공학석사 학위논문

Evaluation of Soft Ground Settlement using Drone-LiDAR Survey

드론 라이다를 활용한 연약지반 침하 산정

2025 년 2 월

서울대학교 대학원

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Abstract

Evaluation of Soft Ground Settlement using Drone-LiDAR Survey

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Managing settlement in deep soft ground is crucial for ensuring infrastructure stability and safety. While many researches on settlement have been conducted, most rely on traditional measurement methods such as settlement plates and total stations. These methods, although widely used, are limited by their relatively sparse measurement points, reducing reliability in unmeasured areas and complicating the analysis of complex settlement behavior. Recently, advancements in remote sensing technologies have shown promising potential for addressing these limitations. Especially, Drone-LiDAR provides accurate and efficient measurements across the entire sites, making it particularly suitable for complex soft ground conditions. Drone-LiDAR measured data contains outliers, surface objects, and large volumes of information, necessitating preprocessing to extract meaningful ground elevation data. However, there are limitations to using directly ground elevation data to evaluate settlement of soft ground sites. Therefore, this study proposes novel settlement evaluation method. First, outliers were removed using SOR technique, followed by bare-earth filtering using the CSF. To generate a DEM, a grid size of 50cm×50cm, optimized for accuracy and data completeness, was selected. A settlement evaluation method was developed based on the DEM to address challenges in estimating settlement from loading during ground elevation increases and in distinguishing settlement from unloading during ground elevation decreases. The proposed method includes a correction factor, $\boldsymbol{\phi}$, derived from the comparison between calculated and measured settlement during loading for increases in ground elevation. For decreases in ground elevation, settlement rates were analyzed to differentiate settlement from unloading. The proposed method was applied to the study site, Busan Newport. Validation against settlement plate measurements at the study site yielded high accuracy, with an average RMSE of 0.134m, MAE of 0.119m, and a coefficient of determination ($\boldsymbol{R^2}$) of 0.956. While the method tended to slightly overestimate settlement, this was attributed to assumption about prior settlement rates during unloading. In addition to settlement evaluation, the proposed method could be utilized for various applications. By evaluating settlement on the study site and distinguishing between loading and unloading, earthwork volumes over time were estimated. Also, degree of consolidation analysis identified settlement risk areas, revealing that areas with concentrated unloading generally met target settlement, while areas with concentrated loading has grids that often fell short of target settlement. This facilitated the identification of areas requiring focused settlement management. The proposed settlement evaluation method and applications offer a reliable framework for settlement monitoring and maintenance in large and complex soft ground sites. This approach enhances the accuracy and efficiency of settlement management, providing valuable insights for infrastructure projects in challenging geotechnical conditions.

Keywords: Drone-LiDAR, Soft Ground Settlement, Ground Elevation, Settlement Evaluation Method

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Chapter 1 Introduction

1.1 Background

Settlement in deep soft ground during construction occurs in three forms: immediate settlement, primary consolidation, and secondary compression (Cater and Bentley, 2016; Fei and Zekkos, 2013). Most settlement takes place over months or years during the construction phase, primarily as long-term consolidation settlement (Shi et al., 2019). This prolonged consolidation process often results in geotechnical issues, such as differential settlement, which can ultimately lead to significant structural stability problems, including tilting and cracking.

To address these issues, it is essential to accelerate the dissipation of pore water pressure through ground improvement techniques, enabling the target settlement to be achieved within a shorter period. (Feng et al., 2020; Kim et al., 2013; Ramirez et al., 2022). Consequently, during the design and construction of soft ground, various ground improvement methods are employed to enhance ground strength. Among these, the preloading method combined with prefabricated vertical drains (PVDs) has proven particularly effective in accelerating consolidation settlement. As a widely adopted method in soft ground construction, it plays a crucial role in expediting settlement and ensuring ground stability (Cai et al., 2018; Geng et al., 2017).

Inaccurate settlement prediction and management can lead to severe structural problems, such as tilting or overturning of structures. This underscores the importance of precise settlement prediction and management during ground design and the implementation of improvement methods to ensure stability. Accordingly, numerous studies have analyzed the settlement behavior in soft ground (Barron, 1948; Chen et al., 2023; Hansbo et al., 1981; Terzaghi et al., 1996). Especially, 1D Terzaghi consolidation theory is a cornerstone of geotechnical engineering, providing a fundamental framework for analyzing the time-dependent behavior of saturated soils under effective stress. It forms the basis for controlling settlement through a combination of analytical analysis, measurement-based techniques, numerical simulations, and machine learning approaches during construction. Research into soil behavior using these methods remains active and continues to advance the understanding of settlement processes (Asaoka, 1978; Chung et al., 2023; Hong et al., 2024; Tan et al., 1991).

Currently, field monitoring predominantly relies on traditional methods, including settlement plates and total stations, with most studies on settlement behavior based on data collected through these methods. The traditional method involves personnel manually monitoring total stations on-site. However, settlement plates are installed at only a limited number of measurement points, resulting in relatively sparse data for adjacent areas. This creates significant limitations in accurately understanding the varying settlement characteristics of the ground and the entire site.

Given the limitations of traditional methods, research is being conducted on advanced measurement techniques capable of monitoring the entire field. Remote sensing technologies such as InSAR, photogrammetry, and Drone-LiDAR have been utilized to monitor various geotechnical and environmental phenomena, including airport sites, mining, erosion, landslides, and earthquake-affected areas (Casagli et al., 2017; Dehghani et al., 2013; Hu and Wu, 2016; Li et al., 2017; Rathje et al., 2006; Wu et al., 2020). However, while many remote sensing technologies struggle with capturing small-scale, rapid deformations or deeper ground movements in large fields, Drone-LiDAR is considered particularly suitable for monitoring complex soft ground sites due to its enhanced adaptability and precision (An et al., 2024; Lee et al., 2019; Yang et al., 2023; Zhan et al., 2024).

To effectively monitor soft ground using Drone-LiDAR, it is crucial to preprocess the raw data collected. Drone-LiDAR data often contains noise caused by particles, dust, dirt, and multi-path reflections (Carriho et al., 2018). To address this, the Statistical Outlier Removal (SOR) technique is the most used method, as it statistically eliminates outliers from surface scan data obtained through Drone-LiDAR (Balta et al., 2018). In addition to denoising, Drone-LiDAR data captures a wide range of surface objects, making ground filtering essential. The Cloth Simulation Filtering (CSF) technique is the most widely used approach for separating ground points from other objects in the data (Sarıtaş et al., 2023; Zhang et al., 2016). Once noise is removed and ground points are extracted, the data can be processed into a Digital Elevation Model (DEM) for more effectively analysis (Lu et al., 2017; Zhang et al., 1994)

When a DEM is created through these processes, it provides a comprehensive representation of the ground elevation across the entire site. Over time, changes in ground elevation captured in the DEM can be used to evaluate ground movement, particularly the extent and occurrence of settlement. However, directly evaluating settlement from changes in ground elevation is challenging, as they do not always directly correlate with settlement behavior. Therefore, a method is required to accurately evaluate settlement based on ground elevation changes.

This paper aims to propose a method for evaluating soft ground settlement using Drone-LiDAR. First, Drone-LiDAR measured data from the study site was processed through denoising, bare-earth filtering, and DEM construction. Subsequently, a method for evaluating settlement based on changes in ground elevation was developed, accounting for both elevation increases and decreases. The accuracy of the proposed method was then evaluated using settlement data obtained from traditional method included settlement plates as a reference. Finally, earthwork volumes were estimated based on the evaluated settlement, and settlement risk areas were identified. This study demonstrates the applicability of Drone-LiDAR for analyzing soft ground sites and offers deeper insights into settlement behavior under complex field conditions.

1.2 Objective

The purpose of this study is to develop and apply a settlement evaluation method using Drone-LiDAR. The main objectives of this study can be summarized as follows:

(a) Development of a settlement evaluation method: Establish a method to evaluate settlement from Drone-LiDAR -derived ground elevation, incorporating processes such as data denoising, bare-earth filtering, and DEM construction.

(b) Validation of the accuracy of the settlement evaluation method: Validate the proposed method by comparing its results against settlement plate measurements to ensure reliability and precision.

(c) Application of the settlement evaluation method: Demonstrate the practical applicability of the method by using it for advanced analyses, such as estimating earthwork volume and settlement risk areas, to enhance the understanding of soft ground behavior.

1.3 Outline

The paper documents the evaluation of soft ground settlement using Drone-LiDAR survey. The thesis consists of seven chapters which are introduced as follow:

In Chapter 1, background, objective, and outline were presented.

In Chapter 2, a literature review was conducted to outline the research of remote sensing techniques, such as InSAR, photogrammetry and Drone-LiDAR, as well as data processing methods for Drone-LiDAR measured data. Through the literature review, the limitations of other remote sensing techniques except for Drone-LiDAR were presented and Drone-LiDAR applicability of soft ground settlement.

In Chapter 3, the study site was explained. Overview and geotechnical properties of the study site were presented. Measurements, including Drone-LiDAR and traditional measurements, were also presented and comparisons were made between them.

In Chapter 4, data processing of Drone-LiDAR measured data was applied to the study site. Denoising, bare-earth filtering and DEM construction were performed. Through this procedure, DEMs about ground elevation were constructed.

In Chapter 5, a settlement evaluation method was suggested. Settlement could not be evaluated directly from the DEM for ground elevation. Therefore, a method was proposed to evaluate settlement by dividing the increase and decrease in ground elevation. The results were then validated by comparing them to the settlement plates installed at the study site.

In Chapter 6, application of settlement evaluation method was presented. First, the estimation of earthwork volume was performed. The earthwork volume over time and cumulative earthwork volume were presented. Next, the estimation of settlement risk areas was performed.

In Chapter 7, a summary of conclusions was provided.

Chapter 2 Literature Review

2.1 Introduction

Accurate evaluation and monitoring of settlement are essential to ensure the safety and durability of infrastructure on soft ground. Over time, significant progress has been made in settlement prediction, monitoring, and management methods, ranging from traditional techniques like settlement plates and total stations to advanced remote sensing technologies.

Remote sensing methods such as InSAR, photogrammetry, and Drone-LiDAR have the advantage of enabling comprehensive field-wide monitoring. However, most of these methods face challenges in accurately capturing localized, small-scale, and rapid vertical deformations, particularly in large and complex fields. This limitation arises because such techniques often focus on broader spatial trends rather than the detailed, fine-scale movements typical of soft ground conditions.

In contrast, Drone-LiDAR overcomes many of these constraints by providing high-resolution, accurate, and frequent measurements of ground elevation changes. Its ability to collect detailed point cloud data with greater spatial and temporal precision makes it particularly suitable for assessing settlement in soft ground, offering improved applicability compared to other remote sensing technologies.

This literature review examines the evolution of settlement measurement techniques, transitioning from traditional point-based methods to comprehensive field-wide monitoring using remote sensing. Special attention is given to the potential of Drone-LiDAR in overcoming the limitations of existing methods. Furthermore, the review highlights current gaps in the field and emphasizes the need for robust methods to interpret Drone-LiDAR data for soft ground settlement analysis.

