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Potential of Using Unmanned Aircraft Systems for Landslide Monitoring: the Case of Janowiec Landslide in Poland

ABSTRACT

One of the first visible signs of landslide occurrence is changes in microrelief of the slope. In the classical landslide monitoring procedure to determine the land deformation, direct surveys are used. To get accurate and actual information about the object, the ultrahigh resolution unmanned aerial systems imagery can be applied. A digital surface model can be developed and utilized to create a high-resolution orthophotograph as well as a point cloud, which can be used to develop a digital terrain model. Pictures taken by unmanned aerial vehicles have a ground resolution of a pixel on the level of single centimetres. This type of cartometric material is developed in short time and allows to specify the landslides range and features, and in evaluating the mass movement. Cyclical measurements also allow to determine the resulting deformation although it should be noted that the accuracy of survey depends on the vegetation process. In this study, the methodology of landslide monitoring using unmanned aerial systems as well as comparative analyses to the other techniques such as terrestrial laser scanning or airborne laser scanning, were presented.

Key words: *landslide, erosion processes, unmanned aerial systems (UAS), unmanned aerial vehicle (UAV), airborne laser scanning (ALS), terrestrial laser scanning (TLS)*

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INTRODUCTION

Landslides

Mass movements in past decades became one of the most common geo-hazards (*Plag and Pearlman 2009*). This process may be slow and harmless, or violent and devastating. An occurrence of mass movements is hard to predict due to complex matter of its arising factors. It is possible only to indicate the hazard areas by analysing the landform, geology and climatic factors such as intensity and amount of rain and snow.

One of the main tasks after the occurrence of a landslide is to determine its scope. It can be done on the topographic maps and often is preceded by analyses of available data, like old topographic maps, aerial imagery, digital surface model (DSM) and digital terrain model (DTM). This data allows to determinate its range but since human, had made a very intense territorial expanse in natural areas, a number of these changes were not presented on maps. In the analysis of landslides, it is necessary to determine its morphological parameters. For this purpose actual information about terrain, which can be achieved using the unmanned aerial system (UAS) is needed (*Stumpf et al. 2013*).

The Polish Geological Institute (PIG) develops "Instruction to develop maps of landslides and mass movements risk areas" (*Grabowski et al. 2008*). To define the morphological features of the phenomenon, anumber of relevant parameters should be determined:

a) general landslide dimensions (length, width, the maximal height, the minimum height, difference in elevation, movement azimuth)
b) landslide main scarp parameters (height, determined from the top to the base of the collapse and slope)
c) landslide foot and colluvium parameters (length, difference in elevation, thickness- should be estimated based on data from boreholes, toe height)
d) slope type, exposition and parameters (length, height, difference in elevation)

Also, the presence of cracks above the main scarp should be marked on the sketch of a landslide (*Grabowski et al. 2008*). Most of these parameters can be obtained from high-resolution aerial photos. Only areas of uncertainty must be confronted in the field.

Another landslides issue is monitoring of their activity. There are two main areas of interest in landslide monitoring: surface and subsurface mass movement. Surface measure methods determine deformation, velocity of mass movement, and the nature and displacement range of a landslide. Subsurface surveys determine the surface of rupture that allows to calculate the volume of colluvium and estimate the threat. Leading classic techniques for surface movement survey are tachymetry, precise levelling, Global Navigation Satellite Systems (GNSS), airborne (ALS) or terrestrial (TLS) laser scanning and interferometric synthetic aperture radar (InSAR). Each of them has some advantages and disadvantages but they have two common features – they are not cheap and take a lot of time to conduct and process data into a map or other useful product. Monitoring is not only performing surveys and analyses, but it also should detect threats and alert community. In Poland, after experiencing several landslide disasters, the Minister of the Environment on 2007 (*Regulation Of The Minister Of The Environment 2007*) issued a regulation concerning information of mass movements, forces local governments to conduct surveys of the risk areas where the mass movements occurred that might be causea direct threat to human and infrastructure.

The main aim of the current study is to analyse the possibility of using UAV for the initial analysis of landslide features and range, and in evaluating the possibilities of using UAV for landslide monitoring. The main scope is the use of UAV, and the data of terrain and object obtained from UAV for the analysis and monitoring of the landslide. Object data from ALS and TLS studies were also as reference point and comparative methods. To meet the need of acquiring updated and accurate information fast, the authors propose to use a cheaper but modern technology- the UAS. This solution allows obtaining information about an object, features of the landslide, from aerial photos captured by DSLR (Digital Single Lens Reflex) camera with a ground resolution of 2 cm/px. After processing (matching of photos) detailed data obtained from UAV, the researchers received points cloud and a high-resolution orthophotograph. A points cloud can be used after filtering and classification as the subproduct to develop the DTM. The changes in the surface as a result of the meteorological, hydrological and nature forces as well as human activity can be observed using differential models of minimum two measurement campaigns (*Pilecki 2012, Pilecka and Manterys 2013, Cebulski 2014, Dąbek et al. 2014*).

Survey methods

Landslide activity and morphological parameters can be indirectly determined by observing the surface cracks, bulges and infrastructure deformation. Comparison of a large scale topographic maps and airborne high resolution photogrammetry imagery is also helpful in analysing changing surface. Geodetic methods, as well as remote sensing techniques including TLS ALS, GNSS and InSAR, are very useful for determining morphometric parameters, features, range of landslide as well as activity and monitoring. Modern remote sensing methods like aerial photogrammetry (*Walstra et al. 2004, Corsini et al. 2009, Prokešová et al. 2010, Niethammer et al. 2012, Stumpf et al. 2013, Fernández et al. 2016,*), ALS (*Glenn et al. 2006, Borlat et al. 2007, Cavalli and Marchi 2008, Avian et al. 2009, Baldo et al. 2009, Haneberg et al. 2009)*, TLS (*Rosser et al. 2005, Abellan et al. 2006, Prokop and Panholzer 2009, Teza et al. 2008*) and InSAR (*Mirzaee et al. 2017*) are able to measure deformation of all landslide surface, not only in selected. In recent years the development of technology allowed for use aerial photogrammetry from UAV equipped with a non-metric DSLR camera to landslide monitoring and research.

Specifically, GNSS surveying allows to define basic linear landslide dimensions, assessment of dynamics of mass movement that can be used for landslide monitoring (*Fastellini et al. 2011, Palmerini 2012, Wang et al. 2014*). Post-processing GNSS data reach millimetre accuracy and the real-time GNSS measurement reach centimetre accuracy, (*Bellone et al. 2014*). However, GNSS measurements give correct results only in relation to the points measurement. This method allows to determine the landslide activity and dynamic, but volume of colluvium assessment and survey under the trees are difficult. Any attempt to build profiles, cross sections or 3D models is performed by the linear interpolation between the measurement points, which may cause a big averaging and significant errors.

Nowadays, laser scanning (ALS, TLS) is the most common survey technique obtaining data for analyses of landslides and any others terrain transformation (*Jaboyedoff et al. 2010*). Scanning systems, called full-waveform LiDAR (Light Detection and Ranging), have the ability to record multiple reflections of a single pulse and register not only the top levels of vegetation but also ground (*Mallet and Bretar 2009*).

This allows to study the terrain surface, regardless of its coverage. In addition, ALS data should be classified so the ground points are separated from all point cloud.

The ALS allows to show terrain deformations of large areas in a short time. Unfortunately, operating cost is high and there are many conditions to be fulfilled. The first main limitation of using ALS is weather condition. Rain or fog limits the penetration of laser light and causes a noise. To avoid mapping vegetation, it is recommended to perform the measuring campaign from autumn to spring. The second limitation is the cost of measurement, especially if the object area ranges only one landslide (*Graniczny et al. 2012*). The ALS delivers very detailed information about the landslide morphometric, microrelief, range of mass movement, and the identification of landslide active areas. ALS data reach dozen centimetres accuracy. Additionally, in the case of differential analysis of at least two datasets, it is possible to get information about changes of the landslide active area (*Pfeifera and Briese 2007, Jebur et al. 2014*).

