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GEODETIC MONITORING OF GEOTECHNICAL STRUCTURES DISPLACEMENTS: A CASE STUDY OF RADIOWO LANDFILL SITE IN WARSAW

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ABSTRACT

Geodetic monitoring of deformation has an important role in ensuring the safety of geotechnical objects by monitoring of not exceeding the critical states defined for slope stability and monitoring the uniformity of the object settlement process. A special case of such objects are landfills built of various anthropogenic materials. Heterogeneous building material causes increased values of displacements in relation to other geotechnical objects and requires that measurement works be carried out throughout the entire life cycle of the landfill: both in the exploitation phase, during the reclamation period and in the post-exploitation phase. This study presents the methodology of geodetic measurements of deformation of geotechnical objects on the example of the Radiowo landfill and the results of this type of measurements carried out for 30 years on this object. The analysis of the literature has also shown that, in addition to the commonly used geodetic methods, it is possible to use modern measurement methods such as laser scanning and photogrammetry, which are more and more often successfully used in the measurement of this type of structures. These methods can be an interesting alternative in measuring the displacement of landfills or constitute their perfect supplement.

Key words: geodetic monitoring, displacement measurement, landslide, landfill, geotechnical structure, slope stability

INTRODUCTION

Landfills are geotechnical structures that can be compared to earthen structures made of anthropogenic materials, supplemented by protective structures such as seals, drains or reinforcements. The specificity of these structures is also due to their large area (up to several tens of hectares), large volume (up to several million m^3), significant thickness (up to several tens of meters) and long exploitation period (several decades). According to the 2020 statistical data of the Statistics Poland (GUS), there are 283 landfills in Poland, 12 of which are closed. Due to the construction of the landfill, these structures can be divided into above-level structures (located on a flat area), sub-level structures (created on land depressions) and side structures (based on slopes). Usually, these facilities are located outside of cities or in their vicinity, in zones that will minimize the negative impact on people and the environment, such as: air and groundwater pollution, unpleasant smell, birds (Główny Urząd Statystyczny [GUS], 2020). Due to the common policy of the European Union regarding waste landfills, the method of managing landfills in Poland and in other Member States is similar. The EU Council Directive of 26 April 1999 on the landfill of waste provides for the monitoring of landfill topography changes and landfill body subsidence on an annual basis (Council Directive 1999/31/EC). The requirement to conduct geodetic monitoring for this type of facilities in Poland is specified in detail in the Regulation of the Minister

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of the Environment of 30 April 2013 (Rozporządzenie Ministra Środowiska z dnia 30 kwietnia 2013 r. w sprawie składowisk odpadów). The regulation defines the minimum frequency of geodetic measurements on a landfill site as every 3 months during the operational phase and every 12 months during the post-operational phase. The monitoring defined in the regulation consists in controlling the subsidence of the surface of the landfill using geodetic methods based on measurements of displacements of survey points (benchmarks) stabilised on the surface of the facility and assessing the stability of slopes determined using geotechnical methods. The measurement of such points is carried out with high accuracy (of the order of millimetres), but their number is small, so a parallel method is used, which consists in making observations of changes in the geometry of the object. This involves measuring the natural surface of the object without stabilising the points. The measurement covers points characteristic for the landfill body, points on selected cross-sections and points on discontinuity lines (edges). Assessment of deformation of an object is performed by comparing results of current measurements with measurements from previous measurement periods in the form of cross-sections, contour lines or 3D models created on the basis of these measurements, and changes with reference to the so-called zero measurement, i.e. the first measurement performed after stabilisation of the benchmarks (Toś, Wolski & Zielina, 2008a).

