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ORIGINAL PAPER

DESCRIPTION OF THE SPATIAL DEFORMATION PROCESS IN SELECTED CRACOW MOUNDS BASED ON THE SURVEYING MONITORING DATA

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ABSTRACT

Historic Cracow mounds (prehistoric: the Krakus Mound and Wanda Mound and relatively new ones: the Kościuszko Mound and Piłsudski Mound) are among the biggest anthropogenic objects of this type in Poland. They are made of loess, which is the earthwork material of problematic quality and very susceptible to the atmospheric factors, i.e. precipitation (rain and snow) and wind, getting seriously damaged. Because of the damage, sometimes they have to become closed to visitors for some time. This mainly refers to relatively new mounds (Kościuszko and Piłsudski), which are often described as "made with heart" (which can mean enthusiasm, but also the lack of durability of the material). The applied so far ways of the stabilization of the slopes, despite huge costs and implementations of modern geotechnical solutions did not bring the expected results. Particular susceptibility of the mounds to natural factors demands particular analytical methods and preventive measures. Both deep seated methods and surveying methods allow geotechnical services to undertake specific actions to halt the deformations in zones particularly threatened by landslide. Surveying point monitoring based on classical measurement methods, i.e.: traverse sand precise levelling, sometimes supported by GNSS technology and the grid of control points located on the surface of Earth cones, facilitate defining the scale of changes in geometry, in time and the directions of these changes. Surveying observations have been carried out for several years in the framework of surveying monitoring. They confirm and make more precise the specific characteristics of these changes. Apart from subsidence of the surface and the phenomenon of twisting the solids determined based on horizontal dislocation vectors, the attempts to define the correlation of the values of these changes with the sum of atmospheric precipitation and the mean wind direction. In the article the authors presented similarities in the characteristics of these changes referring to the most important atmospheric factors such as precipitation and wind.

1. INTRODUCTION

A particular group of engineering objects of anthropogenic origin consists of historic mounds and barrows. In Poland, there are over 350 documented constructions of this type. Four of the biggest in Poland mounds, i.e. Piłsudski, Kościuszko, Krakus and Wanda are located within the present borders of Cracow, fulfilling of tourist, educational and cultural functions. Referring to other objects of this type in Europe, the only bigger mounds are: Butte du Lion in Waterloo (Belgium) and a prehistoric mound of Silbury Hill in England (McAvoy, 2005).

The size of the mounds makes the impression that these monumental constructions are long-lasting and stable. In reality they are very delicate, susceptible to external factors, especially atmospheric phenomena. Thus they are subdued to various destructive processes (Bryt-Nitarska, 2006), depending on physical and mechanical properties of the applied materials and factors affecting the ground, as well as accidental phenomena. The technical state of the mounds changes in time and is directly connected with the progressing deterioration of mechanic properties of the ground (among others: resistance to curdling, compressibility of the ground). Small decrease of the resistance of the scarp's ground construction can cause the movement of the medium alongside the slide surface. In natural conditions, without human intervention, this phenomenon is a long-lasting process. Due to the change of the natural external factors, such as: the saturation of the medium with water, strong degradation and erosion of the slope (Stopkowicz and Cała, 2004; Eltner and Baumgart, 2015; Handwerger et al., 2013) the stability of the scarp can suddenly diminish and a distinct landslide form on the surface can occur (Stopkowicz and Cała, 2007). The process of the stability assessment of the scarps is complex because of the complicated geological structure (heterogeneous medium). The more complicated geology, the more factors decisively influencing the conditions of stability (Cała and Betlej, 2010) and the difficulties in

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defining the state of stress, strain and dislocations of the scarp (Cała and Flisiak, 2000).

So far, any works related to security and revitalization of all the Cracow mounds were carried out in zones of significant changes in the form of landslides, cracks of scarps and walking paths. In particular, in case of many modern geotechnical solutions on the Kościuszko Mound were applied in the form of geo-nets, bolts, geo-mats, gabion baskets, but because they were not implemented in the full range, the results were insufficient and the deformation process could not be halted.

A great role in diagnosing and recognizing the processes of landslide is played by geo-technology and geology based on deep seated methods of the description of the phenomena taking place inside the Earth structure and on the basis, in reality responsible for the size and characteristics of the construction deformations. Surface surveying data are very useful for the full description of the characteristics of the changes in the earthwork construction. They allow us to characterize the phenomena in the surface zone more precisely and to define zones of the increased speed of horizontal and vertical dislocations indicating the presence of shallow landslips of ground material. Early detection of threatened zones allows necessary preventive measures for quick stabilization of the scarp and protection from further erosion of its deeper layers.

The article presents the most important results of the point surveying monitoring of three historic mounds: Wanda, Kościuszko and Piłsudski and similarities in the directions of changes in their geometry in time on the background of the weather characteristics of the region of the Krakow town, which significantly shapes the process.

2. THE CHARACTERISTICS OF THE CONSTRUCTION WEARING, PROTECTION OF THE CONSTRUCTION

Technical state of Earth construction changes in time. Changes are directly connected with the progressing deterioration of endurance and usefulness of its individual elements (Srokowski, 1971). This process is called natural wearing and mainly depends on the factors such as the use and the state of stress (Ściślewski, 1994).

The maintenance of this type of Earth constructions in full technical functionality demands continuous expert assessment, including: geo-technical, geological, mining, conservation and surveying, etc., allowing the assessment of the state and prediction of possible changes. Thus it is necessary to carry out the assessment of the technical shape in the framework of the cyclic audits (Michalik, 2014). The control of the safety of the use of Earth constructions of this type should be carried out every time in case when excessive atmospheric phenomena affecting the construction occur (strong winds, intensive rainfall, landslide), and the result can be the damage to the object.

According to article 62, part 1 of the Construction Law, the assessment of technical state and technical wearing is carried out during the audits and check-ups looking at the technical state.

Because of its rank and localisation, the Kościuszko Mound is the only of the Cracow's mounds where technical and preservation works are constantly carried out, including the audits and preservation works. So far, the particularly wet periods of 1996 – 1997 and 2010 (typical of Cracow) strongly affected the geometry of all the Cracow's mounds, causing local landslides of scarps. Especially the biggest mounds: Piłsudski and Kościuszko were seriously damaged, which made them totally closed (Kościuszko Mound – overhaul) or partially closed (Piłsudski Mound – emergency renovation) for the visitors. The limitations in the revitalization works carried out for the Cracow's mounds are caused by the lack of funds in the city budget for the maintenance of this group of monuments.

3. THE CHARACTERISTICS OF ACTIVE FACTORS AFFECTING EARTH MOUNDS OF CRACOW

In case of Cracow mounds, as artificial elevations of the terrain, a particularly dangerous for the stability of scarps phenomenon is intensive rainfall. The biggest damage to the solids of Earth cones occurs, first of all, in the periods of intensive, but not necessarily long-lasting precipitation (heavy rainfall or torrential rainfall) occurring in late spring, summer and early autumn, although a long duration of rainfall is an important stimulus facilitating the processes of deformation. The consequences of these phenomena, such as mass landslide movements were noted in 1996, 1997 and 2010, making it necessary to close the large fragments of the mound for the public. In those times, damage affected all the Cracow mounds.

