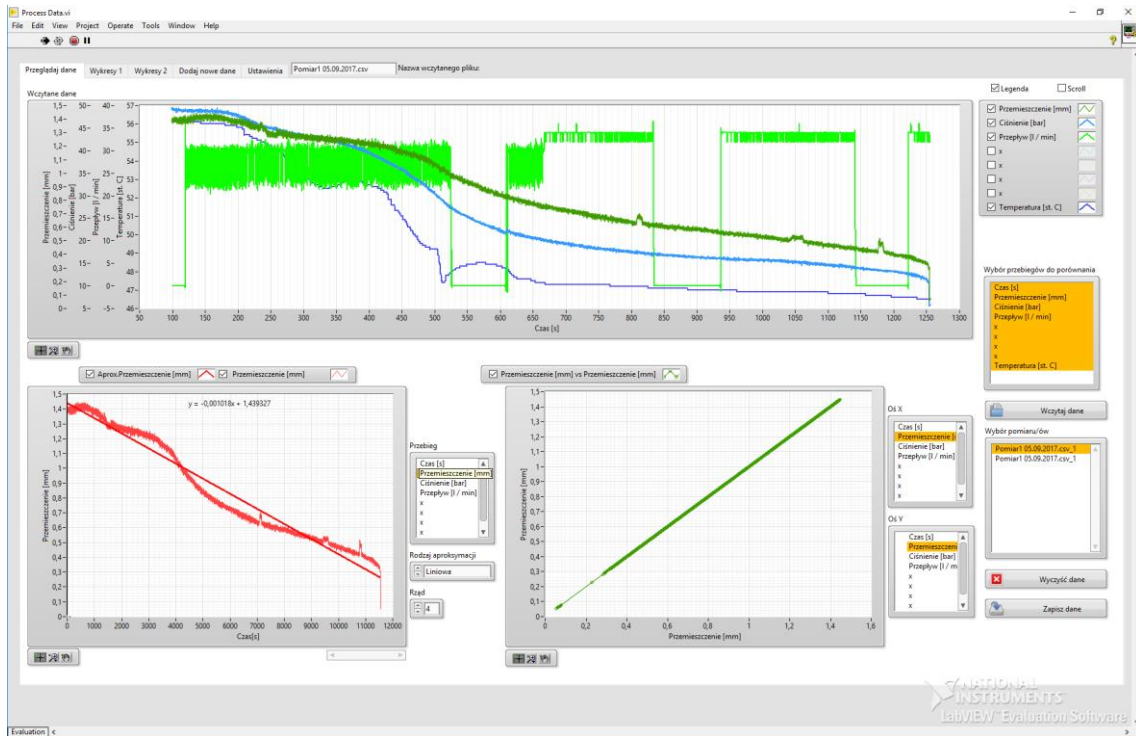
Fig. 9. A view of the main window of processing application

Figures below present user screen previewing graphs according to settings (Fig. 10) and a view of data loading interface (Fig. 11). A graph with loaded data can be seen in the Fig. 11. Cursors A and B, used for data fragmentation, are displayed on the graph. There is a table in the bottom left corner, where a user can enter measurement data other than loaded, like sample's area. The graph in bottom right corner presents data entered in the table and its approximation (in the figure there is no data entered in the table and the graph shows quadratic function approximation curve). Different settings can be applied using settings window presented in Fig. 12.
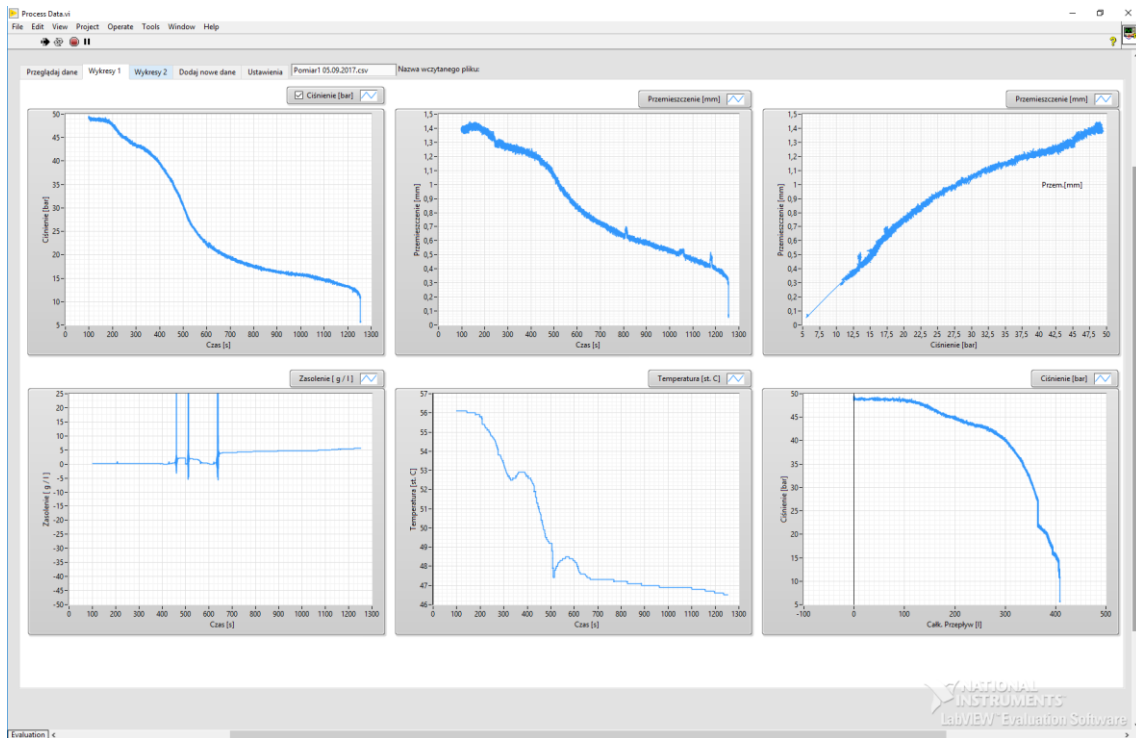

