Geospatially Resolved UAV-Enabled Waste Settlement Monitoring at Xerolakka Landfill in Greece

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ABSTRACT

Settlement monitoring of Municipal Solid Waste (MSW) is valuable for the operation, closure, and post-closure development of landfills. Conventional techniques for settlement monitoring are cumbersome, expensive, and lack the temporal and spatial resolution needed to provide valuable insights on the full-scale compressibility of MSW. Repeated deployments by Unmanned Aerial Vehicles (UAVs) equipped with optical cameras at a landfill in Western Greece have allowed the generation of 3D models of the landfill that vary with time for a monitoring period of three years. These models were used to track settlements and calculate the long-term settlement rate of the waste. The long-term settlement rate is found to vary with time and is not constant as often assumed. This finding is consistent with the underlying biological and physicochemical processes that occur at landfills. The data also has a geospatial resolution that enables the localization of higher waste settlement areas. Such information provides insights into the full-scale behavior of MSW without affecting landfill operations.

INTRODUCTION

The full-scale, short-term, and long-term performance of waste containment facilities to enhance their resiliency and sustainability has been a major area where Dr. Rudolph Bonaparte has led intellectually, and professionally and made numerous and lasting contributions for several decades (e.g., Bonaparte 1987, Bonaparte 1995, Bonaparte et al. 2002, Bonaparte et al. 2020). Settlement monitoring of Municipal Solid Waste (MSW) is essential for several aspects that affect the sustainability and resiliency of landfills as waste containment facilities. As the waste settles, additional airspace is generated that can be used to dispose of MSW. Thus, a reliable estimate of the waste settlement could be incorporated into facility planning by overfilling a facility so that the long-term waste settlement results in a landfill surface that complies with the permitted airspace. In addition, because the dominant component of long-term waste settlement is due to biochemical waste decomposition (El-Fadel and Khoury 2000; Ivanova et al. 2008) waste settlement monitoring can provide insights into the rate and degree of waste decomposition. Also, a reliable prediction of long-term waste settlements, and by extension, differential settlements, can ensure that landfill covers, which are prone to differential waste settlement, remain intact, or are properly monitored and repaired. Finally, long-term settlement rates are a key consideration when considering the post-closure and beneficial use of closed landfills.

Presently, waste settlement monitoring is most often conducted using settlement plates and surface monuments. Such installations affect waste operations and thus are not installed early on.

Most often, they are installed once waste operations have been completed and closure or post-closure development is considered. Monument or plate surveying is typically conducted at certain time intervals and provide a "point measurement", i.e., the observed settlement is representative of the exact location where the monument or plate is installed. No information about waste settlement is collected in between monitoring locations. Although automation is available to conduct such settlement measurements using robotic total stations and can provide mm level accuracy in measurements, most often these measurements are conducted manually, are costly and thus infrequent, and are prone to errors. As a result, the data collected is sparse in both time and space, reducing confidence in predicting future system performance. Waste settlement variability within a landfill due to the disposal of different waste types, variable waste composition, or changes in landfill operation conditions (e.g., compaction, amount of cover soil used, water infiltration) can be significant (Durmusoglu et al. 2005; El-Fadel 1999; El-Fadel and Khoury 2000).

Aerial mapping by Unmanned Aerial Vehicles (UAVs) can provide an alternative to the current settlement monitoring approaches. UAV mapping using optical sensors (cameras) or UAV-mounted lidar technologies can result in the creation of high-resolution (cm level) three-dimensional models that provide an estimate of landfill surface that is geospatially continuous and not discrete. UAV-enabled surveys allow for a quantification of settlement as a function of time (by conducting repeated surveys at desired time intervals), but also as a function of space (i.e., geospatially). The data collected enables an estimation of variability in settlement due to variations in stresses, waste composition, and associated engineering properties.

