AN ATTEMPT TO APPLY TENSOR CALCULUS TO EVALUATE THE DEFORMATION CONDITION OF VERTICAL UPPER EMBANKMENT ZONES FOR A LANDFILL LOCATED IN A MINING AREA, BASED ON SATELLITE MEASUREMENT RESULTS

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RESUME

Safe usage of post-flotation waste reservoirs (landfills) requires carrying periodical geodesic measurements in order to control their embankments' stability. This is particularly important if mining operations are performed under the landfill or in its neighbourhood. On the basis of the measurements results, various coefficients of the terrain deformation are determined and their values, together with the results of other observations, are used in order to evaluate the safety status of the facility further usage.

The paper presents the results of experimental calculations, using satellite measurements of the landfill observation network fragment, including the middle zone of its embankments. 35 geometrical structures were selected in this zone, named "triangular rosettes". Vertices of relevant triangles are selected points the co-ordinates of which shall be determined with the satellite technology. Three annual cycles of GPS observations in the landfill controlled network were used in calculations, performed in 2004-2006. On the basis of the annual sets of point co-ordinates, periodical horizontal displacements of points making up the rosettes were determined. In turn, for the interior zone of each rosette, components of a two-dimensional deformation tensor were calculated, allowing for determining the values for horizontal extreme deformations and the directions of their occurrence in each rosette zone. Calculations were performed for three time periods: 2004-2005, 2005-2006 and 2004-2006. The results of evaluating the condition of horizontal deformations were presented against the background of mining operations performed in these time periods in the landfill region, as well as against the background of settlements in the analysed points in relevant annual periods obtained from classical observations, realised by precision levelling technology.

1. EXPERIMETAL FACILITY

The facility for which the experimental evaluation of the horizontal deformation status was performed is the post-flotation reservoir of a facility producing zinc and lead ore concentrate. Fluid medium produced in the flotation process is transported wit pipelines to the landfill interior, where solid fractions sediment and water, clarified and accumulated in the central part, is transported back to the processing plant. The general view of the landfill is presented in Fig. 1. The landfill has been and still is developed by forming further, higher embankment slopes in order to increase its volume. Up above the elevation +297.5 m, further embankment slopes are formed from thicker fractions of the material deposited in the landfill. The landfill perimeter (at the embankment base) is c.a. 4 km, and the volume of waste deposited currently inside is around 22 million m^3. The elevation of the currently highest formed slope is +335.0 m, and the average elevation of the embankment base at the whole perimeter is +284 m. A simplified vertical section through the landfill embankments and its foreground has been

Fig. 1. General view of the landfill.

shown in Fig 2.

In the landfill region, mining operations are conducted: underground mining of zinc and lead ore. The mining was generally conducted with pillar-chamber system, with hydraulic filing. In previous years, mining operations were performed at the depth of over 200 m below the surface. In the recent years, mining was performed in the upper section of the deposit, from 150 to 200 m below the surface where the landfill is located. The thickness of the removed layer of the deposit differed a lot and changed within 3-12 m. [2].

Currently in the landfill protective pillar, mainly removal liquidation works are implemented, realised by distributed frontlines.