Most of intensive precipitation of multi-scale character and intensity not changing in time (including long-term rainfall, even lasting for several days, with just small breaks (Kotowski et al., 2010) is connected with air masses moving from the south-west and west (air currents from the Atlantic Ocean and the Mediterranean Sea). They bring a lot of humidity concentrating over warm seas, while the intensity of atmospheric phenomena (mainly precipitation) is caused with a large thermal contrast between the eastern (front) part of the low pressure air masses, and its western (rear) part (Buchert et al., 2013). Thus the second important active factor causing changes in the geometry of mounds is wind its characteristics, i.e.: the direction, value and frequency.

Geomorphology of the Cracow town and vicinity makes this part of the province a subject necessary for the individual analysis of weather conditions, which form the characteristics of atmospheric precipitation and air currents. Intensively developed part of the town is located in the valley, within the borders of

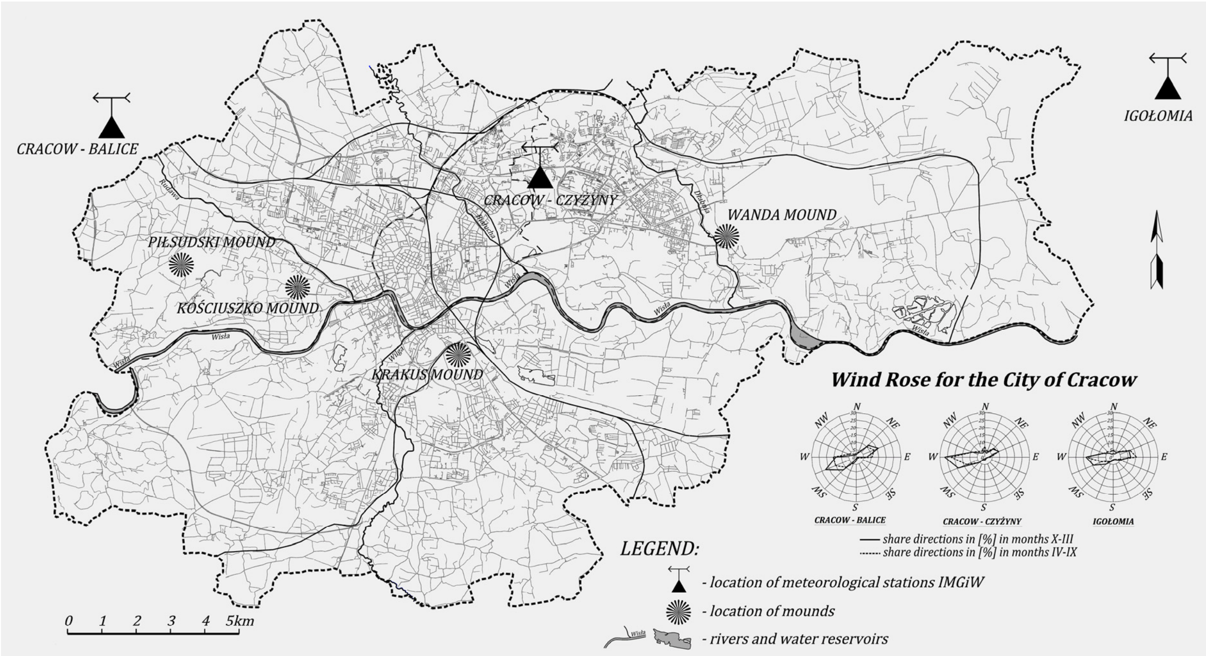


Fig. 1 Location of meteorological station IMGW and mounds with the city contour and graphic interpretation of air currents (wind compasses for observation – measurement stations).

a narrow belt called Brama Krakowska (Sokołowski, 2009), while the region of Cracow is often defined as the Crakow Elevation – Rygiel Krakowski (Ney, 1968). From the south the valley is limited by the hills built of resistant Jurassic limestone and partially, of less resistant Cretaceous marls (Wieliczka Foothill). One of them, i.e. the Lasota Hill, makes the fundament of the Krakus Mound in Krzemionki. Within the isolated tectonic edge – the Cracow Gate – Brama Krakowska, in the west part of the city, the chain of the Sowiniec Hill is situated, consisting of two massifs: Sowiniec and St. Bronisława Hill, making the foundations for the highest Polish mounds: Piłsudski and Kościuszko. These hills are within the range of Carpathian Foothill - Crakow Upland – Wysoczyzna Krakowska making higher level of the Sandomierz Valley (Tyczyńska, 1968). From the north – the Vistula Valley is limited by elevations making southern border of the Cracow – Częstochowa Upland. Such a geo-morphological characteristic makes the situation that in the micro-scale meteorological parameters of the city of Cracow and adjacent area are changed locally, which is shown by the compass rose in 3 stationary observation-measurement stations of the Institute of Meteorology and Water Management (IMGW) in Cracow and Cracow District – Figure1. Their location causes that meteorological data are represented for the urban space and the main corridors of their airing. That is because of relatively small distances of observation-measurement stations of IMGW from the examined mounds (Piłsudski Mound – IMGW Balice ~4.2 km; Kościuszko Mound – IMGW Balice ~6.9km; Wanda Mound – IMGW Czyżyny ~5.6 km).

Based on wind data of two meteorological stations in Balice (Cracow airport) and Czyżyny one can make conclusions about the characteristics of these currents (Fig. 1). Three types of wind dominate:

- the west - warm and humid polar-maritime air;
- the north-east – dry and cold polar-continental and arctic air masses.

Air currents of such a variable characteristic and properties come across an Earth obstacle and slightly slow down. Here we have turbulent movements at the surface and slight turbulent movements with the obstacle in a so-called zone of aerodynamic silence.

The presented mounds: Wanda, Kościuszko and Piłsudski are geotechnical objects, with significantly different values of morphometric parameters, which are put in Table 1.

Despite large disproportion in size (also the way of securing the surface), these objects are subdued to spatial deformations of very similar directions of these changes in time. Applying geodetic technologies allows precise recording of these movements based on the networks of discrete points of the analysis in the field of dislocations.

4. GEODETIC MEASUREMENT TECHNOLOGIES APPLIED IN THE MONITORING OF CRACOW MOUNDS – METHODS

Knowing the specifics of active and passive factors destabilizing Earth constructions requires geotechnical monitoring at the application of geodetic methods, properly selected for the characteristic of changes and the size of the objects, terrestrial, airborne or satellite measurement technologies. More and more often, to obtain the information on the characteristics of geometric changes of engineering constructions (size and directions of these changes) modern measurement, technologies limiting to

Table 1 Basic morphometric parameters of the Cracow mounds.