In this study, results from four UAV deployments at an MSW facility that were conducted by the authors as part of the landfill's monitoring operations from July 2019 to August 2022 are presented. The landfill is a canyon landfill in western Greece that receives Municipal Solid Waste from the nearby city. The results are analyzed to calculate settlement rates and assess at full-scale spatial and temporal settlement variability. The climate at the location of the landfill is Mediterranean, with an annual precipitation of 678 mm, according to the Institute for Environmental Research of the National Observatory of Athens (IERSD/NOA) (https://w1.meteo.gr/ClimaticData/CD_Patra.htm).

METHODOLOGY

Field Data Collection. In this study, the Structure-from-Motion (SfM) technique was implemented for the creation of the three-dimensional (3D) models. The SfM technique involves the collection of overlapping imagery using an optical camera mounted on a UAV. Before the UAV flight, ground control points and ground checkpoints covering the landfill area were marked on the landfill surface, and their location was surveyed using a dual frequency GPS T30IMU GNSS. In total, 22 locations were surveyed ensuring geospatial distribution within the landfill as shown in Figure 1. The ground control points are used for georeferencing the model, whereas the ground checkpoints are used for quantifying model errors calculated as the difference between the known location of the checkpoint (measured using the RTK GPS) and the location of the checkpoint as projected by the 3D model. Subsequently, a DJI Phantom 4 Pro quadcopter UAV equipped with a 1-inch 20MP CMOS camera was used to collect 5472 × 3648 pix images. The UAV flew at an average altitude of 80 m on a double-grid pattern and acquired images with an 80% longitudinal and lateral overlap at an angle of 70º compared to the vertical axis. As an example, for the August 2022 deployment a total of 2172 photos were collected. The imagery was stitched together to create an orthophoto and a digital surface model (DSM) as well as a Digital Terrain Model (DTM). The locations of the photos overlayed on the 3D digital model of the landfill are shown with green symbols in Figure 2. A total of four surveys were conducted, specifically in July 2019, December 2019, February 2021 and August 2022, as shown in Table 1.

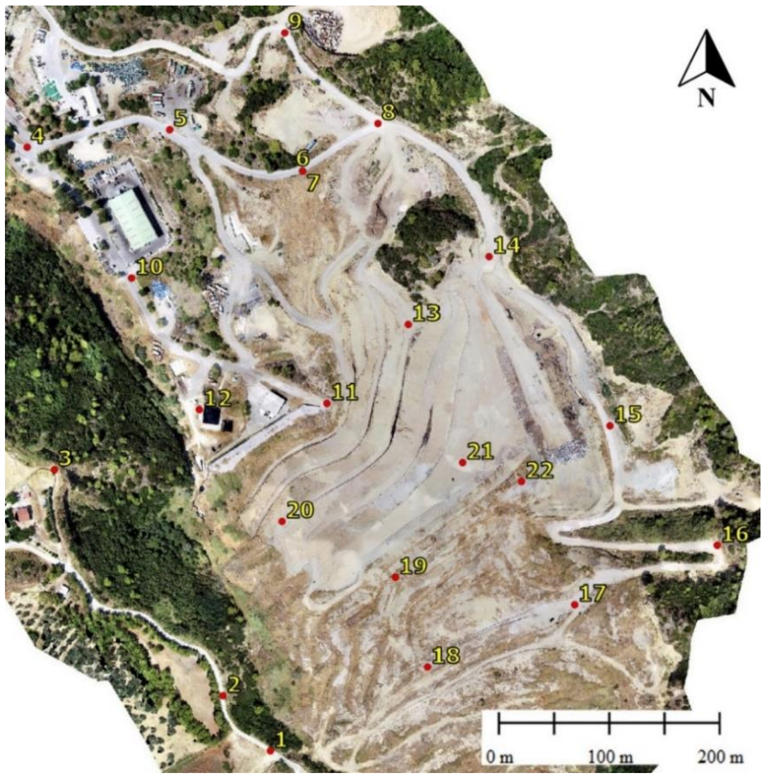


Figure 1. Geospatial distribution of ground control and checkpoints within and around the landfill. Orthophoto shown for August 2022.