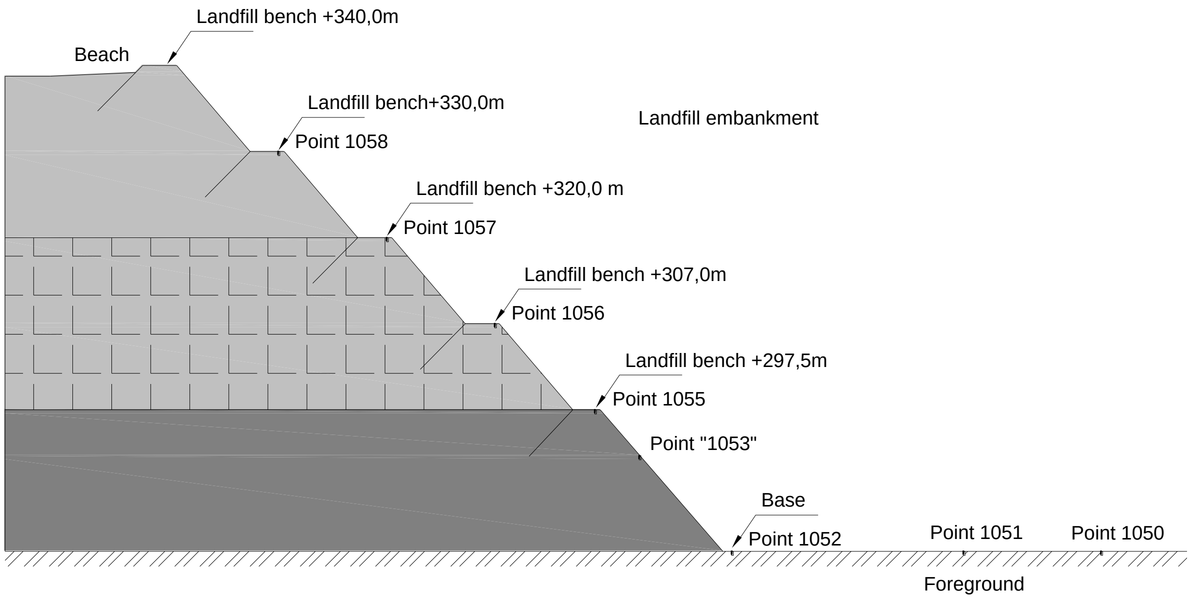

Fig. 2. A simplified vertical section through the landfill embankments in a selected profile line "1050".

As per the requirements of the legal regulations in force, the agreements of relevant state mining supervision organisations, a mining facility running underground mining under significant surface facilities (and the lanfill is such) is obliged to perform cyclical observations of the performed mining outcome, revealing on the terrain surface [6].
Periodical analysis of such observations results in the context of the protected facility's operating security and the forecasts for further deformations course as the basis for issuing an approval for further mining operations [5].

2. SOURCE MATERIALS TO BE USED IN THE RESEACH

For this research's need, partial results of cyclical geodesic observations were used, of the control observation network designed and implemented by the AGH Section of Mining Surveying in Krakow in 1992.
The landfill control network including its direct foreground and embankments was developed successively, as its embankments increased. The whole control network currently consists of over 150 control points stabilised with special signs. These points create 15 so-called "profile lines" and an additional network of distributed points. The method of locating the points in a selected profile line is shown in Fig. 2, while the assumed method of numbering control points was illustrated upon an example of three selected lines in Table 1.
On all points of the control network, there are cyclical height observations performed, using precision levelling technology, with precision c.a. 0.9-1.5 mm/km. These observations are performed in quarterly cycles with reference to a point of fixed height, located outside the underground mining influence zone. On the basis of further height observation cycles, periodical and total settlings of the control network points are calculated and other

parameters, characterising the vertical deformation points as the function of time for the foreground region and the observed part of the landfill embankment [1].

Table 1. Principles of numbering control points in profile lines.

Benchmark placement	***Section number***		
	1050	3040	1010
	Numbering of points		
far foreground	1050	3040	1010
close foreground	1051	3041	1011
Base	1052	3042	1012
Bench +297.5 m	1055	3045	1015
Bench +307.0 m	1056	3046	1016
Bench +320.0 m	1057	3047	1017
Bench +330.0 m	1058	3048	1018

Satellite measurements with the use of GPS technology are realised in annual cycles, on selected points of the control network (58 points). On the basis of the observation results referenced to the "Fix" constant point, periodical and total horizontal displacements of the observed points are determined. From 2001, the observations are realised with statistic method, in accordance with specially developed schedule, with parallel usage of 13 double-frequency GPS receivers. The applied measurement guarantees obtaining precision of determining the site location of points observed in the network, at the average error level of c.a. 1-2 mm. In Fig. 3, a sketch of vectors was presented, determined in the measurement cycle 2005, together with a precision evaluation obtained from solving this network, assuming that the point "2020" is constant.

In this figure, in the assumed scale, for each average error ellipsis point, for a site solution and in the form of a vertical rectangle, a precision measure in vertical direction was illustrated.

For the needs of this work at the attempt to evaluate the condition of horizontal deformations in the distinguished landfill embankment zone in Fig.2 and in Table 1, results of three consecutive cycles of satellite measurements were used, made in the landfill region in 2004, 2005 and 2006 [1].