Geodetic measurements are a prerequisite for ensuring geotechnical safety by monitoring the impassibility of not exceeding the critical states defined for the slopes of the landfill, they make it possible to monitor the uniformity of settlement of the facility, and on their basis it is possible to model the directions of future displacements and deformations of the facility, which are of fundamental importance in planning the target land management after completion of reclamation works. Geodetic data also provide information on the dimensions, surface area and volume of the facility and their variability over time. Due to the high heterogeneity of the stored waste (different mechanical, physicochemical and biological-chemical factors), the course of the settlement process is difficult to predict (model). Compared to soils, wastes show very high compressibility, which makes the settlement of the facility a very dynamic process, especially during and just after the exploitation phase. Referring to the processes occurring in soils, three phases of settlement can also be distinguished: primary, intermediate and secondary (Koda, 2011). Primary settlement is caused by the dead load of the structure and by waste consolidation work (squeezing water and air out of the waste). Intermediate settlement (pseudo-consolidation) is caused by mechanical, biological and physico-chemical processes within the landfill (e.g. oxidation, incineration, fermentation, leaching, compression) and by creeping processes (secondary compression). Secondary settlement is caused by mechanical creep of the solid phase of the waste at a constant effective stress (Koda, 2011).

The measurement methods currently used in geodesy can be divided into so-called classical measurements, which are identified with tacheometric and levelling measurements, and the so-called modern measurement methods, which include Global Navigation Satellite Systems (GNSS) measurements, laser scanning and photogrammetry. Currently, the dominant methods used in landfill measurements are classical methods, sometimes supplemented with satellite methods (Adamcová et al., 2020). These solutions allow to obtain high accuracy of measurement while maintaining its reliability (measurement of the same points). Unfortunately, the disadvantages of these methods are time-consumption and limitation in the number of measured points. Monitoring of displacements by these methods consists in measurement the position of selected, previously stabilized points (control points – benchmarks) on the surface of the landfill in relation to reference points located outside the area of influence of the facility (Prószyński & Kwaśniak, 2015). The laser scanning and photogrammetric method, on the other hand, allows for measurement of the so-called point cloud, which is a dense representation of the surface of the measured object. Although the measurement of natural points is associated with lower accuracy of the deformation, the advantage of these methods is less time-consuming compared to classical methods, and high resolution of the measurement of the object surface allows for a more detailed representation of the object in the form of a 3D model (Zaczek-Peplinska & Strach, 2017).

This paper reviews the geodetic methods used in monitoring geotechnical objects and presents the results of many years of geodetic surveys conducted at the Radiowo landfill as part of landfill monitoring.

STUDY AREA

The Radiowo landfill is an overground facility located on the border between the city of Warsaw and Stare Babice commune (Fig. 1). The height of the Radiowo landfill in relation to ground level is ca. 58 m and it covers an area of ca. 17.3 ha. The Radiowo landfill was established in 1961 and received unsorted municipal waste for 30 years. The site's location in very unfavourable geotechnical conditions (wetlands) and the lack of set rules for waste incorporation (no earthwork rules) contributed to many landslides and fires in the 1980s and early 1990s. Since 1992, only ballast waste generated from the production of compost from the Radiowo composting plant, such as: foils, tyres textiles, scrap metal and a reduced amount of organic waste (5–15%) has been deposited in the landfill. In the years 1999–2017 the landfill was reclamated in a series of ways to protect the body of the landfill against landslides, including rebuilding slopes and shaping the body of the landfill considering stability conditions, building a leachate, and degassing system and constructing protective bunds as part of the mineral covering of the surface of the landfill (Koda & Przysiadka, 2007). Long-term extended geotechnical monitoring