3D Model Computations. The SfM methodology is presently well-established and has been described in detail by a number of authors, including Snavely et al. (2008), Westoby et al. (2012), and with a focus in geotechnical engineering by Zekkos et al. (2018). The methodology involves the extraction of features and an incremental 3D scene reconstruction to generate a low density, or “sparse” point cloud and. As part of this error-minimization process, also the cameras’ intrinsic (focal length, sensor size, principal point, lens distortion) and extrinsic (position, orientation) parameters are derived. This is achieved through a sparse bundle adjustment process (Snavely et al., 2008) that includes algorithms for matching selected points, triangulation of 3D points, and the automatic elimination (or filtering) of moving objects that typically are identified by a large error in their position in different images compared to their neighboring points. To georeference the model and improve the 3D model reconstruction accuracy, the Ground Control Points (GCP) collected in the field, are identified throughout the photoset and are included. Subsequently, the derived sparse point cloud is significantly densified through stereoscopy algorithms that are used to generate the final dense point cloud. Post-processing of the model includes the creation of a digital surface model (DSM) that includes a surface model that includes all physical features (such as vegetation, gas wells and structures). A digital terrain model (DTM) can then be generated by removing features that do not represent the terrain surface. This is achieved by classifying all features into ground and non-ground categories. An example of the August 2022 DSM and DTM at a 3 cm ground sampling distance is shown in Figures 3a and 3b, respectively.

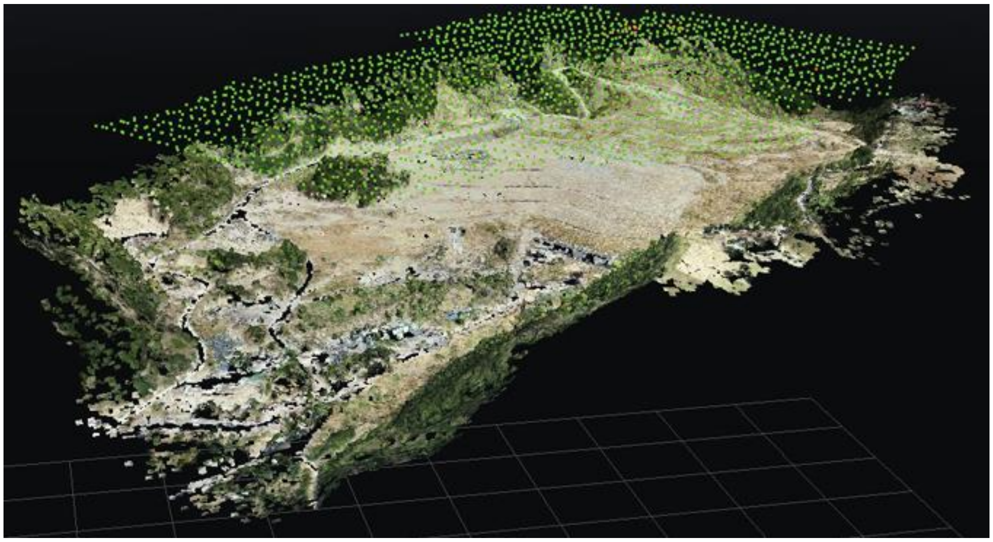


Figure 2. Location of imagery collected by UAV for landfill mapping.

