THE EVALUATION OF GEOMETRIC CHANGES IN SPECIAL TYPE STRUCTURES BY SURVEYING METHODS ON THE EXAMPLE OF THE SPODEK DOME IN KATOWICE*

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ABSTRACT

The paper presents an example of surveying field works carried in the main hall of The Entertainment-Sport Hall in Katowice. Both the technology and program of surveying were determined by the main goal that was an evaluation of the main hall construction performance and enablement of periodic observations for displacement evaluation in future. The individuality of presented survey results analysis relates to the structure characteristic and knowingness about primary geometry properties of the construction that was affected by mining.

1. INTRODUCTION

Due to the end of mining activity, a new sense of development is involved on the area of Katowice. This development relies on erection of new buildings and modernization of existing ones as well. All this activity requires adequate geodetic surveys. Those engineering surveys are conducted to obtain data for the various phases of construction activities but a detection of ground stability on the area affected by mining is important as well. The basic observations according to regulations included in European Standards EN 1997.1 concern a ground stability that can be evaluated on detected displacements.

Presented surveys were conducted as typical periodic observations on post mining area and preliminary observations of geometry changes of the Spodek for its forthcoming modernization. The special value of presented work is an approach in analysis that was required to determine geometrical changes of the structure although there was very limited information about initial surveys. Unfortunately, the limitations of presented remarks result form existing documentation with incomplete surveying data (benchmarks with saved horizontal and vertical coordinates). Nevertheless, obtained results of carried surveys demonstrate performance of the structure affected mostly by mining. For that reason only some selected data surveys are presented in the paper just for description.

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2. A SHORT DESCRIPTON OF THE SPODEK

Spodek is a multipurpose arena complex in the central part of Katowice. It is known as a place with major contribution to the cultural and sport significance of Katowice. The complex includes the main dome with the arena and stands for 11.000 people, a gym, an ice rink, a hotel and three large car parks. Maciej Gintowt and Maciej Krasiński were architects of the Spodek and they designed it as one of the first major structures due to the principle of tensegrity. The roof uses an inclined surface held in check by a system of cables holding its circumference up. The main aim for the construction requirements was the ground instability. What's more the construction had to be proof against real harms resulting from mining influence.

Fig. 1. The aerial views of the study area with localization of leveling benchmarks.

The main part of the dome is a rounded basement with several levels making stands for the audience. The internal stiff of the ring was compensated of its flexibility in movements accordingly to direction of ground displacements. This attribute secures the stability of the ring's top surface (in elliptical shape and planar) and it was designed in the mining of future affect of mining workings.
Moreover, the overturned dome (bowl) uses an outward push that is balanced by the inward pull of the roof cables at the perimeter. The roof is the earliest known actual use of a cable structure based on the tensegrity principle, in which compression members are connected only to cables, and not to each other. The idea of the construction resembles bicycles wheels.

3. FIELD SURVEYS

The surveys were carried in several steps to detect geometrical changes resulted as from former mining activity and the property use. Primary measurements included the following:

- **levelling of benchmarks located around the structure to detect the ground subsidence on the area of interest (Fig. 1.),**
- **topografic survey of the outer terrace (as the most affected part of the structure, constructionally not connected with the building) to establish the model of its displacements.**

The other surveys were carried inside the building and they include:

- **levelling of the main sport arena,**
- **levelling of the structure stand levels (round passages being various levels of the foundation ring), carried for detection of denivelation originally flat surfaces,**
- **tacheometric surveys of circle geometry of mentioned levels (carried for detection of changes in their circularity).**

The tacheometric surveys were conducted by laser technology with the use of Leica TCR 303, a reflectorless total station instrument. The instrument measures distances up to 80 meters with ±3mm ±2ppm accuracy. It provides high angular accuracies ±10cc as well. With the use of Leica prism reflector mentioned accuracies are even higher. The levelling surveys by Leica Na 3003 level proved high accuracy of determined benchmark heights (most of them are fixed in the building walls). The maximum error was there – ±2.8 mm.