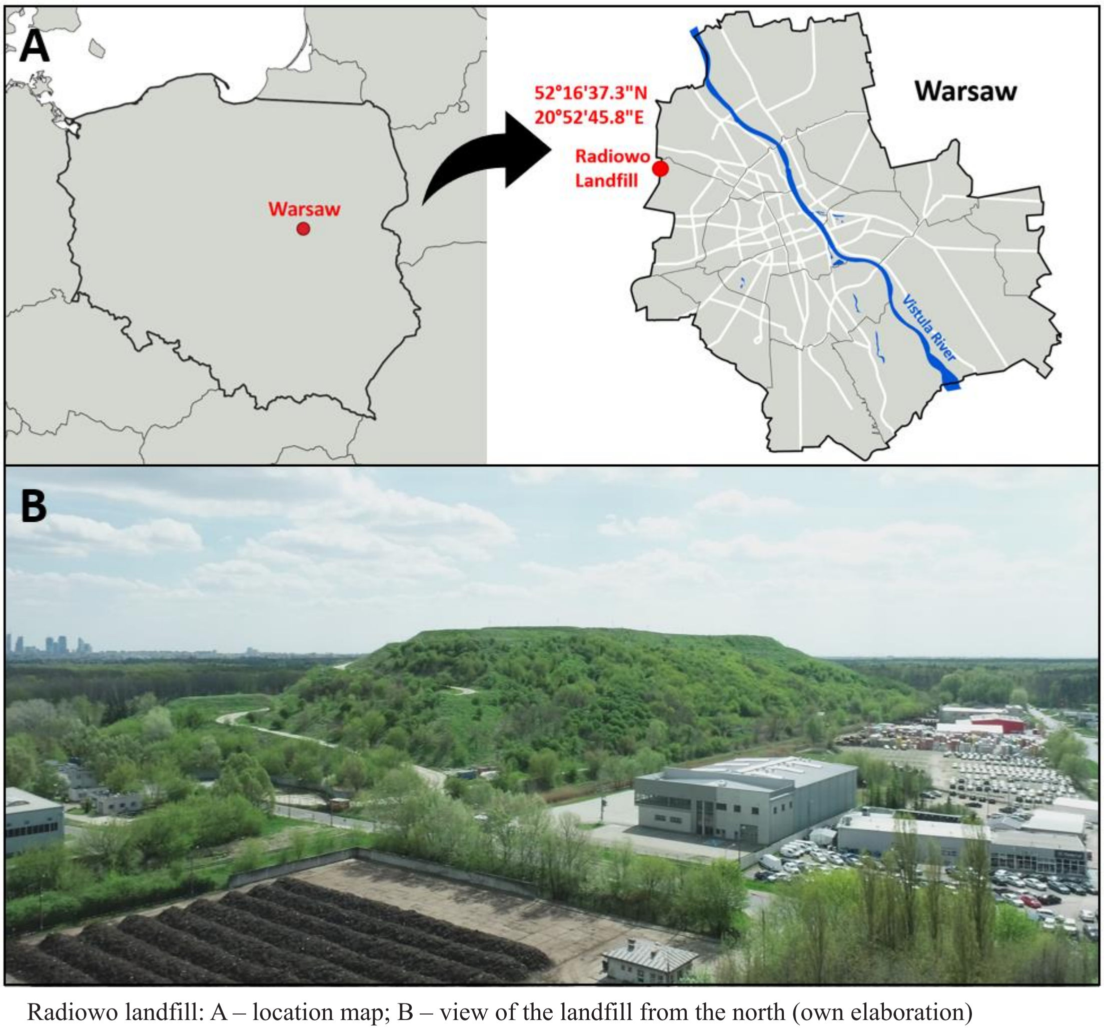

Fig. 1. Radiowo landfill: A – location map; B – view of the landfill from the north (own elaboration)

of the landfill, including slope stability analysis and measurements of deformation of the landfill body, was carried out not only to fulfil requirements stemming from law regulations but was also used to implement the Observation Method, allowing to modify applied design solutions (Koda, Kiersnowska, Kawalec & Osiński, 2020). Reclamation materials such as soil, debris, slags and ashes as well as compost were used at that time to reconstruct the body of the landfill (Koda, 2011). The reclamation of the Radiowo landfill was completed in 2017, thus ending the operational phase of the facility. The landfill body was finally shaped in accordance with the project created in 2012 assuming the concept of the target development of the Radiowo landfill with the direction of reclamation as a skiing area (Koda et al., 2009; Koda et al., 2022).

GEODETIC MONITORING OF RADIOWO LANDFILL

Geodetic monitoring of the Radiowo landfill has been carried out continuously since 1993 on a quarterly basis, i.e. almost 10 years before the compulsory measurements of subsidence on the landfill were imposed by the decree of the Minister of Environment in 2002. All measurements, studies and geodetic maps was the basis for technical and economic works carried out on the landfill. They made it possible to assess solid deformations and determine the geotechnical safety of slopes. Thanks to these aspects, it was possible to achieve the maximum capacity of the landfill site and thus to extend its operational life. The results of geodesic works are therefore also an important aspect in the decision-making process during construction works carried out using the observation method (Koda, 2011).