Morphometric Parameter	Wanda Mound	Kościuszko Mound	Piłsudski Mound
Maximal mean of the base [m]	62.87	78.67	112.75
Field base [m^2]	2 910	4 120	9 818
Maximal height [m]	13.17	32.58	32.91
Cubature [m^3]	~9 000	~130 000	117 236

minimum the human factor impact on the final results of the measurement are applied. These technologies are:

- TLS (Terrestrial Laser Scanning), allowing large density of observations and quasi-continuous point model of the inventoried object, which is particularly important in the monitoring of structural deformations. The accuracy of situation of the determined point is the resultant of several errors, inter alia: distance measurement, beam inclination angle, twist of the reflecting surface and the recognition of reference signals. Thus the error of the situation of the point in space stays on the level of at least several millimetres;
- ALS (Airborne Laser Scanning), providing a cloud of points of smaller resolution, i.e. standard 8 points/m^2. The experience of authors (Gawałkiewicz et al., 2015) shows that ALS technology, in case of artificially shaped elements (roads, pavements), provides height accuracy of the model, given by the mean error on the level of ±20 mm, while for grass surface ±44 mm, which is not enough for mound monitoring.

The characteristic of the grass cover of Earth cones (changeable height and density in time), significantly limits the degree of confidence in scanning observations on the stage of the analysis and interpretation of deformations in the spatial system. According to the authors, obtaining the highest accuracy is guaranteed by the observations based on discrete points formed on the surface of Earth cones by the geometrically defined network. Thus obtaining the highest accuracy of points positioning (defining spatial coordinates XYH in the accepted system), guaranteed by integrated measurements. Combining the methods of traverses (linear-angular measurements) and precise levelling gives reliable discrete data, representing the system of changes in geometry within the whole construction.

Studying the size of the deformation of surface layers of mounds was carried out based on permanently stabilized points of control networks. The values of horizontal dislocations was made at the application of precise total station TC1800 Leica and the set of signals Nestle, while vertical dislocations were measured with the use of precise leveller Na3003 Leica and code invar level staaf GPCL3. The parameters of instruments were put in Table 2.

Angular-linear and height measurements, in case of every mound are referred (in case of every mound) in every measurement series, to the points of the reference points located out of the outline of the construction. At the same time the control of the stability of the reference line, according to the accepted calculation algorithms described e.g. by Mrówczyńska (2010), Mąkolski and Kuchmister (2008). Using calculation algorithms of GeoNET program by AlgoRES, by rigorous adjustment, for each independent measurement of a given mound, present spatial co-ordinates from each observation network with marking mean situation errors of point m_P (horizontal plane) and m_H (vertical plane). This allows defining the value of the limiting error value m_{gr}, which in fact interprets the movement of the point, or its lack – Table 2. The values of limiting errors m_{Pgr} and m_{Hgr}, for the studied period, were determined based on previous measurement error and present measurement error from the relation (Table 3):

$$m_{p_{gr}} = \pm\sqrt{m^2_{p_{śr}(i-1)} + m^2_{p_{śr}(i)}}$$

where:

$m^2_{p_{śr}(i-1)}$, $m^2_{p_{śr}(i)}$ - mean point situation errors (XY) in the previous measurement (*i-1*) and the analysed measurement (*i*);

$m_{H_{śr}(i)}$ $m_{H_{śr}(i-1)}$, - mean point height errors (H) in the previous measurement (*i-1*) i and the analysed measurement m (*i*);

The carried out accuracy analyses in the periods presented in Table 2, can provide certain indications referring to the adjustment of time intervals of subsequent measurement series to real values of the changes, assuming changes at relatively uniform motion of the points. Assuming maximal measured length d_{max} = 70 m (Piłsudski Mound), accuracy measurement angle on the level ±3^{cc} (TC1800 Leica) and the error of the direction resulting from instrument centring errors (m_{ei} = ±0.5 mm) and signal (m_{es} = ±0.5 mm) equalling ±9^{cc} (Gawałkiewicz, 2016), linear error of determining the coordinate of a single point from the points of reference control line equals ±1 mm. According to the authors, one can assume horizontal dislocations of the value smaller than limiting situation error of the point, in shorter period of the studies can, however, show the reliable direction of the trend of these changes.

Table 2 Basic parameters of accuracy instruments used in geodetic monitoring.

Instrument	**Total Station TC1800**		**Leveller Na3003**
Measurement Accuracy	Measurement Accuracy		Standard Deviation (per 1km of double levelling)
	Distance	Angle	
Error	±1 mm +2 ppm	1”	±0.3 mm/km

Table 3 Mean errors of the determination of the coordinates of the points in horizontal plane m_P, and vertical plane m_H and their limiting errors for the analysed mounds and periods of time.

Name of the mound	**Measurement date**	**Empirical mean error unit**	**Mean errors of positioning XY [mm]**		**Limiting error (*) [mm]**	**Mean errors of height H [mm]**		**Limiting error (**) [mm]**
		M_o	$m_{Pśr}$	m_{Pmax}	$3 \cdot m_{Pśr}$	$m_{Hśr}$	m_{Hmax}	$3 \cdot m_{Hśr}$
Wanda	12.2013	1.43	1.1	1.8	-	0.31	0.37	-
	04.2014	1.52	0.8	1.1	**4.1**	0.14	0.18	**1.0**
	08.2014	1.30	0.6	1.7	**3.0**	0.33	0.39	**1.1**
	03.2015	1.43	0.5	0.6	**2.3**	0.29	0.35	**1.3**
Kościuszko	06.2012	1.06	0.8	1.3	**-**	0.53	0.71	**-**
	03.2014	0.96	1.2	1.9	**4.3**	0.44	0.60	**2.1**
	03.2015	1.18	0.9	1.1	**4.5**	0.40	0.57	**1.8**
	08.2015	1.01	1.0	1.7	**4.0**	0.65	0.82	**2.3**
Piłsudski	08.2012	1.12	0.8	1.2	**-**	0.67	1.01	**-**
	10.2012	1.22	1.3	2.2	**4.6**	0.28	0.36	**2.2**
	09.2014	1.28	0.9	1.5	**4.7**	0.42	0.51	**1.5**
	08.2015	1.12	1.1	1.7	**4.3**	0.55	0.67	**2.1**

5. ANALYSIS OF CHANGES IN IN THE GEOMETRY OF SELECTED HISTORIC MOUNDS

5.1. ANALYSIS OF HORIZONTAL DISLOCATIONS

In practice physical point in the areas of landslide usually means uncontrolled movements with changeable velocity and the directions of dislocations. In surveying, determining this movement is carried out in the framework of regular measurements, which simplify the phenomenon to the resultant vector between base measurement and current measurement or previous and current one (Fig. 2). In case of Earth cones this movement reminds curved trajectory, which was shown in the further part of this article. In this case the analysis of surface deformation of the ground layer to the resultant vectors between the two analysed states (Fig. 3).