Referring to former leveling observation results it was possible to determine benchmarks height changes. The benchmarks located on the area of the Spodek had been measured before in the year 1995. Expected subsidence demonstrated by mentioned points height changes could be caused mainly by mining. Unfortunately, there were no stabilized points inside the arena (on levels and the arena that could be useful for precise vertical displacement analyses). The same problem occurred in the tacheometric measurements of rings circularity. But in the both cases estimated displacements are just unevenness referred to theoretical geometry (surface).
The main sport arena topography was derived from conducted surveys. The point's height distribution was compared with a topographical map worked out in 1995 (in undefined vertical coordinate system). No horizontal coordinates of points measured in 1995 were saved and the arena central point is the only one that can be identified and

compared. So, excluding measured benchmark heights other results describe just the actual condition of measured elements (not occurred displacement).
The main effects of carried surveys were as follows:

- **height changes of benchmarks placed on the building wall,**
- **topographical map of the main area surface (based on about 150 measured points) – the level 0 (elevation 271.0 m),**
- **elevation profiles of the arena stand levels:**
  - **the level 0 (elevation 271.0 m), the high accuracy position (vertical and horizontal) of about 35 points were measured,**
  - **the level 1 (elevation 272.7 m), the position of about 50 points were measured,**
  - **the level 2 (elevation 277.8 m), with about 70 measured points position,**
  - **the level 3 (elevation 280.1 m), the position of about 90 points were measured,**
  - **the level 4 (elevation 280.7 m), with about 120 points with measured heights (there were different points for horizontal observations),**
- **precise horizontal distribution of points on mentioned above the arena levels. That determines the geometry for the arena circularity analysis.**

Nevertheless the limitations of initial data, the global model of the structure geometry changes was possible to be elaborated.

4. SURVEY RESULTS AND ANALYSIS

Presented results of carried on the area of Spodek are limited to report on displacements observed and calculated for its main arena. The derived data is an example of analysis based on insufficient information related to former surveying data. The carried conclusions involved: vertical displacements of benchmarks placed outside on the Spodek walls; differences in elevations between measured points (denivelations) on selected levels of the arena (foundation ring levels), circularity of ring on various levels. As it was mentioned, the obtained results give an analytic demonstration of the structure displacements model.
Hence, there are to be concerned: ground vertical displacements, vertical displacement various levels of the building including the arena field, horizontal ring extensions (based on measurement of its circularity). Presented profiles of the analyzed levels combined with distribution of ground height changes in the period 1995-2006 (derived from levelling observations) show a certain similarity (Fig. 3). The round profiles (clockwise) of initially flat surfaces of the levels demonstrate denivelations that can be considered as a subsidence (caused by mining). The values of the dinivelations correspond to observed ground displacements. The level 4 was the only not planar (according to the structure project). Having documented heights determined within former surveys, it was possible to calculate height changes by comparing with actual profiles (Fig. 4).

All lowered parts of the profiles are located at the southern part of the building (accordingly to direction of former mining workings). Although at the first look the vertical rises on the levels look comparably but numerically they increase upwards quite linearly. This observation is better noticeable on the charts presented on the next figure (Fig. 5).

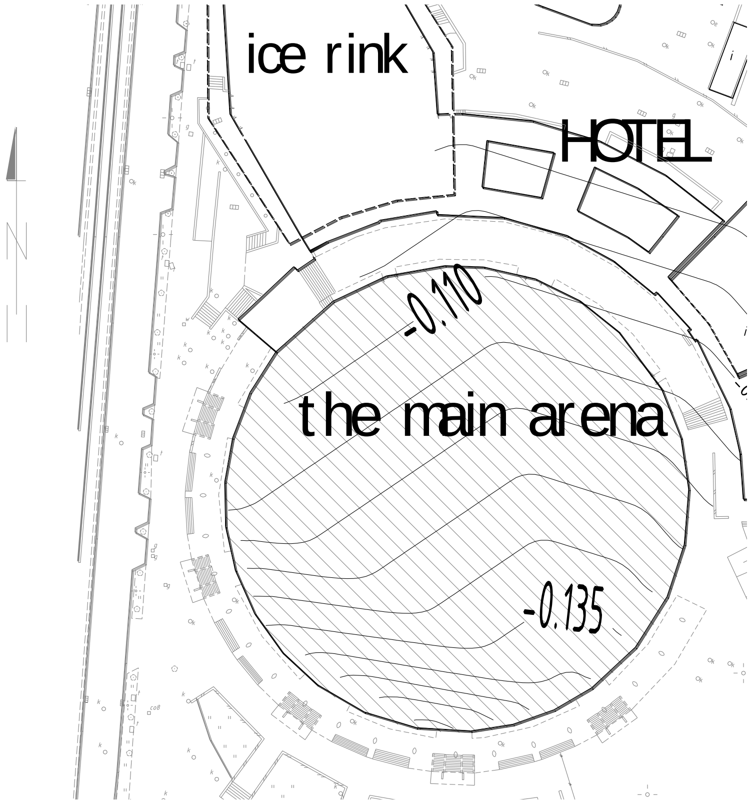

Fig. 2. The subsidence map of the Spodek area, 1995 to 2006.