2.2 Field monitoring methods

Traditional methods for measuring settlement primarily rely on settlement plates and total stations. This process involves on-site personnel manually monitoring settlement plates using total stations at intervals ranging from 1 to 10 days. Settlement plates are installed at only a limited number of measurement points, resulting in relatively restricted monitoring coverage compared to the broader field (Chen et al., 2010; Liu et al., 2012). Consequently, settlement monitoring based on these traditional methods is often insufficient for identifying the varying settlement characteristics across adjacent ground areas and the entire site.

To address the limitations of traditional approaches, an increasing focus has been placed on leveraging remote sensing technologies for large-scale ground deformation monitoring. InSAR, in particular, has been extensively utilized to measure ground deformation caused by natural and anthropogenic processes, such as earthquakes, landslides, and vertical deformation in urban areas (Casagli et al., 2017; Dehghani et al., 2013; Prati et al., 2010; Rathje et al., 2006). Its application has also been demonstrated in monitoring airport ground deformation (Wu et al., 2020). InSAR enables both spatial and temporal tracking of deformation behavior, offering valuable insights into the evolution of ground deformation. For instance, long-term InSAR analysis as shown in Fig 2.1 revealed that cumulative deformation at an airport site reached up to 40cm over the past two decades, showcasing its potential for capturing both gradual and localized deformation patterns with high precision.

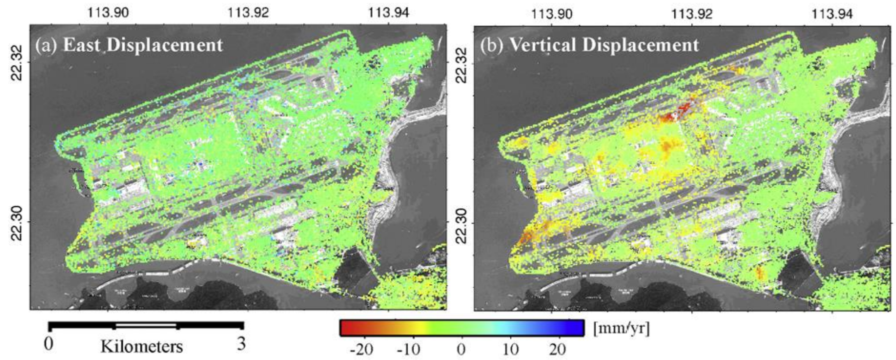


Figure 2.1 The estimated displacement in eastern and vertical directions (Wu et al., 2020)

Photogrammetry has also been widely utilized to monitor ground deformation, particularly in areas affected by mining activities and settlement in landfills (Baiocchi et al., 2019; Hu and Wu, 2016). For example, Fig. 2.2 illustrates elevation changes observed in mining areas, highlighting the effectiveness of photogrammetry in detecting spatial deformation patterns. A specific photogrammetry-based technology, UAV Structure-from-Motion (UAV SfM), has gained significant attention for its versatility in detecting deformation patterns. It has been extensively used to monitor mining sites, urban environments, fault zones, and construction management projects, providing high-resolution data and detailed insights into ground deformation (Gül et al. 2020; Lee and Park 2019). For example, Fig. 2.3 shows the aerial distribution map of the mass movement formed by UAV photogrammetry.

Similarly, Drone-LiDAR has emerged as a powerful tool in geospatial fields due to its ability to capture precise vertical deformation data over large areas. It has been applied to monitor ground deformation caused by underground mining, detect ground deformation triggered by earthquakes, and assess landslides' impact on terrain stability (Jóźków et al., 2021; Bouziou et al., 2015; Zieher et al., 2019). Furthermore, Drone-LiDAR has been effectively employed to monitor erosion processes, providing valuable insights into landscape changes and sediment transport dynamics, as shown in Fig. 2.4 (Li et al, 2024).

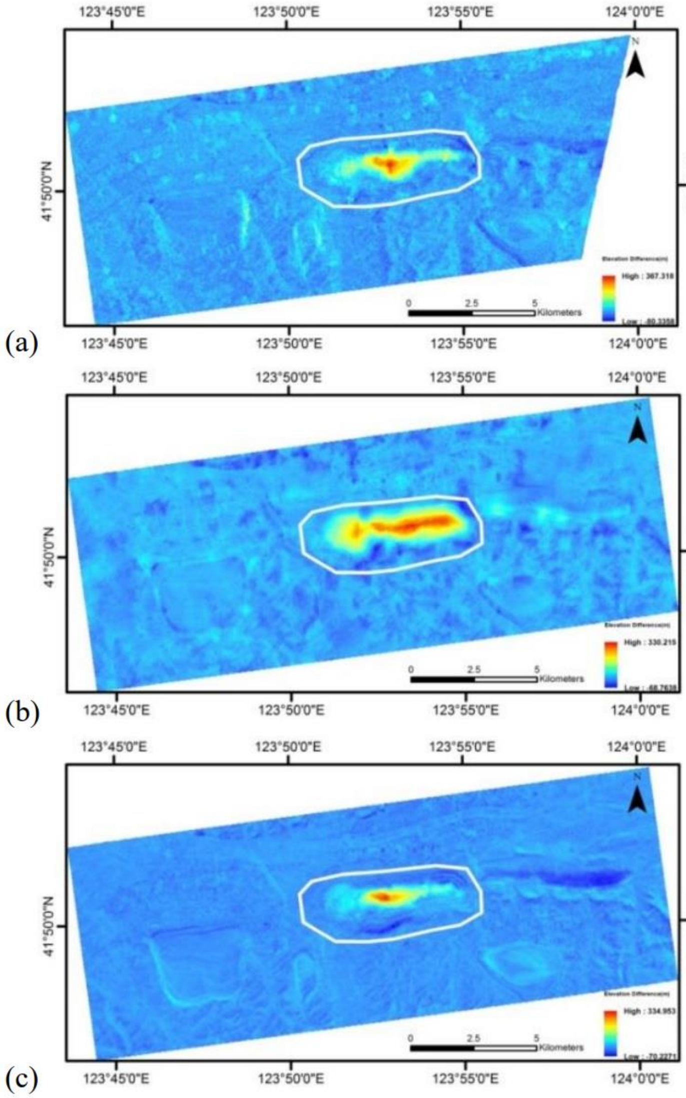


Figure 2.2 Examples of elevation changes in mining area (Hu et al., 2016)

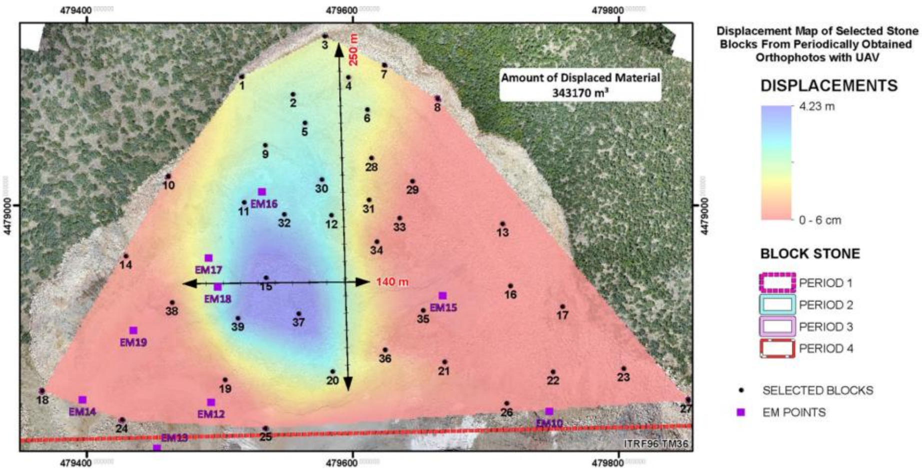


Figure 2.3 Aerial distribution map of the mass movement formed by UAV photogrammetry (Gül et al. 2020)

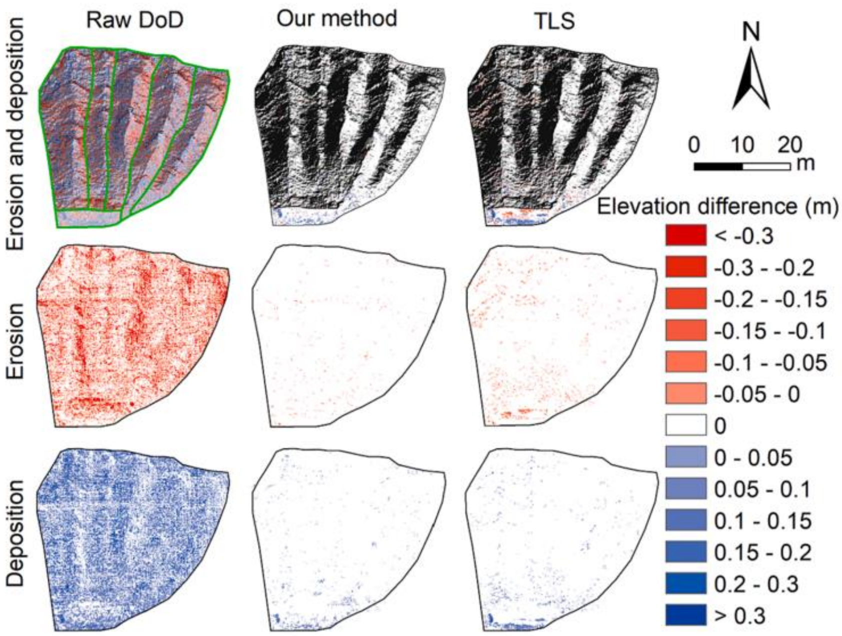


Figure 2.4 Examples of monitoring soil erosion by utilizing UAV LiDAR (Li et al., 2024)

However, the precision of UAV SfM is often compromised during the photo alignment process due to various factors, including the quality and placement of ground control points (GCPs), the accuracy of global navigation satellite systems (GNSSs), and the overlap ratios of captured images (Kim et al., 2021; Kim et al., 2022). These limitations can reduce the overall accuracy of surface models, particularly in challenging environments.

Most remote sensing technologies, including InSAR and photogrammetry, also face inherent limitations in capturing localized, small-scale, and rapid vertical deformations in deeper or larger fields. These limitations are particularly pronounced in complex environments such as soft ground construction sites, where precise and reliable monitoring is critical. In contrast, Drone-LiDAR demonstrates unique advantages in overcoming these challenges. It is relatively less affected by issues such as dense vegetation or the need for extensive ground control, making it more effective in capturing high-resolution data in complex and dynamic terrains (An et al., 2024; Lee et al., 2019; Shi and Wang, 2022; Yang et al., 2023; Zhan et al., 2024). Fig. 2.5 compares the results of Drone-photogrammetry (Fig. 2.5 a) and Drone-LiDAR (Fig. 2.5 b), illustrating that the Drone-LiDAR results exhibit a locally smoother surface. This improvement is attributed to the superior measurement stability provided by Drone-LiDAR. As a result, Drone-LiDAR is increasingly regarded as a more suitable technology for monitoring and analyzing the settlement behavior of complex soft ground sites, offering improved accuracy and reliability in geotechnical applications.

