Chapter

Optimization Directions for Monitoring of Ground Freezing Process for Grzegorz Shaft Sinking

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Abstract

Grzegorz shaft is the first mine shaft sunk in 21st century in Silesian Coal Basin in USA of ground freezing method. Work carried out by Shaft Sinking Company (PBSz S.A.) is characterized by high level of innovativeness. Geophysical measurements were conducted to find directions of optimization of ground freezing process and its monitoring. Data gathered during research is a starting point for finding directions of optimization of particular fields during Grzegorz shaft sinking, as well as to be used in future similar ventures. Proposed solutions might have bring real improvements for safety and effectiveness of work and also for economic factors. Conducted tests and analysis aim at improvement of monitoring of shape, size and quality of frozen rock mass column in a safe and reliable manner.

Keywords: mine shaft, ground freezing, mine safety, geophysics measurements, monitoring methods in mining and civil engineering

1. Introduction. Grzegorz shaft: The first shaft in Silesian Coal Basin sunk using ground freezing method in 21st century

Grzegorz shaft is one of the biggest today's projects in Polish mining industry. Difficult conditions in its geological cross-section forced application of special shaft sinking method, which is ground freezing. This method was in common use in Silesian Coal Basin back in the days, but nowadays it is rarely used, mostly because of a small number of new shafts sunk. This venture was entrusted to Shaft Sinking Company (PBSz S.A.), part of the JSW Group and a leader of highly specialized mining services market in Poland. Company has got 75 years of experience in shaft sinking, including projects in extremely hard conditions, as well as in use of ground freezing method [1].

Application of typical shaft sinking method in case of Grzegorz shaft is impossible because of high rock mass' water accumulation and rock's low soaking resilience. Utilization of different methods, such as rock mass drainage and grouting, were analyzed, but expected low effectiveness effected in their abandonment. As the most effective, safe and reliable, ground freezing method was chosen for purpose of Grzegorz shaft sinking. Its essence is creating a column of frozen ground and it is realized by pumping freezing medium to boreholes. Mine shaft is sunk in such prepared rock mass using traditional methods, such as drill sand blasts. Column of frozen soils and rocks prevents shaft heading from flooding. It can also play a role of sidewall's support, as frozen rocks and soils are characterized by higher strength than those in natural state. Principles of ground freezing method and solution used for Grzegorz shaft sinking was described in details in following sections [1–3].

Grzegorz shaft was designed as a downcast, man and material shaft. Its inner cross-section is circle with a diameter of 7,5 m. Ordinate of surface level is +258,0 m and its depth is 870,0 m [3].

Shaft sinking is a huge and complicated venture, especially in terms of difficult geological conditions. However, Grzegorz shaft sinking is characterized by high level of innovativeness. One of the biggest innovations is application of the same head frame for both processes of sinking and regular operation of Grzegorz shaft. It is a first such case in Polish coal mining. Up to now, every mine shaft in Polish collieries was sunk using head frame of special construction, which were then disassembled and final head frame was built. But innovative way of thinking applies also to other areas of design and construction of Grzegorz shaft. Geophysical survey was conducted to determine new directions of optimization for processes of shaft sinking in a frozen rock mass and monitoring of ground freezing process [3].

2. Ground freezing method

The essence of special method of shaft sinking, which is ground freezing method is freezing of aquifers and then shaft sinking in frozen rock mass, using traditional methods, such as drills and blasts. It was primarily used in 1862 in England. Rock mass was frozen by freezing medium flow through a spiral pipe placed on a surface of quicksand's layer. In 1883 in Archibald mine, located near Schneidlingen, rock mass was frozen using technology similar to the one used nowadays. In Siberia's gold mines in 1940's shaft sinking method utilizing natural ground freezing was commonly used. It was then neglected, because of low effectiveness [4].

Low temperatures needed for freezing of soils and rocks around sunk shaft are obtained by heat of freezing medium transition from liquid to gas. The most common freezing medium is ammonia NH_3. Freezing boreholes are drilled around contour of the shaft. Distance between them is 0,9 to 1,2 m. They are equipped with casing pipe, so called freezing pipes, with diameter between 100 and 160 mm and pipes with diameter of 25–45 mm inside the freezing pipes. They are called inlet or inflow pipes, and are shorter than borehole depth (pipe do not reach borehole's bottom). Freezing medium is brought to a freezing ring on the surface, where it is distributed to freezing boreholes. It is then pumped into the boreholes through inflow pipes. Freezing medium flows between casing and inlet pipes, cooling rocks and soils via conduction. Constant rock mass cooling leads to freezing of water inside soils and rocks. Column of frozen ground develops around the freezing borehole. Such columns around numerous boreholes combine with each other, which effects in development of one cylinder of frozen ground around the outline of the shaft. This column of frozen soils and rocks prevents shaft heading from flooding and resists pressure of water and rock mass [4–11].

Various liquids can be pumped into freezing boreholes, such as aqueous solutions of calcium, sodium or magnesium chloride. All of them are characterized by low freezing temperature. The role of refrigerant is heat carrying, transferring it from rock mass to evaporator. It flows through freezing pipes in boreholes, collector and evaporator, where it is cooled down [4].

Strength of frozen rock or soil is higher than in natural state. The highest compressive strength characterizes frozen gravel and coarse-grained sand. Fine-grained sands and clays have lower compressive strength. Strength of frozen ground is also dependent on ice strength, which is related to ice grains' size and freezing time.