They show a remark that every 10 m of a vertical distance involves 8 cm of a vertical displacement (subsidence) of the southern part of the levels. Consequently, it demonstrates the leaning process of the structure.
The attribute of the analyzed level's height distributions suggests slopes of the surfaces that are still maintained planar. Generally, it illustrates a movement of the foundation ring – the basic part of the structure.

Tacheometric surveys carried due to observations of the foundation ring circularity enabled round orientated distribution of the measured points' localization on the foundation ring levels. Applying the least square adjustment for the data fitted into the figure of circles. The results of fitted points are presented on Fig. 6. There is a combination of all points measured for circularity of the levels (except the level 1 and the level 4 being in elliptical shape and having a different position of the central point). Numerical computations proved a good fitting of all points. The average values of residuals are mostly in the range of measurement and computation errors. Maximum values of residuals are about 20 mm. However there are certain parts of the levels which demonstrate higher values of residuals. They are located in the northern parts of rounded levels. It slightly indicates the direction of horizontal movements and resulted from that process tensions deforming the analyzed circularities. It is obvious that circularity of the foundation ring was maintained.

The ground subsidence amounting 15 cm (in the last 10 years) involved a few millimeters disturbances in analyzed circularities. The second conclusion to be drawn from this analysis concerns positions of the central points that were computed in fitting

procedures (Fig. 7). The centre of the arena field is displaced about 20 cm horizontally from the position of the other level central points. The central points of levels 2 and 3 are closely located – the difference amounts to 5 mm. The difference in mentioned before subsidence of those levels is 18 mm. Presuming the distance between calculated the central points positions as a horizontal displacement, it makes about 30% ratio between vertical and horizontal components of the displacement vector. It satisfies a typical value of mentioned ration on mining areas.