The ALS is a remote sensing technique that has been commonly used in assessing the dynamics of terrain morphometric parameters changes, including mass movements and other erosion processes in the Poland (*Borkowski 2004, Borkowski et al. 2011, Kasprzak and Traczyk 2011, Wójcik et al. 2013, Wojciechowski et al. 2012*), as well as abroad (*Webster et al. 2006, Jaboyedoff et al. 2010*). However, ALS does not give information of the landslide geological characteristics, the nature of the soil, tectonics and hydrological conditions. These information should be obtained from field recognition. Moreover the use of ALS data coincides with the Landslide Counteracting System (SOPO) instructions in terms of mapping landslides and determination of morphometric traits (*Borkowski et al. 2011*). Nevertheless, field inspection appears necessary to the correct classification of landslides morphological features.

The ISOK project (IT system of the Country's Protection Against Extreme Harazds) is the special programme, which is based on ALS data and was implemented in Poland in recent years. While the ALS data collection for the whole country started in 2011, the whole project was ended in 2016. The first data were collected for the areas with increased flood (*Wężyk et al. 2015*). The density of the point cloud is 4 pt/m^2 and for urban area there is 12 pt/m^2. The classification was done according to American Society for Photogrammetry and Remote Sensing (ASPRS) in .LAS format file ver. 1.2. In studies on mass movements, ALS ISOK data may be the final state of past phenomena (according to obtaining data for the years 2010-2016) or the initial state when researching future landslides. So far, the ALS ISOK data in Poland are used also in the geological and morphometric research (*Migoń et al. 2013, Migoń et al. 2014, Wężyk et al. 2015*). The ALS ISOK data are free of charge for scientific research. It is the largest and only project of this type in Poland where ALS was made for almost the entire country and a classified point cloud and high resolution DTM were developed. This type of work will not be repeated quickly. Therefore, ALS in landslide monitoring may not be appropriate.

The TLS is modern and relatively fast methods allowing for the accurate imaging of micromorphology and for deformation analysis. A short time data acquisition, simplicity of use and high accuracy make TLS increasingly applicable for mass movements' research. Technology utilized in the measurements is similar to that used in ALS. Device surveys distance to object, the horizontal and vertical angles and calculate the XYZ coordinates for each point in the cloud (*Slob and Hack 2004*). Scan resolution can be set up to sub-millimetres value. In TLS method, a number of additional information can be obtained. This data can be classified into groups of points, which represent vegetation (low, medium and high), buildings, noise and others, but the most important in this case is the ground class.

Measurements of morphometric traits and activity of landslides using TLS allow for defining active areas and terrain deformation, determine the size and speed of mass movement (*Cebulski 2014*). Mountainous landslides are often situated in areas partly covered by dense vegetation, where traditional methods do not allow to capture occurring cracks and changes in terrain morphology. An extremely important issue for the accuracy of the measurements is adequate number and scanner station localization on the object with short measurement time, which reduces the amount of shade and allows for accurate reflection of the micromorphology of the landslide relief. The distribution of stations depends on the local topography, the type and density of vegetation, land cover, technical obstacles and limitations of devices (*Dąbek et al. 2018*). TLS is a technology that has been widely used in assessing the dynamics of morphometric traits of land change, including mass movements and other processes of erosion in Poland (*Kramarska et al. 2011, Pilecka and Manterys 2013, Cebulski 2014*), as well as internationally (*Giussani and Scaioni 2004, Abellan et al. 2006, Abellan et al. 2009, Abellan et al. 2010, Barbarella and Fiani 2013, Bechet et al. 2015, Crepaldi et al. 2015, Spreafico et al. 2015*).

Photogrammetry is a technique that allows observation of the entire examined area, which is of great importance and an advantage over classic measurement methods. It allows determining the range of landslides and deformations. Depending on the method of taking pictures, this method can be divided into: terrestrial with a resolution ca. 1 cm, aerial with resolution ca. 5-10 cm and satellite with a resolution > 10 cm. Aerial photogrammetry is prmarily used in documentation and research works. The advantages of this method include, among others, the detail, short measurement time, high accuracy, which is constantly increased along with the development of digital image acquisition technology. The use of digital cameras and improved algorithms for automatic combining of captured images allow for even greater popularization of this measurement method using unmanned aerial vehicles. Through aerial and satellite imagery, information about the entire facility could be obtained in a short time. The only downside is the lack of observation of changes hidden under the vegetation. The use of this method for recording and monitoring mass movements has been described widely (*Maria et al. 2004, Mills et al. 2005, Hu et al. 2008, Liu and Wang 2008, Smith et al. 2009*).

Miniaturization and development of new technology make it possible to use unmanned aerial vehicles (UAV) in the remote sensing of close range. Moreover, compared to traditional devices, UAV as an aerial platform, which is capable to carry various measuring sensors and allows to reduce the cost of equipment purchase and data collecting (*Konieczny 2015*). Assisted by computer programs, UAS is the perfect tool for documentation, measurement and monitoring of phenomena in the natural and anthropogenically transformed environment.

Close-range photogrammetry, implemented by UAS, gives the possibility of acquiring point cloud with the centimetre precision. The high spatial resolution data give the possibility to register the details of the land relief and technical objects, as well as changes in the environment. In addition, the easiness of acquisition and low operating costs make it possible to frequent repetition measurement campaigns. This is a big advantage especially in the registration of the individual effects of natural phenomena. UAS has been successfully used in Poland and in the world to document and monitor different objects (*Jankowicz 2010, Witek et al. 2013, Máthé and Buşoniu 2015, Stöcker et al. 2015, Turner et al. 2015, Tang and Shao 2015, Zahawi et al. 2015*). The results of UAS missions are images with the ground resolution of a few centimetres. The resolution depends on the altitude and this translates into the area which is covered by the single image. With specialized software, it is possible to get orthophoto maps, generate DSM, DTM and 3D models of technical objects (*Konieczny 2015*).

Data obtained by ALS, TLS, UAS need to be filtered to the DTM development. During filtering, the point cloud is divided into classes corresponding (in simplification) to ground, vegetation and buildings. ASPRS developed the specification of point clouds dataset records into .LAS files format. Point clouds obtained from photogrammetry and LiDAR, and the filtration processes produce different results, especially in the number of points in the ground class, and consequently in DTM accuracy. Because there is not penetration through soft elements (eg. vegetation) in photogrammetry. Thus, the application of points cloud and DTM from photogrammetric may not give good results in terrain presentation. To perform the filtration process, the first step is to select few points that are on the ground to create reference surface, then there are algorithms developed to perform almost fully automatic classification (*Axelsson 1999, Hyyppä et al. 2002, Sohn and Dowman 2002, Borkowski 2003, Marmol 2003, Borkowski 2005*). Further performed analysis used ISOK data which is provided in the .LAS file format and contain classified point cloud according to the ASPRS specification. The acquired data from TLS and UAS were classified independently in one of the major leading software – Terrasolid TerraScan. For this purpose, a defined ground routine classification algorithm was used, which classifies points belonging to the terrain class by iteratively building a triangulation surface model (*Soininen 2012*).

MATERIAL AND METHODS

Study area- Janowiec landslide

Performed studies to obtain morphometric information and determination of deformation parameters using different techniques are presented on an example of a localized landslide (N: 50° 30' 6", E: 16° 44' 34"; PL–92: 339976, 295166) in Lower Silesia in the Bardzkie Mts., Sudeten region (**Figure 1**). The study area is located in Ząbkowicki district, near the Bardo city, on the south bank of the Nysa Kłodzka river. In July of 1997 after prolonged rains and flood, the landslide occurred on the slope of Mount Kurzyniec (528 m a.s.l.). In the nearest neighborhood, there is the international railway line CE 59/2 (No. 276), the E 67 international road (national road No. 8), factories, Janowiec village, and the Bardo city. The landslide is located next to the Sudeten Marginal Fault (**Figure 2**).