As rule of thumb, the faster freezing process the higher ice strength. Time of freezing depends on conductivity of casing pipes, freezing installation effectiveness and amount of heat to transfer [4–7].

Project of ground freezing has to be preceded by precise geological and hydrogeological measurements in the vicinity of designed shaft. In particular, it is important to identify hydrogeological conditions, such as number of aquifers, their depth and range, water pressure and its chemism [4, 8].

3. Geological conditions

3.1 Geological structure

Hydrogeological, geological and engineering conditions were determined on basis of data collected from boreholes G-8 and G-8bis, drilled specifically for this purpose. Stratigraphic profile in axis of the designed Grzegorz shaft consists of:

- **Quaternary formations** between 0,00 and 40,43 m – layers of sands, clay and aggregate;
- **Tertiary formations** between 40,43 and 114,43 m – layers of slit, clay, aggregate, claystone and limestone;
- **Triassic formations** between 114,3 and 234,93 m – layers of dolomite, limestone, clay, sandstone and mudstone;
- **Carboniferous formations** below 234,93 m – layers of sandstone, claystone and hard coal.

3.2 Hydrogeological conditions

Four aquifers with sixteen water bearing horizons are located in Grzegorz shaft profile. In quaternary formations there are two water bearing horizons, both with confined water table. It is fed by rainwater. Reservoir rocks are clays, sands and aggregates. Tertiary aquifer consists of single water bearing horizon with confined water table. It is also fed by rainwater. Reservoir rock is a limestone. Three water bearing horizons occur in Triassic aquifer, all of them with confined water table, also fed by rainwater. Reservoir rocks are dolomite, limestone, mudstone and sandstone. There are ten water bearing horizons in Carboniferous aquifer. Reservoir rock for all of them is sandstone. All horizons are also characterized by confined water table. There are fed by water infiltrating from upper stratigraphic layers.

Estimated water infiltration to the shaft heading from different aquifers varies between 0,057 to 0,926 m^3/min. Total expected water supply is equal 5,957 m^3/min.

3.3 Engineering conditions

According to observations made during drilling G-8bis borehole and laboratory tests of core sample there are seven different geotechnical zones, characterized with different geotechnical parameters.

It was found that there are extremely difficult geological conditions in zones I, III, V and VI, caused by low soaking resilience of rocks and high accumulation of water. Shaft sinking in such conditions is impossible without utilization of special methods, because there is a real threat of problems with sidewalls' stability.

Occurrence of these geotechnical zones enforced utilization of ground freezing method for Grzegorz shaft sinking.

4. Freezing installation and boreholes' construction

4.1 Freezing installation

Freezing installation consists of refrigeration plant (primary system) and secondary system and it is suited for cooling calcium chloride aqueous solution to −35°C [1, 3].

Primary system includes three freezing units, so called chillers PAC SAB 283 E eco, which freezing medium is ammonia. They are cooled by cooling towers Evapco AT 18-3 M14. Refrigeration plant consist also of isolated pipes for brine transfer, brine tank, discharge tank, water treatment station, eight pumps and armature. Model of refrigeration plant is presented on **Figure 1**.

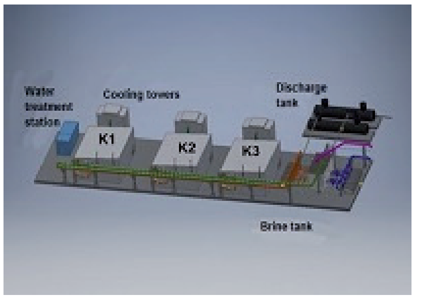

Figure 1.
Refrigeration plant [3].

