APPLICATION OF LASER SCANNERS TO DETERMINE THE SHAPE OF MINE EXCAVATIONS FOR SAFETY ASSESSMENT, USING THE EXAMPLE OF THE CROSS-CUT MINA IN THE SALT MINE WIELICZKA

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1. INTRODUCTION

Mining excavations in salt strata come under impacts of the salt medium, the voids being slowly but incessantly clenched, which is known as convergence. Salt strata, referred to as elastic-plastic in geomechanics, display high resistance to deformations caused by mining activities. That is associated with rheological properties of the medium which cause that the clenching process might last even several hundred years. Average yearly deformation values range from several to nearly one hundred millimetres and is related to the drifting time and the actual depth of the excavation. However, this resistance becomes weaker when in contact with salt water disturbing the gypsum-clay cleading containing up to 95% of clays, in an uncontrollable manner. This situation is illustrated in Fig. 1., showing the face sections of the "Mina" excavation driven outside the cleading. The gypsum cap-rock in the Wieliczka rock strata separates the salt deposits in the north from the Chodenice sandstones and water-bearing features, thus protecting the salt rock from the inflow of water. Such inflow of water might cause the salt rocks to be dissolved and cease to support the mining excavations. Relevant control measures have to be put in place and the inflows of water have to be carefully monitored and duly handled. Furthermore, the convergence rates have to be measured by all possible methods.

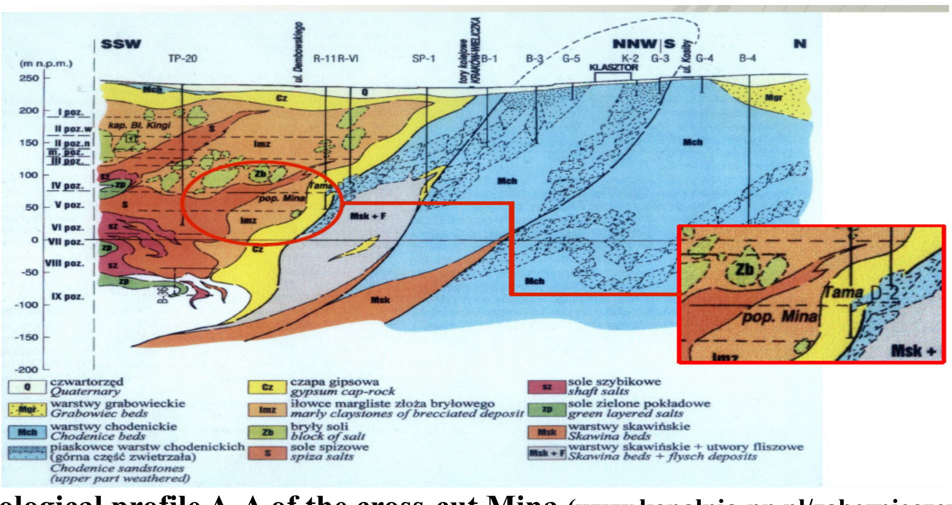

Fig. 1. Geological profile A-A of the cross-cut Mina (www.kopalnia-pp.pl/zabezpieczenie.php).

The methods employed so far included:

- **tensometric methods (stationary convergence meters in the form of tubes, rods, strips or wire, hydraulic cushions (www.minpan.krakow.pl/~chemkop)**
- **geodetic methods (precise levelling, profiling, laser tacheometry, simple measurements using steel tapes), (Szewczyk 2008).**

All methods are constantly modified and improved to make the measurement processes fully automatic, with the remote control capacity. Of major importance, therefore, are tacheometric methods widely applied in surveying and tensometric measurements.

Another method of exploring the voids to determine the level of their deformation in the context of mining safety uses laser scanning systems. This method is now in widespread use in Poland and elsewhere. The Authors quoted the example of the cross-cut "Mina" in the salt Wieliczka to demonstrate the potentials of two types of laser scanners: a 2D scanner fabricated in the Department of Mine Surveying of the Faculty of Geodesy and Environment Engineering AGH-UST (presently the Department of Surface Protection, Geoinformatics and Mine Surveying) and a 3D panoramic scanner, made available by the Scopus Engineering Ltd (Great Britain). Each scanner type serves a different purpose but may support one another to enable their effective use in a wide range of monitoring tasks.

