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The Impact of the Rock Mass Deformation on Geometric Changes of a Historical Chimney in the Salt Mine of Bochnia

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Abstract. There are many ways of the geometry measurement of slim objects, with the application of geodetic and photogrammetric methods. A modern solution in the diagnostics of slim objects is the application of laser scanning, with the use of a scanner of a scanning total station. The point cloud, obtained from the surface of the scanned object gives the possibility of generating not only information on structural surface deformations, but also facilitates obtaining the data on the geometry of the axis of the building, as a basic indicator of the characteristics of its deformation. The cause of the change in the geometry of slim objects is the impact of many external and internal factors. These objects are located in the areas of working or closed underground mines. They can be impacted by the ground and they can face the results of the convergence of cavities. A specific structure of the salt rock mass causes subsequent convergence of the post-exploitation cavities, which has the influence on the behaviour of the terrain surface and the related objects. The authors analysed the impact of the changes in the rock mass and the surface on the changes of the industrial chimney in the Bochnia Salt Mine.
Key words – rock mass deformations, chimney, salt mine, historical objects.

1 Introduction

Underground mining exploitation is always accompanied by the formation of a subsidence trough, which causes changes in the inclination of the surface and all the objects situated within its range (especially directly over the exploitation). To determine forces affecting buildings, in general, a rigid junction between the constructions on the surface with the ground should be taken into account. This means that the inclination of the construction is, in the value and direction, compliant with the inclination of the formed trough. In fact, the vector of the object's inclination is not compliant with the resultant direction of changes in the inclination of the ground in the vicinity of engineering constructions.

Industrial chimneys are particularly sensitive to external factors. They are affected by static and dynamic burden and this way they are getting continuously deformed. The inclination of a chimney in mining areas is initiated by exploitation, which generates diminishing the compactness of the ground and facilitates the influence of other factors (wind, sun, ground

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heterogeneity). The complexity of the phenomenon and its variability is proved by the examples of the recording of geometric states of many chimneys in Poland, localized in the zones of mining influence. In many cases, the direction of the inclination is determined by the depth of the fundaments of the construction and its localization in the external part of the developing trough. In case of chimneys with deep fundaments and situated on the slope of the developing trough, their axes usually incline in opposite direction than the surface of their foundation. This is caused by the specifics of the development of post-exploitation troughs, where the under-surface layers are subdued to stronger deformations and dislocations than the surface layer making the overburden.

Modern measurement methods of the geometry of slim objects provide the users not only discrete data on the state of the construction (axis geometry), but also multi-point sets defining the state of its surface (structural deformations). Their proper mathematical analysis at the stage of post-processing allows generating discrete or continuous image of the central axis, as the main parameter of the characteristic of the chimney's state. One of such slim constructions, having the status of historical monument, is an industrial chimney in the Salt Mine „Bochnia". In the article the authors presented the results of control measurements of the chimney's axis with the application of the scanning total station VX Spatial Station Trimble'a and the analysis of the impact of the changes in ground of the rock mass in the vicinity of the construction's localization.

2 The measurements of the strains of industrial chimneys

Geodetic measurements of industrial chimneys (slim objects) are made to define their geometric characteristic (the value of strains). The range of these activities includes [1]:

- measurement of tilts (fundament of the construction or its base) – requires making observations with the method of precise levelling of the network of stabilized benchmarks in the stem or fundament of the chimney;
- measurement of verticality (deviation from verticality) – making the resultant of the tilt and deflection of the chimney's stem can be every time carried out from newly established measurement base in the vicinity of the observed object.