Additionally, in order to depict the scale of vertical deformations that happened in the same period in the landfill region, the results of three selected height observation cycles were used, made in moments concurrent with the moments of performing satellite observations [1].

For examples, in Fig. 4 (for the period of two years, ie. from autumn 2004 to autumn 2006) point settling was presented in synthetic way for that period in the form of isolines and for the points observed with the use of GPS technology, with vectors (in the assumed scale), horizontal displacements of these points on the same period of time were illustrated. The background for settlement and horizontal displacements on the period of two years is generalised picture of site contours of regions with underground mining in three selected time horizons: up to 2004, from 2004 to 2005 and from 2005 to 2006.

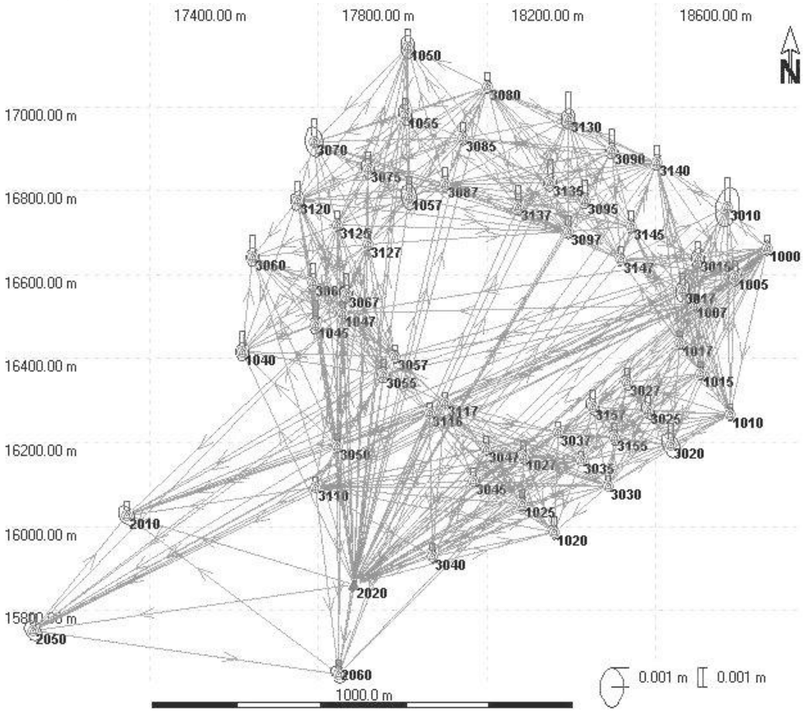

Fig. 3 A sketch of GPS control vectors from 2005 measurement cycle with evaluation of its solution’s precision.