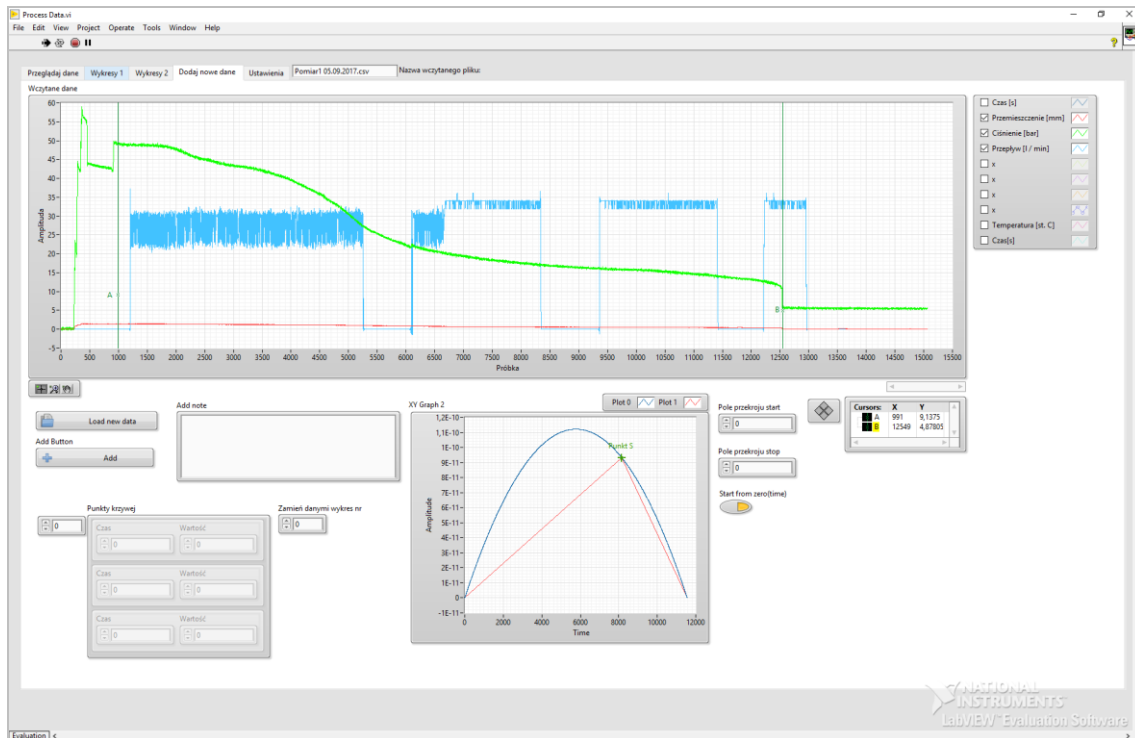**Fig. 10.** A view of the window of graphs
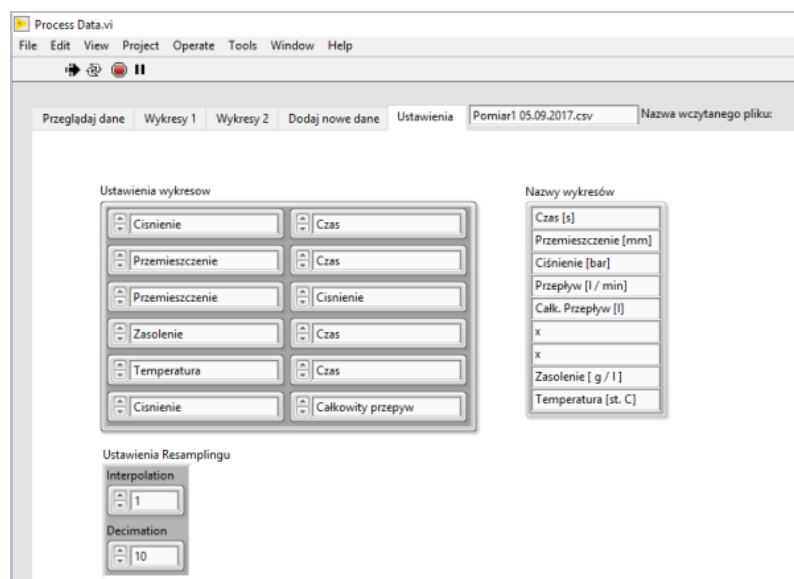
Fig. 11. A view of the data loading