2. CROSS-CUT "MINA"

The heading "Mina', or more specifically: a cross-cut Wilhelmina, lies on the level IV, at the depth of about 130 m underground. It is one of a large number of headings and galleries, the total length of headings driven throughout the ages is estimated to be 200 km. The position of the cross-cut Mina within the geological strata is shown in Fig. 1. Its length approaches 280 m. It was driven in the early 1800s, from the central section of a block of salt, heading in the northern direction. The drifting ended 20 m ahead of the deposit boundary in 1912, thus disturbing the insulating gypsum-clay cleading and exposing water-bearing Chodenice strata (Garlicki et al. 1993; Jackowicz et al. 1994; Szczerbowski, 1996). Leakage from these strata indicated as WIV-27 is located in the front part of the cross-cut.

Mining operations that were continued until 1935 damaged the gypsum-clay rock cap insulating the saline deposit, leading to a minor outflow of water (about 1 l/min) which then caused leaching, suffusion and headward erosion of the rock cap and led to the formation of caverns filled with watery sludge. This outflow continued for a long time and water would seep down to the lower levels in the mine. In 1991 the decision was made to rebuild the cross-cut to handle the water outflow. In 1992 water appeared again, this time seriously flooding the mine. The flow rate was estimated to be 300 dm3/min, though some water streams of 500 dm3/min were reported, too (Stachoń, 2001). Because of a torrent of slime, which soon clogged the water pumps, the historic mine run the risk of disastrous flooding and damage. Luckily, extensive engineering and geotechnical works, injections of the sealing agent and de-watering action continued from the surface did finally bring the flooding under control. However, not only mine excavations and headings were affected. On the surface extensive and discontinuous deformations were registered, revealed as land subsidence, landslide and horizontal displacements, which led to the destruction of railway infrastructure whilst the walls surrounding the historic monastery nearby partly caved in. The danger was that

deformations might extend over vast areas, still enhancing the negative impacts of the flooding. The water outflow was checked when the 30-meter-thick dam was built in the cross-cut to separate the damaged section of the rock-cap from the saline deposit (Fig. 2). In order to keep the water outflow under control, numerous access holes were drilled (up to 100 m in length) to inject the sealing agent. The remaining holes were used for removing water and reducing the water pressure in the surrounding rock strata. The water outflow being stabilised, this de-watering scheme was continued till 2008, as a preventive measure.