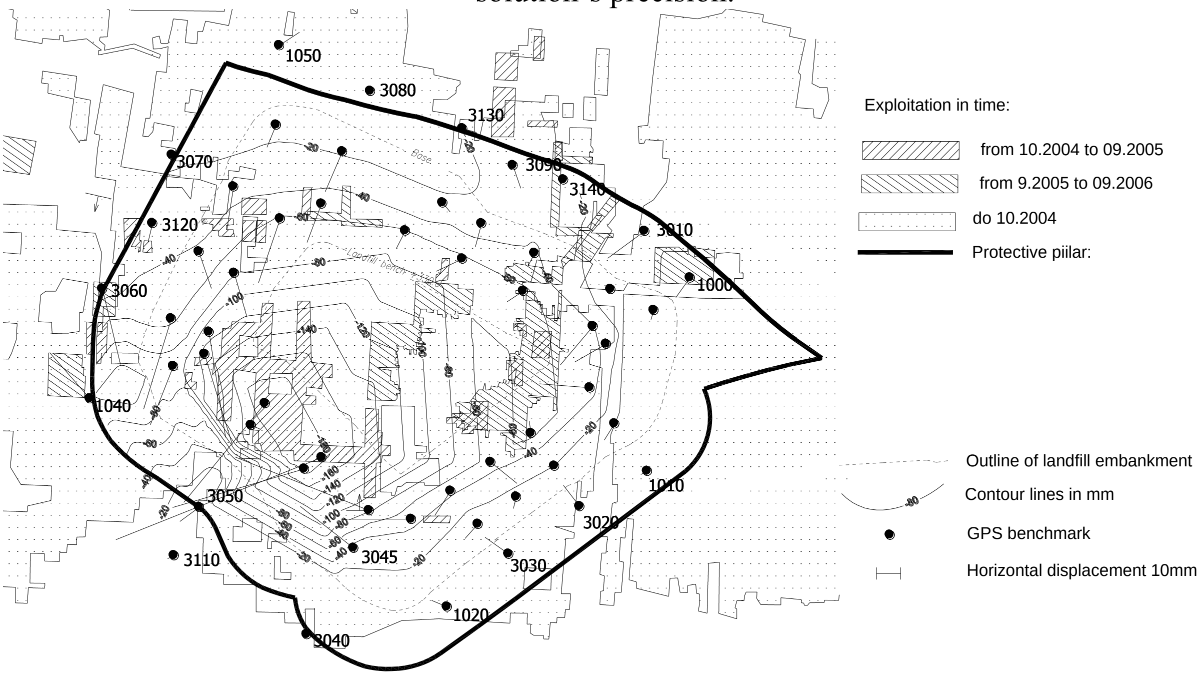

Fig. 4. Horizontal contours of underground mining in the landfill area in three time horizons and the outcome of mining on the surface in 2004-2006 period**.**

3. APPROVED METHODOLOGY OF EVALUATING THE HORIZONTAL DEFORMTION STATUS

On the basis of selected GPS network points, located on the bench +297.5 m and the bench +320.0 m (Fig. 2), a chain of triangular rosettes was constructed; their vertices are relevant points observed periodically with GPS technology. Site location of 35 created rosettes was illustrated in Fig. 5, against the background of the landfill embankment perimeter and the site location of the whole network observed with the use of GPS technology. This landfill embankment zone is constructed of relatively uniform material.

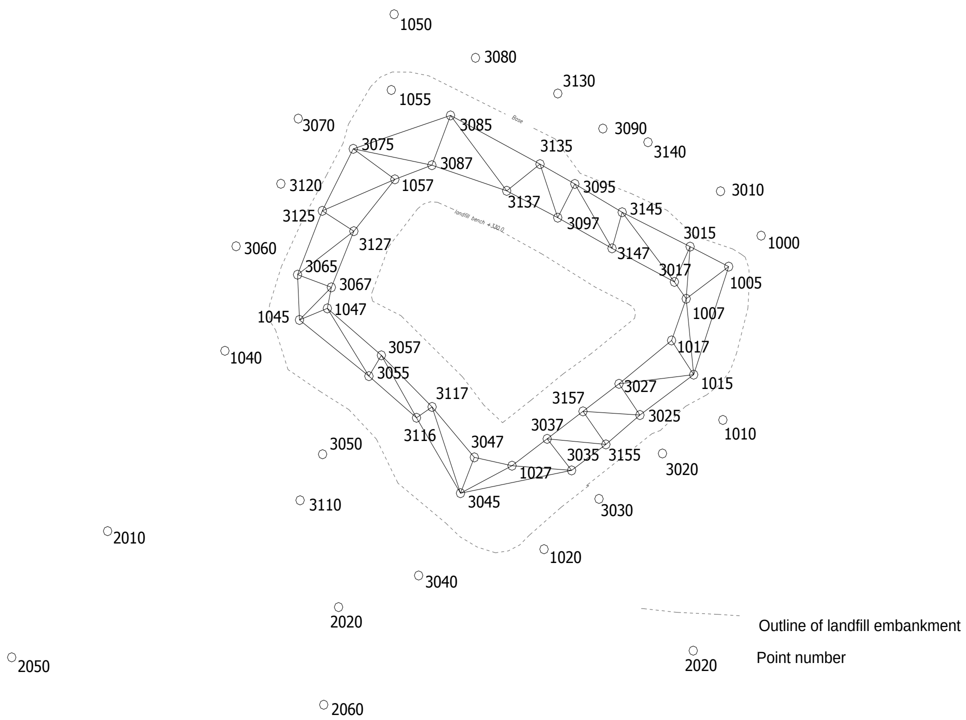

Fig. 5. Site location of the triangular rosettes chain against the horizontal perimeter of the landfill embankments and GPS control network points.