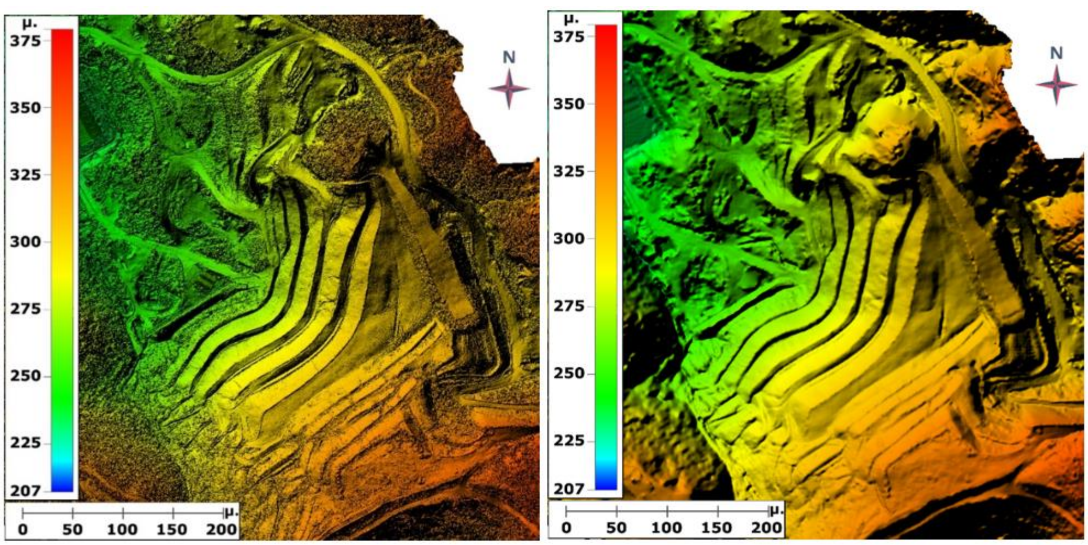
Table 1. Deployment dates and estimated time interval from the average date of waste placement to each deployment date.

	Waste placement	1st Deployment	2nd Deployment	3rd Deployment	4th Deployment
Date	1-07-2015	30-07-2019	18-12-2019	24-02-2021	03-08-2022
Time interval (days)	0	1490	141	434	525

The DTMs created from each deployment are differenced in ArcGIS to calculate the difference in elevation between surveys. Locations that have an increase in elevation due to waste placement, or have visible activities, or ground disturbance (e.g., ground scraping or excavation) based on visual observations in the field or the orthophoto, are excluded. For areas that have not been impacted by waste placement or other landfill activities, the reduction in elevation is calculated and is equal to the amount of settlement that occurred in between deployments.

For the calculation of settlement rates, the thickness of the waste mass is also of interest. This is calculated by developing an elevation model for the base of waste. In this study, the base of waste elevation is derived from the original topography at a scale of 1:5000 that was developed by the Army Geographic Service prior to any landfill activities, because as-built drawings of the landfill base are not available.

The settlement of waste is associated with immediate compression due to load application, as well as long-term settlement. The long-term settlement of waste is due to a number of mechanisms. Fei and Zekkos (2013) divided the long-term settlement in three phases: Phase 1 was termed the transitional phase (P1). It is attributed to time-dependent physical mechanisms such as particle reorientation and movement, raveling, delayed compression of deformable particles as a result of stress redistribution, and potential softening of waste constituents due to moisture introduction in the waste mass (Wall and Zeiss 1995; Bareither et al. 2012). These mechanisms dominate, especially if moisture content is low. Waste may remain in this phase indefinitely. In increased moisture environments, physicochemical and biological dissolution of soluble compounds from waste to leachate creates a suitable anaerobic environment for microorganisms, and biodegradation becomes a major contributor to the long-term settlement. Microorganisms start to grow in the transitional phase, but their population and activity level remain low and with continued moisture presence, MSW settlement shifts to Phase 2, the active biodegradation phase (P2). Phase 2 occurs when most microbial species reach their maximum growth rates, and thus a robust microbial community has been established. Biodegradable MSW is hydrolyzed, disintegrated, fermented, and metabolized to final products such as methane, carbon dioxide, and dissolved compounds (Barlaz et al. 1989; Pohland and Kim 2000). Physical mechanisms such as creep and raveling are also ongoing, but their contributions are significantly lower compared to biodegradation (Elagroudy et al. 2008; Gourc et al. 2010; Bareither et al. 2012). As the availability of biodegradable MSW decreases steadily during the active biodegradation phase, MSW settlement transitions to the residual phase (P3) where settlement slows down. Subdued biodegradation, along with creep, become the two major contributors to settlement (Bjarngard and Edgers 1990; Edgers et al. 1992).