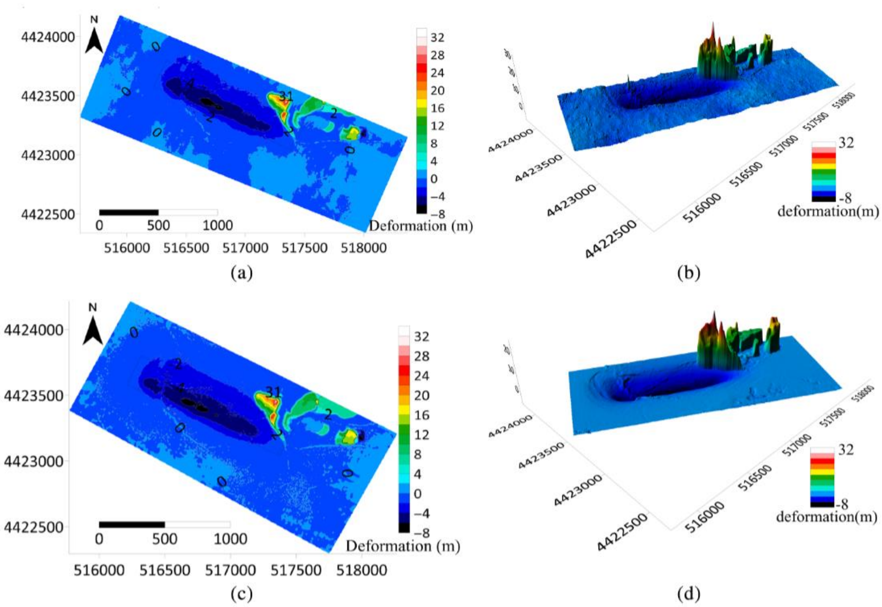


Figure 2.5 Comparison of results between Drone-photogrammetry and Drone-LiDAR (Zhan et al., 2024)

2.3 Drone-LiDAR Measured Data Processing

To effectively perform soft ground site monitoring using Drone-LiDAR, processing the collected LiDAR data is essential to ensure accuracy and reliability. Extensive research has been conducted on point cloud processing techniques to further enhance the precision of Drone-LiDAR measurements, addressing challenges associated with raw data quality and environmental interference (Yang et al., 2022).

One of the critical issues in Drone-LiDAR data collection is addressing data distortion. Raw LiDAR data often contains noise introduced by particles, dust, soil, and multi-path reflections, which can significantly affect the quality of the point cloud, as shown in the Fig 2.6 (Carrilho et al., 2018). To mitigate these issues, various data processing and denoising techniques have been developed. SOR effectively removes statistical outliers from the dataset, improving surface scans (Balta et al., 2018). In addition to SOR, other advanced techniques such as Real-Time Kinetic (RTK) corrections are frequently employed. RTK improves the positional accuracy of LiDAR measurements by correcting errors caused by environmental factors and equipment limitations, enabling precise geospatial mapping (Bi et al., 2021; Li et al., 2022). These processing steps are critical for transforming raw Drone-LiDAR data into high-quality datasets suitable for advanced geotechnical analysis.

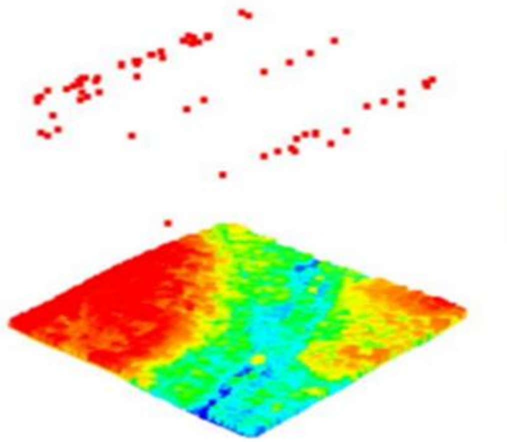


Figure 2.6. Example of outliers (Carrilho et al., 2018)

Drone-LiDAR measurement data often captures a wide variety of surface objects, including vegetation, construction materials, and other non-ground features. Accurately isolating bare-earth data is particularly critical in construction site monitoring, where the presence of materials such as debris and equipment can interfere with precise ground analysis (Tian et al., 2023; Zhang et al., 2023). To address this, Cloth Simulation Filtering (CSF) has emerged as one of the most widely adopted techniques for distinguishing ground from non-ground features. This method effectively separates ground points by simulating a cloth draped over the point cloud, thereby isolating the bare-earth surface as illustrated in Fig 2.7 (Sarıtaş et al., 2023; Zhang et al., 2016).

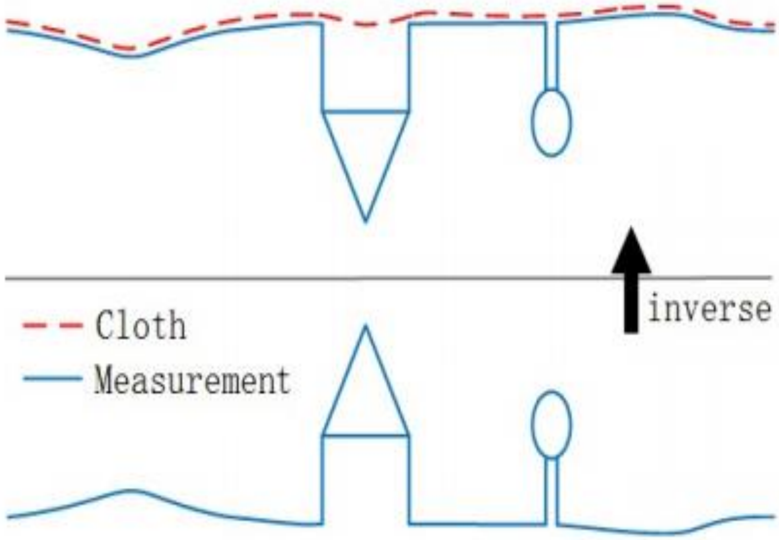


Figure 2.7 Schematic of CSF (Zhang et al., 2016)

Once noise is removed and ground points are identified, the data is transformed into a Digital Elevation Model (DEM), which is an essential tool for more detailed and effective geospatial analysis (Lu et al., 2017; Zhang et al., 1994). DEMs provide a structured representation of the ground, enabling detailed assessments of terrain and settlement behavior. The quality of a DEM, however, depends heavily on selecting an appropriate grid size during its construction as shown in Fig 2.8 and Fig 2.9. Previous studies have underscored the importance of this step, as the choice of grid size can significantly influence the resolution, accuracy, and usability of DEMs derived from 3D point clouds of ground points (Agüera-Vega et al., 2020).

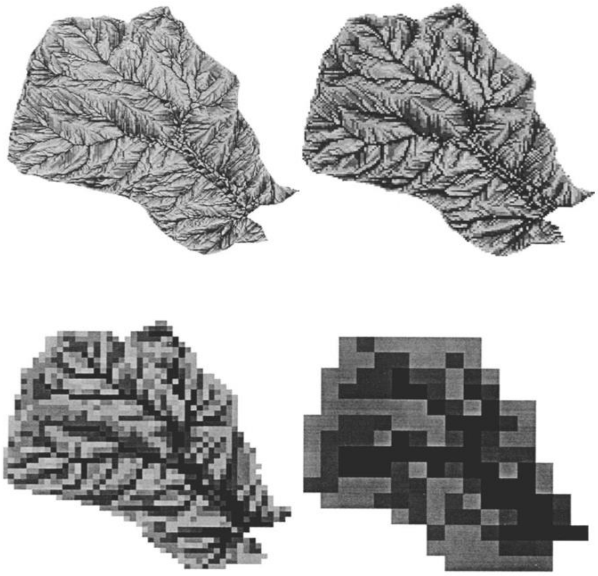


Figure 2.8 Resolution differences according to grid size (Zhang et al., 1994)

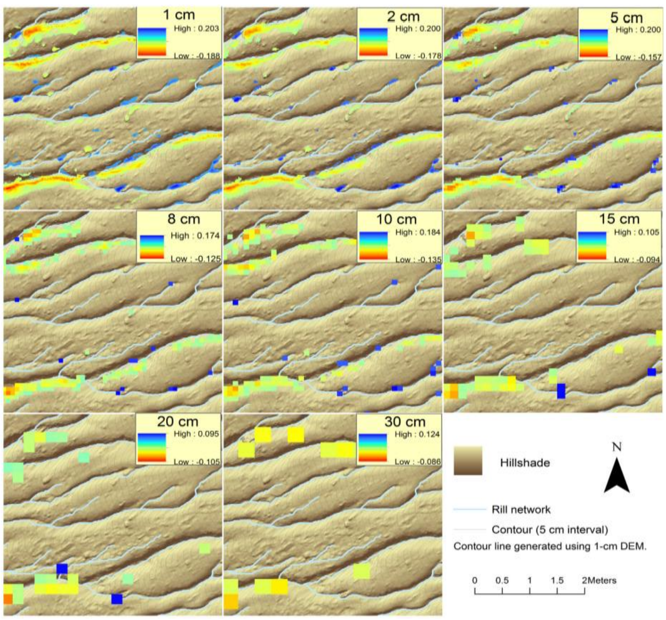


Figure 2.9 Resolution differences according to grid size (Lu et al., 2017)

2.4 Summary

Traditional measurement, such as settlement plates and total stations, are limited by their reliance on a small number of monitoring points and manual measurements, which fail to capture spatial variations across entire sites. Remote sensing technologies like InSAR, photogrammetry, and Drone-LiDAR have emerged as promising alternatives, offering full-field monitoring capabilities. However, many of these methods face challenges in detecting localized, small-scale, or rapid deformations typical of soft ground conditions.

Drone-LiDAR is identified as particularly suitable for monitoring such environments due to its ability to overcome limitations in other remote sensing methods. Effective use of Drone-LiDAR requires advanced data processing techniques, such as Statistical Outlier Removal (SOR) for denoising and Cloth Simulation Filtering (CSF) for distinguishing ground points. The processed data is then converted into Digital Elevation Models (DEMs). Extensive researches emphasize the importance of optimizing DEM construction, including grid size selection, to enhance accuracy and reliability.

Chapter 3 Study Site and Measurements

3.1 Introduction

The study was conducted at Busan Newport, a major maritime logistics hub in South Korea. This coastal site, under construction since 1997, consists of North, South, and West Container, which features extensive ground improvement methods, including preloading with prefabricated vertical drains (PVD). Due to its complex soil conditions and large-scale construction, the site requires effective methods for settlement monitoring and analysis, providing a valuable opportunity to explore advanced techniques like Drone-LiDAR.

3.2 Study site

Busan Newport, situated in the southeastern region of South Korea, manages the largest volume of traffic among Korean ports and serves as a critical hub for the country's maritime logistics (Choi et al., 2022). Construction of the port commenced in 1997, and it has been divided into three main sections: the North Container, the South Container, and the West Container. To date, the North Container has been fully completed, the South Container is partially operational, and construction of the West Container is ongoing.

Fig. 3.1 provides an overview of the study site. This study site covers a total area of approximately 521,700m^2. It is subdivided into 31 distinct sections, each employing various ground improvement techniques, such as the preloading method with prefabricated vertical drains (PVD) and the deep cement mixing method. Among these methods, the preloading method using PVD has been predominantly applied, as it is both cost-effective and straightforward to implement (Chung et al., 2000; Chung et al., 2014; Sakleshpur et al., 2018).