Based on the formed networks of control points on the surfaces of the studied Cracow’s mounds (apart from the Krakus Mound, where during the overhaul in 2014, the network of control points was destroyed), it is possible to give the characteristics of changes in their geometry in time. All the historic mounds are similar in the characteristics of horizontal dislocation vectors (changes in the directions of vectors). For all the three mounds, varying in geometry, cubature and

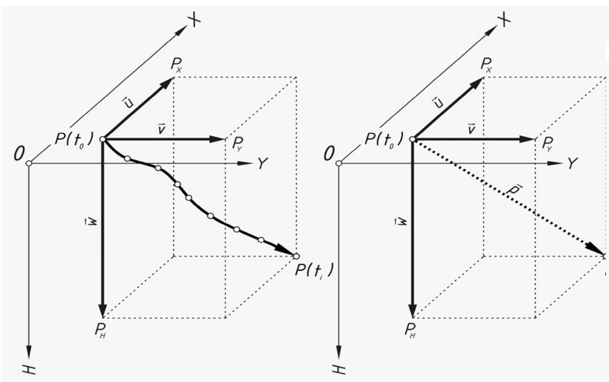


Fig. 2 Typical behaviour of the point in the landslide area.

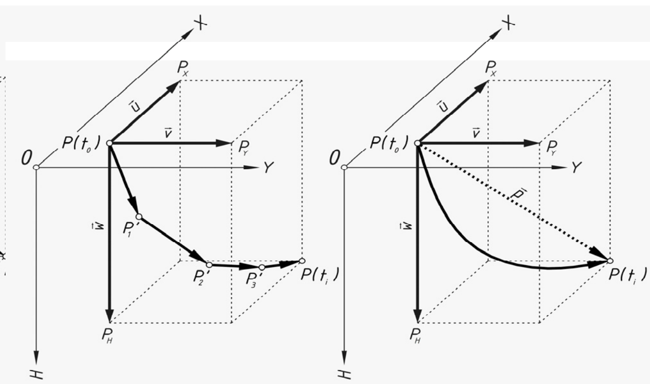


Fig. 3 Typical behaviour of the point in the mounds.

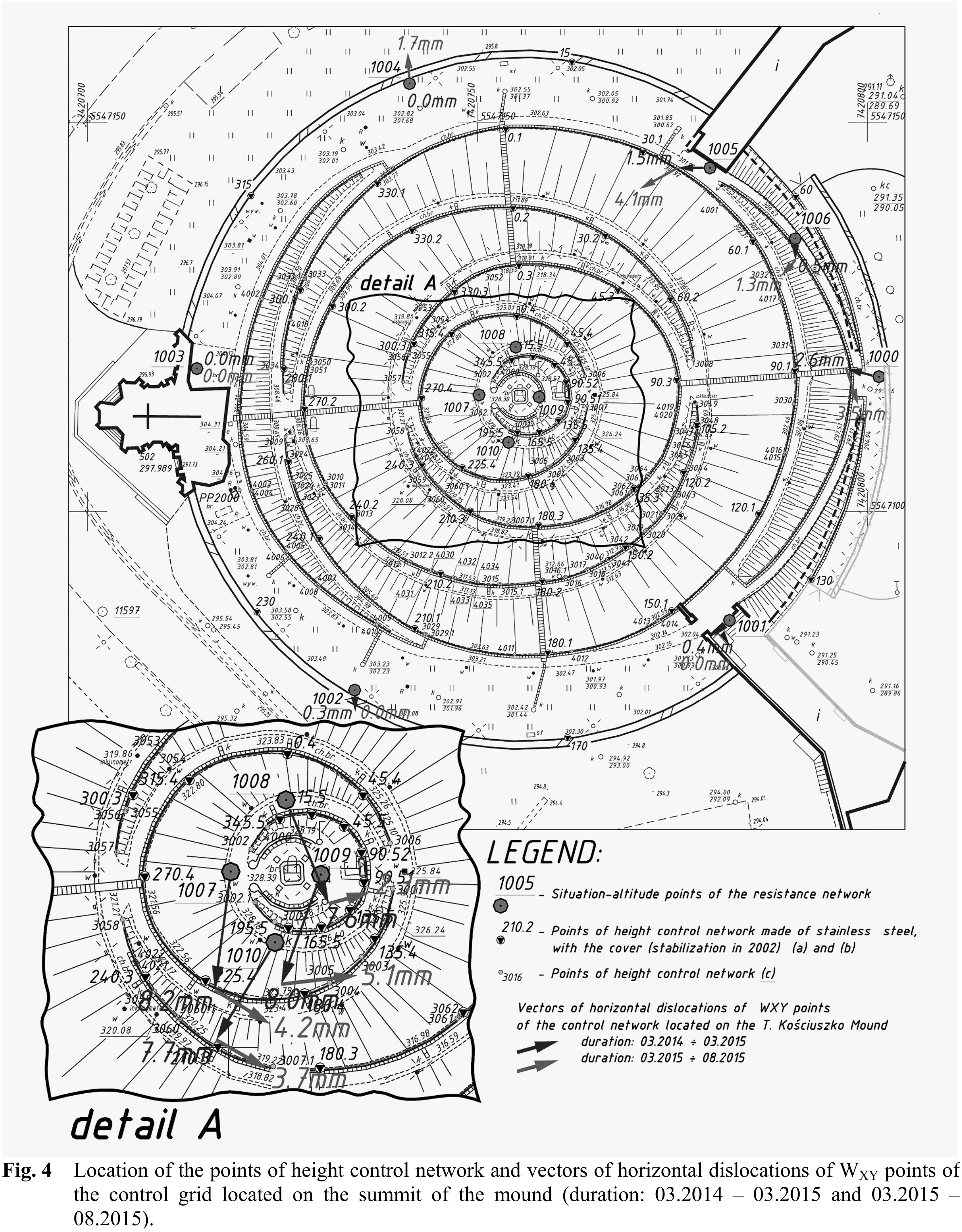


Fig. 4 Location of the points of height control network and vectors of horizontal dislocations of W_{XY} points of the control grid located on the summit of the mound (duration: 03.2014 – 03.2015 and 03.2015 – 08.2015).

the way of securing, the vectors of dislocations show some compliance in the direction and trajectory of the dislocation trails, i.e. anti-clockwise movement (Kościuszko Mound – Fig. 4, Piłsudski Mound – Fig. 5, Wanda Mound – Fig. 6). Especially in case of the Piłsudski Mound, which has many control points making the skeleton reminding a „spider web", regularity can be observed in the preservation of points situated on different heights. Mounds are not stiff solids. That means that every point on the surface can dislocate with different speed and direction. This means that the system of material points being components of the solid moves in the way that it causes changes in its form and volume. The movement of points on the Mounds reminds "a pirouette on ice", where small arm causes quick turn, and the increase of the arm slows down the movement and the whole process. One can observe deviations from this rule, but it results from first of all anisotropy of the ground (grounds of different physical and mechanical characteristics) and heterogeneous system of their securing from the

