13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-062

Application of LiDAR technology in geodetic monitoring of reclaimed landfills

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ABSTRACT: Geodetic monitoring of reclaimed landfills is essential in ensuring the geotechnical safety of slopes and for monitoring the process of landfill settlement caused by biological and physico-chemical decomposition of the deposited waste. Insufficient recognition of the size and directions of displacements may lead to severe damage to the landfill body (landslides, sinkholes) and endanger the environment and the life and health of people living near the landfill. Classic geodetic monitoring of such facilities is based on measurements of single control points (benchmarks) located on the landfill body, the displacements of which often do not represent actual changes occurring in the area of the entire facility. The solution to this problem is to use Light Detection and Ranging (LiDAR) technology, which allows surface measurement of the entire studied area, making it possible to obtain a complete image of changes in the geometry of the landfill body. This paper presents a case study of a reclaimed municipal solid waste landfill located in Poland for which monitoring was applied using Terrestrial Laser Scanning (TLS) and Airborne Laser Scanning (ALS) from an Unmanned Aerial Vehicle (UAV). The acquired 3D data made it possible to obtain reliable information on the deformation processes on the landfill's surface and to decide on the direction of development of the post-remediation landfill as a Renewable Energy Sources (RES) station with solar panels and a biogas plant.

KEY WORDS: LiDAR; ALS; TLS; Deformation monitoring; Landfill reclamation; UAV.

1 INTRODUCTION

Landfilling is still the most popular method of waste disposal in Poland. According to the Central Statistical Office (Główny Urząd Statystyczny - GUS) 2022 data, 259 active landfills in Poland and more than 600 landfills closed and partially or fully reclaimed. The 1999 European Union (EU) Landfill Directive and the EU's overall policy for sustainable waste management imply a gradual reduction in municipal waste sent to landfills. It also imposes technical and environmental requirements that landfills must meet, indirectly leading to the closure and rehabilitation of old, substandard landfills and the creation of new landfills that meet standards [1,2]. There will be a further increase in reclaimed landfills in the coming years. Municipal landfills are usually located near large cities, whose dynamic growth causes landfills to be integrated into the urban fabric over time. Often, in such cases, as compensation for the long-standing negative impacts of the landfill on the immediate neighborhood (unpleasant odor, birds), they are transformed into public facilities with recreational, park, sports, museum, or exhibition functions [3]. It is also common to use these facilities in electricity production (biogas plant, photovoltaic farm, wind farm). An example of such a landfill is the Słabomierz-Krzyżówka landfill site located in Poland, whose future post-remediation development has been earmarked for a photovoltaic farm and where energy is currently being produced from extracted biogas [4].

Geodetic monitoring of deformation is essential in ensuring safety at reclaimed landfills by monitoring the impassibility of critical states defined for slope stability and monitoring the uniformity of settlement of the landfill body. In their design, reclaimed landfills can be compared to earth structures made of anthropogenic materials, supplemented by protective structures such as seals, drains, or reinforcements. The peculiarity of these structures is due to their large surface area (up to several tens of hectares), large volume (up to several million m^3), considerable thickness (up to several tens of meters), and long-time operating period (several decades). Due to the high heterogeneity of the stored waste (different mechanical, physico-chemical, and biological-chemical factors), the course of the subsidence process is difficult to predict. Compared to soils, wastes show very high compressibility, making the site's settlement dynamic, especially during reclamation [5-8].

The dynamics of landfill mass settlement are variable over time. The subsidence process can be divided into three phases: immediate settlement, primary settlement, and secondary settlement. Immediate settlement (pseudo-consolidation) is caused by the load from the weight of the landfilled waste and the process of mechanical compaction of the waste, which can reach up to 20% of the initial thickness. Primary settlement is caused by biological and physicochemical decomposition processes (e.g., oxidation, incineration, digestion, leaching) of the deposited waste and by the creep process. The processes associated with biodegradation of waste take place over a long period (several to several years), and the settlement volumes resulting from these processes can reach about 20% of the initial thickness of the deposited waste [5, 9]. Secondary settlement is caused by mechanical creep, can last for several decades, and can amount to a few percent of the initial thickness of landfilled waste. The course of the landfill settlement process is shown in Figure 1.