The morphology and parameters of the landslide ha

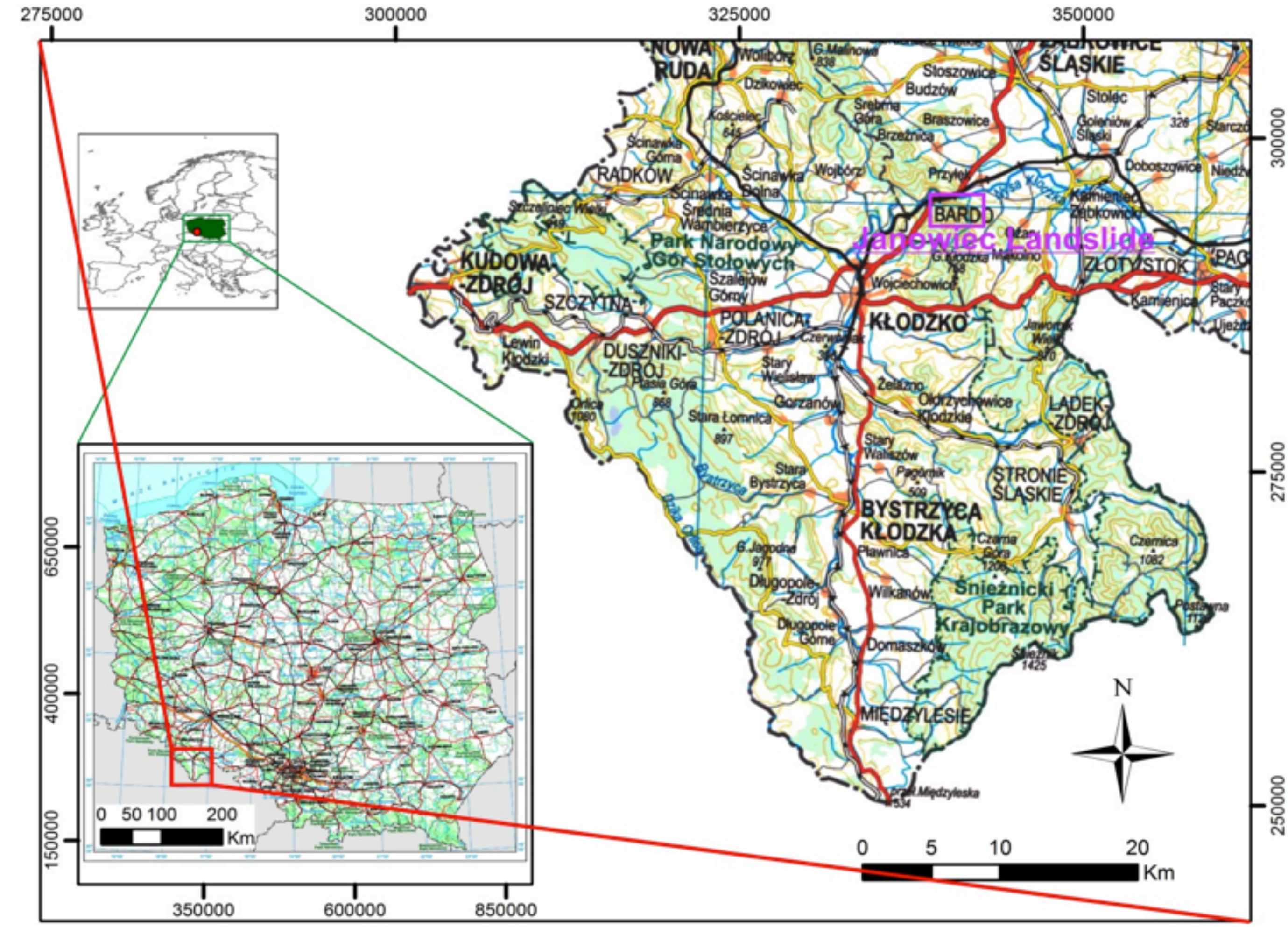

Figure 1. Location of the study area, Janowiec landslide, region of the Bardo City, Poland (coordinate system PL –92).

in Janowiec during fieldwork: landslide area 1.1 developed in the valley of the Nysa Kłodzka river of 20-25 m above. The azimuth of landslide is 10°, the length reaches 130 m and width is 120 m. The maximum relative height was observed in the morphology of the main slope and it exceeds 8 m. Near the main slope begins a ditch with up to 2 m depth. In 1997, within the landslide area, clearly have indicated a secondary slope and many crevices. In the upper part the investigated area, the slopes do not exceed 5°. The study area is used agriculturally as a pasture. The surface area is covered mostly with deciduous trees.

Geology

Most of the landslides in Poland (over 90%) are concentrated in the Carpathian region (*Poprawa and Rączkowski 2003, Grabowski et al. 2008*), therefore area of Poland might be divided into Carpathian and Non-Carpathian regions. Non-Carpathians landslides are associated with the occurrence of a series of Neogene and Quaternary till and loess, whereas Carpathian landslides are associated with Flysch forms (*Grabowski et al. 2008*).

The landslide area is located on the Quaternary formations in particular on the glacial till with the contents of rubble. The oldest rocks in the study area are revealing themselves in the indentations erosion mudstones, till, greywacke sandstones assigned to Lower Carboniferous formation from Opolnica (*Oberc 1987, Cwojdziński and Pacuła 2009*). Development and geological position of the Lower Carboniferous deposits in the Bardzkie Mountains were shown in numerous works (*Finckh 1932, Wajsprych 1978, Wajsprych 1986, Oberc 1987, Chorowska and Wajsprych 1995, Wajsprych 1995, Chorowska and Radlicz 1994*).

The study area is bounded by deep erosion gorges oriented transversely to the slope, with a depth of up to 8 m. Exposed strongly at the bottom are fractured Carboniferous shales. In the eastern ravine due to backward erosion is developing sub-indent of the SW-NE. This direction is analogous to the slope aspect. This may reflect the neotectonic movements that occur