(a) (b)

Figure 3. (a) Digital Surface Model (DSM) and (b) Digital Terrain Model (DTM) for the landfill based on survey in August 2022.

In the field, it may be challenging to track all three mechanisms because data is not collected immediately after waste placement and also because at any given time, the waste at different locations (and depths) in the landfill may be at different degradation stages. However, when careful field data is collected, the various phases can be clearly discerned (Jo and Zekkos 2025). When data collection is delayed, one may only observe an average response between Phase 2 and Phase 3 depending on the field conditions. The rate of long-term settlement can be defined as:

$$C_{LT} = \frac{\Delta H}{H_0 \cdot \Delta \log t} = \frac{e_v}{\log(t_2) - \log(t_1)} \quad (1)$$

Where C_{LT} is the long-term settlement rate, ΔH is the settlement between surveys, H_o is the thickness of the waste mass, t_2 is the time interval from waste placement to the second survey and t_1 is the time interval from waste placement to the first survey. For the analyses conducted in this study, the average date of waste placement initiation was estimated based on the information from the landfill.

Note that the C_{LT} formulation is mathematically identical to the one used for secondary compression of soils $C_{\alpha\varepsilon}$ and was also first introduced by Sowers (1973) for solid waste. However, an important distinction is that the $C_{\alpha\varepsilon}$ is often assumed to be constant, which is incorrect. Several studies in both the laboratory and the field have shown that the rate of settlement in landfills is not constant, but varies as the waste transitions from one phase to the other (Fei and Zekkos 2013). Thus, the use of a varying C_{LT} settlement rate is preferable, and both simplified (Jo and Zekkos, 2024) as well as more advanced models (e.g., Kumar and Reddy, 2021, Zekkos et al. 2021) are available to estimate settlement rates.

RESULTS

Through 3D model differencing, the settlements that occurred between two deployments are calculated. Figure 4 shows an example of the settlement calculation between December 2019 and February 2021. The total amount of settlement observed reached 1 m during that period. Two areas are observed that have greater settlements, although most areas in the landfill also settle.