Table 3.1 presents key characteristics of the site. The final fill height (F) and the final settlement (S_f) vary significantly across the sections. The final fill height ranges from 0m to 8.83m, with an average of 3.85m. Meanwhile, the final settlement upon measurement completion ranges from 0.11m to 2.96m, with an average of 1.28m.

For this study, the focus was placed on the sections within the study site where the preloading method with PVD was utilized. This selection allows for an in-depth investigation of the settlement behavior associated with this widely adopted ground improvement technique.

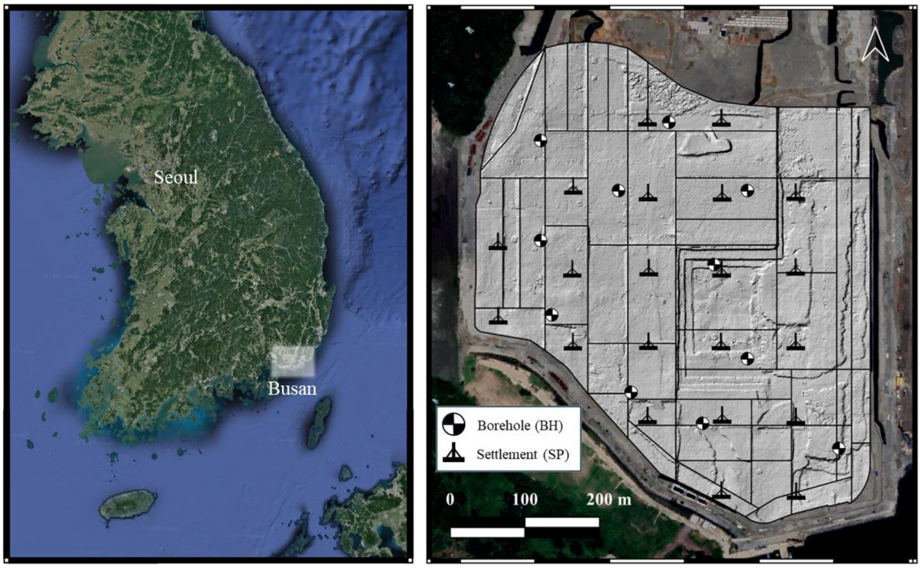


Figure 3.1 Study site

Table 3.1 Final fill height and final settlement

Parameter	Min	Max	Average
F (m)	0	8.83	3.85
S_f (m)	0.11	2.96	1.28

The soil profile of the study site is stratified as follows: starting from the surface, the layers consist of a sandy soil layer (gravel mat), a dredged clayey soil layer, an original clayey soil layer, a lower sandy soil layer, and finally bedrock.

The cohesive soil layers, which include both the dredged and original clayey soils beneath the sandy soil layer, exhibit an SPT-N value of less than 10, indicating their low strength and high compressibility. These cohesive layers are uniformly distributed across the study site, extending from a depth of approximately 5m to a maximum of 52m below ground level.

The results of laboratory tests reveal that the average unit weight of the soil is 16.23kN/m^3, and the average natural moisture content (w_n) is 63.84%. The groundwater level was measured at an average depth of 1m below the surface. Notably, the natural moisture content lies between the liquid limit (w_L) and the plastic limit (w_p), indicating that the soil exhibits high compressibility. The undrained shear strength (S_u) was assessed using both unconfined compression (UC) and unconsolidated undrained (UU) compression tests. These experimental results, analyzed across various depths, demonstrate a linear relationship between undrained shear strength and depth. Specifically, the undrained shear strength was approximately 0.22 times the preconsolidation pressure, which suggests that the soil is in a normally consolidated (NC) state. Further insights into compressibility were obtained through oedometer testing, which provided the compression ratio (CR). The CR value at the study site ranges from 0.15 to 0.45, confirming a state of high compressibility (Coduto et al., 2011). This condition significantly increases the risk of excessive consolidation settlement and highlights the need for stringent control of differential settlement. The preconsolidation pressure, derived from oedometer tests, was found to be lower than the vertical effective stress, further confirming that the soil was in a NC state prior to construction. These findings underline the importance of proper geotechnical design and monitoring to manage settlement effectively and mitigate associated risks. Table 3.2 summarizes the maximum, minimum, and average values of the variables.

Table 3.2 Geotechnical properties of the study site

Parameter	Min	Max	Average
H (m)	4.50	51.50	31.22
W_n (%)	51.40	91.50	71.29
LL (%)	45.90	86.60	76.46
PI (%)	20.90	55.60	47.49
C_c	0.46	1.31	0.90
e_0	1.44	2.83	2.00

3.3 Measurements

Fig. 3.2 illustrates the settlement plates and total stations employed for monitoring in this study. A total of 21 settlement plates were installed across the field, with each plate representing a monitoring area of approximately 100×100m. The settlement plates were strategically placed to monitor settlement during preloading phase and to determine the appropriate for unloading.

Measurements were conducted manually using a total station, with measurement intervals ranging from 1 to 10 days depending on the construction schedule and observed settlement rates. For each settlement plate, data on fill height, settlement, ground elevation, and site finish elevation were collected over time. This time-series data, exemplified in Fig. 3.3, was critical for analyzing settlement behavior and assessing the effectiveness of the preloading process.

(a) Settlement plate (b) Total station

Figure 3.2 Traditional settlement measurement

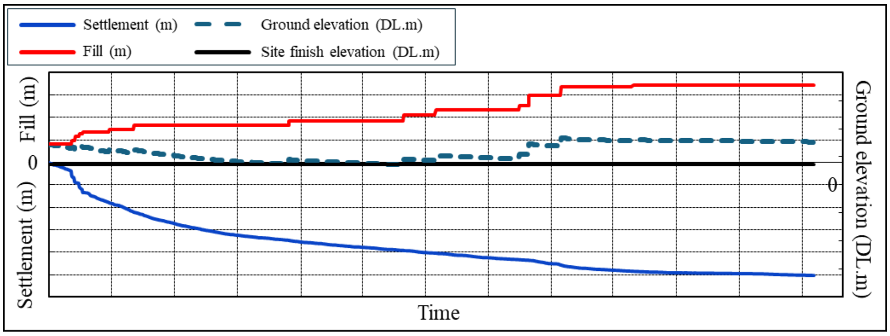


Figure 3.3 Result from the traditional settlement measurement

Fig. 3.4 presents the Drone and LiDAR equipment used in this study. Over an 18-month period, from May 2021 to November 2022, the site was surveyed 33 times using this system. LiDAR operates by emitting laser light that reflects off objects and returns to the sensor, allowing for the calculation of relative distances. However, adverse weather conditions, such as snow or rain, can hinder accurate measurements, as water on the ground introduces significant errors.

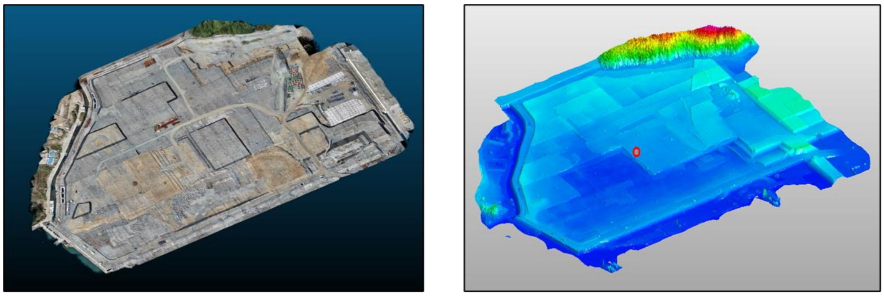
The data collected by the LiDAR forms a “point cloud”, a dense collection of points representing the surfaces of objects within the scanned area. This study utilized a DJI M600 drone equipped with an Applanix 15 GNSS/INS for precise positioning and a Velodyne Puck VLP-16 LiDAR sensor. Due to the drone’s movement speed of approximately 5m/s and the presence of elevated terrain surrounding the site, measurements were conducted at an altitude of about 60m.

To minimize GPS-related errors, Real-Time Kinematic (RTK) corrections were applied, eliminating the need for additional calibration using Ground Control Points (GCP). Given the drone's limited battery capacity, the site was divided into four measurement zones. Data from these zones were subsequently merged into a single, comprehensive 3D point cloud using the DJI Terra program. The geographic coordinates of the drone data were converted into latitude and longitude using the WGS 84 ellipsoid model and further refined with a coordinate correction system (Eastern Origin). Since Drone-LiDAR data wis typically expressed as ellipsoid height, corrections were made to align it with geoid height using the Korean National Geoid Model 2018 (KNGeoid 18) at external reference points within the study site.

The raw 3D point cloud data generated by the Drone-LiDAR, as shown in Fig. 3.5, offers time-series coverage of the entire site, providing a significant advantage over the 21point measurements obtained via settlement plates. A single Drone-LiDAR survey captures approximately 100 million data points, corresponding to a resolution of 5cm×5cm, which is far more detailed than the 100m×100m spacing of settlement plates. Table 3.3 highlights this comparison, demonstrating the enhanced spatial resolution of Drone-LiDAR measurements. Fig. 3.6 illustrates the frequency of measurement periods for the 21 settlement plates compared to the Drone-LiDAR surveys, showcasing the greater temporal and spatial data density achieved with the latter.

(a) Drone (DJI M600) (b) LiDAR (VLP-16)

Figure 3.4 Drone and LiDAR information



(a) Example of Drone-LiDAR measurement (Color) (b) Example of Drone-LiDAR measurement (Elevation)

Figure 3.5 Drone-LiDAR measurement results

Table 3.3 Comparison of the number of measurement points

	Settlement plate	LiDAR
Pts./measurement	21 points (1pt./100m×100m)	100,000,000 points (1pt./5cm×5cm)

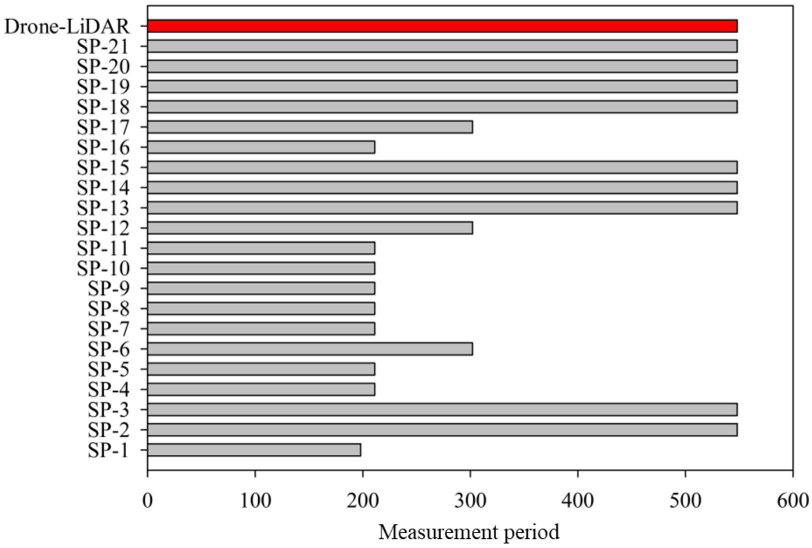


Figure 3.6 Measurement period according to settlement plates and Drone-LiDAR

3.4 Summary

The study site is a large coastal area currently under preloading construction, featuring a diverse soil profile including sandy layers, cohesive clay layers, and bedrock. The cohesive soil layers, characterized by high compressibility and low strength, present challenges for settlement monitoring and management. Traditional methods such as settlement plates and total stations were employed to measure settlement at 21 discrete points, with data collected manually at regular intervals. Comparing this, Drone-LiDAR technology was utilized to capture high-resolution, time-series data for the entire site, enabling a detailed and comprehensive analysis of surface elevation changes.