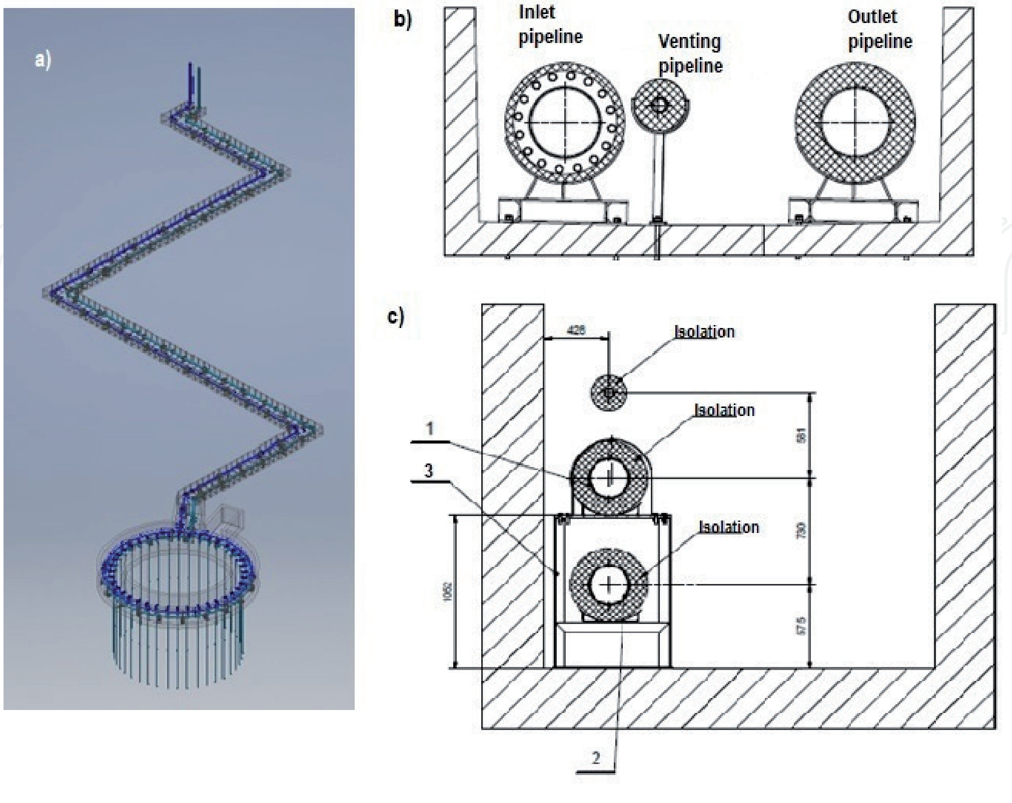

Figure 2.
Freezing channel [3]. a) Freezing channel model, b) cross-section of freezing channel between refrigeration plant and shaft; c) freezing channel around the shaft; 1: Inlet pipeline, 2: Outlet pipeline, 3: Rack.

Secondary system is basically a channel used to transfer coolant from refrigeration plant to freezing boreholes. The channel consists of two main parts, one of them is a circle channel around the shaft outline (containing freezing ring), the other one is a channel between freezing ring and refrigeration plant.

Freezing channel contains two pipelines with diameter of 350 mm – inlet and outlet pipelines and one venting pipeline with diameter of 65 mm. Around the shaft outline, pipelines are circle-shaped and form so-called freezing ring. Freezing boreholes' pipes are connected directly to the freezing ring. Model of secondary system of freezing installation and cross-sections of channels are shown on **Figure 2**.

4.2 Freezing boreholes

For purpose of Grzegorz shaft sinking, 40 freezing and 3 control boreholes were designed and drilled. They are marked with numbers from M1 to M40 (freezing boreholes) and from T1 to T3 (control boreholes; one of them is previously drilled borehole G-8bis). Control boreholes are located on common axis, out of the freezing boreholes' circle. Their task is to inspect shape and size of frozen ground column. Depth of all boreholes is equal 485 m (bottom 10 meters are filled with concrete) [12].

Distance between freezing boreholes varies in practice between 0,9 and 1,3 m. It is determined according to:

- required size of frozen ground cylinder,
- economic factors,
- time required.

In case of Grzegorz shaft sinking distance between freezing boreholes was calculated at about 1,25 m. Parameters of freezing boreholes are presented in **Table 1**.

Construction of freezing boreholes:

- 0–2,0 m – lining pipe Ø508 mm (20″)
- 2,0–40,0 m – borehole's diameter Ø311 mm – 12 1/4″ (rotary drill bit Ø311 mm)
- 40–485 m – borehole's diameter Ø216 mm – 8 1/2″ (rotary drill bit Ø216 mm)

Figure 3 presents arrangement of freezing and control boreholes and Grzegorz shaft's cross-section. Description of shaft's elements represents state of construction at the moment of beginning of drilling.

No.	Parameter	Value
1.	Number of freezing boreholes	40 pcs
2.	Distance between boerholes	1,25 m
3.	Diameter of freezing boreholes circle	16 m
4.	Depth of freezing boreholes	485 m (including 10 m of concrete)
5.	Casing pipes diameter	Ø139,7 mm × 8,0 mm
6.	Inflow pipes diameter	Ø75,0 × 4,5 mm
7.	Refrigerant	$CaCl_2$ aqueous solution

Table 1.
Parameters of freezing boreholes.

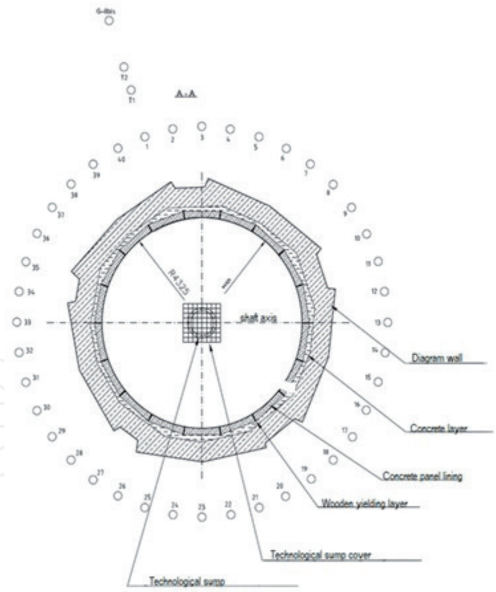

Figure 3.
Arrangement of freezing and control boreholes and cross-section of Grzegorz shaft [1].

5. Geophysical measurements

Monitoring of phenomena occurring in frozen rock mass is crucial for safety of the whole process of shaft sinking using ground freezing method. It is not an easy task, though. Number of geophysical measurements were conducted on Grzegorz shaft's construction plant in order to optimize process of ground freezing and monitoring of frozen rock mass. On a basis of gathered data, practical aspects of presented methods were analyzed.

Potential measuring methods assumed possible to use for Grzegorz shaft monitoring were [13]:

- vertical seismic profiling,
- transmission tomography,
- seismic interferometry,
- surface wave analysis,
- reflection seismology.

Surface waves analysis allows estimation of velocity of transverse wave behind the shaft lining, within few meters. Utilization of reflection seismology helps to anticipate geological faults and some of the parameters of rock mass. Especially prior recognition of faults plays critical role in safety of miners working in the shaft's heading, as well as for economic factors. Application of proposed methods has to be carefully considered and tested in real-life condition. Unfortunately, it was impossible, because of the small depth (20 meters) of Grzegorz shaft during measurement session. Initial assumptions involve utilization of geophones in short distance from shaft's heading [13].