The surveying measurements were preceded by preparation of a survey network project – planning the location of control points on the surface of the landfill and along the main entrance road, as well as reference points for the reference the measurements. The reference points should be located outside the impact zone of the construction, so that their stabilisation can be permanent in time (Prószyński & Kwaśniak, 2015). As reference points was used the existing detailed geodetic control points. During periodic measurements of displacements of control points, reference points were also measured in order to check if they do not show mutual displacements among themselves. The location of reference points is shown in Figure 2.

The period of exploitation and later redevelopment of the landfill required a constant supplementation of the control points by stabilising new points and reconstructing existing ones. A total of ca. 105 points were installed during almost 30 years of geodetic monitoring at various times, 59 of which have been monitored for more than 5 years. The longest measured unbroken points have existed since the beginning of monitoring of the facility and are located on the northern and

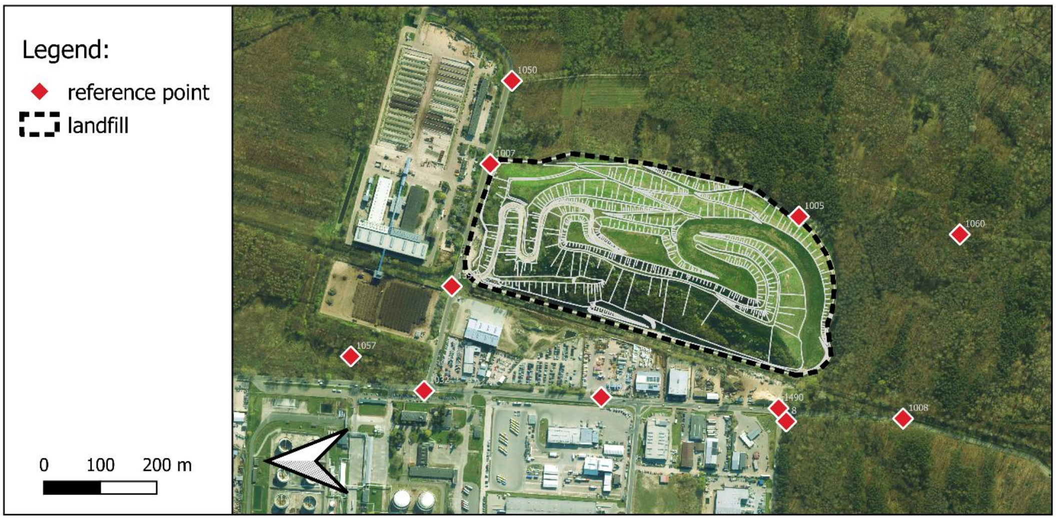

Fig. 2. Location of reference points near landfill area (own elaboration)