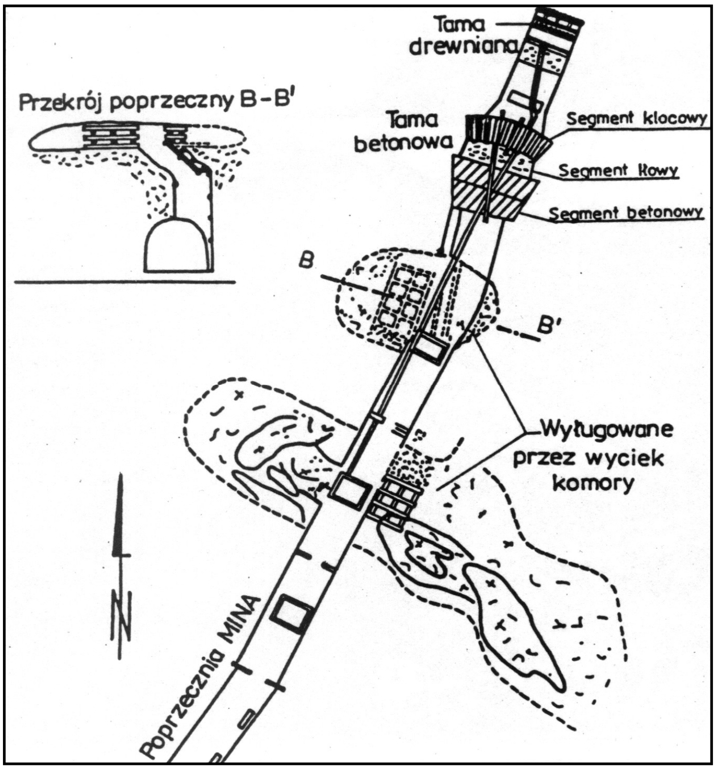

Fig. 2. Sealing dam in the region of water outflow in the cross-cut "Mina" (Maciaszek et al. 1993).

In the last 17 years the flow rate has stabilised on the level of 1.3 dm^3/min, which mining practitioners consider to be normal. It appears, however, that the water contains large amounts of sediments and solid fractions present in the rock strata, which might be indicative of their release. Accordingly, the decision was made to stop the pumping of water, which apparently was coming from other sources than the water-bearing features. This caused the pressure of the water column to increase again to about 15 atm, (this pressure is being monitored on a constant basis), which appears quite normal at the depth of 150 m. However, the risk of the loss of stability of the heading soon became apparent, particularly in the front part of the dam. Hence geodetic measurements were taken, as outlined in this paper, to determine the initial conditions and shapes of the cross-cut. Because of intricate shapes of the mining structures and the number of injection holes and those used for pumping water, conventional geodetic methods would have been tiresome and time-consuming and some crucial details might have been omitted. The Authors chose to use laser scanners because the measurements

are fast and precise and enable a wide range of observations (Fig. 3., 4.). Measurements were taken in collaboration with the Mine Surveying Division. The equipment will be listed in detail in the incoming sections.

Fig. 3. Photo of the same part of the excavation (top) and the scanned image (bottom) of the dam face in the cross-cut Mine in the grey scale in the "intensity' image.

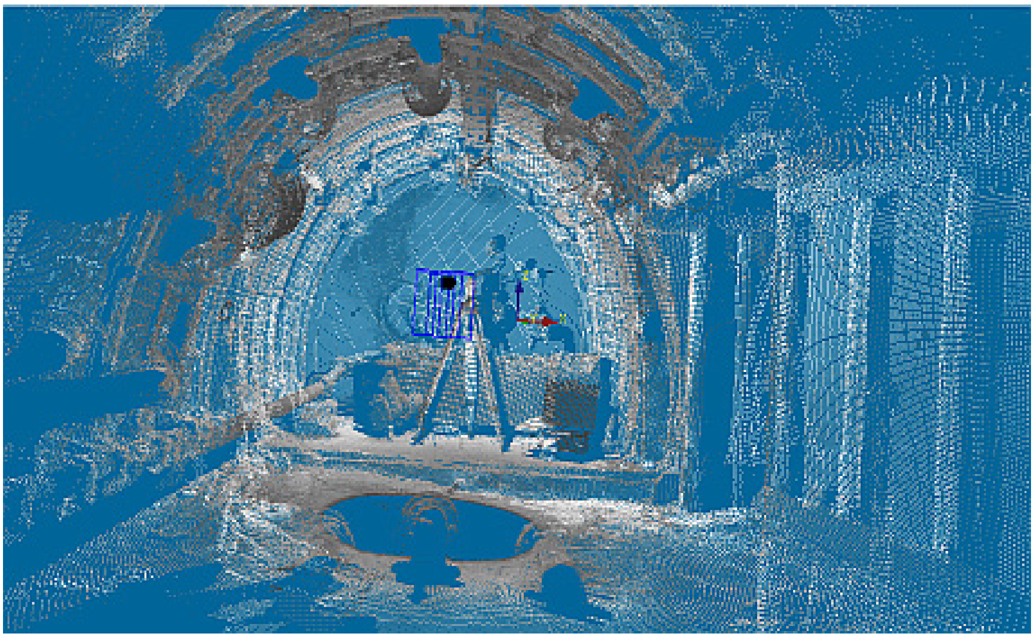

Fig. 4. View of dam face, obtained from the scan in the form of a point cloud in 3D model.