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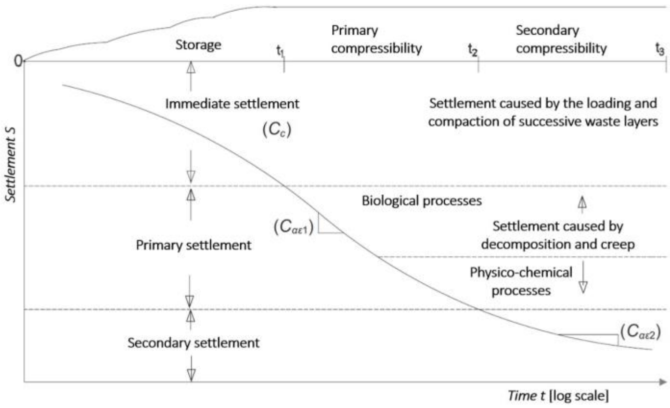

Figure 1. Landfill mass settlement process [8].

The influence of water from precipitation is also a factor in the deformation of the landfill surface. Heavy and torrential rains can lead to soil leaching from the top layer covering and adding weight to the reclaimed landfill. Water infiltration into the landfill can destabilize the slopes and subsequent deformation. Short-term, heavy, and torrential rains are an increasingly frequent phenomenon in a changing climate. The elements of the water balance are shown in Figure 2.

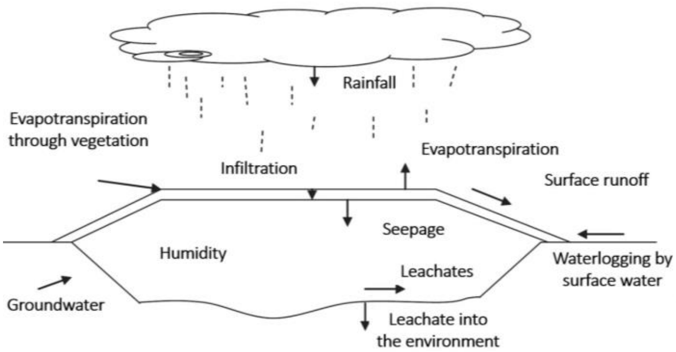

Figure 2. Elements of the landfill water balance [8].

In Poland, the requirement for geodetic monitoring of landfills is set out in the Regulation of the Minister of the Environment of 30 April 2013 on landfills [10]. The Regulation specifies a minimum frequency of landfill surveying every 3 months during the operational and 12 months during the post-operational phases. The monitoring period for landfills is 30 years after closure. The monitoring defined in the regulation consists of controlling the settlement of the landfill's surface by geodetic methods based on measurements of displacements of control points stabilized on the facility's surface and in assessing the stability of slopes determined by geotechnical methods [11]. However, the regulation does not specify the number of monitoring points and their location on the landfill, so the monitored point movements often do not represent the entire landfill area.

Classical geodetic monitoring at landfills is based on the point method - measurements of individual controlled points (points of interest) located on the body of the landfill in various geodetic marks (metal tubes, concrete posts, granite posts). This method makes it possible to accurately determine the movements of the selected points - their size, direction, and speed. It also assumes that the observed points are representative of the phenomenon. A denser network of points approximates the distribution of displacements more accurately but increases costs and time-consuming measurements. In practice, the determined displacements often do not reflect the actual changes occurring in the object area. Insufficient recognition of the magnitude and directions of these changes may lead to severe damage to the body of the landfill and consequently also endanger the environment and the life and health of people near the landfill [4,12,13].

A solution to this problem may be to use a surface measurement method using Light Detection and Ranging (LiDAR) technology. The surface method involves measuring the entire surface of an object - unstabilized points. This method makes it possible to observe any parts and the whole of the surveyed object. This method is free of the fundamental disadvantage of the point method - the surveyed surface is covered by a much larger number of points (in the LiDAR method, the surveyed surface is covered by millions of points). It is also possible to select observation points that depict the phenomenon depending on its dynamics. However, the disadvantage of this method is that the coordinates of the points are determined with less accuracy than in the point method. In the absence of pre-determined observation conditions and accuracy of results, a good solution is to use a hybrid method, a combination of point and surface methods. Such a strategy allows areas at risk of displacement to be detected and new stabilized points to be established in these areas [7, 13-17].