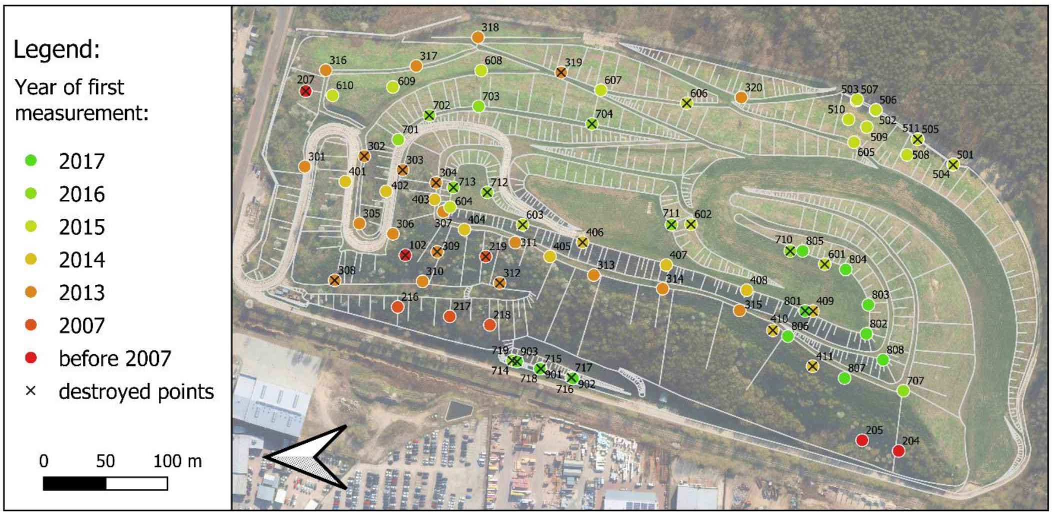

Fig. 3. The location of control points (benchmarks) on the landfill, by year of first measurement (own elaboration)

western slopes of the landfill (Fig. 3). The continuity of monitoring made it possible to use back analysis and prediction of displacements occurring in the landfill.

Displacement measurements of control points at the Radiowo landfill were made by using "traditional" techniques and geodetic measuring equipment, which over time were also supplemented by measurements using GNSS satellite techniques. By "traditional" measurement techniques is meant the use of levelling and tacheometric measurements, which allowed the determination of the height and situation position in reference-to-reference points with sub-centimetre accuracy. Due to the size of the object, these measurements were time and labour consuming, so the use of new technology in the form of a GNSS receiver has significantly improved this process, while increasing the amount of data collected. The larger amount of data resulted in better representation of the model of the studied object, which can be used in the deformation analysis of the landfill (Fig. 4; Adamcová et al., 2020). During measurements at the Radiowo landfill a set of two GNSS real time kinematic (RTK) receivers working in the Base-Rover mode was used (Koda, 2011). In this configuration, one of the receivers, which is a stationary base, sends corrections via radio to a second rover receiver making the measurement. The advantage of this solution is that mutual visibility is not required during the measurement, which is very important in landfills with diversified surface and in areas covered with lush vegetation in the case of

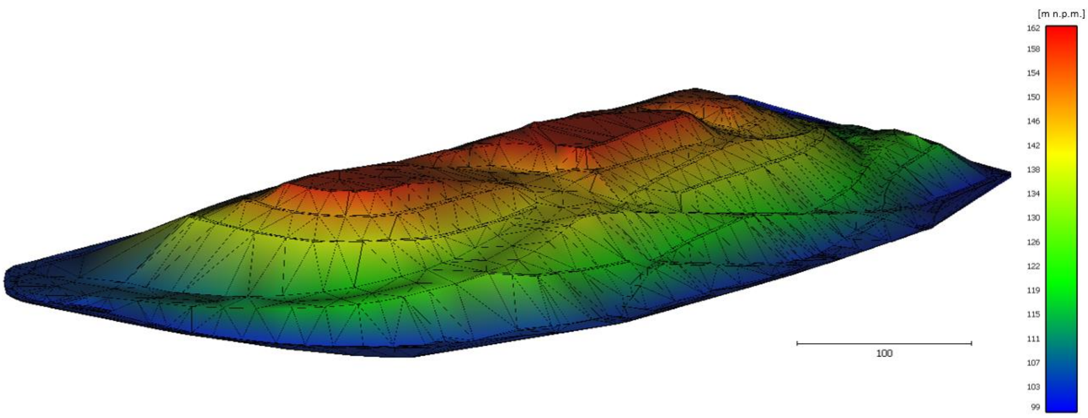

Fig. 4. Mesh model based on GNSS measurements (own elaboration)

reclaimed landfills. Another advantage is that one base station can be connected to several rover receivers, which are used to control construction equipment such as bulldozers, excavators or graders used in earthworks on the landfill.