3. MEASURING EQUIPMENT

Recent years have witnessed a major breakthrough in the development of geodetic survey methods thanks to the application of laser scanning systems. The survey program used the 2D scanner DISTO engineered by the Authors, based on DISTO range finder. Actually it is a profile meter enabling measurements to be taken in the horizontal and vertical plane. It is widely used in many surveying applications, permitting us to quickly find the outlines of the control object against the captured sections. The operating principle is explained in more detail elsewhere (Jaśkowski, 2004). In the present study it was used for the purpose of independent verification of measurement data collected using a panoramic 3D scanner (Z&F).

The 3D scanner IMAGER 5006 (Fig. 5.), manufactured by Zoller and Froehlich, was used to asses the condition of the mine heading or excavation . It enables the images to be obtained over the entire range of the horizon and in the full range in the vertical plane (from 25 to 335^g), counting from the nadir point, so that spatial measurements can be easily taken at the distance from 1 to 79 m from the object being captured. The best available resolution is guaranteed: 100000 pixels per second with the nominal distance definition 0.1 m (www.zf-laser.com). The estimated error involved in measurements taken at the distance of 10 m is less than 1 mm, at the distance of 50 m from the control objects the error amounts to 2-8 mm, depending on the degree of signal reflection. Such high quality of distance measurements is achievable thanks to the phase method being used, unlike most systems that employ the impulse method. The phase method, underlying the operation of electro-optical range finders, uses the phase analysis of wave reflected from the control object, followed by the assessment of its fractional value. Application of this method led to development of the most precise 3D scanners currently available on the market (Froehlich, 2004).

The angular resolution in the both planes is given as 0.0018^0, which means that for the distance of 10 m and for the maximal available scanning definition “ultra-high”, the points can be captured every 0.3 m and at the distance 80 m- every 2.5 m. Apparently, thus generated data sets will be huge (about 2GB), hence the “high’ resolution scanning is recommended as satisfactory for most practical applications. The measurement takes less than 7 minutes and points are captured with the resolution 20000 pixels per 360 degree both for Hz and V. That means that at the distance of 10 m, the points in the space being scanned are captured every 3 mm.

A major advantage of the device is its relatively low weight (about 9 kg), which makes it easily portable even in uncomfortable conditions in mine excavations. Another spark-free version IMAGER 5006, is available that is specially designed for operation in mines and can be well used in excavations threatened by methane or coal dust outbursts. During the research program outlined here the Authors used the standard version, which proved fully adequate even in the conditions of the mine.

Fig. 5. IMAGER 5006- general view.

4. MEASUREMENT PROGRAM

In order to determine the initial condition of the cross-cut (free from potential deformations caused by the impacts of water in the rock strata) panoramic scans were to support the special network. The network would yield the coordinates of the target points, enabling thus registered cloud of points to be transformed to the local network system. The minimal number of target points is 3, which is associated with the number of spatial transformation parameters to be determined (rotation matrices, translation and, possibly, scale) , however, we are not able to control how well the model should fit in the geodetic ‘space’. That is why the fitting procedure should use 5 target points, which is justified also from the standpoint of statistical analysis of accuracy assessment. Thus obtained average fitting accuracy approached 5 mm. The model fitting error involves the errors inherent in finding the geodetic coordinates of points as well as point

modelling errors (Akca, 2003). Nevertheless, this accuracy level is sufficient to correctly establish the spatial relationships between arbitrary points of the space being scanned (Fig. 6, 7). The data processing procedure is similar to the development of a photogrametric model, except that the procedure of "model reregistering' or "model fitting into the geodetic system involving one or more scanning stations" will directly yield the metric space in which one easily finds coordinates of an arbitrary visible points and models can be generated in CAD or 3D formats. Several methods of data processing presented below were successfully employed to determine the geometry of the cross-cut "Mina' and to find the geometric relationships between mining structures, drilling equipment and specialised systems monitoring the dam condition.