This paper presents a case study of the Słabomierz-Krzyżówka landfill site in Poland, where LiDAR-based geodetic monitoring was applied. The measurements used an approach using Airborne Laser Scanning from Unmanned Aerial Vehicles (ALS-UAV) and Terrestrial Laser Scanning (TLS). This paper presents the results of the annual monitoring of one of the slopes of the landfill, which was exposed to both deformations caused by the impact of landfill subsidence and surface water run-off caused by damage to the defenses by wild animals (wild boar, deer).

2 MATERIALS AND METHODS

This section presents the characteristics of the study area (Section 2.1) and the measurement equipment used (Section 2.2). The proposed methodology for determining slope deformation from TLS and ALS-UAV measurements is also described (Section 2.2).

2.1 Study area

The research object is the reclaimed municipal solid waste landfill "Słabomierz-Krzyżówka". The landfill is located ca. 40 km south-west of Warsaw. The landfill was established in 1970 on the site of an old pit after sand and gravel mining. From 1970 to 1992, unsegregated municipal and industrial waste was deposited in the landfill. From 2016 onwards, only construction ballast waste was deposited at the landfill, such as concrete and concrete rubble from demolition and renovation, mixed concrete waste, brick rubble, ceramic materials, non-conforming compost, and soil, soil, and stones. In 2022, the landfill was closed and rehabilitated. A degassing and drainage network and a vertical screen were built to prevent contaminants' escape. The target reclamation of the landfill was set for use as a Renewable Energy Station (RES) with solar panels and a biogas plant. Currently, the landfill site and its

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technical facilities cover an area of approximately 14 ha, and the landfill covers an area of approximately 9 ha. The current height of the landfill body is approximately 27 meters measured from its base to the crown of the landfill. There are 15 controlled points (benchmarks) on the site to monitor the settlement of the landfill body. The current appearance of the landfill is shown in Figure 3.

Figure 3. View from the sky of the Słabomierz-Krzyżówka landfill with the study area (marked in red).

The study was carried out on one of the slopes of the landfill, which was exposed to negative external influences and was a representative part of the entire landfill. The study area is marked in red on Figure 3.

2.2 Methodology

The monitoring of the study area presented in this article was conducted over a one-year period from March 2023 to March 2024. The representative area of the slope selected in the study covers an area of approximately 2000 m^2. Due to the vegetation on the landfill, the measurements were carried out in early spring to minimize the influence of the vegetation on the measurement results as much as possible. The survey adopted two approaches: the TLS and ALS-UAV methods. The TLS measurements used a Leica RTC360 scanner, and the ALS-UAV measurements used a LiAir S50 scanner with a Matrice M600 UAV. The LiAir S50 LiDAR system mounted on the platform consists of a scanner, Velodyne’s VLP-16, and a Sony A6000 RGB camera. The specification of the instruments used is shown in Figure 4.

Figure 4. Overview of the research measurements.

The measurements were related to reference grid points outside the object's influence area. The resulting point clouds from both methods were oriented in the same coordinate system. Reference matrix coordinates were determined in the PL-2000 coordinate system and PL-EVRF2007-NH height system. For the absolute georeferencing, the TLS scanner stations and reference targets were precisely tied to these external reference points, established through GNSS RTK and angular-linear measurements. The angle-linear network was then aligned using the least squares method. This allowed the TLS data to be transformed into a unified, absolute coordinate system compatible with the ALS-UAV data. For the ALS-UAV method, absolute georeferencing was achieved by integrating D-RTK GNSS corrections with onboard IMU data, UAV positioning sensors during the flight, and reference targets, ensuring precise alignment of the point cloud within the same coordinate system as the TLS data. Two measurement series were carried out (March 2023 and March 2024). A flowchart of the research methodology is shown in Figure 5. The research in flowchart consists of 4 stages: a preliminary study, fieldwork, data processing, and data analysis and results.