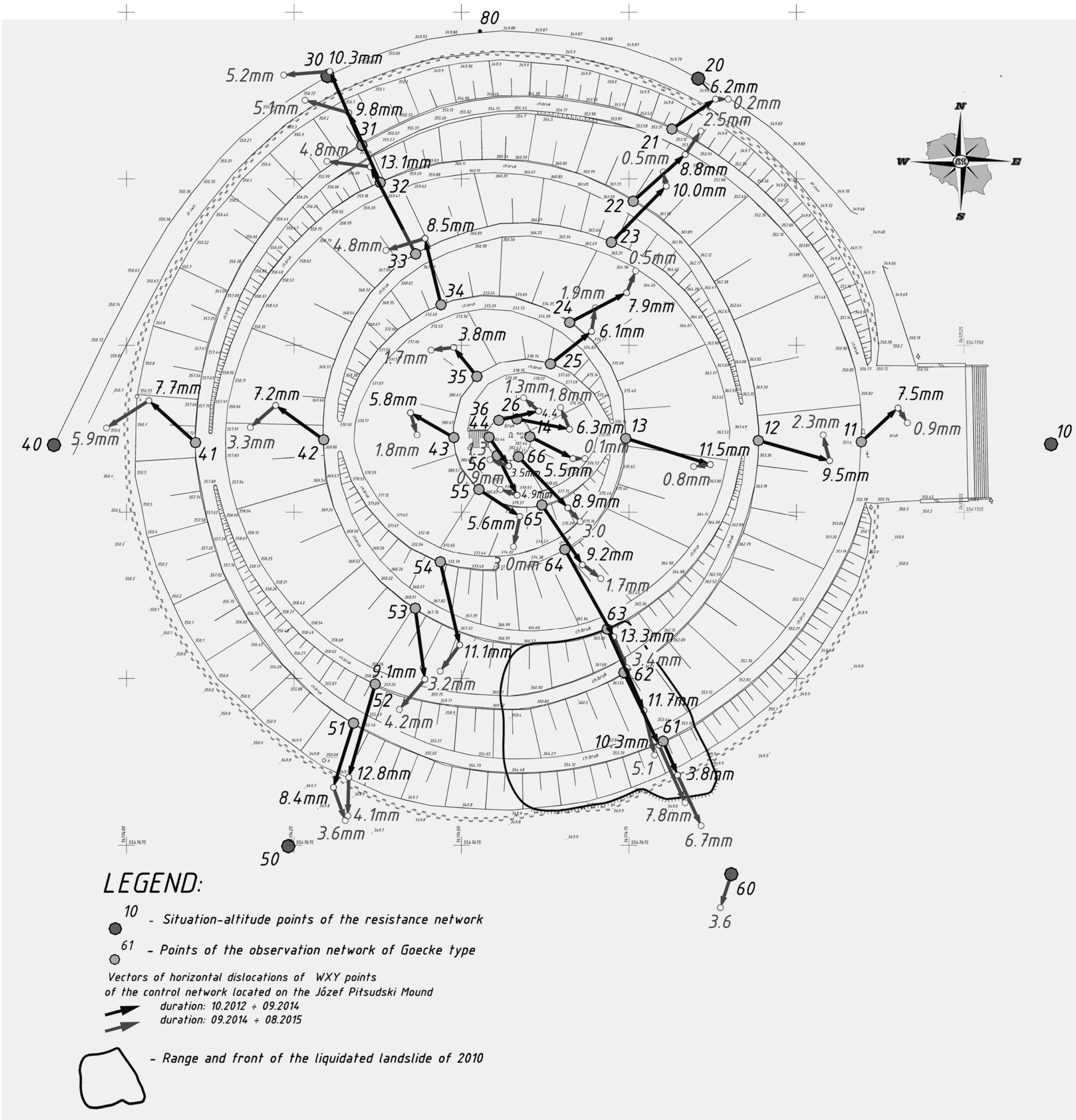


Fig. 5 Location of the points of height control network and vectors of horizontal dislocations of W_{XY} points of the control grid located on the summit of the Piłsudski Mound (duration: 10.2012 – 09.2014 and 09.2014 – 08.2015)

infiltration of precipitation waters to the inside (points of profile 61-66 on the Piłsudski Mound in the area of the liquidated landslide – Fig. 5 or point 1008 on the Wanda Mound – Fig. 6). Now, the authors make attempts to put on the Kościuszko Mound a sibling network of control points, like in the case of the Piłsudski Mound. A similar characteristic of construction and relative symmetry of the construction towards the W-E direction and a sibling system of control points will enable us to confirm a spiral anti-clockwise trend of the turn of points on its whole surface. Nowadays, on the summit of the Kościuszko Mound there are only 4 control points installed (initially they were meant to make base of the inventory measurements), but already based on two measurement cycles one can make conclusions on similar character of changes that occur in the top zones of the highest Polish mound - Piłsudski Mound. In this case there is a clear anti-clockwise movement of these points (Fig. 5).

In case of the Wanda Mound a large dispersion of the characteristics of trajectory points was observed. This mound is, however, still not examined from geological point of view. The behaviour of points and the characteristics of the movements are not as regular as on the Mounds presented earlier. To obtain a credible comparison, in Figure 5 only vectors of the last two years were put. The northern side