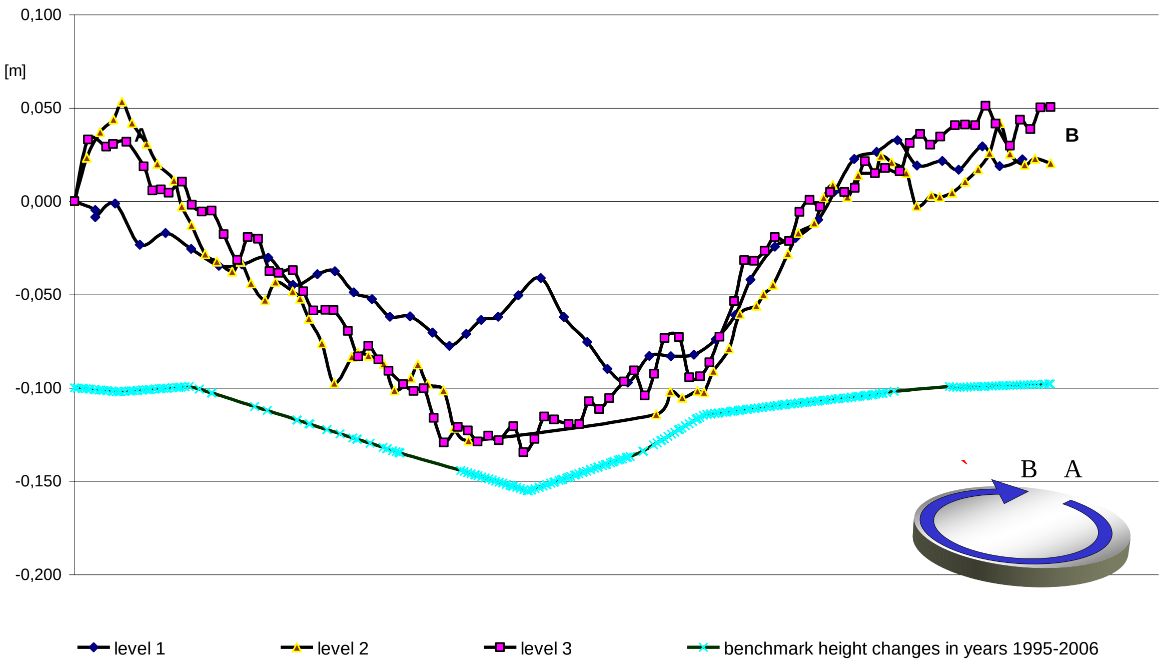

Fig. 3. Juxtaposition of the surface profiles of dome levels heights and distribution of the Spodek ring's vertical displacements (during 1995-2006). The bottom scheme illustrates the direction of the profiles.

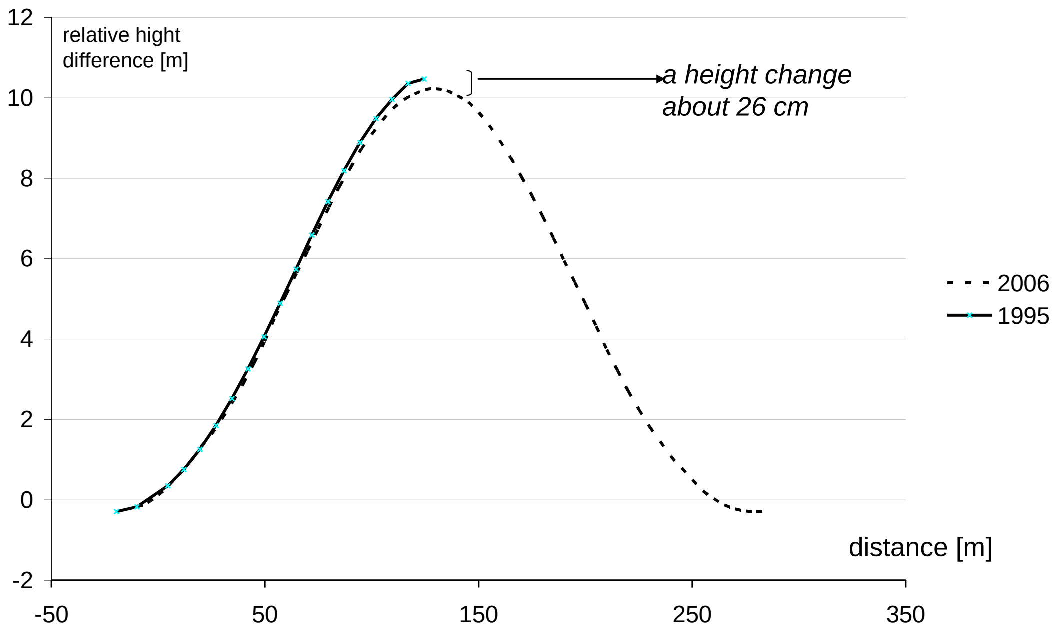

Fig. 4. The profiles of the level 4 in 1995 and 2006.

The extreme different location of the arena field centre results from a constructionally different basement of this part of the structure. The displacement of this centre caused by mining activity (in recent years and older) but the normal use of the property as well (the centre of the arena is not a real stable benchmark; what's more the field of the arena is made of mobile flags). The last conclusion results from the fact that horizontal displacement is comparable with a vertical one, what is not typical on mining areas.