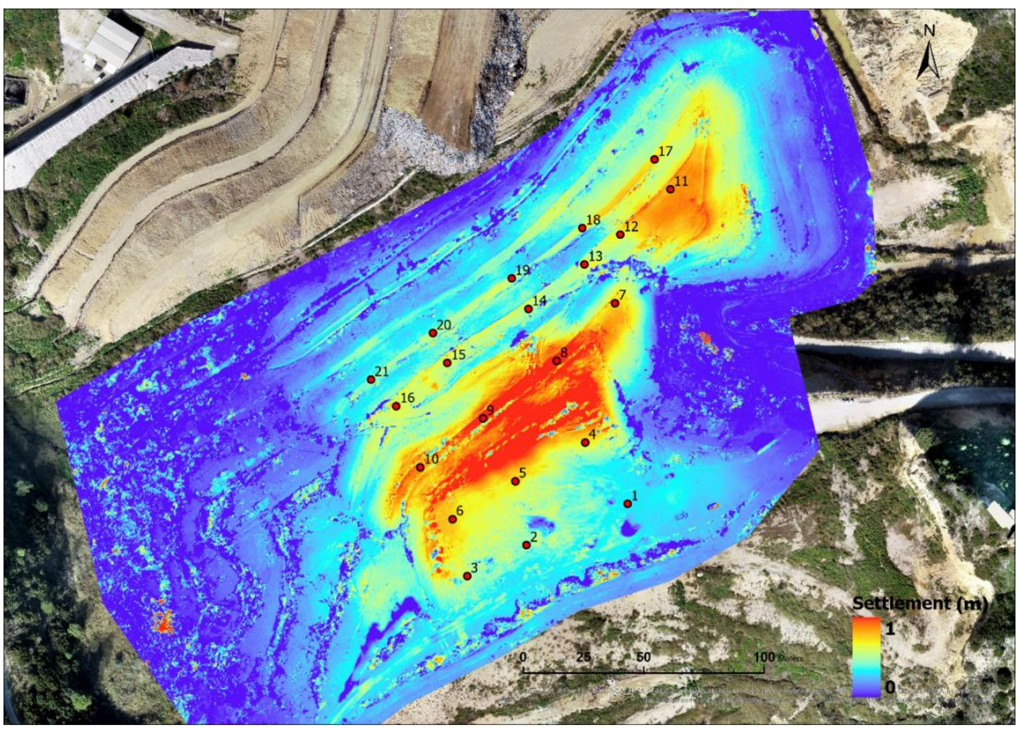


Figure 4. Settlement calculation in meters through 3D model differencing between the December 2019 and February 2021 UAV deployment.

The amount of settlement observed in each location is a function of the ongoing waste degradation processes, but also of the thickness of the waste mass at each location. Considering also the thickness of the waste mass, as well as the average time since waste placement, Equation 1 is used to calculate the long-term settlement rate C_{LT}. The long-term settlement rate is shown in Figures 5-7 for the three deployment intervals. Figure 5-7 show the calculated C_{LT} between July 2019 and December 2019, between December 2019 and February 2021, and between February 2021 and August 2022 respectively. A visual inspection of the figures can confirm that, in general, the areas that have higher settlement rates are the same. The calculated long-term settlement rates range from 0.5 to <0.1, which are consistent with those reported based on field measurements. For example, Sharma and De (2007) proposed settlement rates that were <0.1 for MSW in general, and values that range from 0.1-0.34 for waste undergoing active biodegradation.

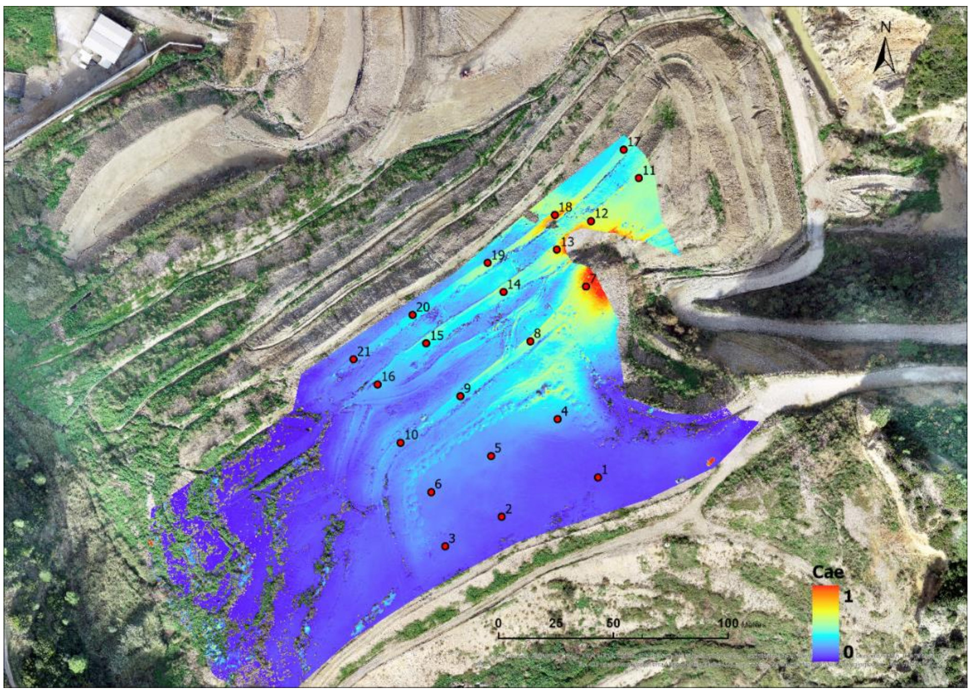


Figure 5. Calculated long-term settlement rate C_{LT} based on surveys in July 2019 and December 2019.