Using the co-ordinates of points being the rosette vertices, the lengths of "l" sides were calculated for all 35 rosettes in three moments in time: 2004, 2005 and 2006.

Comparing relevant "l" lengths in three period of time (2004-2005, 2005-2006 and 2004-2006) was the basis for evaluating the status of relevant horizontal displacements within each rosette.

For each rosette (in three assumed time horizons), calculations of horizontal displacements co-ordinates tensor were performed. Calculations were performed in accordance with known formulae, quoted in numerous publications. [3], [4]. The calculations assumed the elastic model of the embankment medium and two-dimensional and symmetrical status of horizontal displacements.

For each of the assumed time horizons, next to tensor co-ordinates for each rosette, the values of extreme deformations and their orientation in the assumed set of co-ordinates were determined, as well as the value of the form deformation. Algorithms and computer calculations programming was done within the work: [*].

4. RESULTS OF EVALUATING THE STATUS OF HORIZONTAL DISPLACEMENTS

For the synthetic presentation of the calculations results in the scale of the whole landfill, we gave the idea of presenting minimum and form displacements as parameters insignificant to the landfill embankment stability hazard status.
In three consecutive figures (Fig.6, Fig.7 and Fig. 8) determined sizes of the maximum horizontal displacements were presented, as well as their sign and direction in each rosette zone for three assumed time horizons.
The value of maximum horizontal displacements were marked with sections in the assumed scale placed in the centre of each rosette and the site direction of such section is conformant with orientation of the maximum deformation direction determined for a specific rosette.
Ending of a section informs of the sign of a maximum deformation.
In these figures, three shades of grey have been used in order to provide a better perception of numerical values of determined deformations. Numerical ranges of the used three-degree scale are specified in the figure description.
Additionally, generalised depicting of vertical displacements is enriched with a picture of settlements isolines and the vectors of horizontal displacements of control points, registered in appropriate periods of time.
For each assumed time horizons, extreme values of four selected deformation parameters registered in the whole facility scale, were presented in Tables 2, 3 and 4.

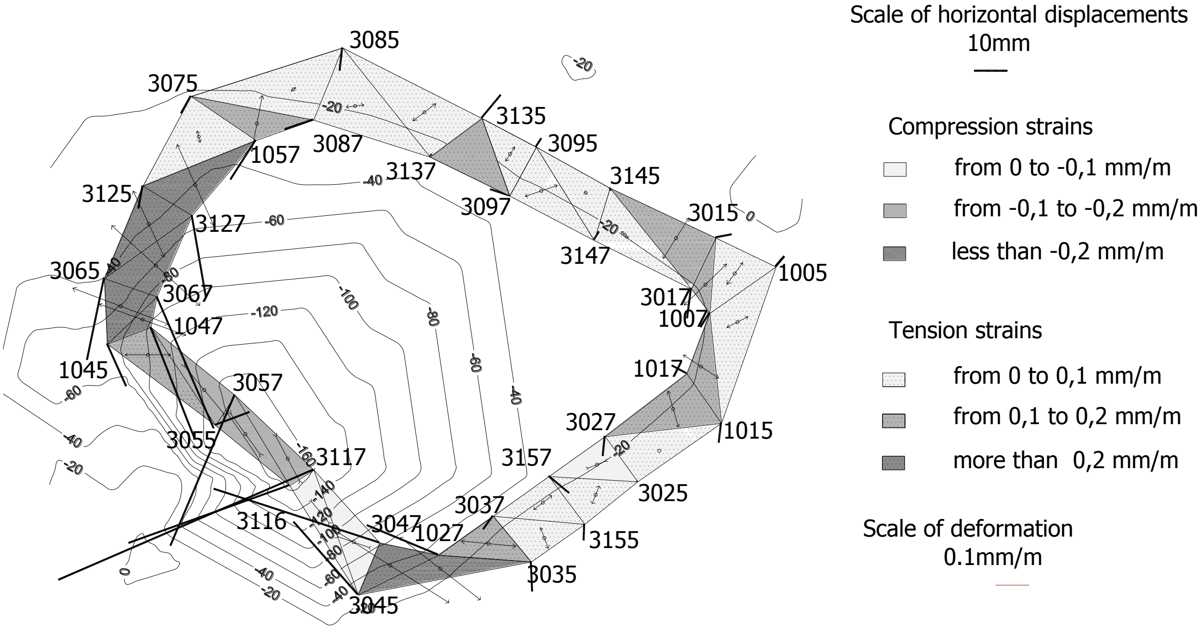

Fig. 6. Result of evaluating the deformation status in 2004-2005 period.