The analysed industrial object is an element of the liquidated boiler station of the old saltworks [2]. Now it is one of the elements of the historic complex of the Salt Mine "Bochnia – Campi street 15. It was registered to the list of historical monuments of the Malopolska Voivodeship as A-238 of 11th December 1981 [3]. The object is located on the slope of subsidence trough (in the borders of the mining area). So far the points of the control network (benchmarks) on the stem or the fundament have not been distributed. The lack of height control line points on the surface of the construction limits the set of information in the area of the full diagnostics of the preservation of the construction and makes impossible to determine the value of the tilt, its direction and optional vertical translation (depending on the calculation methods). Observations of existing, characteristic architectonic elements (ledges, plinths), do not guarantee necessary accuracy of the obtained measurement results. The only element allowing us to define the influence of changes in the ground inclination on the state of the body of the chimney (deviation from the vertical), is the analysis of the changes in the height of the points localized in the vicinity of the chimney points (on the ground and on the wall) and the points of mine's height network (on the exploitation level) in the range of the impact of the excavations on the ground surface and the rock mass. Thus the article analysed the change in the deviation of the chimney referring to the height data of the existing points of the height control line.

The authors focussed on the analysis of the changes in the deviation of the chimney's axis from the vertical (compared to the measurement data of 2007), which did not require the reference of the observations to the same points of the spatial control line (XYH). In case of destroying the points of the geodetic benchmarks, there is a possibility of restoring the points in the terrain or constructing a new, similar geometric construction and marking the coordinates of these points (to give spatial orientation), with the support to other surveying techniques, e.g. GNSS. In this situation the identical system of coordinates is obtained is obtained, which creates the possibility of precise comparison of the results of subsequent measurement series. In such a case the information on the change of the value of the vector of the deviation of the chimney's axis from the vertical change in the azimuth of this vector in time is obtained, which for this brick chimney is connected with the changes in the ground and the plasticity of the halite rock mass (convergence of the cavities).

In the publication the results of the analysing of the characteristics of the geometry of the chimney based on the data of two surveying methods e.g., bisector methods surrounding the tangential and laser scanning with the application of the scanning total station VX Spatial Station by Trimble.

3 The characteristic of the historical chimney

The analysed historical industrial chimney is the construction of full ceramic brick on the cement–lime mortar, located in the area of the liquidated Salt Mine "Bochnia". With the historical building of the old panel saltworks makes a unique complex of post-industrial architecture, despite the fact that these objects were not technologically linked.

It makes the remnants after the engine room of the liquidated of the mining enterprise. Its height is H = 45.4 m (height defined between the upper verge of the crown of the chimney and the base of the cleaning hole). In case of the analyzed body of the chimney one should divide it into three parts [5, 6]:

- lower – a flue, of the geometry of a cuboid of base 6.55 × 6.55 m and height 3.8 m;
- central – base of changeable cross-section in the shape a regular octagon made with a proper security of external areas of spherical triangles;
- upper – the covering of changeable circular cross-section (from 2.668 do 1.602 m), enforced by steel rings of the cross-section of 8 × 80 mm consisting of three segments joint with screw locks (Fig. 1), allowing the regulation of the tension power, which, during the inclination measurements with geodetic methods facilitate the identification of the purpose (observation level).

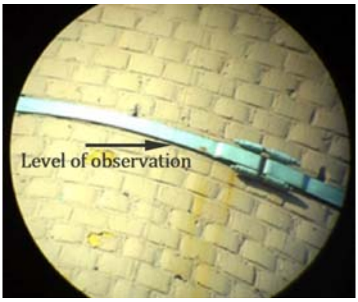

Fig. 1. Rings equipped with screw locks making the marked observation levels 4 Analysis of the deformation of the terrain surface in the region of the chimney

The historical chimney, although localized on the areas under the influence of mining exploitation (completed) was not equipped with the points of the observation network (control points). Thus it is impossible to obtain precise information on the tilt of the fundament, which influences the behaviour of the body of the chimney. To show the characteristic of the ground change in the vicinity of the chimney the height data of precise levelling network of wall benchmarks (control points) stabilized on the buildings (localized in meridian system) of new hoisting machine and steam machine, were used (Fig. 2). The analysis of the change on the surface of the terrain in the analysed region of placing the industrial chimney was carried out based on the data coming from the Surveying Division in Salt Mine „Bochnia".