An objective of tomography test is estimation of 2D wave velocity field between adjacent boreholes. Tests were carried out using vibration source of special construction, made especially for purpose of these tests. This device is presented on **Figure 4**. Two tests were made, first of them with utilization of probe consisting of

Figure 4.
A view of vibration source prototype.

four hydrophones with own frequency of 500 Hz and another one with using two probes equipped with three hydrophones with own frequency of 100 Hz [13].

The results obtained prove that monitoring of the frozen rock mass column using probes and vibration source is possible. High financial expenditures needed for vibration source construction (prototype used for tests is suited for use in control boreholes, final vibration source for use in freezing boreholes has to be constructed) and problematic technology of testing caused neglecting of further development of such solution [13].

Utilization of scattered waves allows monitoring of deformational phenomena occurring in rock mass. The appearance of cracks, rifts and microfractures affects velocity of wave propagation and its amplitude. What is even more important in case of ground freezing is high sensitivity of coda wave velocity for (even small) temperature changes in rock mass [13–16].

Utilization of seismic interferometry was proposed for purpose of monitoring of phenomena occurring in frozen rock mass caused by temperature changes in the vicinity of the Grzegorz shaft. Sources of seismic noise, which is needed for such measurements, are operating freezing boreholes. This method of monitoring provides near real-time information.

Tests were conducted to prove correctness of initial assumptions. Measurements were carried out using two probes consisting of three hydrophones with own frequency of 100 Hz each. **Figure 5** presents 5-minute record of seismic noise. Channels 0, 1 and 2 represent hydrophones located in control borehole T2, channels 3, 4 and 5 represent hydrophones used in borehole T1, located closer to freezing boreholes. High amplitude values about 13:02 are caused by tests of vibration source used in the tomography measurements.

From the practical point of view, the most relevant is the period of stationary seismic noise. It is probably an effect of freezing boreholes operation and its frequency varies between 10 and 200 Hz **Figure 6**. Presents record and spectrogram of channel 0. Spectrogram's scale upper limit is 300 Hz.

On the basis of scattered wave interferometry correlation functions, representing estimated scattered wave propagation between hydrophones, were obtained. Further tests and analysis are required for purpose of utilization of this method for real life application, including tests covering long time period of measurement.

To sum up, coda wave interferometry method can be used in practice, for monitoring of ground freezing process and become convenient and reliable monitoring method. High sensitivity for temperature changes can prevent potential unexpected failures, which are real threat for miners working in the shaft heading and for shaft

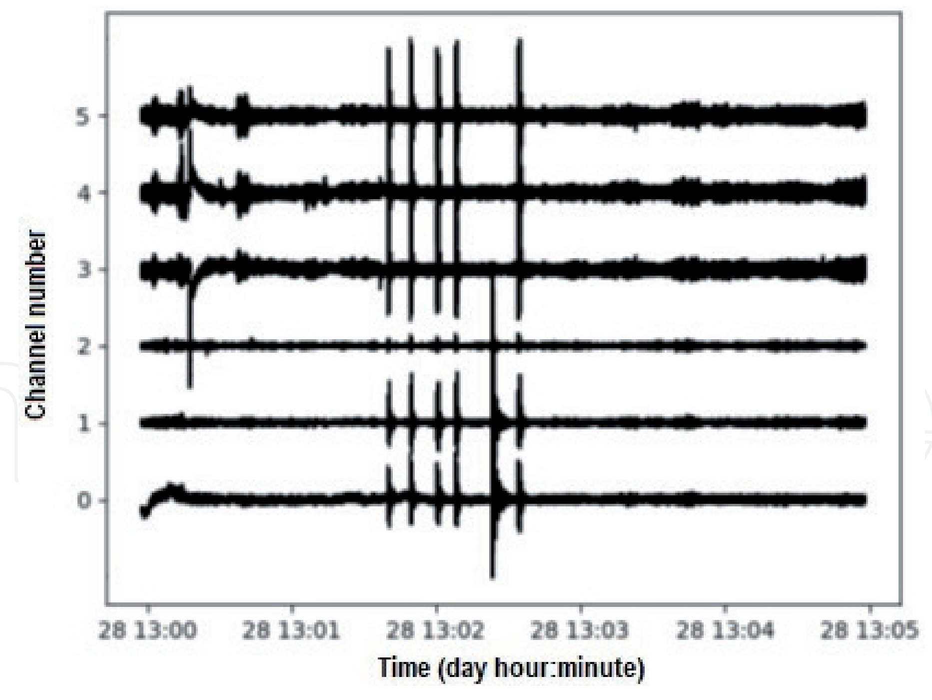

Figure 5.
Example of seismic noise record.