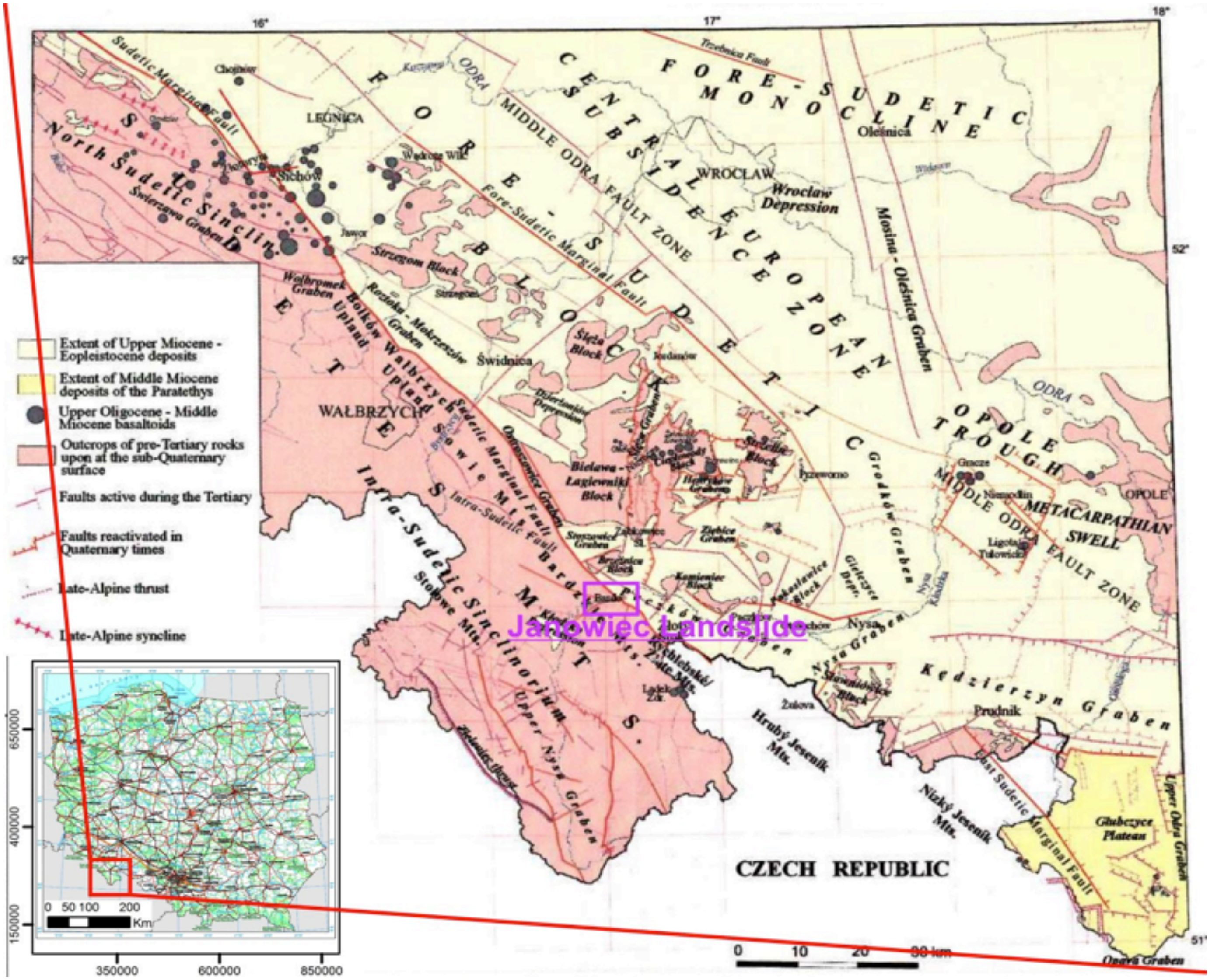

Figure 2. Neotectonic map of the region of the Bardo city, Lower Silesia, Poland (*Badura et al. 2004*).

along the sub-block faults coupled with a system of the Sudeten Marginal Fault (*Oberc and Dyjor 1969, Krzyszkowski et al. 1995, Badura et al. 2003*). After fieldwork conducted by Polish Geological Institute (PIG) a landslide cross-section was developed (**Figure 3**). But there is another hypothesis about the location of slide surface which requires further research already conducted by PIG.

Landslide moves directly to the bottom of the Nysa Kłodzka river valley. However, this did not result in flow limitation of the river due to the small volume of moving material. It covered part of the hillside from 295 m a.s.l. to the bottom of the valley (225 m a.s.l.).

METHODOLOGY

The main aim of the research was to demonstrate the possibility of using UAS for the analysis of landslide features. As part of the objective, analysis of available materials on the Janowiec landslide from central- state sources (topographic maps, BDOT, ALS) as well as data generated by other methods (TLS) was performed. Based on them, the landslide features were determined or the uselessness of data was demonstrated. The analysis of the resources with which landslide DTM can be obtained (TLS, ALS) was also used to implement the differential models method in order to preliminarily assess mass movements in this area over the last few years.

The methodology for analysing processed data consisted in creating differential models. From the control model (model created from the previous measurement campaign), the original DTM (model from the later campaign) was subtracted, as a result, the terrain differential model was obtained. The differential DTM developed allows for observation of changes in the terrain relief of the area of the analysed

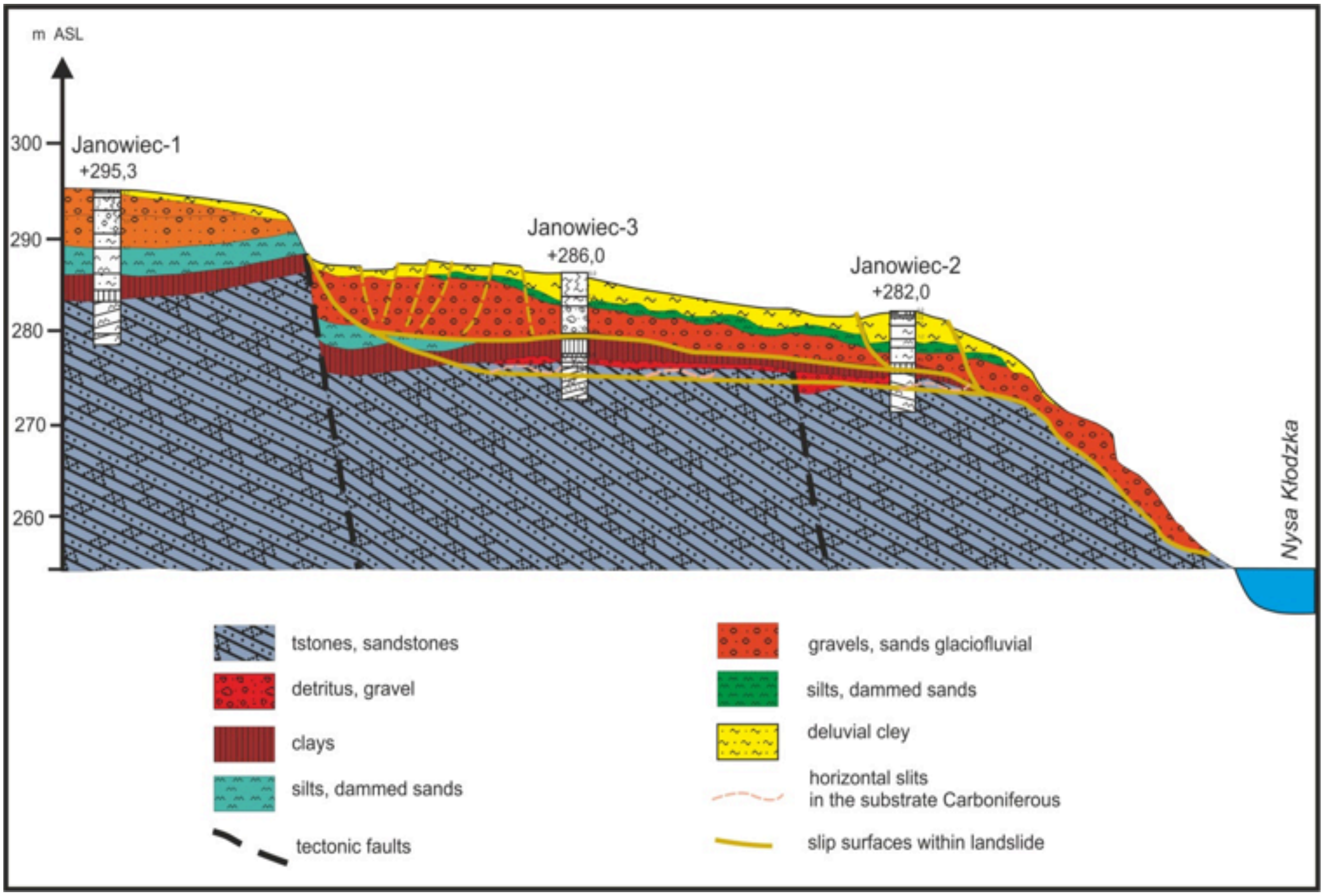

Figure 3. Cross-section of the Janowiec landslide (*Wojewoda and Kowalski 2016*).

object (landslide). If in the period between measuring campaigns erosive phenomena occurred, which resulted in a change in the terrain relief, both in the vertical axis (change in height) and horizontal axis (mass movement, range), the differential model enables the location of the terrain changes and allows their analysis.

The sketch made on field vision of the landslide was made in accordance with the SOPO instruction (*Grabowski et al. 2008*) (**Figure 4**). Despite the experience of the sketching expert, many elements of microrelief was omitted, the shape of the main scarp and the landslide foot is significantly different from the real. The presented sketch does not identify morphological features, however, due to the correct topology it simplifies orientation in the field and finding the measuring objects (boreholes).