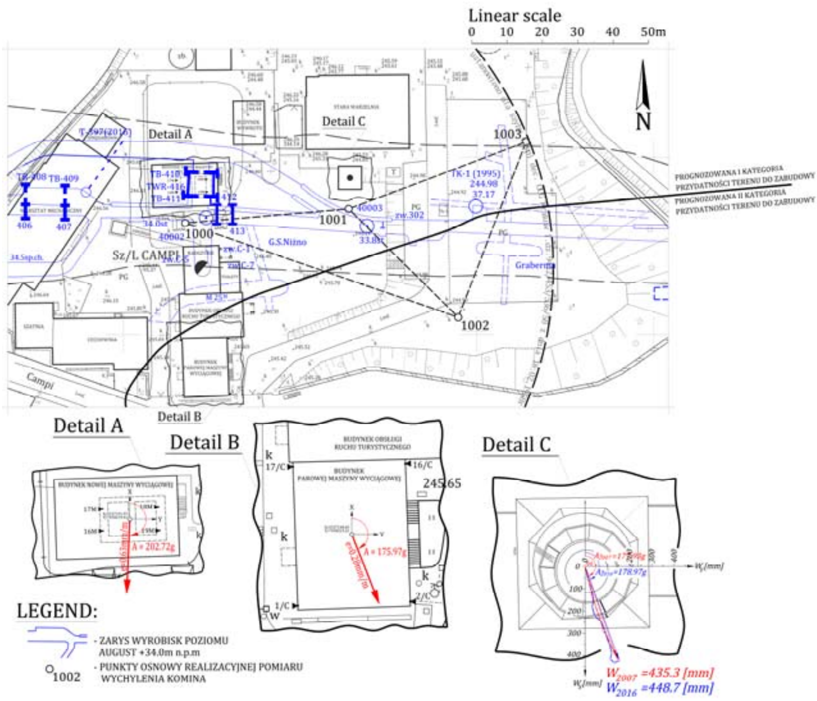

Fig. 2. Localization of the measurement stands on the background of situation details on the surface of mining excavations on Level August (the shallowest level connected with Shaft Campi)

The analysis of the change in height points in the analysed period of time 2007–2016, allowed the measurement the phenomena of inclinations and the subsidence of fundaments in these buildings, which, due to a small distance (44–67 m) from the chimney can be regarded as representative values of the changes in the region of the chimney.

The analysis of the inclinations and subsidence in selected buildings was based on the algorithm described by [7]. To geometrically interpret vertical dislocations, the equation of plane was fit into the measured points (4 points for each object according to Fig. 2), defined by the formula:

$$u_i = x_i \cdot e_x + y_i \cdot e_y + z_0 \tag{1}$$

where:

- u_i – subsidence of the control point,
- x_i – coordinate x of the reference point to the system of the object with the beginning in the gravity centre of the object,
- y_i – coordinate y of the reference point to the system of the object with the beginning in the gravity centre of the object,
- e_x – inclination of the plane alongside axis *x*,
- e_y – inclination of the plane alongside axis *y*,
- z_0 – mean subsidence of the body (vertical dislocation of the starting point of the system).

The solution of the system of equations are the unknowns of the inclination components of the plain inclination e_x and e_y and the value of mean subsidence of body z_0, calculated with the smallest square method, according to the relationships:

$$X = \left(A^T A\right)^{-1} \cdot A^T L \qquad (2)$$

where:
- A – matrix of the coordinates of benchmarks in the local system,
- L – matrix of the difference in the height of benchmarks in the discussed period of June 2007 – November 2016.

The applied algorithm of calculations, allowed the determination of basic values defining the characteristic of spatial changes in both buildings. The error of fitting the plane was preceded by the determination of adjustment corrections, according to the formula:

$$v = A \cdot X - L \qquad (3)$$

The values were put in Table 1.