Figure 8 illustrates the evolution of C_{LT} at 21 indicative locations. Most locations have a relatively constant or small reduction in the rate of settlement with time for the monitoring period. Four locations indicate a significant reduction in settlement rates from high rates (greater than 0.5) to lower rates. A similar study was also conducted by Champagne et al. (2020) at a landfill in Michigan using similar methods to the ones described herein. A portion of that landfill was operated as a bioreactor and was estimated to have a mean settlement rate of 0.31 to 0.36, whereas the bioreactor section had mean settlement rates that were as high as 0.6, but subsequently slowed down as recirculation ceased.

As described in the previous, the data collected allows for the assessment of the spatial and temporal variation in settlement rate throughout the landfill. This approach facilitates the systematic assessment of settlement trends, such as areas of higher settlement rates that may be related to higher degradation rates, or temporal variations that may be indicative of other changes in waste materials or landfill operations.

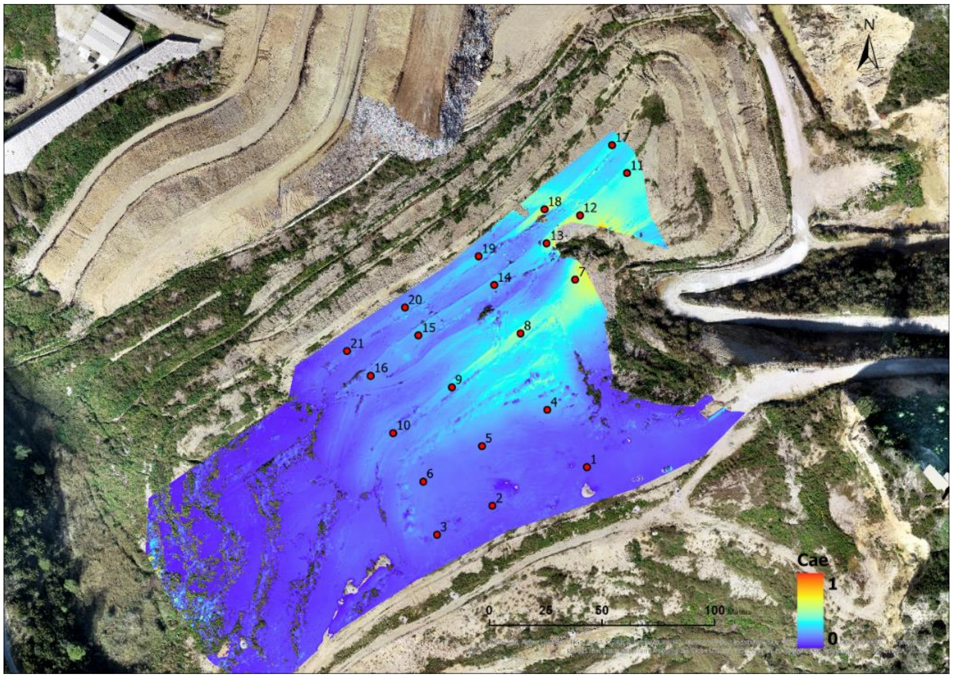


Figure 6. Calculated long-term settlement rate C_{LT} based on surveys in December 2019 and February 2021.