Chapter 4 Determination of Ground Elevation

4.1 Introduction

To utilize data collected Drone-LiDAR, a preprocessing step is essential. This chapter outlines the preprocessing process required before evaluating settlement using data obtained from the study site measurements. The process includes denoising, extracting bare-earth information, and converting the point cloud data into a Digital Elevation Model (DEM) to enable effective analysis.

4.2 Drone-LiDAR Measured Data Processing Results

The study site, located in a coastal area, is subject to environmental conditions that can introduce outliers into the raw Drone-LiDAR data. These outliers typically arise from dirt, dust, and water droplets, which interfere with the accuracy of the measurements. To ensure precise and efficient analysis, it is necessary to preprocess the data by removing the data by removing these outliers using a denoising technique.

In this study, the Statistical Outlier Removal (SOR) method was employed for this purpose. SOR is widely regarded as one of the most reliable and effective techniques for outlier removal in point cloud data. By analyzing the statistical distribution of point distances within the dataset, SOR identifies and eliminates anomalous points that deviate significantly from the majority.

The application of the SOR method resulted in the successful removal of outliers, as illustrated in Fig. 4.1. This preprocessing step improved the quality of the data, laying the foundation for more accurate and efficient analysis in subsequent stages of the study.

(a) Before applying SOR　　　　(b) After applying SOR

Figure 4.1 Comparison of before and after applying outlier removal

The study site remains an active construction area where preloading operations are ongoing. As a result, various objects, such as construction materials, are present on the ground surface and are inevitably captured in the raw Drone-LiDAR data. These objects must be identified and removed to ensure accurate estimation of the ground elevation.

In this study, the Cloth Simulation Filtering (CSF) method was employed to separate ground points from non-ground objects effectively. CSF is particularly well-suited for large-scale terrain modeling as it simulates a cloth draped over the point cloud, distinguishing ground surfaces from above-ground objects.

Table. 4.1 outlines the specific CSF parameters optimized for the characteristics of the study site, ensuring robust filtering performance. The application of CSF successfully removed non-ground objects, as demonstrated in Fig. 4.2. This preprocessing step was critical for producing a high-accuracy Digital Elevation Model (DEM) for subsequent analysis.

Table 4.1 Configuration of parameters for applying CSF

	Rigidness (RI)	Slope Smooth	Time step (dT)	Iteration	Threshold (h_{cc})	Grid resolution (GR)
Value	2	True	0.65	500	0.3	3.0

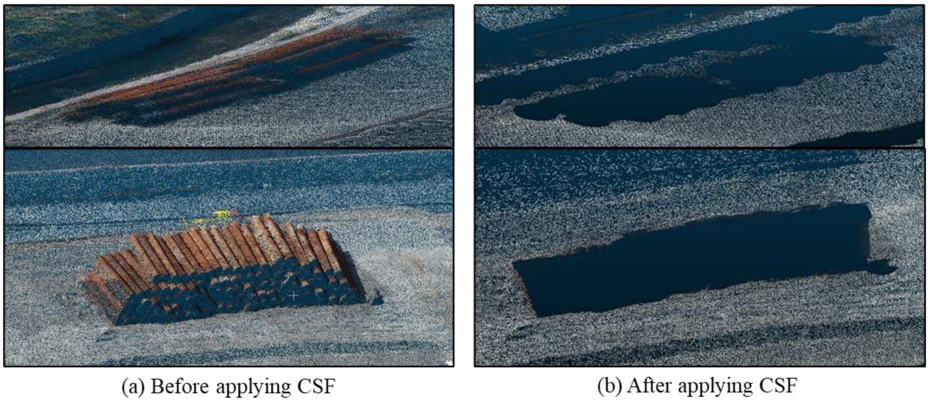


Figure 4.2 Comparison of before and after applying bare-earth filtering

4.3 DEM Construction

Once outliers are removed and bare-earth filtering is applied, the resulting data consists of a refined set of point cloud points. To facilitate efficient analysis, it is essential to convert this point cloud dataset into a Digital Elevation Model (DEM). In this study, the most suitable grid size for constructing the DEM was carefully determined to ensure both accuracy and computational efficiency.

The optimal grid size was selected as the smallest grid that ensures complete coverage of the study area, avoiding instances where grid cells contain no points. Fig. 4.3 illustrates the selection process and the resulting DEM, highlighting the balance achieved between resolution and data completeness. This optimized DEM forms the basis for subsequent analysis and ensures a detailed representation of the ground elevation.

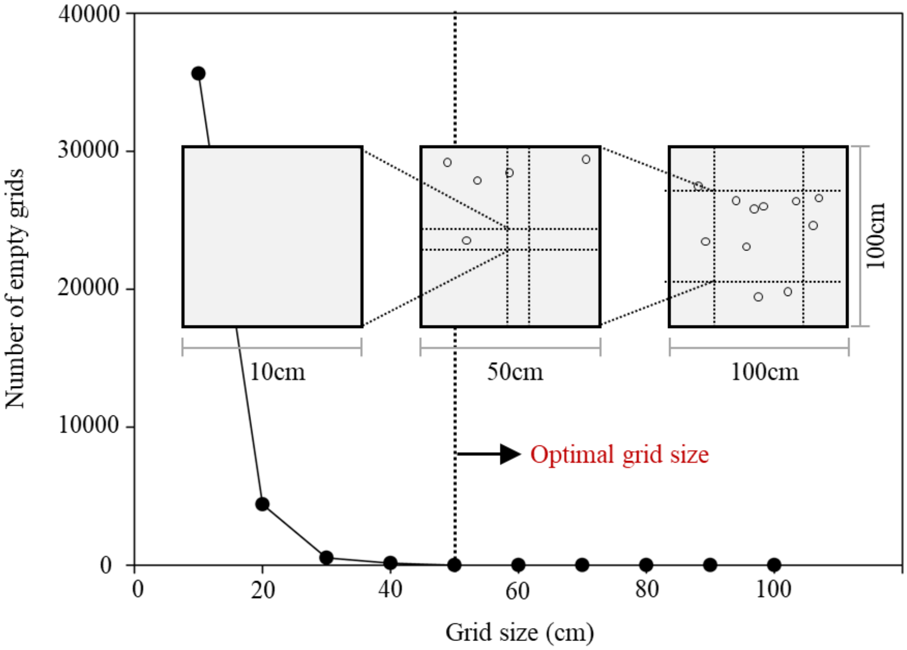
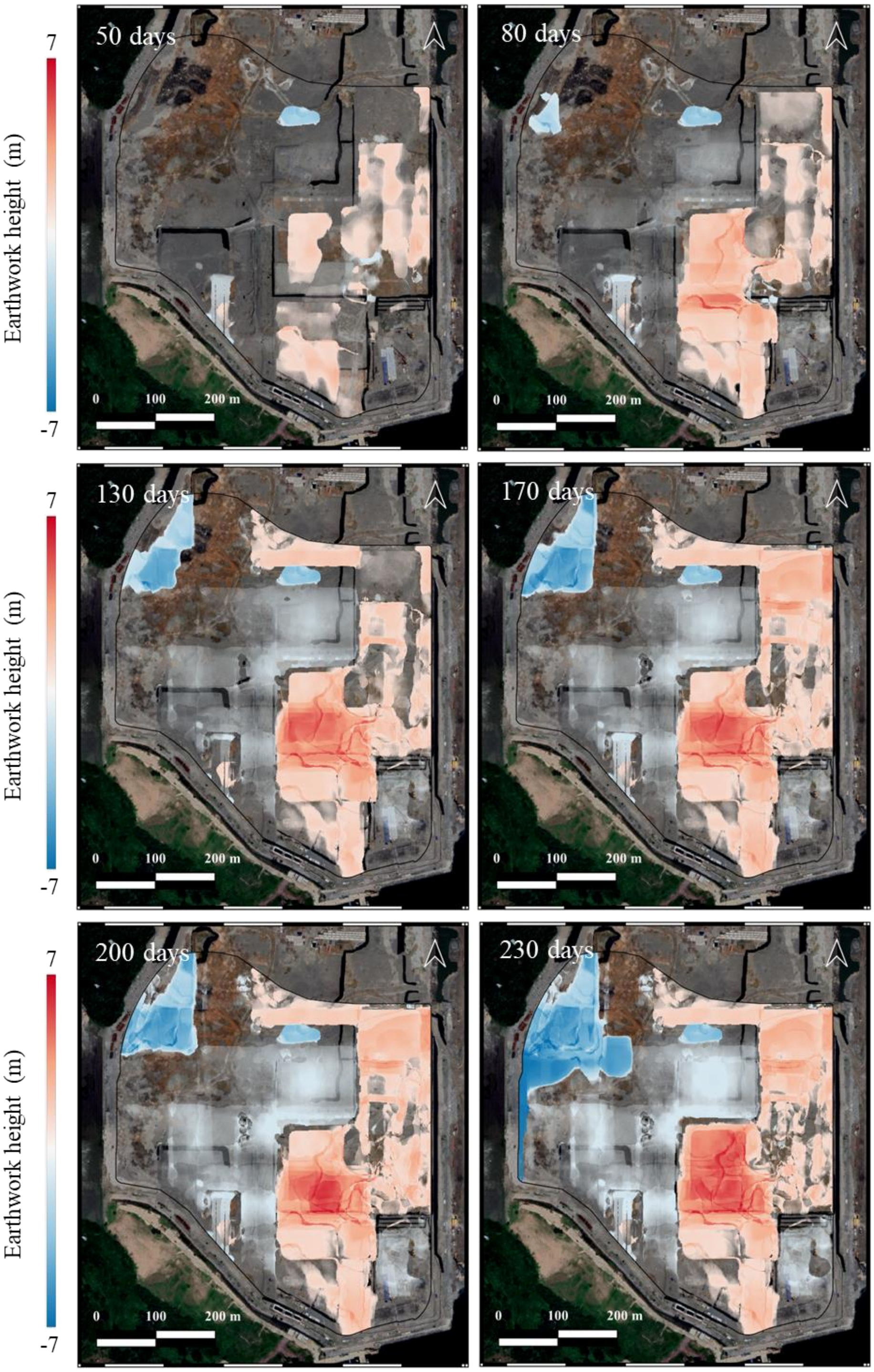
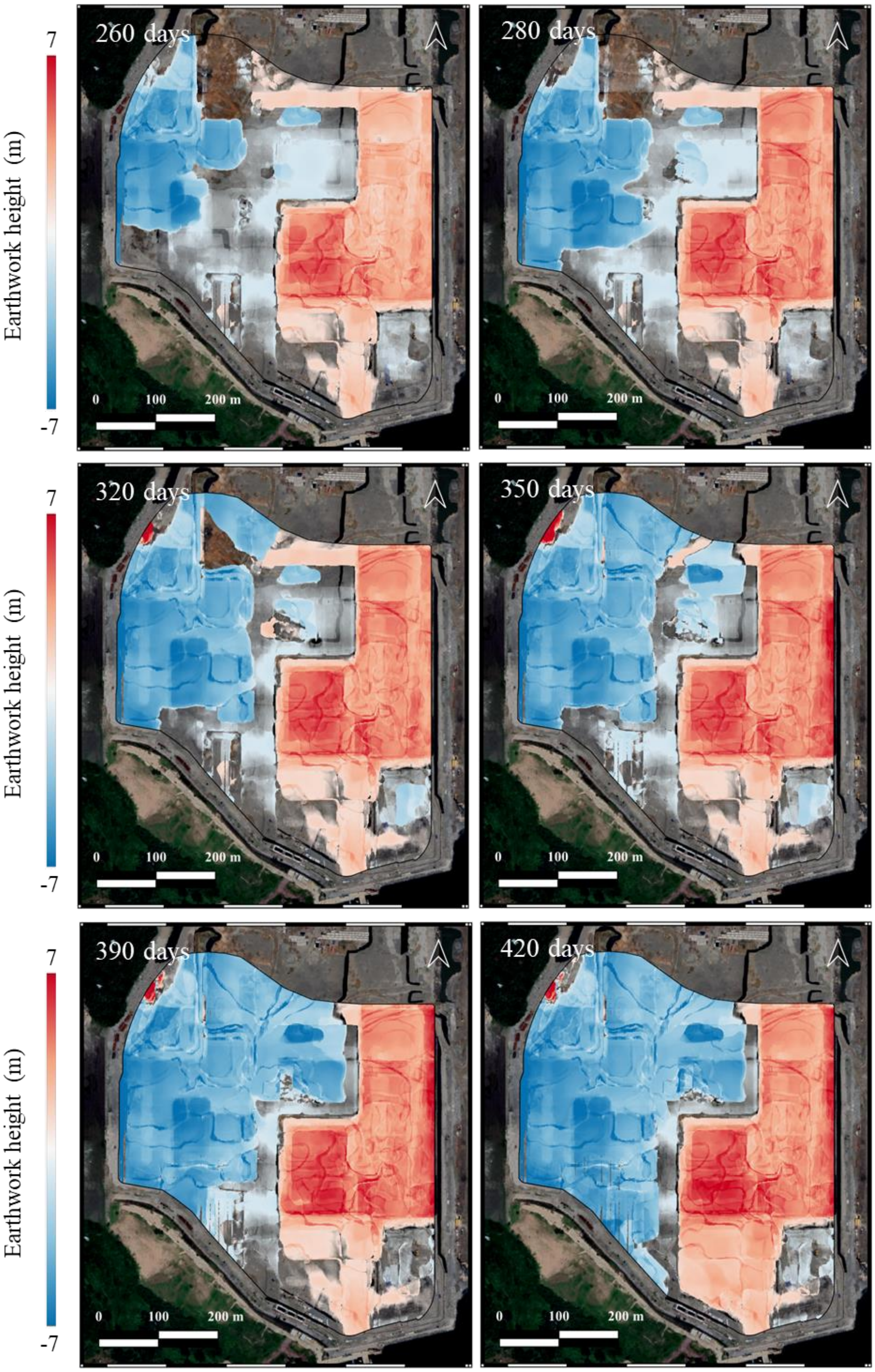