Fig. 6. Finding the gallery height - measurements on the basis of "intensity' images (LFM Modeller).

Fig. 7. Finding the distance and coordinate increments between control points in the cross-cut- measurements on the basis of “intensity’ images (LFM Modeller).

The dedicated scan processing software (LFM Modeller) enables the sections to be created in the vertical and horizontal plane. Selected interconnected sections, obtained using the model, are shown in Fig. 8.

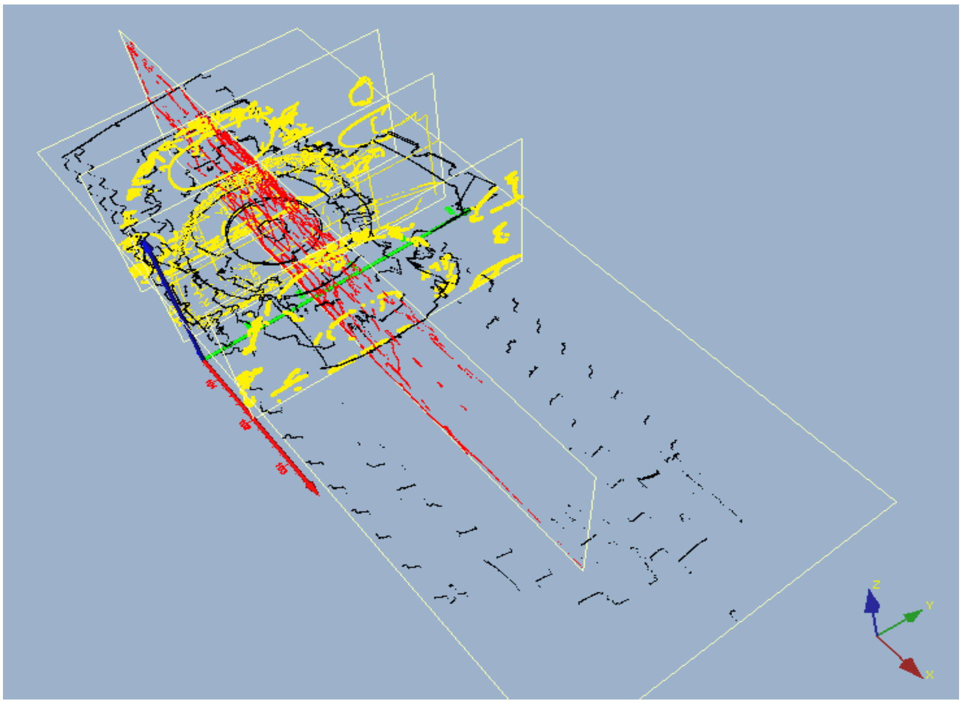

Fig. 8. Interconnected vertical and horizontal sections against the horizontal background.

Measurements taken with the 3D scanner were supported by measurements with a 2D scanner, engineered specifically for the purpose of profiling. Measurement data were utilised to develop independent profiles of the excavation to verify the quality of 2D images obtained from the repeated processing of the point cloud in the 3D model. This comparison is illustrated below (Fig. 9.), showing the outlines of the excavation obtained by the two methods.