Some morphometric parameters shall be taken from the old topographic map or topographic objects visualisation, which is now created using, inter alia, a database of topographic objects (BDOT) and DTM. Contours generated from DTM are generalized before map edition. If contour interval on the topographic maps is minimum 2.5 m, the contour line is smoothed. The

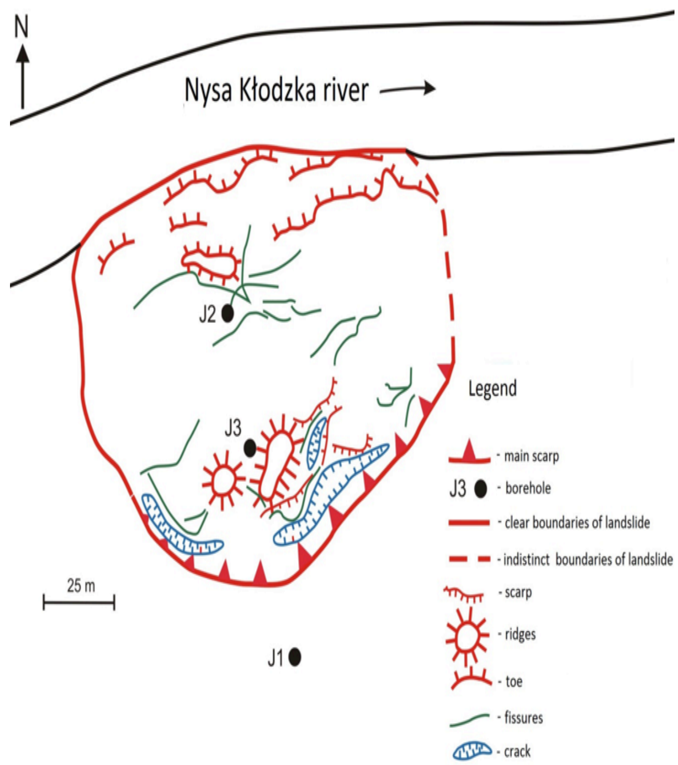

Figure 4. Sketch of the Janowiec landslide (*Wojewoda and Kowalski 2016*).

accuracy of positioning the contour on slopes exceeding 6° can be equal to contour interval, then the accuracy of reading the elevations from the map may exceed assumed 1 m. Furthermore, the final officially released topographic map of the Lower Silesia region was in 1998, the accuracy of contours was a few meters. Visualization of BDOT (2011-2013) is only illustrative and does not contain any contours (**Figure 5**). More rational seems to be using measurement data obtained from UAS.

One important element on the landslide studies and monitoring is to determine the area of occurrence as well as its micromorphology. To define parameters of landslide, several methods of surface measurements like tachymetry, GNSS and hand-held GPS loggers can be used. In the beginning of the landslide monitoring in 2009, the toe of the landslide and the slope above was surveyed using GPS RTK technique, ca. 600 pickets were measured. However, only selected features of the landslide were analysed at that time, which in this analysis can not be part of the differential models method. Moreover, the data are intended to be used at a next deformation research as a monitoring element.

In 2009, TLS measurements using Leica ScanStations 2 have been done on the Janowiec landslide. A total of 27 stations acquiring more than 110 million points have been set up on the area of 10 ha. All surveys took four days of fieldwork. At the time of gaining access to modern measuring devices, it was decided to use a laser

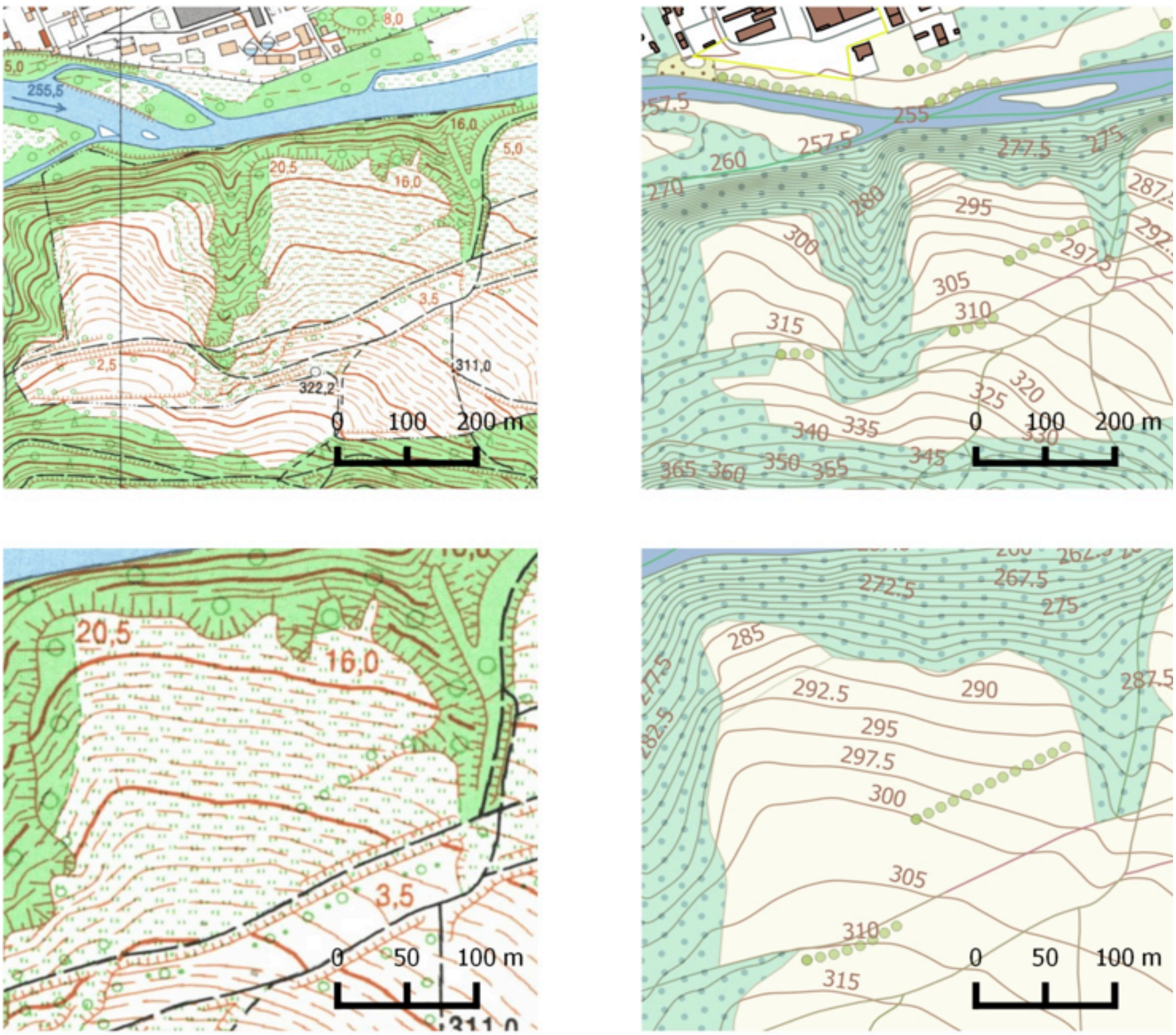

Figure 5. Topographic map (on the left) and visualization of BDOT (on the right) of the Janowiec landslide area.

scanning technology in the area of the landslide as part of the monitoring. This was the next stage of the study of mass movements in this area. After TLS point clouds classification, the ground class was used to develop the landslide DTM with 10 cm resolution, which was necessary to analyse morphometric information of the landslide.

The ALS points cloud of the study area from Central Geodesy and Cartography Documentation Centre, Poland has been obtained under the ISOK project in 2011 and have a density between 4 and 12 pt/m^2. ISOK data are classified and saved in .LAS file format under the contract by a government agency. Users of these data do not have the opportunity to view the procedure of classifying or processing aerial data. A DTM with 40 cm resolution was created on the basis of the point.

In 2015 to obtain UAS data of landslide authors used homemade six-rotor copter equipped with Canon EOS M camera with a 22 mm focal length lens mounted on stabilizing arm (gimbal). In less than an hour of flight at an average altitude of 120 m, 1400 images (ground resolution 2.5 cm/px) of the landslide and its neighbourhood (75 ha) were obtained. To conduct the flight along the waypoints the Mission Planner program was used (**Figure 6**). The points were evenly distributed throughout the entire landslide area, with densities in the places of significant change of the terrain relief, as well as outside the landslide area on the other side of the river (**Figure 7**). Calibration and validation of the obtained images based on the points were used to create the pointscloud (**Table 1**).