Figure 4.3 Grid analysis for reliable DEM construction

Finally, the changes in ground elevation over time at the study site, as determined through DEM construction, are shown in Fig. 4.4. By observing the ground elevation change at a single point, it is evident that both increases and decreases in elevation accumulate, leading to a final increase in ground elevation. As a result, it becomes apparent that directly evaluating the settlement from the DEM alone is challenging.


50 days
80 days
130 days
170 days
200 days
230 days
Earthwork height (m)
7
-7
0
100
200 m


260 days
280 days
320 days
350 days
390 days
420 days
Earthwork height (m)
7
-7
0
100
200 m

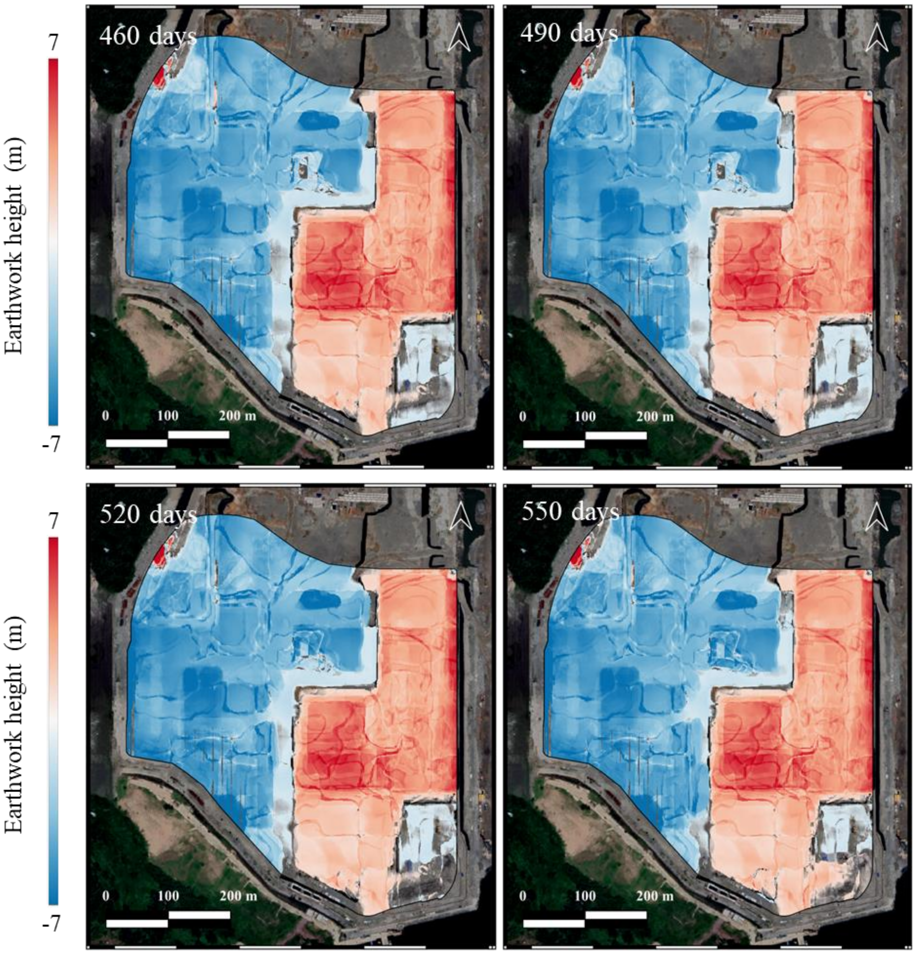


Figure 4.4 DEM changes in the study site over time

4.4 Summary

To utilize Drone-LiDAR data effectively, preprocessing was performed to ensure accuracy and usability for settlement analysis. The raw LiDAR data contained outliers caused by dirt, dust, and water droplets, which were removed using the Statistical Outlier Removal (SOR). Additionally, objects like construction materials on the surface were filtered out using the Cloth Simulation Filtering (CSF) to extract accurate bare-earth information. The processed point cloud data was then converted into Digital Elevation Models (DEMs) using the most optimal grid size, 50cm×50cm, to ensure efficient analysis. These preprocessing steps were critical for obtaining high-quality data suitable for precise settlement evaluations and monitoring.

Chapter 5 Settlement Evaluation Method

5.1 Introduction

In Chapter 5, a method to evaluate settlement using DEM that contains ground elevation information is proposed. When ground elevation increases or decreases, challenges arise in accurately evaluating settlement because of loading and unloading. To address this, a correction factor representing the ratio of calculated settlement to measured settlement is applied when ground elevation increases. By comparing the calculated settlement rate to the measured settlement rate, settlement and unloading are distinguished. The total settlement of the study site is then evaluated, and the accuracy of the proposed method is validated by using settlement plate results as a reference.

5.2 Cases for Evaluating Settlement

The generated DEM represents the ground elevation of the study site. By analyzing changes in ground elevation captured in these DEMs over time, ground movement can be assessed. Specifically, this approach is expected to detect both the presence and extent of ground settlement. However, since ground elevation changes can result from various factors beyond settlement, interpreting these changes presents significant challenges.

Changes in ground elevation can generally be categorized into two cases. First, if the ground elevation increases over time, it may indicate that new material, such as fill, has been added to the area. However, settlement may still occur beneath the surface. In Fig. 5.1, the ground elevation change observed in the DEM reflects both the added material and the settlement occurring below it. Simply analyzing the increase in ground elevation does not provide an accurate measure of the settlement taking place beneath the fill.

Conversely, when ground elevation decreases, it is not immediately clear whether the reduction is caused by settlement beneath the surface or by the removal of material near the surface. Fig. 5.2 (a) shows a case where the decrease in ground elevation was due to unloading, and (b) shows a case where it was caused by settlement. To accurately evaluate settlement, it is necessary to distinguish between settlement and intentional surface removal such as unloading. To address this issue, this study proposes the following method:

(1) Evaluation of settlement when ground elevation increases: When the ground elevation increases, it is not immediately possible to determine the amount of settlement caused by the added fill. Therefore, the increase in ground elevation is utilized to independently estimate the settlement. First, a theoretical equation is applied to calculate the settlement corresponding to the observed increase in ground elevation. Subsequently, this calculated settlement is compared with the measured settlement using Drone-LiDAR. From this comparison, a correction factor is derived. The estimated settlement is then refined by multiplying the increase in ground elevation by this correction factor.

(2) Evaluation of settlement when ground elevation decreases: When the ground elevation decreases, it is critical to distinguish whether the change is due to settlement or unloading. To achieve this, the measured settlement rate, which reflects all reductions in ground elevation, is compared with the calculated settlement rate, which reflects only the expected settlement. If the measured settlement rate increases in a section where the calculated settlement rate decreases, the change is attributed to unloading. In such cases, the settlement in that section is assumed to continue at the previously measured settlement rate.

In summary, a detailed method for evaluating settlement in two cases: when the ground elevation increases and when it decreases will be proposed. By accounting for these factors, it becomes possible to more accurately evaluate the actual settlement across the study site based on DEMs generated through Drone-LiDAR measurements.