Fig. 12. A view of settings window

5. Results

The main goals of research carried out were:
- Validation of the thesis that periodic salt sidewalls leaching, supported with coarse grained porous material is possible and allows to regulate (reduce) loads acting on the shaft lining.
- Initial research on processes occurring during salt side walls leaching and an impact of load reduction on the shaft lining.

It was observed during tests that on the contact between the salt sample and aggregate a salt tenon (bridge) is developed. Its shape is truncated cone or pyramid like, dependent on the process of the test. Moreover, an influence of the contact area between the salt and aggregate on the salt bridge

development was observed. Thus an attempt to simulate different conditions of contact between the salt sample and aggregate was undertaken.

Conducted tests allowed to obtain formulas describing a process of salt tenon development. These formulas are presented below.

$$a = -0.0232 * \sqrt{t} + T + 0.0456 + U \tag{1}$$

where:
a – percentage salt tenon surface, %,
t – time, s,
T – temperature, °C,
U – flow discharge, dm3/min.

Preceding formula was adapted to measurements, thus in time T=0, 100% is not always obtained. This relationship presents general tendencies with respect to temperature and flow discharge, and it indicates approximate time of growth of the salt tenon of a specizied area.

In result of formula (1) transformation, leching time to achieve critical surface $A_{critical}$ was obtained:

$$t = \left(\frac{0.0376*T+0.0456*U-a}{0.0232} \right) \tag{2}$$

where:

$$a = \frac{A_{critical}}{A_{wall}} \tag{3}$$

$A_{critical}$ – critical surface, mm^2,
A_{wall} – salt wall surface, mm^2.

The ultimate relationship is as follows:

$$P = \frac{h_S}{v_{wall}} \tag{4}$$

where:
h_S – salt tenon height, mm,
v_{wall} – side wall advance rate, mm/day.

Factor P informs about the time (in days) needed to create salt tenons of critical surface, which are then destroyed with rate adapted to the side wall relocation. Leaching time is calculated from former equation (2).

On a basis of the salt tenon height, block wall flushing rate was determined. Similary to the previous case, linear regression was applied. Salt rock leaching rate was assumed as constant and it was expressed as a ratio of the flushed salt height and its leaching time. Explanatory variables comprised flow discharge in litres per minute and temperature. It was observed that salt is also flushed out from the frontal tenon surface on the salt block contact with the obstacle. Height of the leached salt was is about 20%.

Accordingly empirical formula for the salt wall leaching rate was combined with leaching time formula, which allows to determine dissolved salt height H [mm]:

$$H = V_{leaching} * t \tag{5}$$

where:

$$V_{leaching} = 0.66 * t + 2,15U + 89.42 \tag{6}$$

6. Conclusions

The issue of the stability of mine workings located in salt rock deposit was analysed and presented in numerous publications by different authors and researchers in many countries all over the world [7-11].

Further development of copper mines of KGHM Polska Miedź SA, located on the Pre Sudetic Monocline and advance of mining areas to the north requires development of new vertical and horizontal workings, including mine shafts which sections are to be located in salt rock mass. In order to provide proper level of safety of the mine and staff working underground, it is necessary to ensure sufficient stability of mine shafts for the period of few decades and proper geometry of the shaft furniture to provide safe and fast transport with conveyances.

Further research carried out to solve this problem has lead, among other solutions, to project of the new shaft lining construction and method of regulation of loads acting on it, presented in [17-19]. To verify assumptions on which described construction of the shaft lining is based, it was necessary to design a test facility of special construction, briefly presented in this work and described in details in [18-19]. This research required also software, which had to be designed and developed especially for this purpose, because of lack of suitable programmes available on the market.

Software designed for purpose of this project was developed in LabVIEW environment and it consists of two application, of which one is used for data acquisition during investigations using test facility and another is responsible for processing of this data. The application cooperating with measuring devices is based on Event-Driven Queued State Machine pattern and allows full control of test facility elements and convenient near real time data acquisition using clear and convenient graphical user interface.

Similarly, for purpose of processing of gathered data, another application was developed using LabVIEW environment. It was based on Producer-Consumer pattern. It provides convenient data processing and analysis.

Analysis of gathered data allowed to describe behaviour of salt rock mass acting on the design shaft lining and process of salt leaching, which is an inherent element of proposed solution. Laboratory research with use of custom designed test facility showed promising results [18], which indicates a possibility of application of the designed lining in the mine shaft. However, it has to be verified in the real life conditions.

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