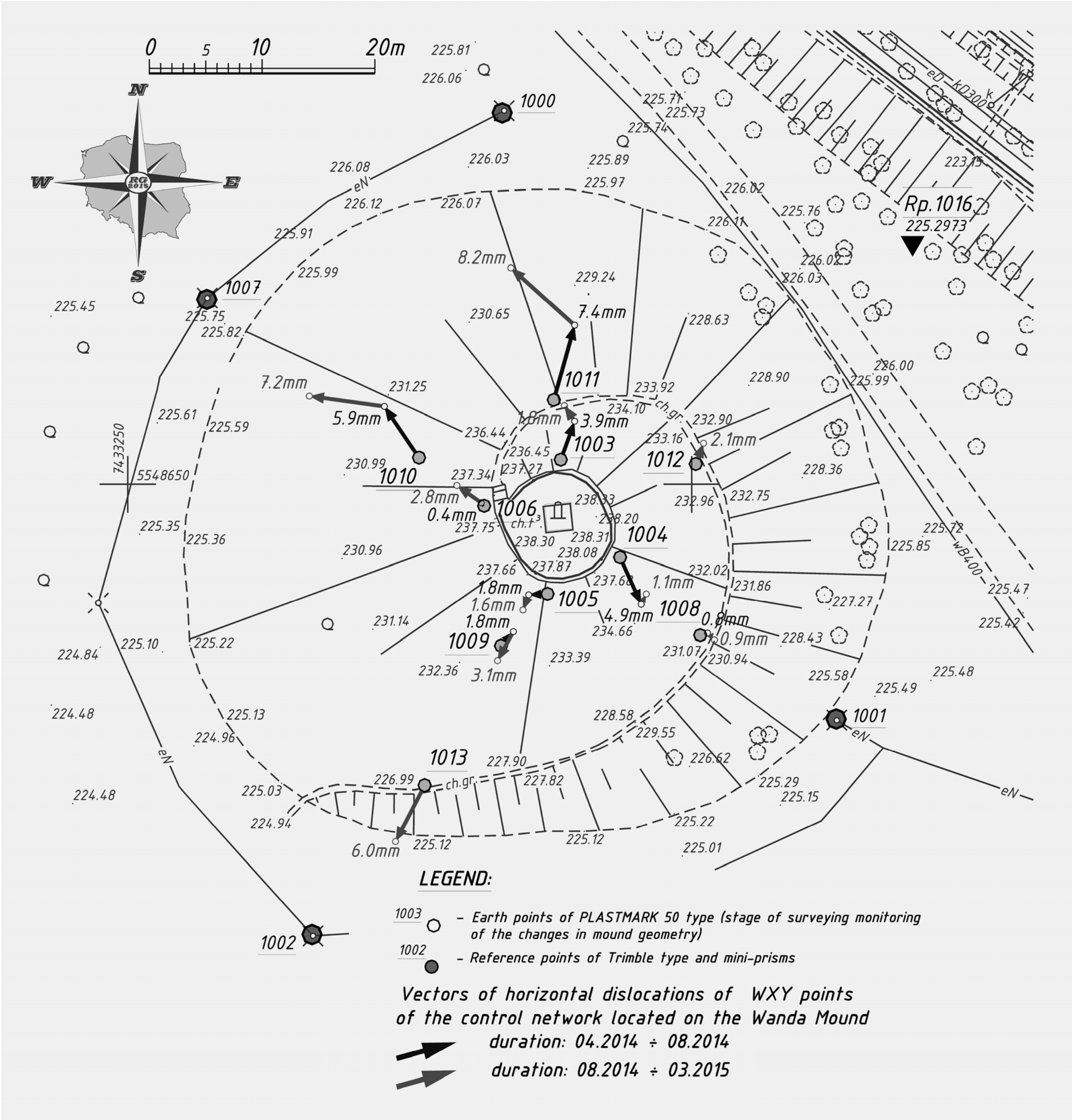
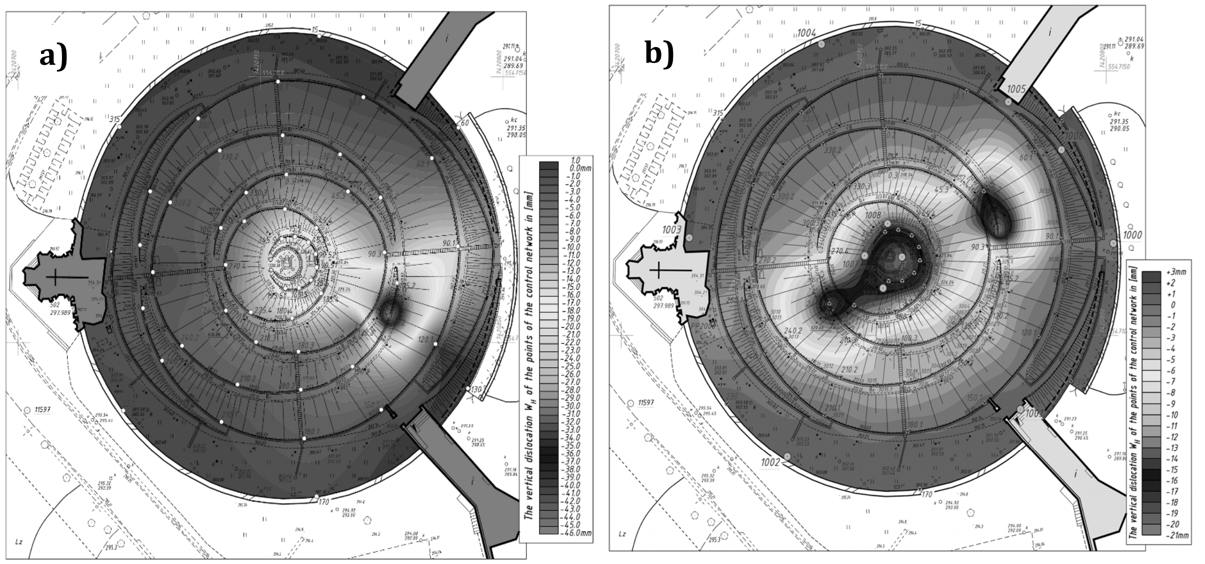


Fig. 6 Location of the points of height control network and vectors of horizontal dislocations of W_{XY} points of the control grid located on the summit of the mound (duration: 04.2014 – 08.2014 and 08.2014 – 03.2015).

reflects clear trends of the anti-clockwise movement; the southern one reflects them only in the highest part of the mound, but the values of horizontal dislocations are small. The Wanda Mound has only received provisional security measures of the surface of the paved view gallery. This system of security measures was seriously damaged, as a result of the impact of long-term and intensive rainfall in 2010. Enhancing the effect of the destruction of the view gallery occurred in August 2013, also during more intense atmospheric precipitation. The scarps of the Wanda Mound, as the only have not been professionally secured with new technologies of hydro-isolation of earth masses and enforcement of the ground. The only element protecting the surface from erosion is the layer of the overgrowing grasses.

5.2. CHARACTERISTICS OF THE TRAJECTORY OF THE CONTROL NETWORK POINTS IN THE RELATION TO AIR CURRENTS

Objects localized on the Earth surface are influenced by the rotation of the Earth. This movement causes many phenomena and forces affecting the elements of environment. One of the hypotheses of the similarity in the characteristic of the trajectory of the movements of the points on the studied mounds includes the impact of atmospheric factors on Earth cones. According to the authors, in shaping the field of dislocations for all the mounds, the characteristic of air circulation around the Earth solid also plays certain role. Wind velocity affects Earth structure of mound (pressure of the air masses onto the surface of the scarps) is growing with height.



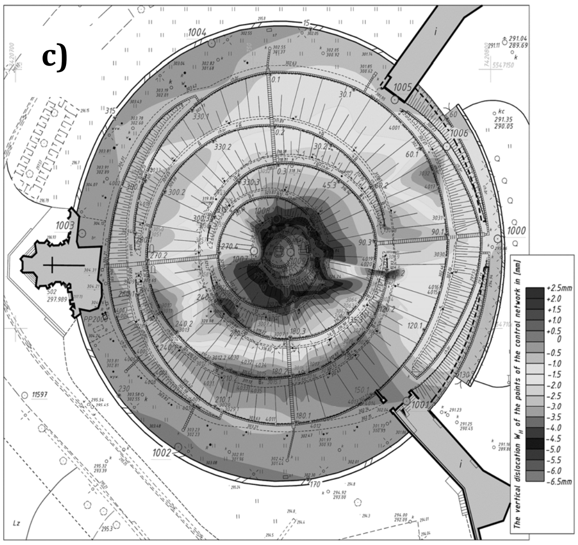


Fig. 7 Hypsometric map of the values of subsidence W_H of the points of the control network located on the retaining ledges of scarps and tambour:

(a) duration: 05.2012 - 06.2012 (1 months);

(b) duration: 03.2014 - 03.2015 (12 months);

(c) 03.2015 - 08.2015 (5 months).