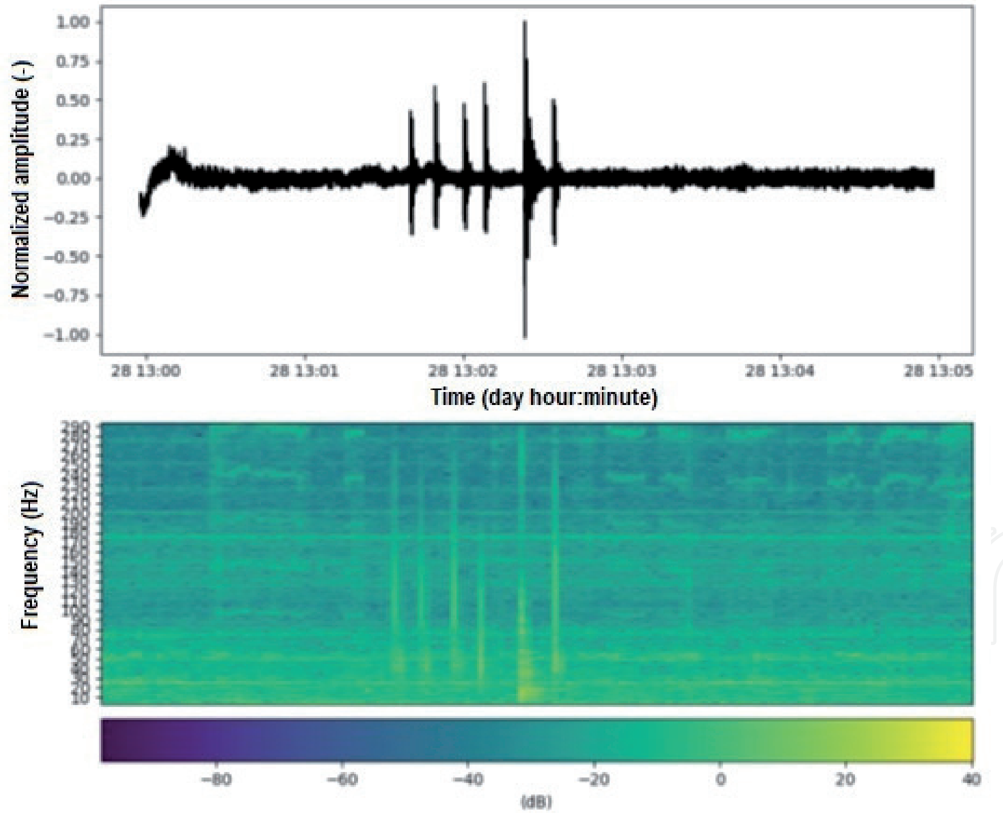

Figure 6.
Record and spectrogram of channel 0.

itself. However, this method has to be tested in long period tests, spanning for several days, as well as in situation of controlled stoppage of operation of freezing borehole, to check if the monitoring system work well in hazardous situation [13].

The most promising data was obtained in a test of vertical seismic profiling. Tests were conducted using device with parameters presented in **Table 2**. The source of seismic wave was generated on the surface in the near vicinity of a borehole by a 5 kg sledgehammer [13, 17, 18].

Seismograph	**Geode 24CH Geometrics**
Probe	4 hydrophones with own frequency of 500 Hz
Distance between hydrophones	0,2 m
Measuring step	0,6 m
Amount of hits	1 for each probe position (each 0,6 m)
Record time	0,5 s
Frequency	4000 Hz
Depth	0–200 m

Table 2.
Parameters of seismic profiling record [13].

Figure 7 presents results of seismic record initial analysis for single measurement in the borehole T1. Traces were filtered in frequency range between 150 and 800 Hz and normalized to common average. Regular amplitudes, effecting from wave propagation, can be observed in the figure.

Basing on data obtained from profiling boreholes T1, T2 and T3, a collective map of wave velocity distribution was computed. It is limited to a depth where data obtained is characterized by high quality. Resulting map is shown in **Figure 8**.

There is a relationship between temperature (data collected at the beginning of ground freezing process), presented in **Figure 9**, and velocity distribution, shown in **Figure 10**. Data obtained from borehole T1 was chosen for presentation, because of the shortest distance to freezing boreholes.

Temperature and wave velocity were also compared on one graph, presented in **Figure 11**. Relationship between them was estimated.

Non-linear, polynomial function with constant parameters was obtained. Function was suited with high correlation factor, equal 0,82. It is clear that there is a relationship between temperature and velocity.

Consequently, graphical correlation of frozen rock mass column development, temperature curve and map of velocity distribution was prepared. It is shown in **Figure 12**. Blue sections represent temperature and velocity drops, red color indicates temperature and velocity rises. Relationship is clear [13].

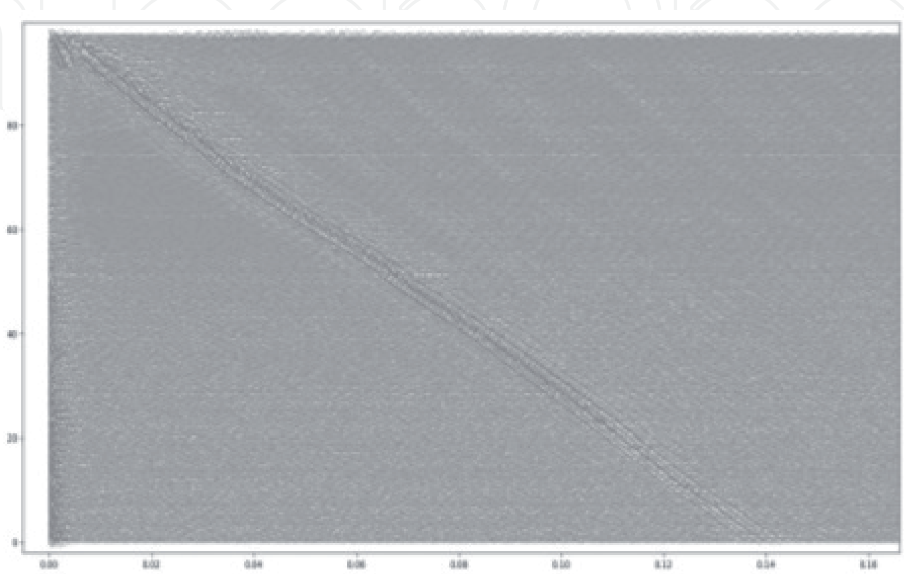

Figure 7.
Example of seismic record in the borehole T1; vertical axis – Numbers of traces, horizontal axis – Time in ms.