MODERN METHODS OF GEODETIC MONITORING

Modern measurement methods such as laser scanning and photogrammetry are more and more frequently used in the monitoring of construction objects including geotechnical objects (Toś, Wolski & Zielina, 2008b; Zaczek-Peplinska, Pasik, Adamek, Kołakowska & Łapiński, 2013). These methods can also be successfully adapted in landfill measurements due to the advantages they offer: speed of measurement, detailed object representation (high resolution), measurement of natural points, texture representation of the object under study. The result of measurements of both methods is the so-called point cloud, i.e. a set of points with known XYZ coordinates. Based on such data it is possible to create accurate numerical models of objects, create analyses of variability of object shape and height of terrain obstacles, mutual height, distance, and surface relations and conduct numerical analyses of stability of object geometry and prediction of their changes (Zaczek-Peplinska & Popielski 2013; Zaczek-Peplinska & Strach, 2017).

The method of laser scanning can be classified on the basis of the measurement method into terrestrial laser scanning (TLS) and mobile laser scanning (MLS), which includes, among others: airborne laser scanning (ALS), scanning with the use of unmanned aerial vehicle (UAV), or handheld laser scanning (HLS). Laser scanning can also be classified according to the principle of measurement used in the scanners, into pulse-based and phase-based scanners. The selection of appropriate technology depends on the type of object to be measured and the need to obtain a result with the required precision and accuracy. The most popular and commonly used methods in precision measurements of construction objects are TLS measuring systems (Zaczek-Peplinska & Strach, 2017). The development of a model of an object, especially in the case of such a large facility as a landfill, requires several scans from different positions, for which mutual interconnection is necessary. For this purpose, various types of marks, targets or reference spheres are used, which play the role of tie points between neighbouring scanner stations. Each point registered by the scanner, apart from its spatial position, contains information about the reflection intensity. This parameter is very important in the context of filtering the acquired data in order to filter out recorded vegetation (Olivier, Lhomme, Gourc & Hidra, 2005). The scheme of work is shown in Figure 5.

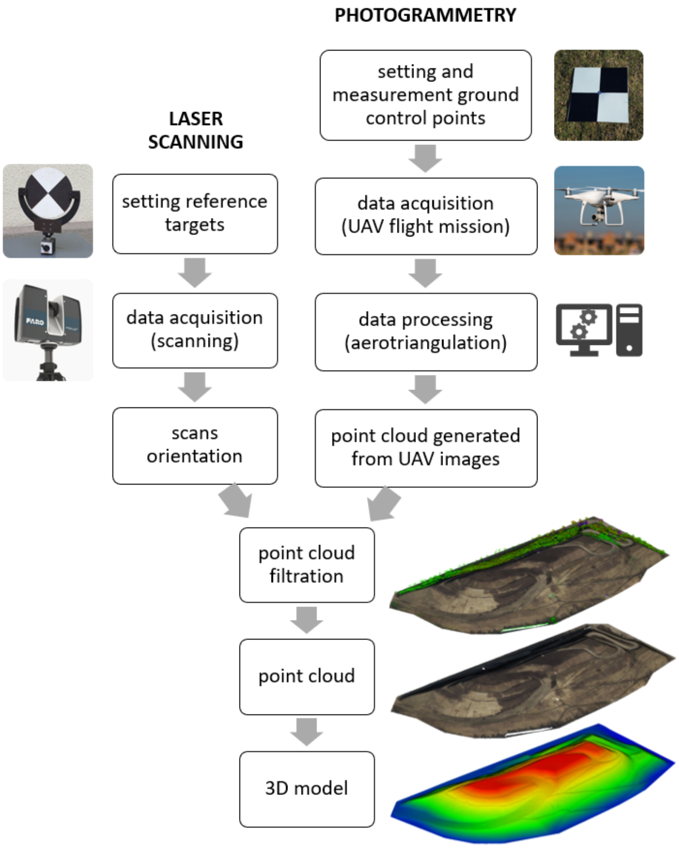

Fig. 5. Scheme of making a 3D model by laser scanning and photogrammetric method (own elaboration)

The photogrammetric method is also more and more often used in inventory measurements of geotechnical objects, especially in calculations of surface and volume measurements. This has become possible due to the use of drones (UAV) in photogrammetry (Ulvi, 2018; Kaamin, 2019). This method is based on the use of digital images taken with a high overlap, which allows the determination of homologous points on neighbouring images. Appropriately processed data acquired from an unmanned aerial vehicle makes it possible to obtain high-resolution digital terrain model (DTM), digital surface model (DSM) and orthophotomaps. The accuracy of this method depends on the camera resolution and the flight altitude from which the images are taken. The disadvantage of this method in the issue of landfill monitoring is the limitation of the possibility to filter out vegetation, which can be a problem in the case of reclaimed landfills (de Sousa Mello, Salim & Simőes, 2022).