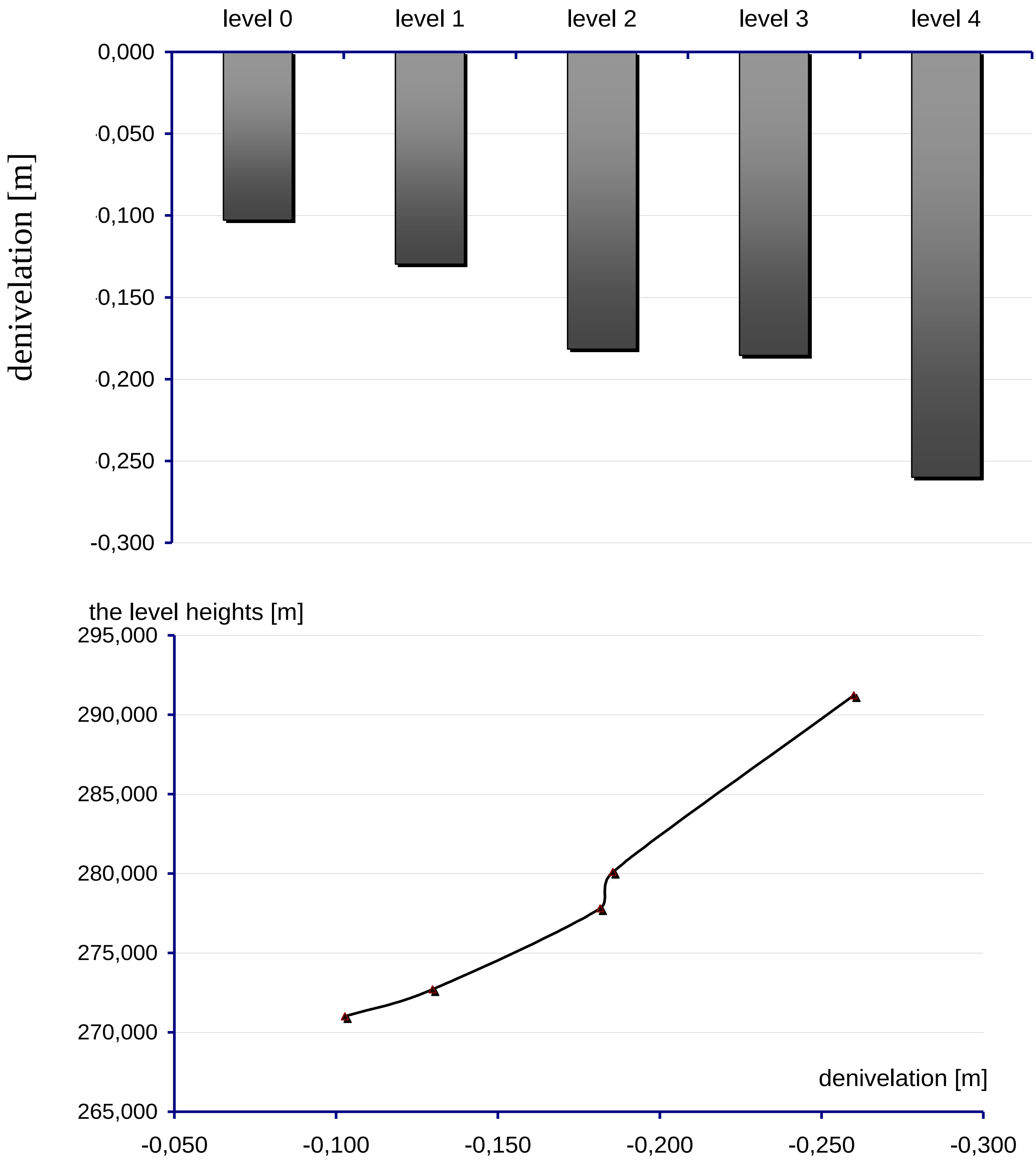

Fig. 5. Relationship between elevations and the dome levels subsidence (lowered parts of the ring).