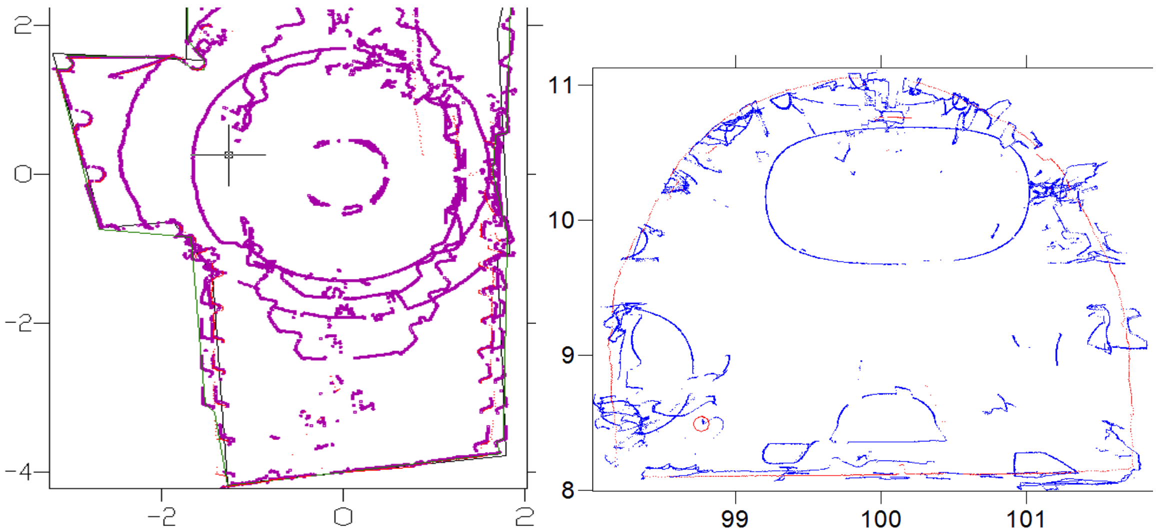

Fig. 9. Comparison of profiles in horizontal and transverse projections obtained from 2D scan profiles and a cloud of points obtained from 3D scanning.

Figure 9 reveals minor discrepancies between the profiles captured by the two methods,

which are attributable to approximate locations of profiles within the excavation. The outline of the excavation is clearer in 2D scans while compared to 3D 'cluster' images. Excess of information in 3D scan profiles is associated with the projection of points onto one plane out of the defined thickness of the intersection plane. This effect can be reduced, however, by generating a spatial model developing an intricate surface based on simple geometric figures. The cloud of measurement points being duly processed (Fig. 4.), a spatial model was generated based on the network of triangles (Ohtake et al. 2005), shown in Fig. 10. The model enables arbitrary visualisation and covering the surfaces with texture, furthermore, the model dimensions can be determined and relevant cross-sections (horizontal, vertical and oblique) developed.

Creating a network of triangles is a major step involved in the development of the spatial model. Wrong parameters can lead to an incomplete model. That is why this stage is typically repeated until the results prove satisfactory. Examples of such optimisation procedure are shown in Fig. 10.

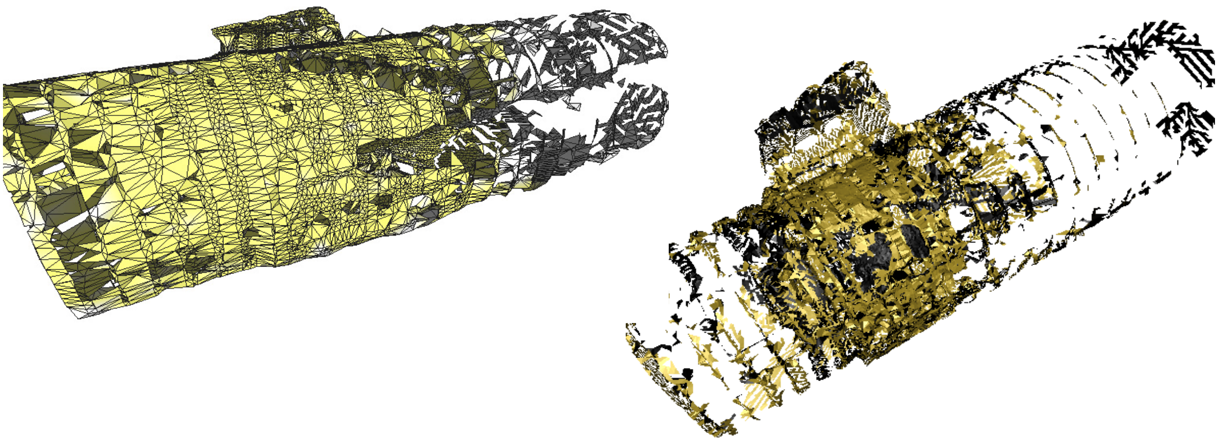

Fig. 10. Spatial models of the cross-cut generated automatically based on the cloud of scanned points.