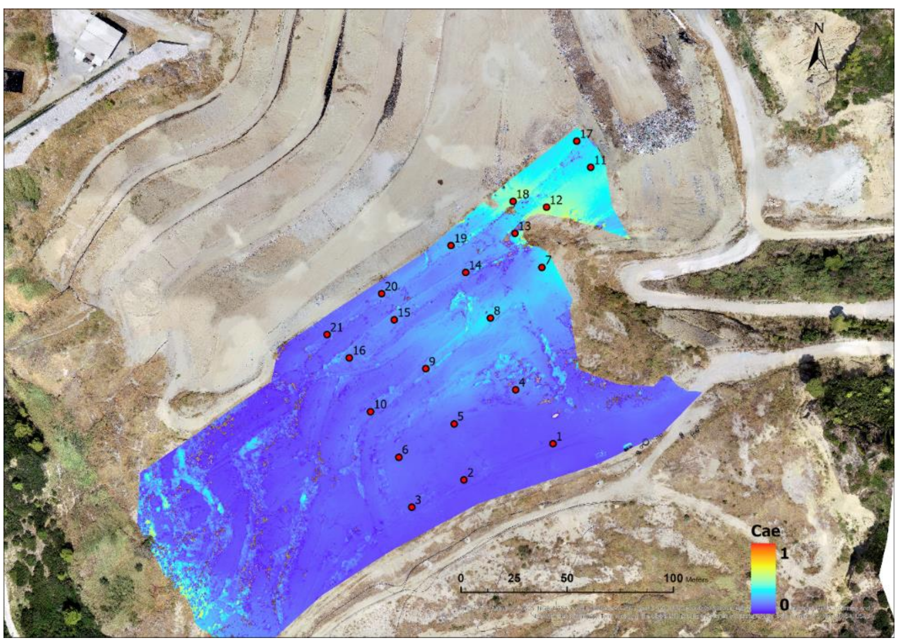


Figure 7. Calculated long-term settlement rate C_{LT} based on surveys in February 2021 and August 2022.

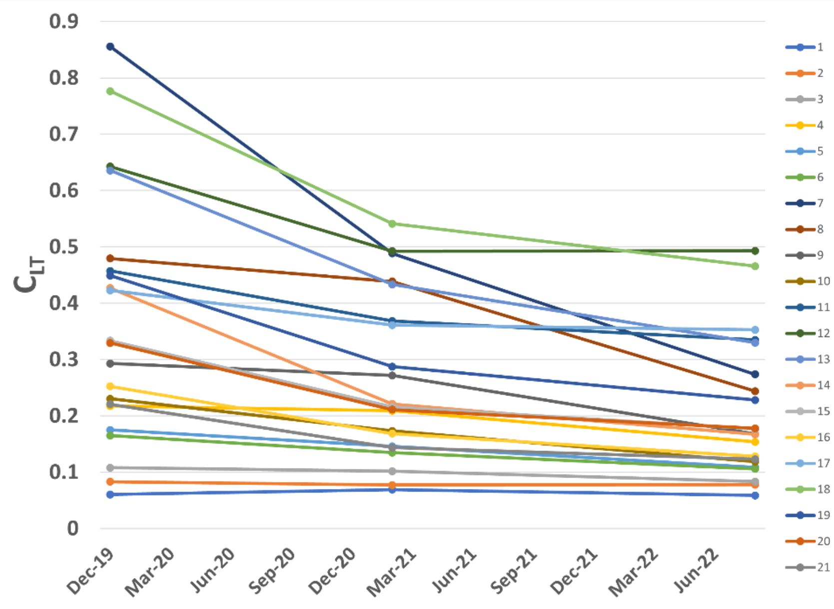


Figure 8. Temporal variation of long-term settlement rate (C_{LT}) at 21 locations shown in Figures 4-6.

CONCLUSIONS

In this study, the results of a UAV-enabled settlement monitoring program from 2019 to 2022 at the Xerolakka landfill in Western Greece are presented. Optical data is collected during each survey, and the data is used to generate 3D models by implementing the Structure-from-Motion technique. 3D model differencing enables the collection of spatially resolved settlement data without obstructing landfill operations and without the need for any permanent installations at the landfill. The settlement rates, C_{LT}, at this landfill, were found to vary geospatially and temporally but are, on average, 0.3 (±0.1). Such a monitoring program can be conducted not only after landfill closure but also while the landfill is operational, providing valuable site-specific data that have implications for understanding the waste degradation processes, as well as for the closure and post-closure development of a landfill.

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