Table 2. Presentation of extreme values of the selected deformation coefficients in 2004-2005 period.

Horizontal deformation ε [mm/m]		Vertical deformation ε [mm/m]		Depression w [mm]	Displacements u [mm]
tension	**compression**	**tension**	**compression**		
+0.41 (rosette: 1027, 3047, 3045)	-1.21 (rosette: 3116, 3057, 3055)	+0.52 (line 3110)	-3.80 (line 3050)	-173 (point 3057)	83 (point 3117)

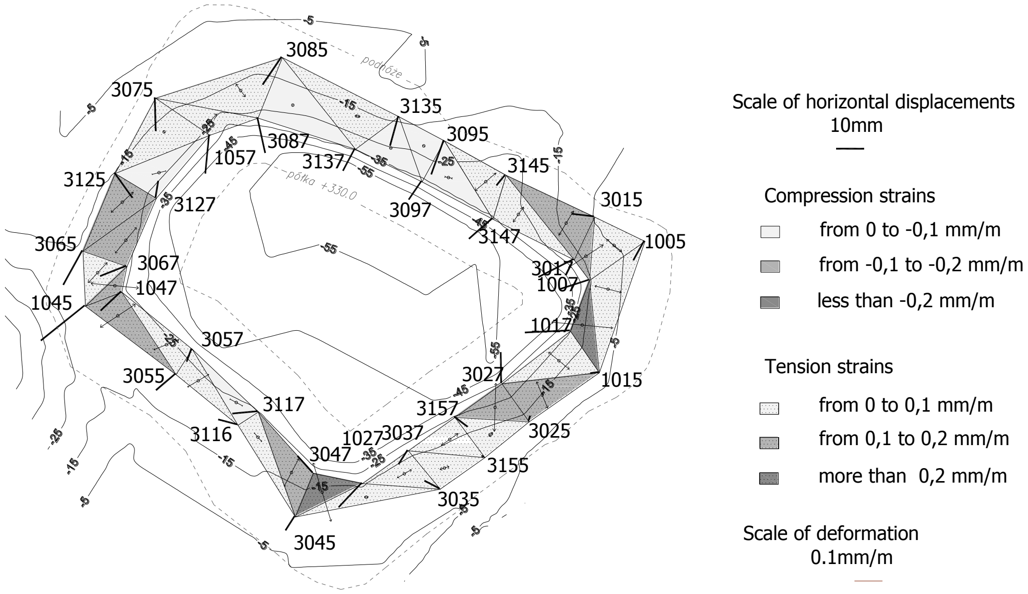

Fig. 7. Result of evaluating the deformation status in 2005-2006 period.

Table 3. Presentation of extreme values of the selected deformation coefficients in 2005-2006 period.

Horizontal deformation ε [mm/m]		**Vertical deformation ε [mm/m]**		**Depression w [mm]**	**Displacements u [mm]**
tension	**compression**	**tension**	**compression**		
+0.22 (rosette: 1007, 1017, 1015)	-0.24 (rosette: 3127, 1057, 3125)	+0.08 (line 3040)	-1.16 (line 3130)	-37 (point 3097)	29 (point 1040)