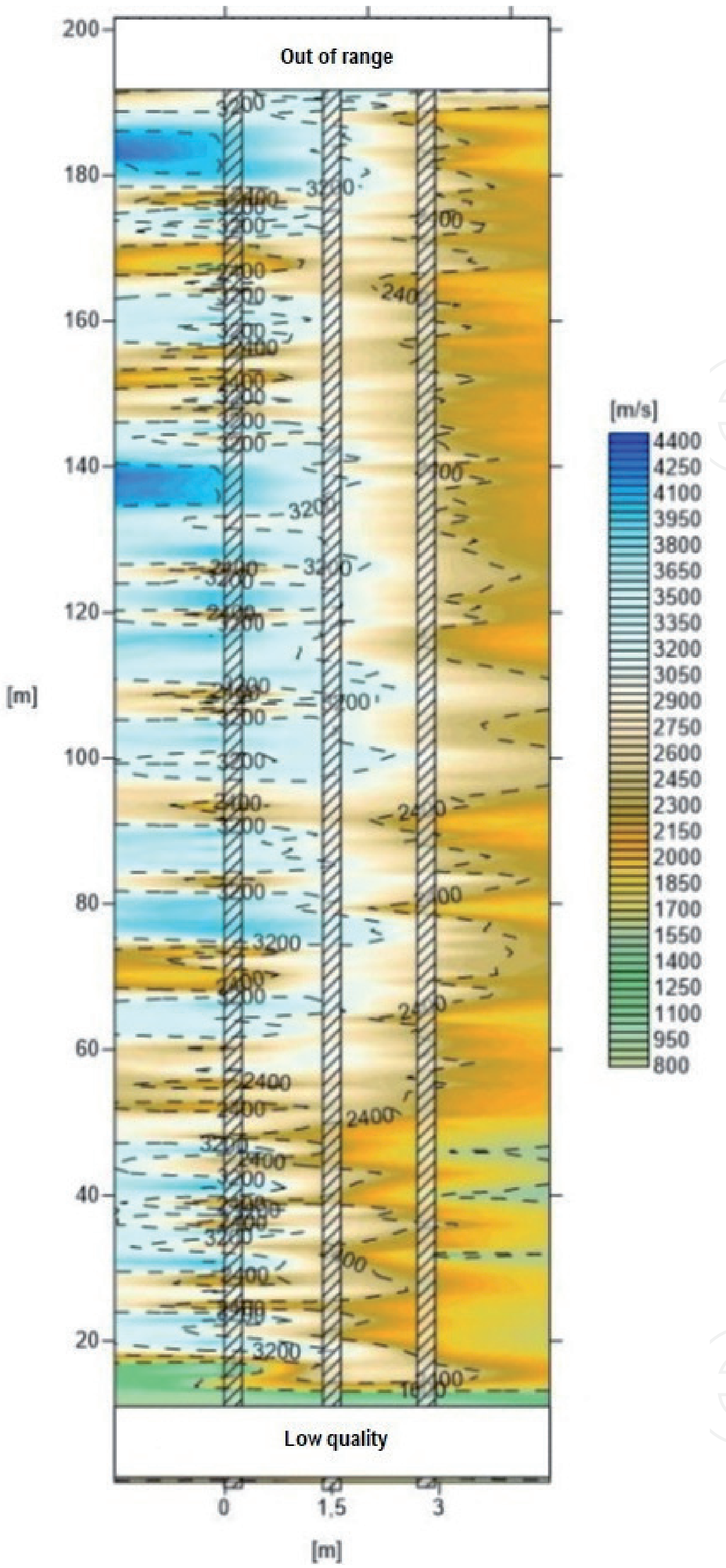

Figure 8.
Map of wave velocity distribution.

1,5 months after test described above, another measurements were carried out, within the stage II of the research. Another map of velocity distribution was made. This map, together with the previous one (**Figure 9**) are presented in the **Figure 13** [18].

On the basis of conducted research, conclusions were made [13, 18]:

- there is a clear relationship between frozen rock mass temperature changes and wave velocity measured. Ground-freezing process monitoring can be conducted using seismic methods.

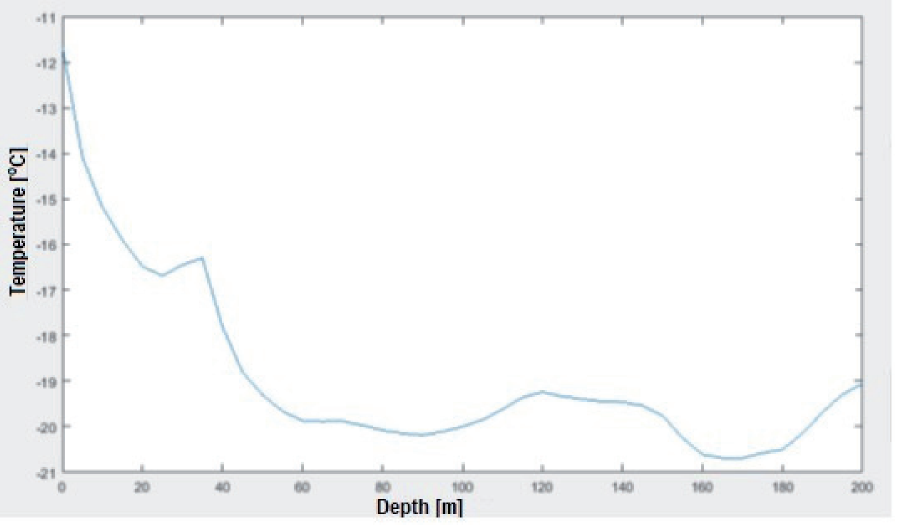

Figure 9.
Temperature in the borehole T1.