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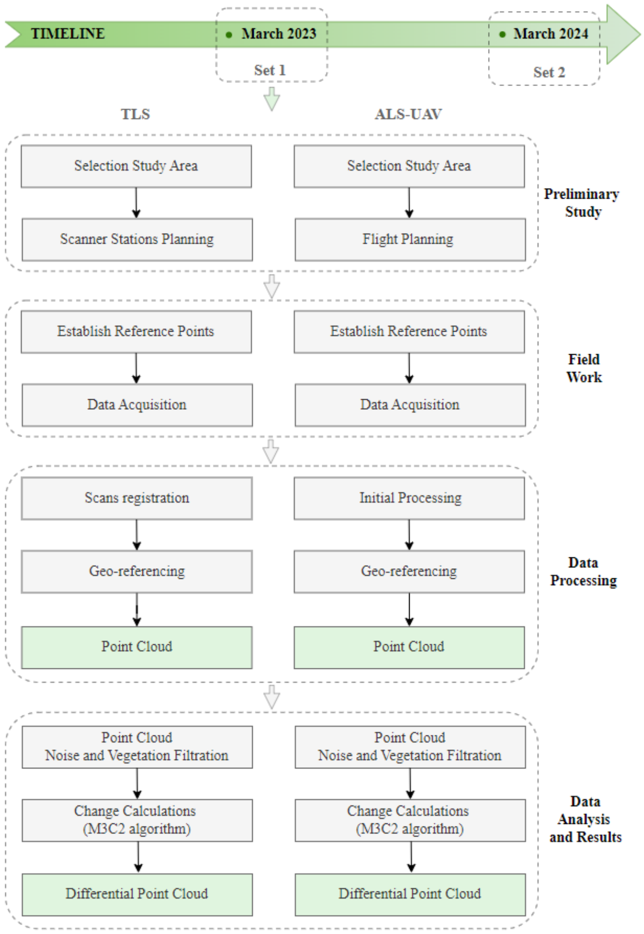

Figure 5. Flowchart of research methodology.

The TLS method first required planning the positions of the scanner stations and reference points (targets on tripods), which were referenced to the reference points (Preliminary study). The positions were planned so that the mutual coverage of scans from successive scanner positions was not less than 50%. It allowed the mutual orientation of the scans to be performed using the cloud-to-cloud (C2C) method. Additionally, overlapping stations were used to strengthen the "connections" between the scans. This strategy allowed mutual orientation of all sites even in the case of a weak "connection" - too few common points between scanner sites. The problem of mutual orientation of the scans is particularly relevant in the case of reclaimed landfills, which are overgrown with lush vegetation. Branches, leaves, and blades of grass moving in the wind can make it difficult to orient the scans using the C2C method. A solution to this problem may be the use of reference spheres. A diagram of the scanner positioning strategy is shown in Figure 6.

The Leica RTC360 scanner used in the survey has a dedicated Leica Cyclone FIELD 360 application, which allows a rough mutual orientation of the scans locally directly in the field. It enables the assessment of whether adjacent scans have the required percentage of mutual coverage and whether there is a need for additional stations. The scans were acquired at a resolution of 3 mm at 10 meters. A total of nine scans were acquired (Field work).

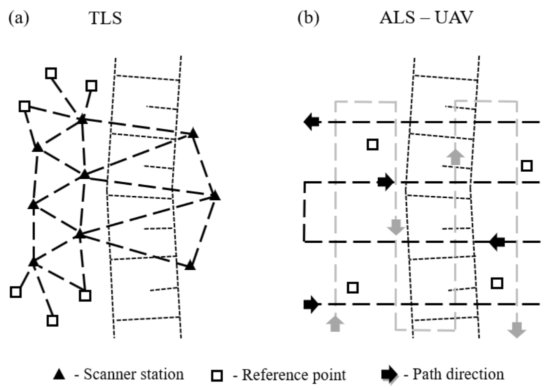

Figure 6. Scheme of measurements by a) TLS and b) ALS – UAV method.

Orientation of the scans was performed using the dedicated Leica Cyclone REGISTER 360 PLUS software (Data processing). The resulting point clouds were de-noised (SOR Filter) and filtered from vegetation (CSF Filter) in Cloud Compare v.2.13.2 [18]. The parameters of the applied filtering were selected empirically (Data analysis and results). The average density of the resulting point cloud was approximately 10,000 pts/m^2.
(18).