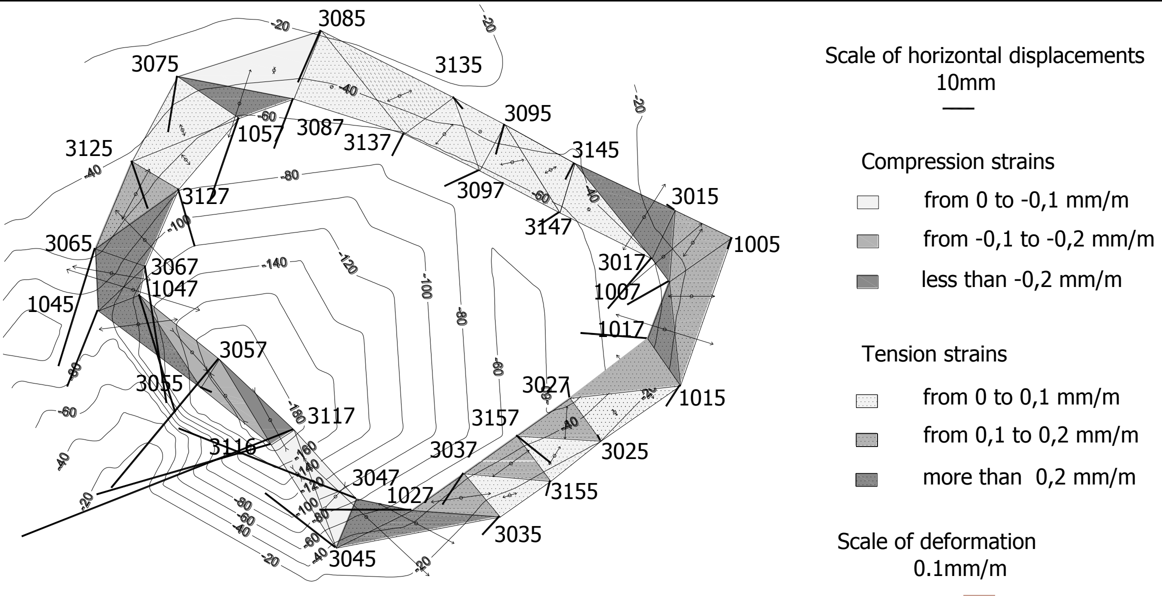

Fig. 8. Result of evaluating the deformation status in 2004-2006 period.

Table 4. Presentation of extreme values of the selected deformation coefficients in 2004-2006 period.

Horizontal deformation ε [mm/m]		**Vertical deformation ε [mm/m]**		**Depression w [mm]**	**Displacements u [mm]**
tension	**compression**	**tension**	**compression**		
+0.54 (rosette: 1027, 3047, 3045)	-1.12 (rosette: 3116, 3057, 3055	+0.31 (line 3110)	-4.24 (line 3050)	-202 (point 3057)	92 (point 3117)

5. FINAL REMARKS

1. GPS technology allows for efficient and economical determining of horizontal deformation in regions influenced by underground mining operations. Performing a measurement of absolute horizontal displacements using classical technologies in spacious mining regions is practically impossible, as it requires large additional expenditures of labour and time for the control matrix in the facility with points showing spatial stability as the function of time.
2. The performed evaluation of the horizontal deformation status in the landfill region is generally conformant with the mining damages theories.
- Horizontal relative deformations (determined in the accepted way) in the bottom zones of local settlement basis have negative signs (compression), while in the basin wings they have generally positive sign (tension).
- Horizontal displacements of points determined from satellite measurements (in three periods of time) are directed (in terms of location) to the local depression basin periodical centres.
- Relative vertical deformations determined independently (from periodical levelling) with positive sign (tension) are at the similar level in terms in size to the horizontal relative deformations in all three periods of time. However, vertical relative deformations with negative sign (compression) are generally c.a. three times greater than horizontal tensions and several times greater than vertical tensions in analysed periods of time. Such status (domination of compression deformations over tension deformations) is favourable for the stability of the landfill embankments, because it results in consolidation, not loosening. It is a result of carefully planned location of mining extraction works performed in this period under the landfill and in its neighbourhod.
3. The determined amounts (numerical values) of horizontal deformations cannot be **uncritically** used in strength calculations due to the assumed (simplified) physical model of the landfill embankments.
4. The embankment stability analysis must be conducted with taking into account geomechanical parameters of the material creating the embankments, their structure and hydrogeological conditions.
5. A problem still awaiting a good theoretical solution is the problem of developing principles for selecting bases lengths for observing relative horizontal deformations, adjusted to specific mining and geological conditions and the protected facility type.
6. Measurements of relative horizontal deformations in triangular rosettes and determining the maximum deformation for each rosette seem to be a more favourable method than measurements in observation lines. Differentiated sizes of observation bases and three horizontal directions of these bases guarantee, in the authors' opinion, better "statistic sampling" of the examined zoned within each rosette and in its direct neighbourhood.

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