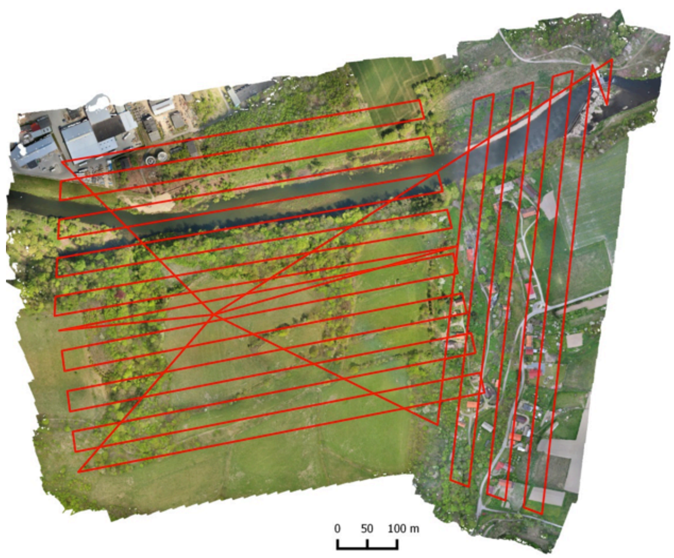

Figure 6. Mission plan for UAS on the Janowiec landslide area.

Table 1. The report of calibration and validation images from UAS mission.

Control points						
Label	**X error (mm)**	**Y error (mm)**	**Z error (mm)**	**Total (mm)**	**Image (px)**	**Projections**
k001	-9	5	1	10	0,217	19
k004	-8	11	7	15	0,542	19
k006	10	-11	-5	15	0,237	25
k009	-10	1	-1	11	0,09	35
k010	0	-2	-4	4	0,162	26
k011	6	14	1	15	0,193	31
k013	19	13	-21	31	0,171	28
k015	-11	-26	7	29	0,186	24
k016	6	-4	-3	7	0,218	13
k018	-6	1	0	6	0,064	13
k019	-2	1	-1	2	0,215	17
k020	3	-2	1	4	0,304	12
Total	8	8	4	13	0,217	
Check points						
Label	**X error (mm)**	**Y error (mm)**	**Z error (mm)**	**Total (mm)**	**Image (px)**	**Projections**
k002	9	-7	-20	23	0,534	7
k005	-14	0	10	18	0,287	19
k007	8	-6	2	10	0,213	14
k008	5	10	-5	12	0,146	27
k012	-8	0	6	10	0,214	27
k014	8	9	-1	12	0,106	23
k017	-4	-10	17	20	0,156	36
Total	8	6	9	15	0,237	

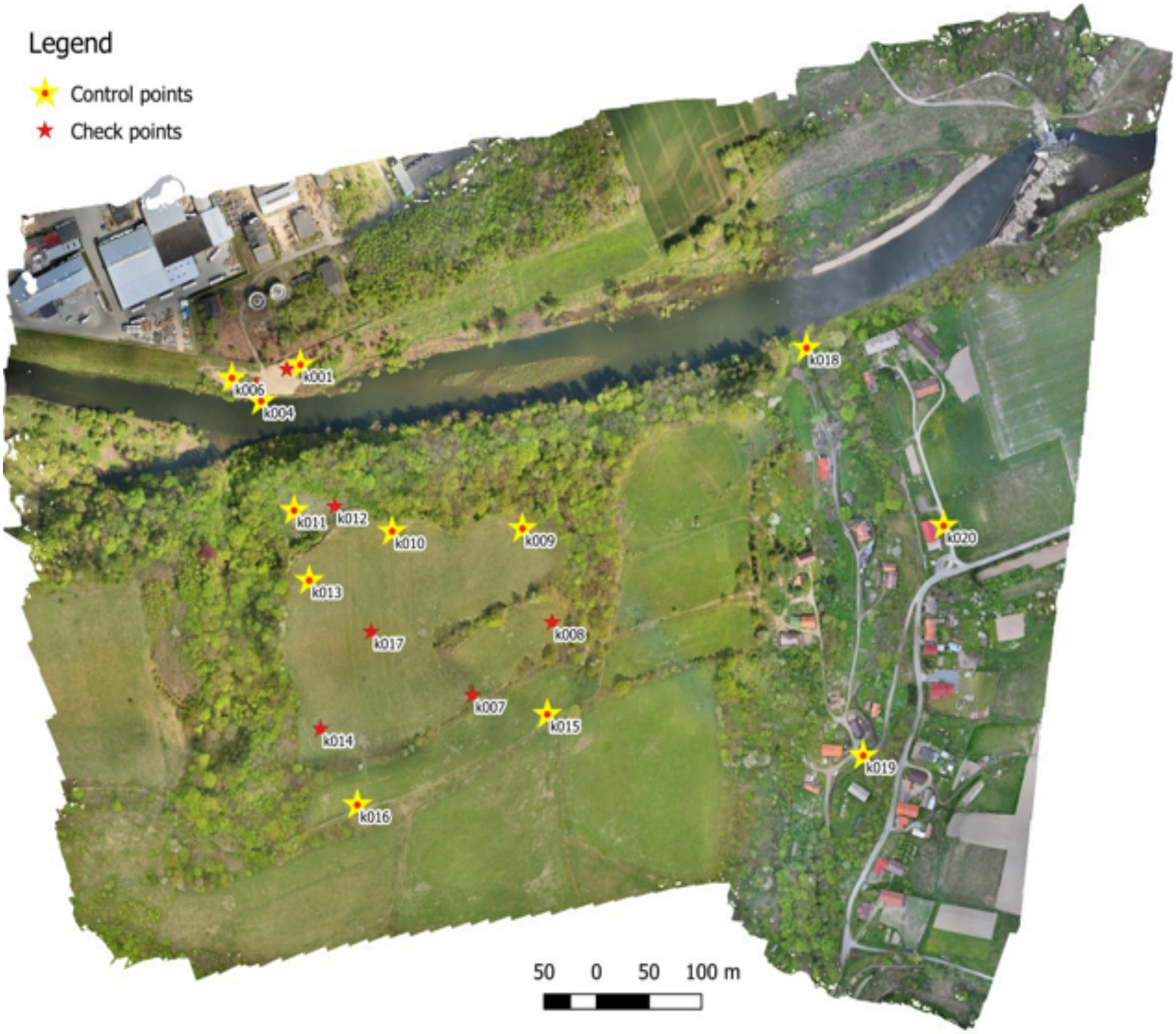

Figure 7. Ground control and check points of the UAS mission.

Then, in the Agisoft Photoscan software there was generated (based on 19 control points, **Figure 7**, **Table 1**) a calibrated unclassified points cloud of 400 million points of the landslide and adjacent areas. The points cloud of the landslide was ca. 100 million points. After classification the points cloud of the ground class of the landslide area was ca. 21 million. To manage this aim working station equipped with an Intel Xeon E5-2650 processor, Radeon HD-7990 graphic card and 64 GB RAM was working permanently for 35 hours. Afterwards, dataset was classified to obtain points of the ground class. This way developed DTM with 10 cm resolution of the landslide was used to specify morphometric parameters.

RESULTS AND DISCUSSIONS

Landslide morphometric parameters

Data obtained by different measuring methods were used to develop DTMs (**Figure 8**). All of them are different each other because of the techniques limitation. The most detailed DTM is based on TLS data, because it was made from the ground under trees, but surveys took the most time on fieldwork. The best time to obtain data has the ALS technique, but costs limit the usefulness of this technique only for large areas or for larger central projects. Thus, the reserchers proposed the UAS as the solution connecting low-cost, low time and adequate accuracy.