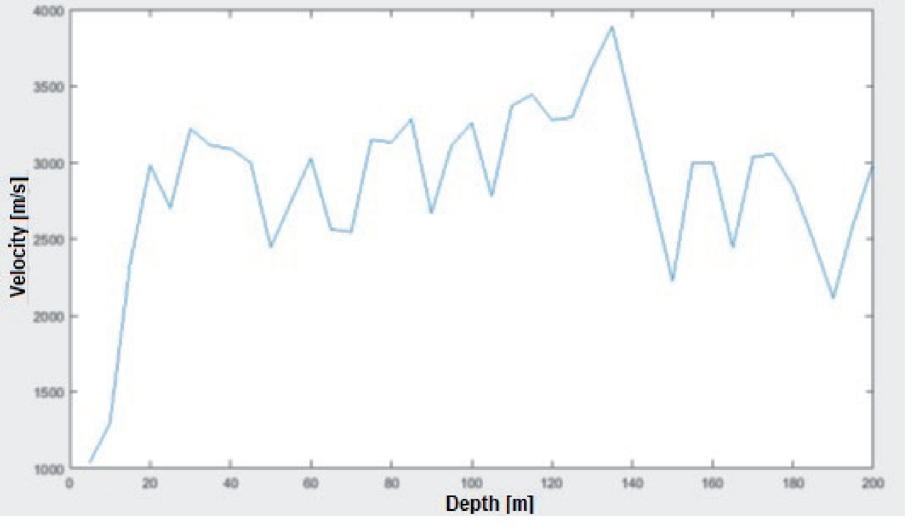

Figure 10.
Velocity in the borehole T1.

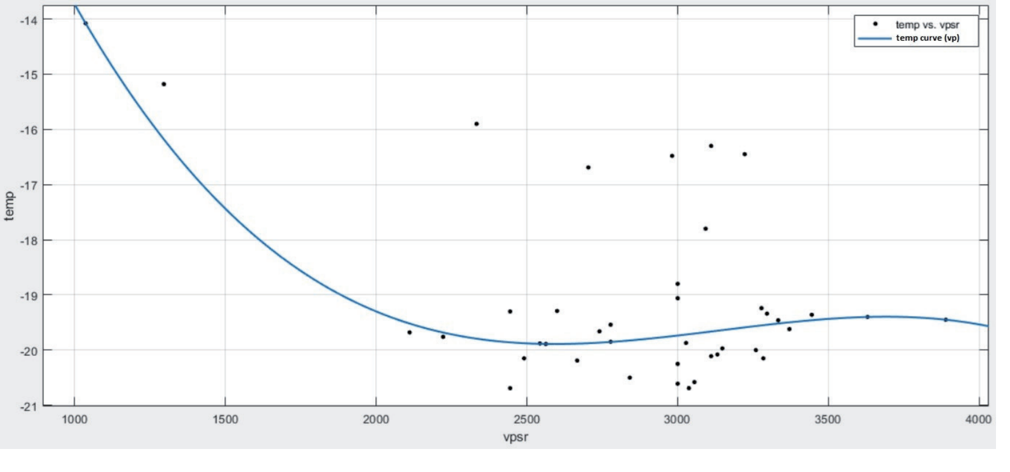

Figure 11.
Relationship between temperature and velocity.

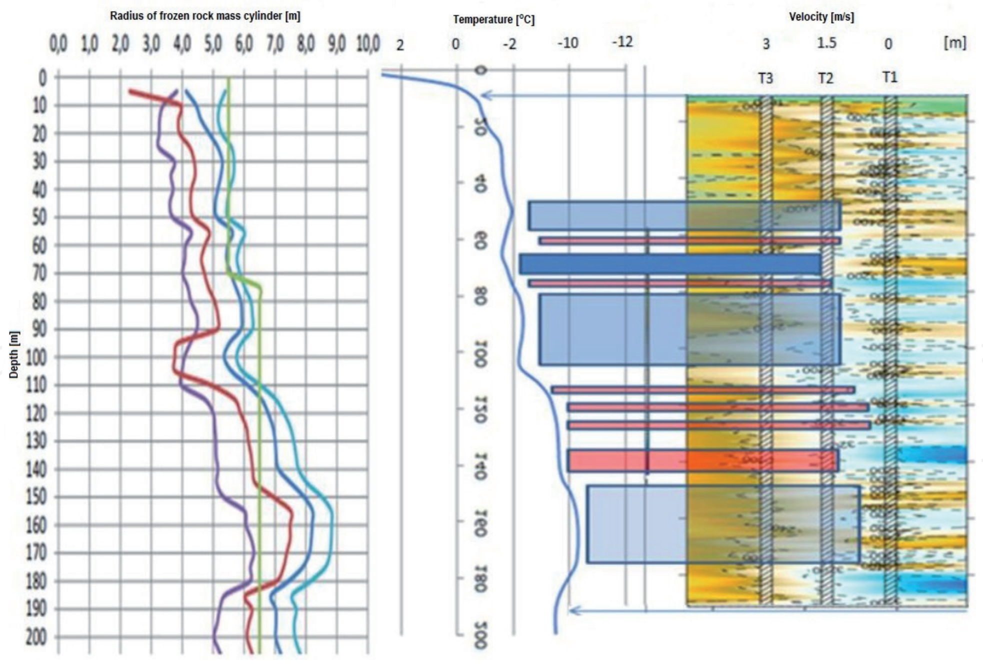

Figure 12.
Graphical correlation between velocity distribution, temperature and frozen rock mass cylinder shape.