The ALS-UAV method first required planning a flight path (Preliminary study). The flight was performed in two transversely oriented directions (Fig. 6) at an altitude of 50 m. The distance between each flight path was 20 m. During the flight, a D-RTK reference station was used for data reference (Fig. 4). The field-acquired data (Field work) was processed in the dedicated Green Valley LiDAR360 software. The geo-reference of the resulting point cloud was given based on the data from the D-RTK station and the antenna and IMU on board the UAV. As with the TLS data, the resulting point clouds were de-noised and filtered from vegetation in Cloud Compare. The average density of the resulting point cloud was approximately 250 pts/m^2.

3 RESULTS

Based on the obtained point clouds, a differential point cloud was calculated in the Cloud Compare program, representing the deformation of the slope over the annual period for the TLS method (Fig. 7a) and ALS-UAV (Fig. 7b). Differential point cloud was calculated using the Multiscale Model to Model Cloud Comparison (M3C2) algorithm [19,20]. The M3C2 algorithm determines the distance along a local normal vector, estimated from each point's neighborhood. The method considers the surface's local orientation in the distance calculation process. The general principle of the algorithm is based on developing search cylinders along normal vectors to locally average the changes between two point clouds. The parameters in the M3C2 algorithm used were chosen empirically. The best results were obtained with a cylinder size of 25 cm, which was used in the study [19].

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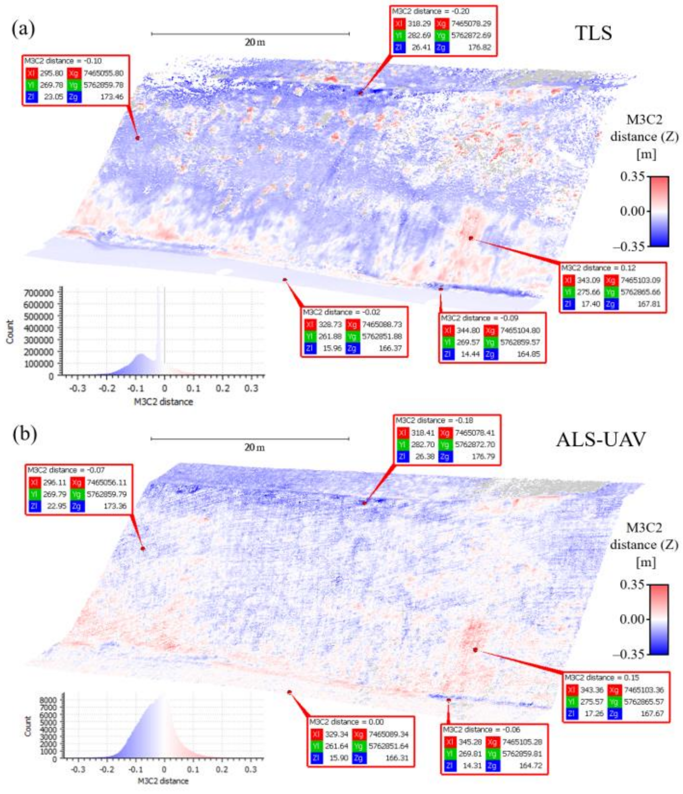

Figure 7. Differential point cloud showing vertical slope displacements from a) TLS and b) ALS-UAV.

Figure 7 shows deformations occurring between March 2023 and March 2024. Figure 7a shows the TLS measurement results, while Figure 7b shows the ALS-UAV measurement results. The blue color shows subsidence, while the red color shows uplift. The absence of changes is marked in white, as indicated in the legend. The range of these values is between -35 and 35 cm. Similar results can be seen in both figures. The most significant subsidence can be seen in the upper and middle parts of the slope, while uplift is noticeable in the lower part of the slope. The values of these changes are approximately -20 cm for the upper part of the slope, approximately -10 cm for the middle part of the slope, and 10 cm for the lower part. This is an expected result and is related to the plastic deformation of the slope caused by the dead weight of the soil and the compaction of waste embedded in the body of the landfill. A diagram of this phenomenon is better shown in Figure 8.