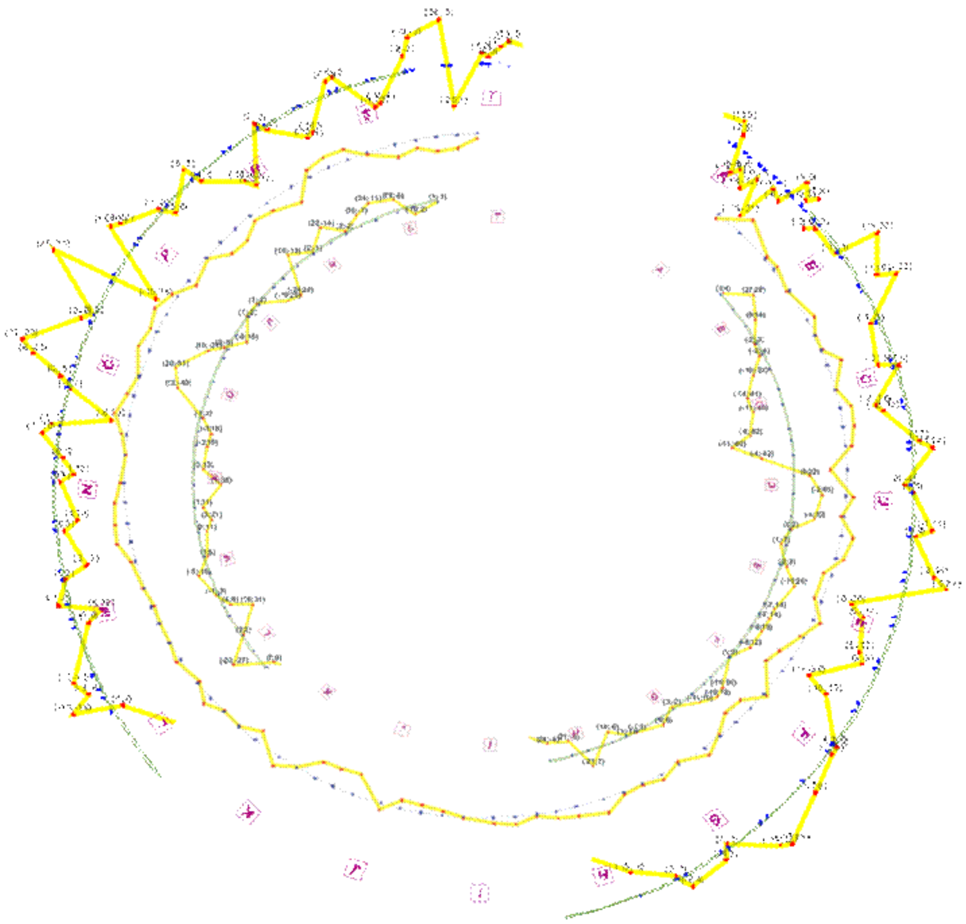

Fig. 6. The surveying data for circularity control and circles geometry fitting results.

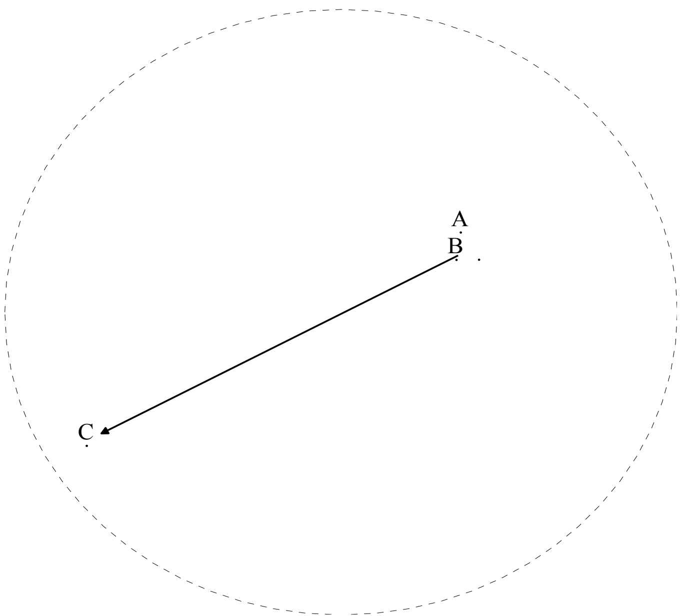

Fig. 7. The diagram of central points location (A - the level 2 central point, B - the level 3 central point, C - the arena field central point).

5. FINAL CONCLUSIONS

The main purpose of the surveying was a detection of potential geometrical changes of the building. They could be resulted as much from ground displacements induced by mining as a normal use of the property. The simply surveying data were involved for this analysis. Unexpected results illustrating the levels denivelations and their circularity make a global model of changes in the structure geometry. The dome was displaced toward to mining workings (a typical process resulting from a subsidence movement process). The displacement vector had a horizontal component (with different values for various levels, especially for the arena field that is a different construction) and a vertical one (a lowered southern part of the levels, denivelation increases upward). Computed value of the slope caused by lean angle of lowered part of the dome is 0.8 % . It is impossible to calculate total horizontal displacements without initial coordinates but relative value of the process is not very significant. The most important for the use of the structure are very minimal values of the rounded levels tensions. In fact there is no significant changes in a geometry of the circles. That's evidence of the Spodek's successful proof against real harms resulting from mining influence. It was a quite safe process and intended design requirements were achieved successfully. It gives another sense to the structure as a monument of cultural significance and moreover engineering challenge.

6. ACKNOWLEDGEMENTS

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