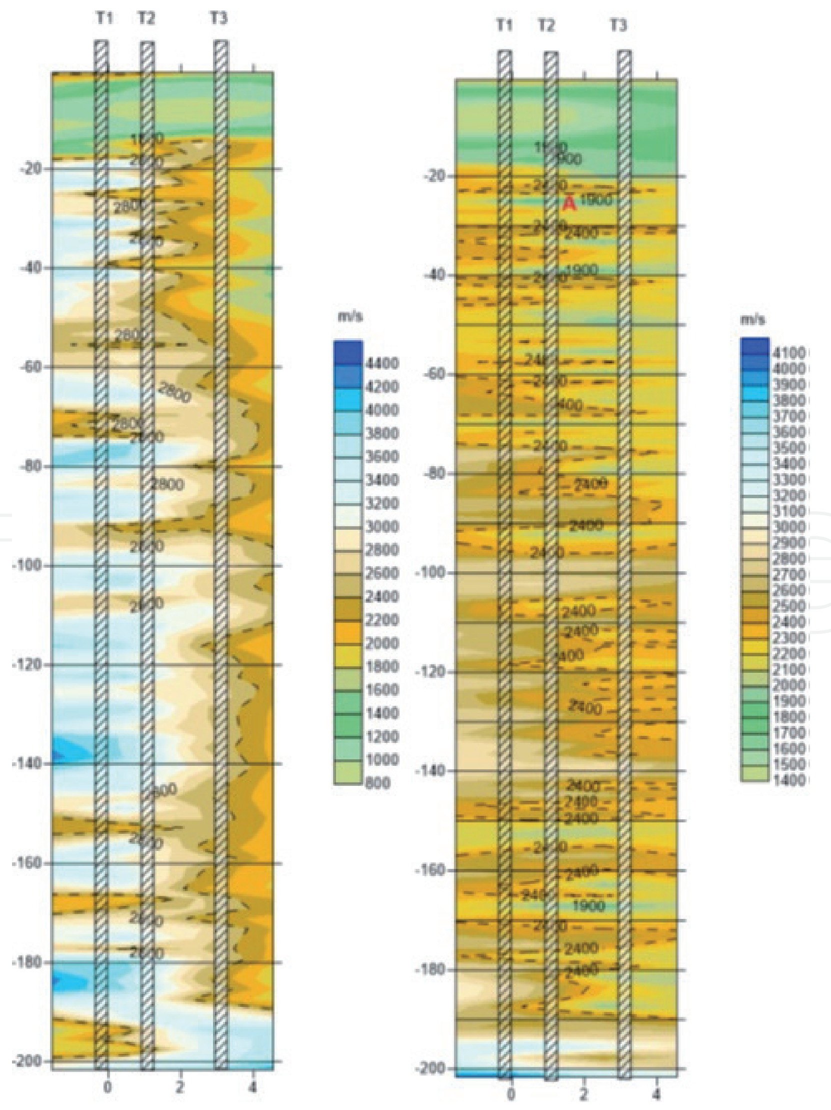

Figure 13.
Maps of velocity distribution.

- development of frozen rock mass column is correlated with velocity. It is in stronger relationship with velocity than just temperature, because temperature value only does not give complete information about geomechanical state of rock mass.

- relative temperature and velocity changes are complementary. Their correlation might have an impact on rock mass imaging state.

6. Summary

Number of seismic methods can be used for measurements of frozen rock mass parameters, such as frozen ground cylinder shape and size during shaft sinking. However, some of them might be too expensive or problematic in use, not effective enough, etc. Important factor is also time needed for measurements.

Different methods were proposed for the purpose of frozen rock mass column monitoring during Grzegorz shaft sinking. Scattered waves interferometry and vertical seismic profiling were assumed the most convenient.

Seismic interferometry method is favorable because of possibility of conducting near real-time monitoring. High sensitivity for temperature changes can provide accurate indication of failures in freezing installation operation. However, technology of such measurements needs further research, spanning for a long time and covering controlled stoppage of freezing installation operation. Financial aspect of this kind of technology is also an issue to consider.

Vertical seismic profiling provides information about shape and size of frozen ground column. Constant measure is impossible, but periodic measurements might find application, because of possibility of determination of shape of frozen rock mass cylinder for tens of meters forward the shaft heading. Therefore, it helps to forecast potential hazards before the beginning of successive sinking stages. Similar to seismic interferometry method, vertical seismic profiling needs further development and analysis of economic factors. However, this method is considered prospective.

To sum up, geophysical methods of frozen ground column monitoring are prospective direction of research. Technological aspects of these methods should be analyzed and developed to make them economically reasonable.

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Conflict of interest

The author declares no conflict of interests.

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