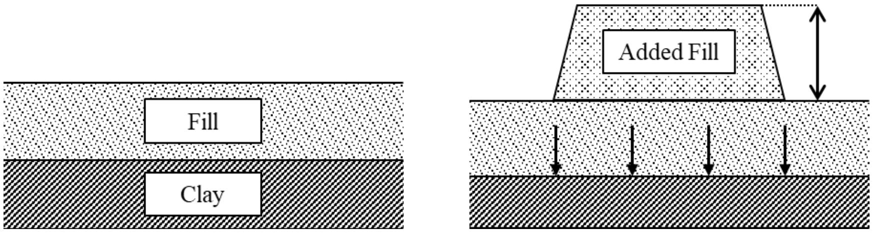


Figure 5.1 Case 1. $\delta_{EL.} > 0$

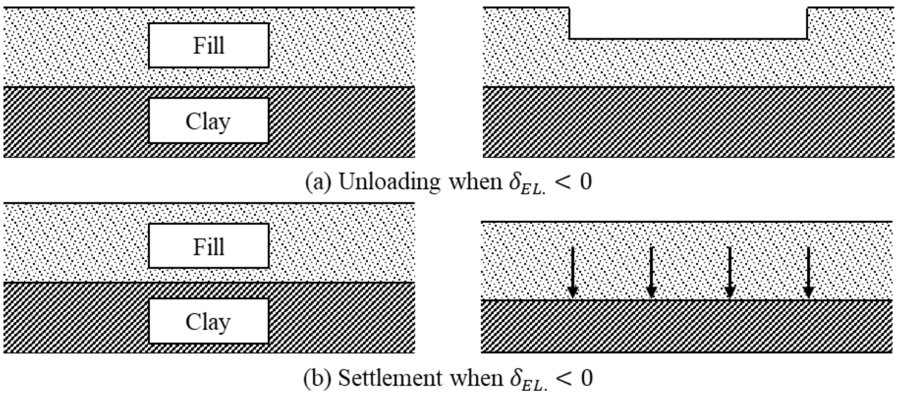


Figure 5.2 Case 2. $\delta_{EL.} < 0$

5.3 Case 1: Ground Elevation Increases ($\boldsymbol{\delta_{EL.} > 0}$)

When ground elevation increases, it is generally due to the loading of fill material. However, simply observing the increase in ground elevation does not directly reveal the amount of settlement occurring beneath the fill. To accurately evaluate settlement during loading, a detailed analytical approach is necessary. For this purpose, a back analysis method using a correction factor, ϕ is proposed. The following outlines the step-by-step methodology:

(1) Fig. 5.3 (a) shows the calculation of settlement during the loading period using the Hansbo theoretical equation. When an increase in ground elevation is first detected (t_2), it can be assumed that fill material has been loaded. This loading causes an increase

in ground elevation and applies additional stress to the underlying soft ground, resulting in settlement. Theoretical calculations, particularly the Hansbo theoretical equation, are employed to estimate the settlement beneath the fill. The Hansbo theoretical equation is commonly used to predict settlement in soils where vertical drains are installed. It accounts for the smear effect, which means the impact of disturbed zones caused by drain installation and well resistance, which means the efficiency of vertical drains. Using this equation, the settlement during the loading period is preemptively calculated.

(2) Fig. 5.3 (b) shows the measurement of settlement ($\delta_{EL.}$) through Drone-LiDAR immediately after loading (t_3). After loading, Drone-LiDAR measurements provide additional data on ground elevation changes over time. If ground elevation decreases immediately after loading, this indicates that settlement is actively occurring. This settlement is primarily influenced by the weight of the newly added fill. The settlement measured during this phase is crucial for interpreting the impact of the fill on settlement behavior during loading.

(3) Fig. 5.3 (c) shows the calculation of the correction factor, ϕ. To refine the settlement estimated using theoretical calculations, ϕ is introduced. This factor aligns the theoretical settlement values with measurements, enabling a more precise evaluation. ϕ is calculated using the following equation 5.1.

$$\phi = \frac{Measured\ settlement\ amount\ (after\ loading)}{Calculated\ settlement\ amount\ (from\ Hansbo\ equation)} \quad \text{(Eq. 5.1)}$$

The correction factor represents the ratio between the measured settlement and the theoretically calculated settlement, allowing for the consideration of factors not fully captured by the Hansbo equation, such as complex site conditions or non-uniform soil behavior.

(4) Fig. 5.3 (d) shows the adjustment of calculated settlement during loading period, using ϕ. Once ϕ is determined, it is applied to the estimated settlement during the loading period. This is done by multiplying the theoretical settlement by the ϕ. This adjustment accounts for the combined effects of loading and ground deformation, yielding a more accurate estimation of settlement.

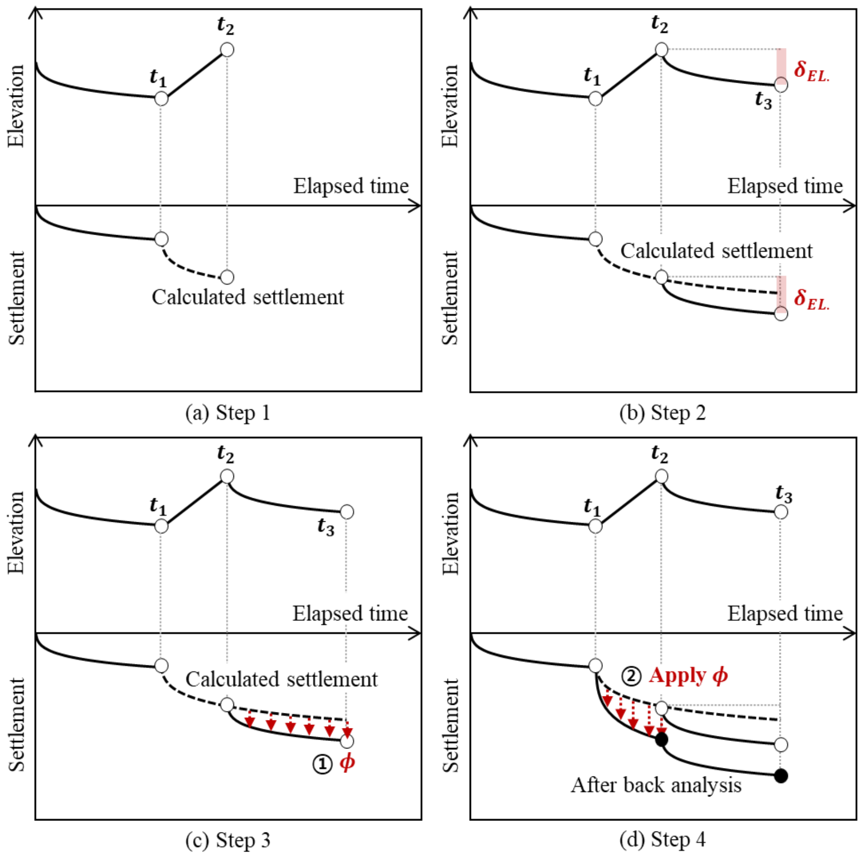


Figure 5.3 Settlement evaluation in Case 1 ($\delta_{EL.} > 0$)

5.4 Case 2: Ground Elevation Decreases ($\delta_{EL.} < 0$)

When ground elevation decreases, it is typically indicative of settlement. However, it is essential to distinguish whether the decrease in ground elevation is caused by settlement due to the consolidation and compression of soft clay layers, or by unloading, where material near the surface is intentionally removed. To address this, a method comparing settlement rates is proposed. In this context, the settlement rate refers to the rate of change in settlement over time. The two settlement rates used in this method are measured settlement rate and calculated settlement rate. Measured settlement rate represents the cumulative decrease in ground elevation observed by Drone-LiDAR over time. This rate accounts for all causes of ground elevation reduction, including both settlement and unloading. Conversely, calculated settlement rate represents the expected trend of settlement over time, calculated using the Hansbo theoretical equation. This rate reflects settlement due to soil compression and is unaffected by unloading. The methodology is outlined as follows:

(1) Fig. 5.4 (a) shows the evaluation of calculated settlement rate. The Hansbo theoretical equation is applied to determine settlement based on the ground elevation increases measured through Drone-LiDAR, with the results accumulated for each valid measurement. Fig. 5.4 (a) illustrates the settlement calculated by applying the Hansbo theoretical equation to ground elevation increases at 210 and 550 days, respectively. It shows the expected trend of settlement over time.

(2) Fig. 5.4 (b) presents a comparison of the calculated and measured settlement rates at 210 and 550 days, respectively. The analysis begins by identifying sections where the calculated settlement rate decreases. In these sections, the calculated settlement rate is compared with the measured settlement rate. If the measured settlement rate also decreases in a section where the calculated settlement rate decreases, it can be interpreted as settlement, as it reflects the natural deceleration of ground settlement due to continuous soil compression. Conversely, if the measured settlement rate increases in a section where the calculated settlement rate decreases, it deviates from the expected settlement trend and indicates that the surface material has been removed, suggesting unloading activity. In Fig. 5.4 (b), no unloading activity was detected at 210 days. However, at 550 days, a section was observed where the measured settlement rate increased while the calculated settlement rate decreased, confirming the occurrence of unloading.

For sections where unloading is confirmed, settlement is reevaluated by assuming that the measured settlement rate immediately prior to the unloading continues instead of using the measured settlement rate during the unloading. This correction eliminates the influence of unloading on settlement evaluations, enabling a more accurate evaluation of the actual settlement trend.

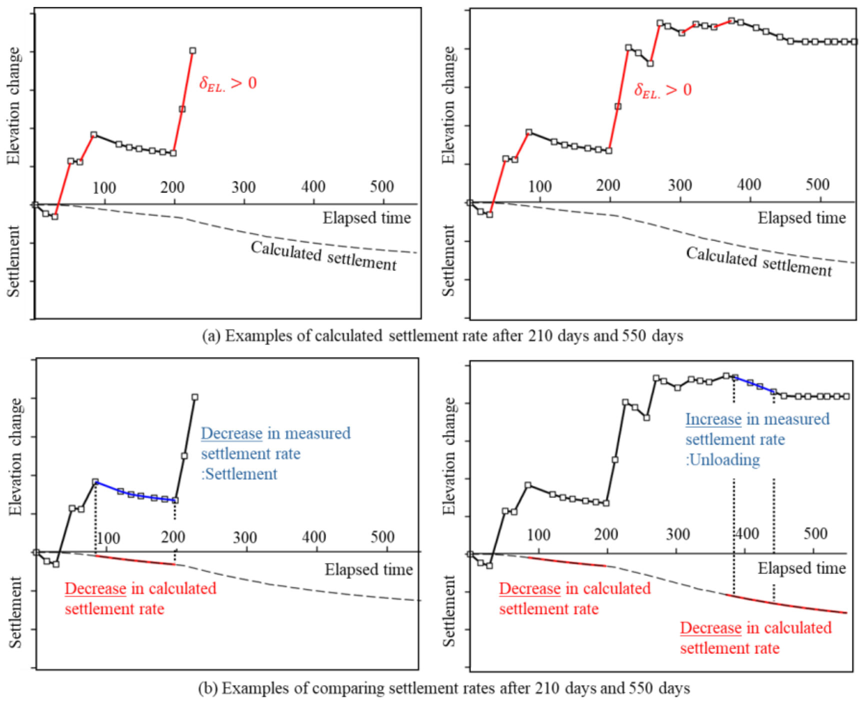


Figure 5.4 Settlement evaluation in Case 2 ($\delta_{EL.} < 0$)

5.5 Validation of the Proposed Method

In this study, a method was proposed to evaluate settlement by determining ground elevation changes using Drone-LiDAR and analyzing increases or decreases in ground elevation. The proposed method was applied to the study site and its accuracy was evaluated. To validate the method, settlement measurements obtained from settlement plates at the study site were compared with settlement values evaluated at the same locations using the Drone-LiDAR based the proposed method. A total of 21 settlement plates were included in the comparison. Fig. 5.5 illustrates the settlement measured at 8 of the 21 settlement plates, along with the ground elevation changes measured via Drone-LiDAR and the corresponding evaluated settlement. This visually demonstrates the agreement between the settlement measured using settlement plates and the settlement evaluated using the proposed method.