Table 1. The basic values of spatial changes of the buildings of: the new hoisting machine and steam hoisting machine in the period of June 2007 – November 2016

Parameter		The building of the new hoisting machine	The building of the steam hoisting machine
		Value	
The value mean subsidence Uz_0 in [mm]		–28.5 ±0.5	–51.5 ±0.5
The components of the inclination of the building	e_x in [mm/m]	0.632 ±0.292	0.258 ±0.063
	e_y in [mm/m]	0.027 ±0.118	–0.102 ±0.078
The value of the biggest inclination e in [mm/m]		0.632	0.277
The azimuth of the biggest inclination in [g]		202.7181	175.9678

5 Analysis of the deformation in the body of the chimney in 2007–2016

The protection of construction objects in the mining areas is ordered by the regulations of the Geological and Mining Law [8]. This protection means periodical diagnostic of the construction in the form of (inter alia) control measurements my by surveying services. This means the determination of geometric parameters of constructions crucial for the safety of the building and its users. Moreover, in the framework of interdisciplinary expertises, the border states of the bearing capacity (excessive strains in the construction or ground, excessive scratches on the construction or vibrations) and usability were defined [9]. Today chimneys are built of reinforced concrete or steel, while brick chimneys belong to the group of historical objects. Thus the safety of brick construction will depend on the ability to safe interception of the influence of:
- curvatures and horizontal strains of the surface;
- inclinations of the surface;
- mining-originating tremors.

In case of the halite medium, the decisive influence on the safety of the construction is inflicted by curvatures and strains of the ground surface layers and the change of the ground slope in the place of the construction fundament. These parameters mainly decide on the direction and the values of geometric strains of slim constructions.

The article presents the results of the measurements of the deformations of the stem of the brick chimney with the application of commonly applied classical measurement method, i.e. bisector of the tangential directions, carried out according to [4] and modern laser scanning making alternative for traditional methods. Measurement data obtained with the use of the scanning total station VX Trimble'a, were post-processed, according to algorithms described in [5].

In case of the application of the laser scanning methods to define the geometry of the stem chimney from the points of the established control line (Fig. 2), the algorithm of the approximation of circles directly from the selected point cloud (band) was applied on selected levels (in case of the circular cross-section of the construction) described in [5]. Laser scanning actually generates dense point data, which, if properly interpreted and processed allow us making 2D or 3D documentation in the modelling process.

To analyse deformations of the chimney's the method of the approximation of circles into the bands of the points projected on the surface of the chimney with the smallest square method. This means that the geometric analysis of the construction was based on the determination of physical parameters of approximated circles on the defined study levels, i.e.:

- coordinates of the centres of circles Xi, Yi, Hi (Hi – height of ith level);
- radiuses of the circles of subsequent study levels.

Analysis of the coordinates of the centres of circles of subsequent study levels directly allows the determination of the tilt vectors W_i and their directions in the accepted local or geographic system of coordinates. Multi-point cover of the chimney surface (Fig. 3) provides surplus observations, which increase the accuracy of the results on the stage of the analysis and minimize the influence of human factor (including the aiming error), on the final results of the analysis. One should emphasize that in the above example the mean of the points lying on a certain level in the whole circuit of the chimney's shield is 53 points (we accepted the band of height-attributing of points to cross-section on level $h = \pm 5$ mm). Basic parameter defining the present geometric state of the slim construction is the resultant vector of the inclination of its stem W or the inclination of generalized axis Wz (Table 2). According to the formula contained in [10], the border value of the inclination of the axis of the studied chimney (regarded dangerous) is 2.13 m.