RESULTS

The results of geodetic monitoring are annual reports containing tables and graphs showing displacements of monitored points in time. On the basis of these data, it is determined whether critical states defined for slopes are not exceeded. The slope stability is adversely affected when, over a long period of time, larger increments of horizontal displacements of benchmarks are observed than of vertical displacements, which indicates an increase in the slope inclination. This process is due to the fact that the landfill site is loaded with waste stored farther and farther from the bottom edge of the slope, which leads to "pushing" the waste to the centre of the landfill site and "pushing" it towards the bottom of the slope, thus increasing the slope inclination. In 2017, the landfill completed its reclamation and consequently its exploitation period ended, so currently the phenomenon of increasing slope gradients does not exist significantly at the facility, but still requires continuous monitoring over many years. According to the Regulation of the Minister of the Environment of 9 December 2002 (Rozporządzenie Ministra Środowiska z dnia 9 grudnia 2002 r. w sprawie zakresu, czasu, sposobu oraz warunków prowadzenia monitoringu składowisk odpadów), this period is up to 30 years from the date of the decision to close the landfill. Analysing the results of displacements from the beginning of the facility's existence to the present time, it can be observed that the exploitation of the landfill translates into higher displacements of points. In the post-exploitation phase displacements of points are less dynamic and have a constant tendency, which probably is a result of waste creep processes (secondary compressibility) (El-Fadel & Khoury, 2000). Currently, the average annual vertical displacement is ca. 7 cm, and the horizontal displacement is ca. 6 cm. The results of annual vertical and horizontal displacements of points are presented in Figure 6. As of 2017, i.e. after formation of the target body of the landfill, the largest recorded total vertical displacements of points are ca. 1.8 m and horizontal displacements are ca. 1.3 m and they concern the southern slope formed along the designed exit route and the western slope in the area of the entrance road to the landfill. Thus, these are still very large values which influence the target

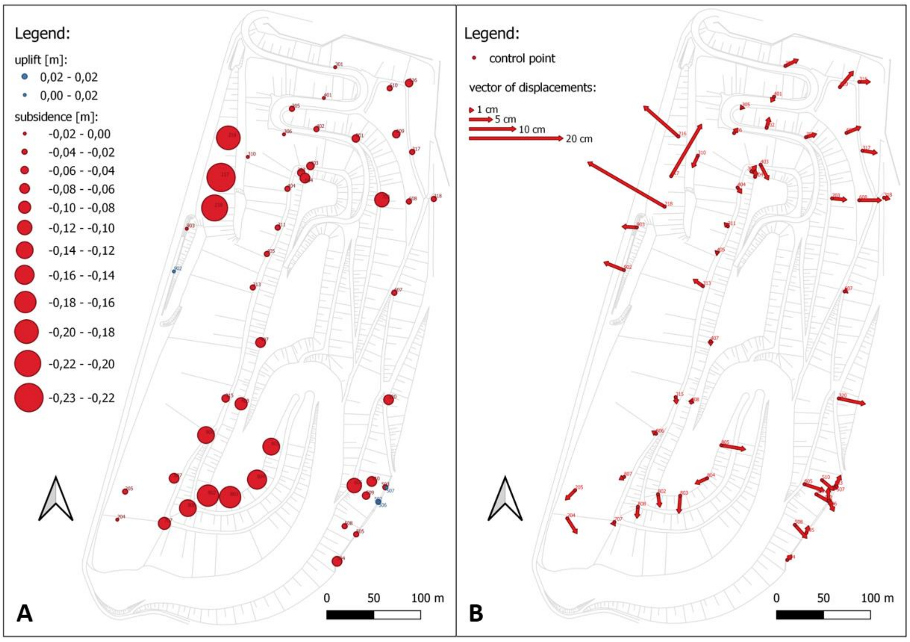

Fig. 6. Map of annual displacements of control points (years 2020–2021): A – vertical displacements; B – horizontal displacements (own elaboration)

shape of the landfill body before the landfill is handed over for post-reclamation exploitation and new development. Monitoring is therefore of control significance in relation to the geotechnical safety of the facility as well as of application significance in relation to landfill target development.