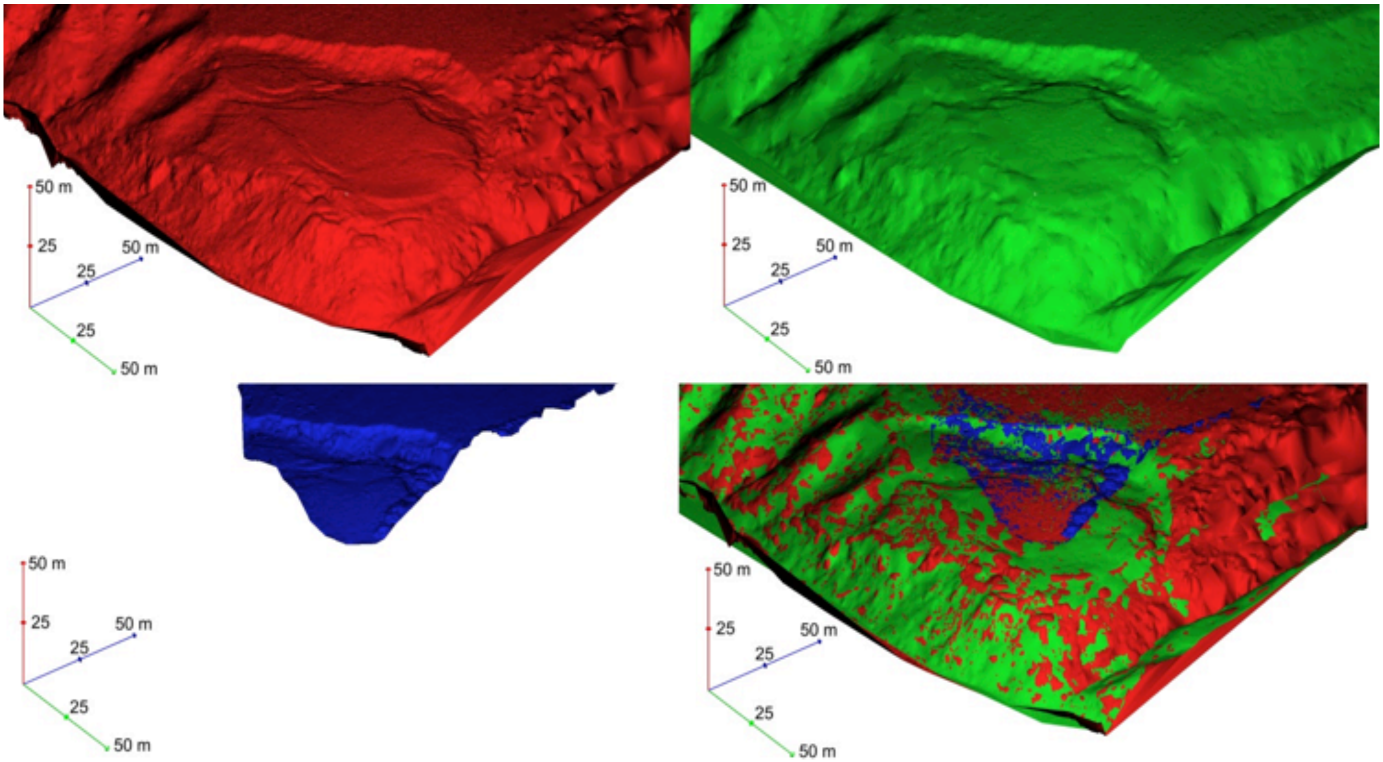

Figure 8. DTM of the Janowiec landslide developed from: A – TLS (2009), B – ALS (2011), C – UAS (2015), D – compilation of all techniques.

The UAS data are used to develop measurable orthophotographs that could supply missing information. This technique is not suitable for all terrain, especially fails on the forested area, because it does not penetrate vegetation, therefore, the DTM presented below from UAS has a smaller range and was possible to obtain in high resolution only in the case when vegetation is not dense. In many cases, integration of TLS and UAS allows obtaining complete information about a landslide in a short time.

Next, an assessment of the suitability in the process of identifying the landslide morphometric has been done according to *Grabowski et al.* (*2008*) (**Figure 9**) (**Table 2**).

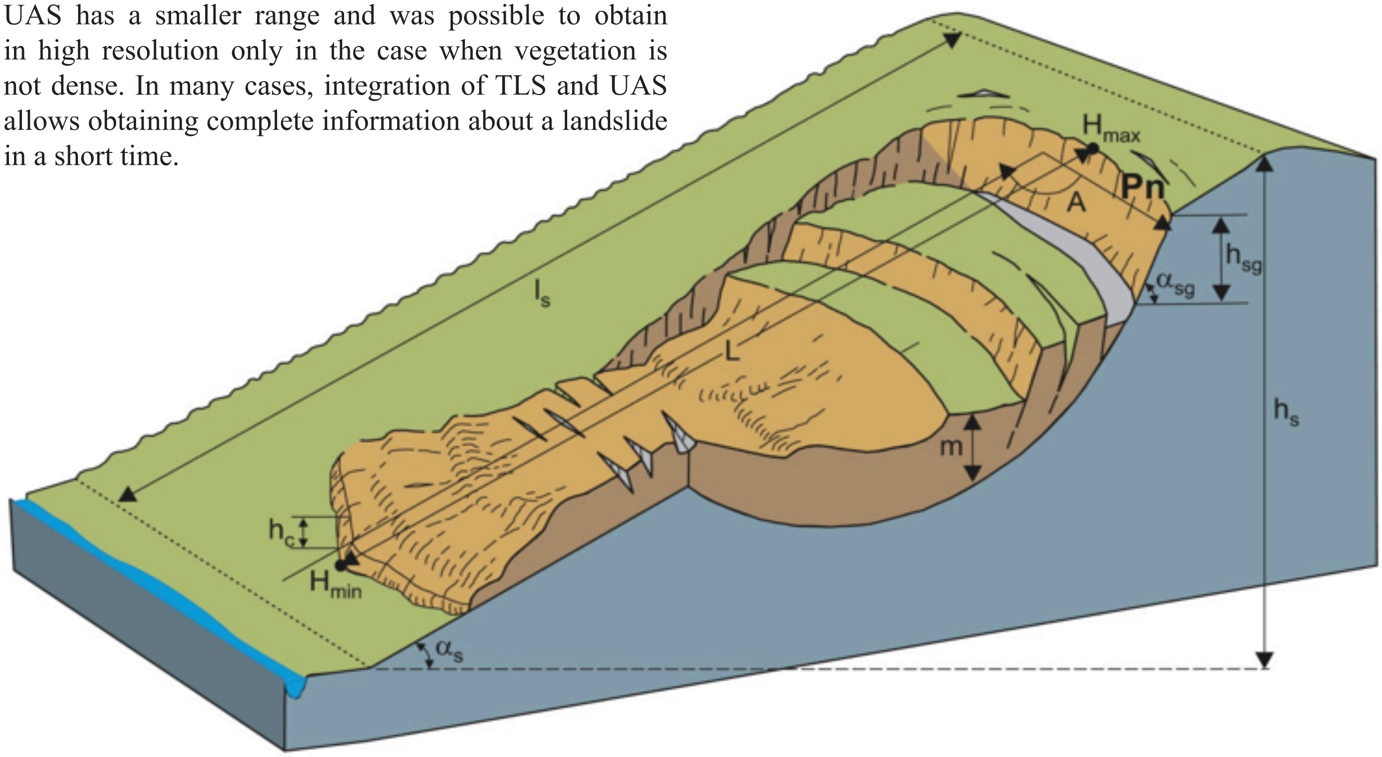

Figure 9. Morphometric parameters of a landslide (*Grabowski et al., 2008*).

Table 2. Comparison of maximum monolayer adsorption capacities of different adsorbent for methylene blue.

Morphometric parameters		Survey method		
		ALS ISOK	TLS	UAS
General	Area So [ha]	1.064	1.062	n/a
	Length L [m]	140.2	145.2	140.3
	Width W [m]	114.1	115.3	80.9*
	Maximal abs. height H_{max} [m]	293.0	293.1	293.0
	Minimum abs. height H_{min} [m]	255.4	255.2	255.9
	Spread R [m]	37.6	37.9	37.1
	Gradient α [°]	15.6	15.1	15.3
	Azimuth [°]	320	320	320
Scarp	Main scarp height h_{sg} [m]	6.6	6.6	6.8
	Main scarp slope α_{sg} [°]	29	28	29
	Fissures above the main scarp [YES/NO, how many, length, width, azimuth]	-	-	-
	Minor scarp [YES/NO, how many]	-	-	-
Toe and colluvium	Toe height h_c [m]	24.7	24.2	30.7*
	Colluvium surface length L_k [m]	109.1	111.3	110.5
	Colluvium Surface slope α_k [°]	16.5	16.3	15.9
	Colluvium thickness [m]	n/a	n/a	n/a
Slope	Type of slopes (classification of slopes due to their longitudinal profile. Select one of the options: 1 - convex; 2 - concave; 3 - convex-concave; 4 - simple (uniformly inclined); 5 - different.)	1	1	1
	Gradient α_s [°]	2.5	3.5	2.5
	Exposition (N; NE; E; SE; S; SW; W; NW)	N	N	N
	Length l_s [m]	n/a	n/a	n/a
	Slope Height h_s [m]	n/a	n/a	n/a

* gross error caused by vegetation

Surface transformation

The main aim of the research was to demonstrate the possibility of using UAS for the analysis of landslide features and for this purpose only DTM from UAS may be sufficient. Additional objectives were to demonstrate the possibility of monitoring landslides by UAS and DTMs obtained by various methods. All measurements have been executed at different times (2009–2011–2015), that made possible to analyse deformation occurred in time and conduct monitoring. For this purpose, the method of differential models, commonly used in surveys of terrain changes with the use of DTMs, was used. Calculations and development of differential models have been processed in the Surfer10 software.