Table 1. The most important parameters of the chimney's deformation

The date of the measurement:	**June 2007**		**November 2016**		**November 2016**	
Measurement method: / Parameter	Laser scanning method		Method of adhering tangents		Laser scanning method	
Components of the inclination of the generalized axis of the chimney in [mm/m]	e_x	e_y	e_x	e_y	e_x	e_y
	–10.9	3.9	–11.1	3.81	–11.3	3.79
Total inclination of chimney's axis e in [mm/m]	11.1		11.7		11.9	
Vector of the inclination of chimney's stem *W* in [mm]	435.3		448.7		443.7	
Inclination of the generalized chimney's axis *Wz* in [mm]	503.9		531.2		540.3	
The angle of the direction of the inclination of the generalized chimney's axis *Aw* in [g]	177.93		178.97		179.40	

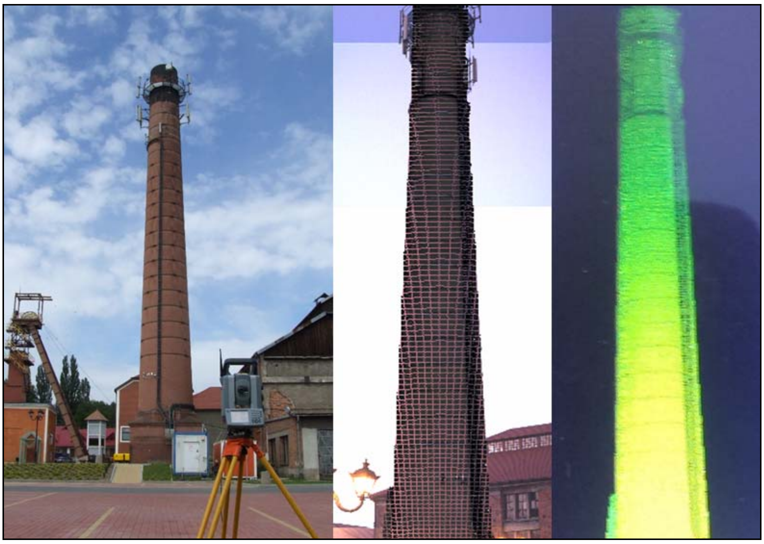

Fig. 3. View of the historic chimney – point cloud – the image of the power of the reflected signal (the measurement of the geometry of the chimney with the use of the scanning total station VX Trimble)

Conclusion

The application of laser scanning technology in the inventory processes and control measurements of tall and slim constructions simplifies and accelerates the implementation of surveying tasks both indoors and outdoors. This allows comprehensive geodetic assessment of geometric deformations of the object with the preservation of high accuracy. The presented in the article example of the application of a modern scanning total station equipped with the integrated digital camera and the obtained results of the inclination, on selected observation levels, referring to classical methods prove great usefulness of this class of instruments and high accuracy. This is confirmed by the difference of the values of the vectors of the inclination of chimney's stem of the applied measurement methods on the level of 5 mm.

As a difference from the bisect method, which requires a definite measurement space to preserve high accuracy, such modern scanning total stations facilitate the measurement. Due to the precision of the measurement and multi-point cover of the measured area (surplus observations) the image of structural deformations and the control of the data is obtained, although the process of post-processing is more complicated. In practice, the high number of data, indirectly facilitates precise determination of elements allowing the users mutual adjustment of the sets of points coming from various check points. Precision of angular–linear measurements guarantees high accuracy of determination of vectors of the inclinations of various levels in the relation to the base, physical parameters of the horizontal cross-sections of the shield of the chimney, i.e. radiuses and coordinates of the centres of circles, but also the registration of local structural deformations of its coating. Moreover, laser scanning, due to the possibility of increasing the density of observations, full control over the results of measurements is possible and points charged with gross errors are eliminates from the data sets. Their cause can be the reflection of the impulse from more than one surface. In the relation with this, in case of the surfaces possible to be defined mathematically, the neighbouring points make the control of the point model.

The presented in the article example of the chimney located in the mining area and subdued to the influence of the carried out exploitation, showed a real character of the deformations of the stem of the construction. The resultant vector of inclination is compliant with the direction of the localization of excavation of subsequent exploitation levels and the direction of their collapse (structure of the deposit). Results of measurements of 2007 and 2016 indicate slight growth of the vector of the inclination of stem chimney by the value of 8.4mm and the change of azimuth by 1.47 g, in the direction of the slope of the subsidence trough (localization of the deepest mining excavations).

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