CONCLUSIONS

Geodetic monitoring plays a very important role in ensuring the safety of geotechnical objects and is related to the entire life cycle of the object. The requirement for geodetic monitoring of landfills is set out in the Regulation, however, it does not specify where and in what number the measured points should be stabilised, therefore in this task it is important to plan their uniform distribution on the object and on the cross-sections of slopes subject to monitoring, especially exposed to large deformations. The regulation also does not mention the accuracy of the measurement of control points, which is defined at the stage of the construction project and may be different for different objects – depending on their specificity or size. Apart from the measurement of points stabilised on the surface of the object, it is also important to measure the body of the landfill on the basis of which it is possible to monitor changes of the surface and volume in time and to provide geometrical data at cross-sections selected for the analysis of slope stability.

Modern measurement methods such as laser scanning and photogrammetry can be an excellent supplement to classic measurement methods due to a more detailed representation of the model of the studied object obtained in a shorter measurement time. It is also possible to texture a model on the basis of RGB (red, green, blue) images taken and present it in real colours or in a pseudo-colour on the basis of additional multispectral or thermal images. This makes it possible, for example, to assess the state of vegetation on the facility and their periodic inventory, as well as to indicate places with elevated surface temperatures associated with biogas fumes, which is an unquestionable added value about the landfill, compared to classical methods. In addition, these methods are less time-consuming in comparison to classical measurements. Integration of various types of measurement data may allow to understand the course of displacements and deformations of the studied object in a more precise and detailed way and to collect additional data important for ensuring geotechnical safety and target management of the landfill surface after completion of reclamation activities.

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GEODEZYJNY MONITORING PRZEMIESZCZEŃ OBIEKTÓW GEOTECHNICZNYCH NA PRZYKŁADZIE SKŁADOWISKA ODPADÓW RADIOWO W WARSZAWIE

STRESZCZENIE

Monitoring geodezyjny odkształceń odgrywa ważną rolę w zapewnieniu bezpieczeństwa obiektów geotechnicznych poprzez monitorowanie nieprzekraczalności stanów krytycznych określonych dla stateczności skarp oraz równomierności przebiegu procesu osiadania obiektu. Szczególnym przypadkiem takich obiektów są składowiska odpadów zbudowane z różnych materiałów antropogenicznych. Niejednolity materiał budulcowy przekłada się na zwiększone wartości przemieszczeń względem innych obiektów geotechnicznych i wymaga, aby prace pomiarowe prowadzone były przez cały cykl życia składowiska: zarówno w fazie eksploatacji, w okresie rekultywacji, jak i w fazie poeksploatacyjnej. W niniejszej pracy zaprezentowano metodykę pomiarów geodezyjnych odkształceń obiektów geotechnicznych na przykładzie składowiska odpadów Radiowo oraz wyniki tego typu pomiarów realizowanych od 30 lat na tym obiekcie. Analiza literatury wykazała ponadto, że oprócz powszechnie stosowanych metod geodezyjnych możliwe jest stosowanie nowoczesnych metod pomiarowych takich jak skaning laserowy i fotogrametria, które coraz częściej z powodzeniem znajdują zastosowanie w pomiarach tego typu obiektów. Metody te mogą stanowić ciekawą alternatywę w pomiarach przemieszczeń składowisk odpadów lub doskonale je uzupełniać.

Słowa kluczowe: monitoring geodezyjny, pomiary przemieszczeń, osuwisko, składowisko odpadów, konstrukcja geotechniczna, bezpieczeństwo geotechniczne