The coloured scale shows the change in the vertical axis of the terrain elevations (**Figure 10**). Negative values indicate the lowering of the terrain in the next period from the previous one, positive values inversely. By using the same coordinate system it was possible to perform this analysis. ALS and TLS were conducted close to each other, while the UAS mission was performed a few years later. Despite the dense vegetation, which limited the DTM range from UAS, the results obtained allowed analysis of changes in the terrain.

Differential model between ALS and TLS data (2011–2009) showed the reduction of the terrain height in the slope over the main scarp. In the area of the landslide toe occurred the lowering of colluvium and simultaneously the increasing of material volume occurred in area of landslide foot. Measurements taken by TLS technique from the front of the landslide foot confirmed the mass movement toward the north. On the entire landslide foot below the declivity of the slope occurred convexity towards the north. It was observed soil mass increases below the main scarp in the crack over the head of the landslide.

In differential model between UAS and ALS data (2015–2011) lack of points under vegetation made it impossible to observe the activity of landslide toe. The areas of activity overlap the areas detected in the previous period. The trend over the main scarp has also been detected. Raising terrain in the northern part of the toe is caused by the parent rock cranks that formed the shaft locking material transport along the surface of separation.

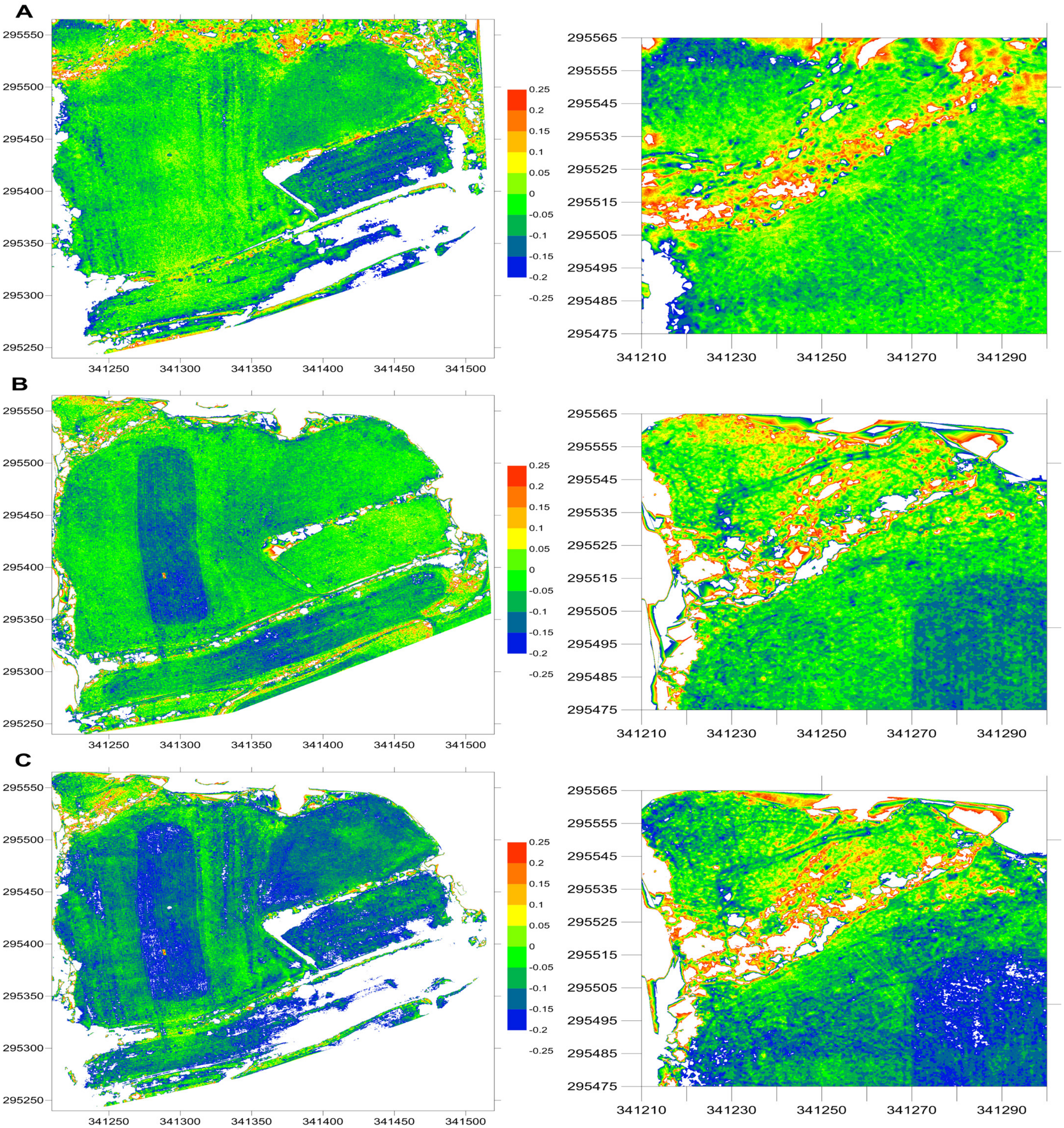

Figure 10. Differential model of the Janowiec landslide: A – 2009–2011 (TLS – ALS), B – 2011–2015 (ALS – UAS), C – 2009–2015 (TLS – UAS) (coordinate system PL–92).

Differential model between UAS and TLS data (2015–2009) confirms mass movements below the main scarp observed in previous intervals. Less distinct movement occurred in the western part of the landslide toe can be seen only in the long-term interval observation. The differential model shows that the slope surface above the main scarp is sliding down (**Figure 10**).

CONCLUSIONS AND RECOMMENDATIONS

The studies have shown that using UAS allows to acquire the data needed to develop a DTM of the landslide in a relatively short time. Using UAS to obtain information about the area, this study managed to create a DTM with a resolution of about

10 cm/px, which is comparable to TLS, and better than available data from the ALS from the state resource. Accuracy of data - the points cloud from the UAS was on the level of several centimeters, where the accuracy of the points cloud from the ALS assumed an error of up to 20 cm.

Usefulness of UAS only slightly differs from the other methods, like TLS or ALS. An inability to penetrate the vegetation, which occurs in errors and missing measurement data is the most important disadvantage of this technique.

The results of measurements of landslide features using DTM from UAS showed similar values as for the DTMs analysis obtained with other methods. The use of UAS for assessment and monitoring of landslides seems to be particularly recommended for areas without dense, high vegetation.

The possibility of using DTM from UAS for monitoring landslides using the differential models method, even with DTM created by various techniques such as TLS or ALS was confirmed.

Measurement speed of numerous objects and the relatively low cost of homemade UAS make this measurement method worth consideration. The solution seems to be even more attractive due to the parts availability and using open source software, therefore its cost is significantly lower in comparison with commercial devices.

Presented measuring method demonstrates the effectiveness in obtaining information about the terrain. Arguments for its use are both low time consuming and low cost of receiving data. UAS can successfully be an alternative tool for acquiring spatial information. However, it should be noted that photogrammetry is not able to penetrate through the vegetation in contrast to laser techniques.

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