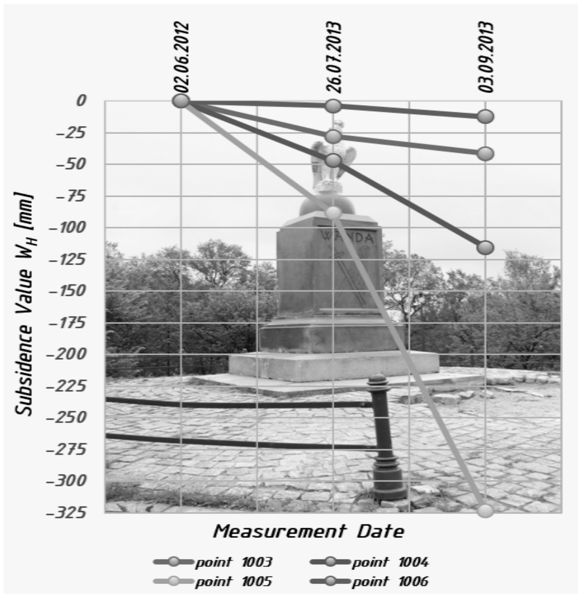


Fig. 8 The effect of the impact of precipitation on the geometry of the Wanda Mound after intensive precipitation - duration: 07.2013 – 09.2013 (~1 months)

The momentum of the acting force τ is defined as vector product: vector r joining the axis of turn and the place of putting the force and the vector of F, can be interpreted as the ability of the force to turn the solid, according to the formula (5.1):

$$\tau = r \times F$$

In the situation, when the turn is anti-clockwise, the value $\tau > 0$. The momentum of the force causing the highest turn of the solid (making the work) is observed when the component of force $F{\cdot}sin\varphi$ is parallel to the element of arc ds (surface of the scarp).

Namely, arising and character of air movements is influenced by forces such as:

- the force of the pressure gradient (caused by the pressure gradient), giving acceleration to the particle and causing the flow of air masses from the area of high pressure of the area from high to low pressure;
- the force of friction and connected aerodynamic co-factor of roughness; the more developed and covered by forest surface is, the lower air velocity at the surface;
- the Coriollis force, causing the deviation of the trajectory of the solids moving eastwards, while in case of the air currents the deviation is to the right. The movement of control points observed on 3 mounds and the trend of these movements complies with the direction of the air movements in the zones of the occurrence of low air pressure. This means that the movement is compliant with

the anti-clockwise direction and typical of air masses forming cyclone-type wind son the northern hemisphere, being the effect of the Coriollis force. As a result of the air friction, apart from the decrease of wind velocity, its twist also occurs.

Thus, curved and counter-clockwise trajectory of the dislocation of points on all the analysed mounds requires detail analysis and explanation of the causes (possible identification of factors responsible for this movement) shaped in such a way and synchronized movement of the points.

5.3. ANALYSIS OF VERTICAL DISLOCATIONS

The second component of total dislocations of discrete points characterized by the geometry of the field deformation (marked by the precise levelling method) is vertical dislocation W_H. Also in this case one should look for the correlations between typical directions of the flow of air masses and atmospheric precipitation in the Cracow region and the values and directions of changes in the vertical plane of the points of the height control network. The great significance of heavy precipitation on the Earth construction of the mounds is documented by the results of the observations obtained from the levelling measurements on the stabilized Kościuszko Mound in June, covering less than a month – late May – early June 2012 (Fig. 7a), when the local subsidence of the fragment of the solid took place. It was 45mm in the parallel direction. Another example of this type is the slide of the tambour of Wanda Mound, after the period of long precipitation in June and August (Fig. 8), recorded on 3rd September 2013. This is the mound, which so far was only fragmentarily secured – e.g., the balustrade was secured by geo-textile. The mound was then not only subdued to uneven horizontal dislocations of the value up to 11 cm, but also vertical dislocations of the value above 32 cm. The obtained results show that water is the main factor causing destruction, even in case of the application of many modern construction methods.

An excellent example of the reaction of the Earth cone, showing the impact of water and wind from the directions, according to the wind rose is the Kościuszko Mound. The biggest subsidence was recorded in WSW – ENE direction, i.e. main (typical) directions of the movements of the polar–maritime air currents (west winds) as well as polar–continental air currents and arctic air (north-east winds) in the Cracow region. The impact of currents with completely different characteristics (i.e. warm and humid versus dry and cold) on the Earth cone is reflected in the distribution and shape of iso-cata-bases (Fig. 7b). However, not only wet season shapes the process of the mounds deformation. Also dry season stimulates the changes in geometry. Exceptionally dry summer of 2015 decreased the speed of subsidence, but the biggest changes of heights of the points in the control network were observed in WSW – ENE direction. Moreover, in this direction, also the greatest height change is observed in terms of the sign, which means that local subsidence, but also zones of small ground elevations (Fig. 7c). One has to emphasize that, among the three analysed constructions, only the Kościuszko Mound is fully exposed and dominant over the horizon, thus it is assumed that the obtained distributions in two presented periods of time illustrated in Figures 7b and 7c, perfectly correspond the characteristic of the distribution of air fronts in Cracow. The Piłsudski Mound, despite its monumental look in now covered by the overgrowing trees, making a natural protective screen to the 2/3 of its height, thus the distribution of subsidence is not so distinct. Only in the summit part (uncovered) there is a direction WSW – ENE and W – E (or parallel) of the biggest height changes (Fig. 9).

Only combination of the vectors of vertical and horizontal dislocations in the duration of 35 months confirms the direction of the trend close to the direction of maximal values of the wind rose. In the case of the Mounds Kościuszko and Piłsudski, one more important trend of changes is seen, i.e. the perpendicular direction to the main axis of deformation.

6. DISCUSION AND CONCLUSIONS

Based on the obtained spatial data and the analysis of mean and limiting measurement errors, the conclusion can be made about the selection of frequencies of certain surveying works. Applying the principle that the value of dislocation is bigger than the limiting error defining the real movement of the point, one can make an initial analysis of the frequency of measurements for individual objects. Assuming time criterion that points of the dislocation value fulfilling the conditions $m_P \geq m_{Pgr}$ and $m_H \geq m_{Hgr}$ are the indicator of the classification of measurement intervals, assuming that minimal quantity threshold equals 25 % (the smallest percentage value of the participation of points fulfilling the condition $m_P \geq m_{Pgr}$ obtained for the Piłsudski Mound in the time interval of 11 months – Table 4), one can preliminarily define the time of geodetic works (from the economic point of view), neglecting the analysis of the changeability of the characteristics of the atmospheric conditions in time (e.g. division into wet and dry periods).