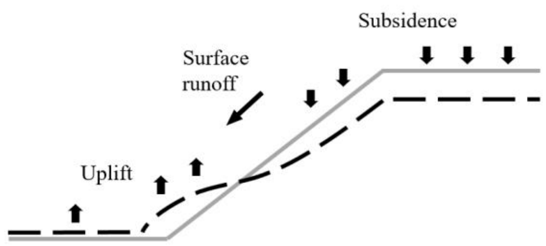

Figure 8. Diagram of the landfill slope deformation process over time.

Figure 8 shows the process of slope deformation over time. Settlement is noticeable in the upper part of the slope, while the slope in the lower part is uplifted by compression of the soil mass. Sometimes, uplift at the foot of the slope may also be caused by the so-called apparent uplift - surface water run-off and deposition of washed-out soil at the foot of the slope. Such a phenomenon can also be observed in Figure 7. At the foot of the slope, between the technical road and the slope, the dark blue longitudinal stripes are a remnant of washed-out soil, which the landfill workers removed as part of maintenance works. The values in this area are approximately -10 cm.

In Figure 7, characteristic features appearing in the two data sets are marked with red references to compare the results. The average difference between the selected points is approximately 3 cm. A differential point cloud was created to compare the two results better, showing the differences between the displacement results of the two methods, TLS and ALS-UAV (Fig. 8).

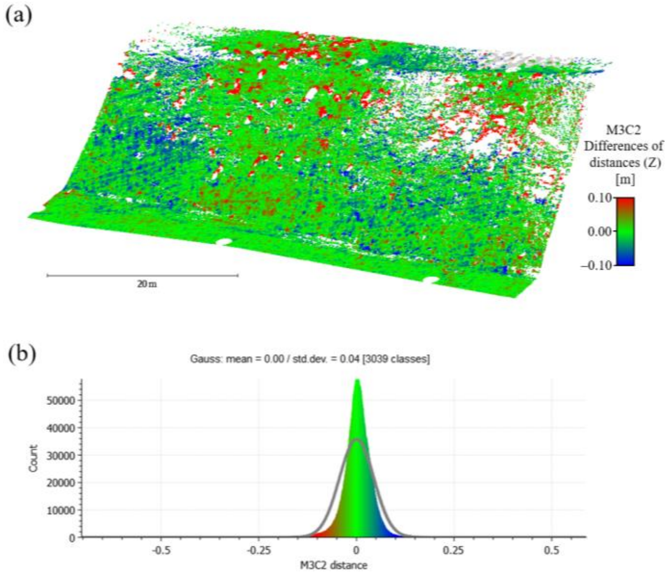

Figure 8. Differential point cloud of displacements from TLS and ALS-UAV (differences of vertical displacements) (a) and histogram of a differential point cloud of displacements (b).

Figure 8 shows the difference between the results of the TLS and ALS-UAV methods (Fig. 8a) and a histogram of the distribution of score values (Fig. 8b). The red and blue colors show significant differences in the results. In contrast, the green color indicates no differences in areas with low or zero values. These values range from -10 to 10 cm. Fig. 8 predominantly shows green points - close to the zero value. This means that the results of both methods were very similar. Possible differences are due to the accuracy of the two measurement methods, the different roughness of the point cloud, the different densities, orientation errors, and the effectiveness of the vegetation filtering. It can be assumed that the TLS method is more accurate than the ALS-UAV method and could be the reference method in the study. However, the TLS method in the application presented here has one key disadvantage - the unfavorable slope scanning angle. The laser scanner beam hits the slope at a vast angle, both in positions below and above the slope, preventing effective vegetation penetration. In contrast to the TLS method, in the ALS-UAV method, the laser beam

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strikes almost perpendicular to the scanned area, allowing better vegetation penetration and ground scanning. The most significant differences between the two methods are particularly evident in the central part of the slope, where the ground scanner beam does not reach the ground but only scans the grassroots. This situation can lead to errors in interpreting phenomena occurring in the landfill regarding slope deformation processes.

The histogram in Figure 8b shows the statistical distribution of the differences between the TLS and ALS-UAV methods. The distribution has the character of a normal distribution, with a mean of 0.00 m, showing that there is no systematic shift between the methods. The standard deviation is 0.04 m, which means that most of the differences are within ±4 cm, confirming both measurement methods' high consistency and precision.