A well captured spatial object can be further processed graphically to develop the required profiles, arbitrarily oriented. Selected profiles are shown in Fig. 11. It is worthwhile to mention that these are all vector images, scalable, allowing them to be connected to CAD objects in any scale, without any loss of quality. Further processing should yield the dimensions and surface area of the cross-section of the mine excavation or gallery and its total volume (Maciaszek, 2008). Comparison of physical parameters characterising the given excavation in subsequent measurements reveals the progress of deformation to identify the deformation zones.

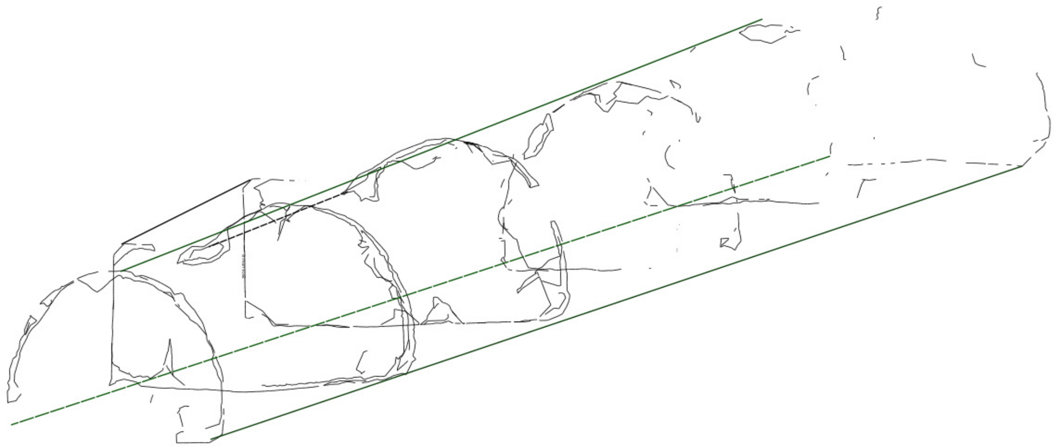

Fig. 11. Cross-sections of the excavation developed basing on the 3D model, intersected by vertical planes every 1.5 m.

Scanning measurements taken in the cross-cut :Mina' were utilised to determine its actual geometry. A post-processing of scan data enables the spatial model to be created which can be visualised and projected in an arbitrary manner and connected to other objects, in the CAD environment. Such models permit us to generate scaled projections onto the given intersection plane to prepare the technical documentation and specifications and to monitor the changes of the cross-cut's shape. The dedicated software supporting the scanner Z&F- LFM Modeller (or Z+F LaserControl) enables the measurements to be taken directly on the model in the local network system. Comparison of measurement data obtained in subsequent cycles reveals the deformations of the excavation, which can be presented in a required graphic form. In the future such observations are going to be repeated in the cross-cut to verify the effects of the increased flooding of the rock strata in the front part of the cross-cut "Mina".

5. CONCLUSIONS

Evaluation of laser scanning systems applied to finding the shapes of mine excavations and galleries confirmed their full adequacy in this type of measurement tasks.
Major advantages of scanning systems applied in mine excavations include:

- **comparability of scans taken at different times, and hence the progress of deformation, without the need to maintain the local network system**
- **the scans yield arbitrarily oriented sections of the given excavation, the coordinates between any characteristic points can be found and any measure between these points can be determined**
- **automatic generation of a spatial model of an object supporting automatic generation of multi-plane sections in various configurations, giving information about the convergence of mine excavations and volume changes**
- **scans can be successfully used in design and implementation tasks. That is of major importance in mine excavations threatened by methane outburst or coal dust hazard, where the welding of steel elements might pose a danger. The spatial image of an excavation being available, the welding jobs can be completed on the surface and ready-made elements and components can be then assembled in the excavations.**

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