Based on data from Table 4, it can be preliminarily stated that the situation and height measurements of the control network should be carried out (economically justified) not rarer than:

- for the Wanda Mound – every 4 months (at least 3 times a year);
- for the Kościuszko Mound – every 6 months (at least twice a year);
- for the Piłsudski Mound – every 12 months (once a year).

The density of intervals in the future for all the studied objects and the established quantitative threshold (i.e. 25 %), will allow stricter definition of

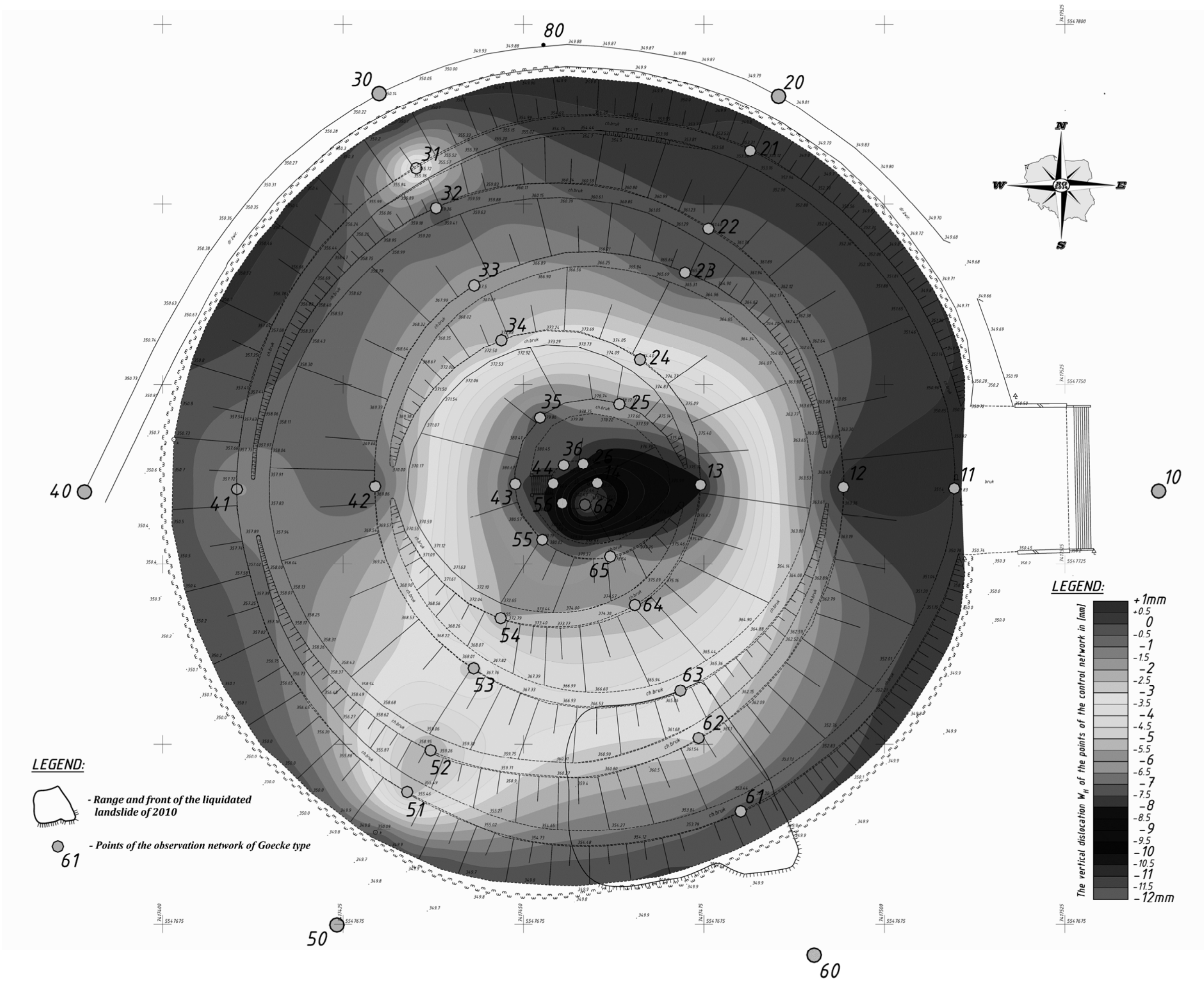


Fig. 9 Hypsometric map of the values of subsidence W_H of the points of the control network located on the edges of paved paths of the Józef Piłsudski Mound, duration: 10.2012 – 09.2014.

Table 4 Percentage of points recognized in the assumed time intervals.

Mound:	**WANDA**		**KOŚCIUSZKO**		**PIŁSUDSKI**	
Duration in [month]	**4**	**8**	**12**	**6**	**23**	**11**
Percentage of points fulfilling condition $m_P \geq m_{Pgr}$ in [%]	62	62	100	50	91	25
Number of control points	8	10	4	4	32	32
Percentage of points fulfilling condition $m_H \geq m_{Hgr}$ in [%]	88	90	63	64	75	81
Number of control points	8	10	51	53	32	32

the number of measurements and their quantitative differentiation (angular – linear measurements and levelling measurements). From the analysis of the data in Table 3, one can notice that in case of the Piłsudski Mound one could make height measurements more often than 1 measurement / year.

Apart from the Kościuszko Mound, the other analysed mounds were not subdued to detail geological studies. Thus there is no foundation to forecast possible threats resulting from the processes taking place in their inside. Today, the only source of the data on the directions and the range of changes taking place in the near-surface zone are surveying observations carried out based on sets of points permanently stabilized on the surface of the construction. The limitation of surveying methods is the fact that they only examine the behaviour of Earth masses on the surface. Their advantage is minimal cost of making measurements based on the network of discrete points, the density of which is adjusted to the characteristics of the object and the range of changes defined during the initial examination of the phenomenon and repeatability of studies, according to the accepted pattern. This means that the shape of the network changes in time due to the need of increasing point density with higher number of points in the areas of particular anomalies to define deformation phenomena more accurately.

Based on the presented results of surveying surface monitoring, one can state that these methods allow efficient identification of the landslide processes taking place in the zone near surface. They make excellent information source on the size and directions of horizontal and vertical dislocations in the networks of the stabilized control points. Changes presented in the selected time intervals on the background of the characteristics of atmospheric factors, allow us to draw conclusions on an important influence of rainfall as well as the intensity and typical directions of air currents affecting the historic mounds. All the analysed Cracow's mounds show similarity in the characteristics of horizontal dislocations, where the trajectories of the motions of the observation network points show curved movement in the anti-clockwise direction. Moreover, all of them show more intense and often variable in sign vertical movements of the points of the network in the direction NE (azimuth of about 60°) and SW (azimuth of about 240°). It should be stressed that western and south-west air currents carry water masses, which, as rainfall, influence the geometry of Earth cones in the form of subsidence on main directions of their main directions of impact.

Thus the correlation of the characteristics of active factors of environment and arising changes in the geometry of the mounds is not accidental and requires further measurements, which can make important source of information for the proper selection of the way of securing the construction and efficiency of these methods.

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