4 DISCUSSION AND CONCLUSIONS

This paper presents a case study of the Słabomierz-Krzyżówka landfill located in Poland and the results of annual measurements of one of the slopes of the landfill exposed to damaging factors causing its deformation, such as the influence of soil gravity, waste compaction, and surface water run-off. Two measurement methods were adopted in the study: TLS and ALS-UAV.

The results showed that both methods can be effectively used for periodic monitoring of the landfill surface. Similar results were obtained for both methods, demonstrating their effectiveness. Possible differences may be caused by:

- different accuracy of the measurement methods,
- different roughness of the point cloud,
- different density,
- different observation geometry,
- orientation errors,
- or the effectiveness of vegetation filtration.

The TLS method should be assumed to be more accurate than the ALS-UAV method, assuming a suitable measurement methodology. Nevertheless, each method has its advantages and disadvantages. In the case of the TLS method, it was possible to measure with high accuracy and resolution. The disadvantage, however, is the scanner's position, which, in the case of slope scanning, creates an unfavorably wide scanning angle and makes it impossible to scan the ground in the case of high vegetation. The partial solution to this problem can be telescopic tripods, which allow the scanner position to be raised several meters. Changing the scanner's height to a higher one may allow scanning the slope at a better angle but will not solve the problem completely. Another disadvantage is the time-consuming nature of the measurements. In paper [13] the authors compare the acquisition time and processing time of TLS and ALS-UAV measurements. The results show that scanning reclaimed landfills, by the TLS method, is 5 times more time-consuming than by the ALS-UAV method. In the case of large objects, it is necessary to set up additional control points to establish the measurements and maintain adequate accuracy of the results. The overabundance of measurement data can also be a problem. The scanner records two million points per second, which, in the case of measurements at the landfill, translated into the acquisition of approximately 70 million points per measurement site (when using the highest resolution mode). In the case of the ALS-UAV method, an advantage is the ability to scan a large area of land, which is particularly useful in landfill measurements characterized by a large surface area (up to several tens of hectares). Another advantage is better vegetation penetration and the laser scanner's beam reaching the ground because of almost perpendicular laser beam to the scanned ground. However, the disadvantage of the ALS-UAV method is its lower accuracy than the TLS method. Measurement solutions of this type offer measurement accuracy similar to that of the GPS RTK method. One should also know that using UAVs in air traffic requires appropriate authorizations and competencies. Using this technology is impossible everywhere and under all conditions (direct vicinity of airports, detention centers, and military units).

An important aspect to consider when selecting a measurement method is cost-effectiveness, especially if both methods meet the required accuracy criteria. TLS, while offering higher accuracy, typically incurs higher operational costs due to longer measurement times and the need for specialized equipment and personnel. Conversely, the ALS-UAV method can rapidly cover larger areas, potentially lowering labor and time expenses. However, initial investment in UAV equipment and obtaining necessary flight authorizations can be significant. Compared to traditional surveying methods, both TLS and ALS-UAV provide improved efficiency and richer data, but the overall cost-effectiveness depends mainly on the specific project scale and requirements. Including an economic evaluation alongside technical factors offers a more comprehensive basis for choosing the optimal measurement approach.

The LiDAR monitoring applied allowed for a comprehensive assessment of slope deformation on an annual basis. Comparison of the data between the two measurement series made it possible to identify the general trends of the landfill slope settlement and the local deformations caused by external phenomena, such as surface erosion caused by rainwater.

The use of LiDAR technology - in both the TLS and ALS-UAV methods - significantly increased the efficiency of the measurements compared to the traditional point method. Thanks to the obtained point clouds, it was possible to detect displacements, visualize them spatially, and analyze the direction and intensity of deformation. The ALS-UAV method allowed a larger area to be measured quickly and comprehensively, while TLS provided data with a higher local resolution.

Periodic monitoring using LiDAR can be critical in the decision-making and design process. The ALS-UAV method allows data collection over a large area in a short time with high spatial and temporal resolution. It is also a non-invasive method. The person carrying out the measurement is not exposed to direct contact with factors negatively affecting human health, such as biogases or leachates. On the other hand, the TLS method provides high-accuracy data, allowing detection of even the smallest damage. The best way to monitor reclaimed landfills will be to integrate both methods and use each method's advantages. TLS data can also be a source for referencing or validating ALS-UAV data to improve accuracy.

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