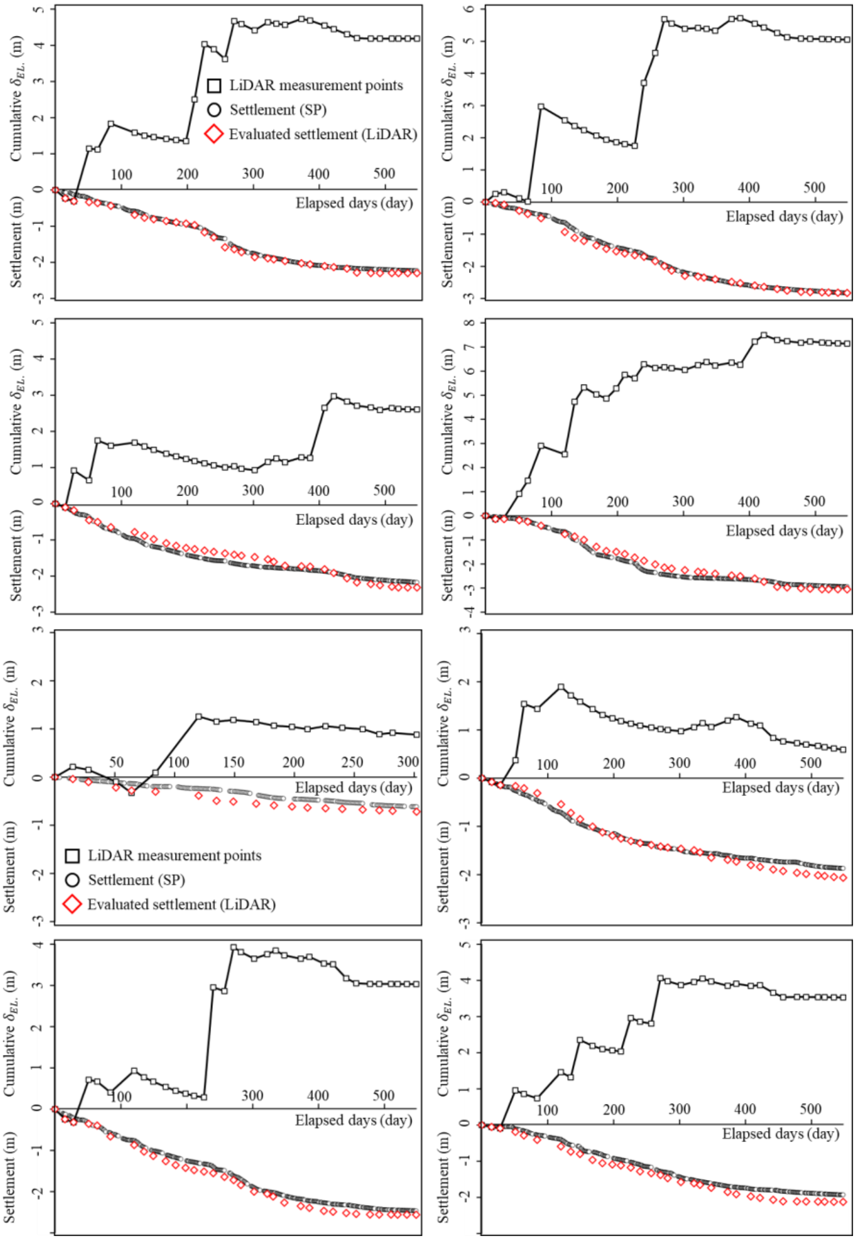


Figure 5.5 Comparison of settlement obtained from SPs and the proposed method

When compared to the settlement measured at 21 settlement plates at the final measurements, the proposed method yielded an average RMSE of 0.134m, an MAE of 0.119m, and a correlation coefficient (R^2) of 0.956. Fig. 5.6 illustrates the boxplot of RMSE, MAE, and R^2 values at the final measurement. These quantitative values show the validity of the proposed method.

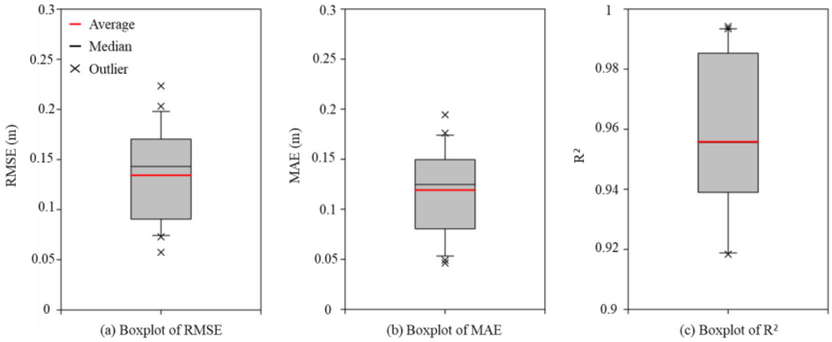


Figure 5.6 Boxplot of RMSE, MAE, and R^2 based on final measurements

Additionally, Fig. 5.7 shows the time-series boxplot of absolute errors at the settlement plate locations for each measurement over time. This demonstrates that the accuracy of the proposed method using Drone-LiDAR remains consistent over time. Fig. 5.8 further highlights the absolute error over time at the settlement plate locations in unloading concentration zone and loading concentration zone, respectively. The average absolute error in the unloading concentration zone is smaller than that in loading concentration zone, and the variance of the absolute error is also lower in unloading concentration zone. This discrepancy can be attributed to the greater complexity in loading concentration zone. In unloading concentration zone, only unloading and settlement occur, resulting in relatively straightforward ground behavior. In contrast, loading concentration zone experiences a combination of unloading, loading and settlement, leading to greater variability and complexity in ground elevation changes.

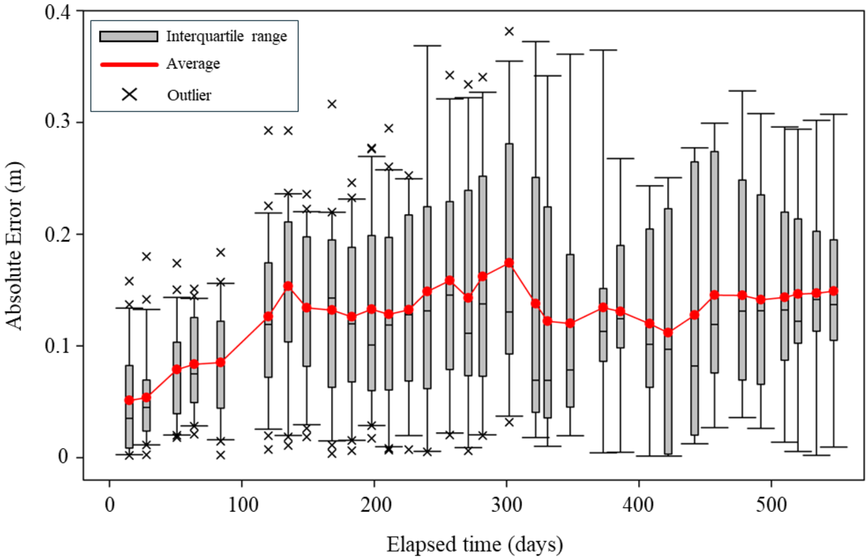
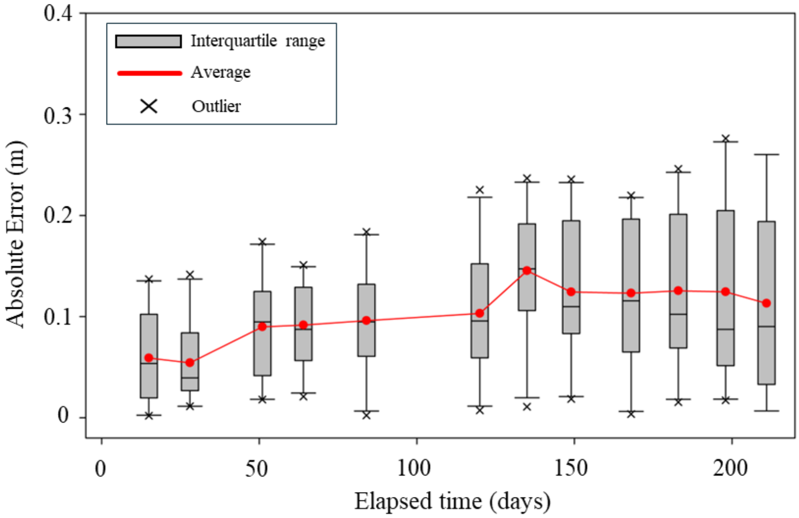
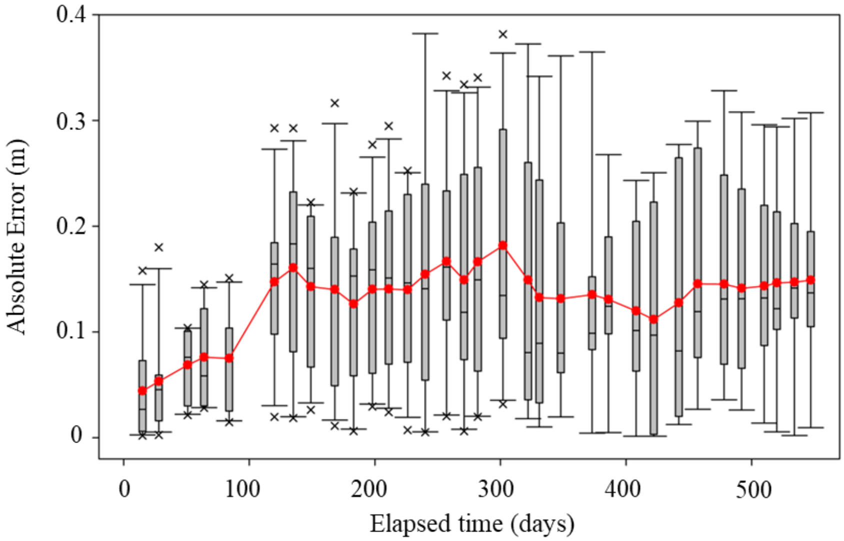


Figure 5.7 Absolute errors between SPs and Drone-LiDAR measurements over time



(a) Unloading concentration zone



(b) Loading concentration zone

Figure 5.8 Absolute errors between SPs and Drone-LiDAR measurements over time in different zones

Fig. 5.9 also illustrates the relationship between settlement measured at settlement plates and evaluated settlement using proposed method over time. As evidenced by the clustering of points around the equity line, the two data sets generally show good agreement. However, there is a noticeable trend where most points are located slightly below the equity line. This indicates that the evaluated settlement using the proposed method is slightly larger than that measured by the settlement plates. This slight overestimation is attributed to the settlement evaluation method using Drone-LiDAR, which assumes the previously observed settlement rate when evaluating settlement during unloading. This approach results in conservative settlement estimates.

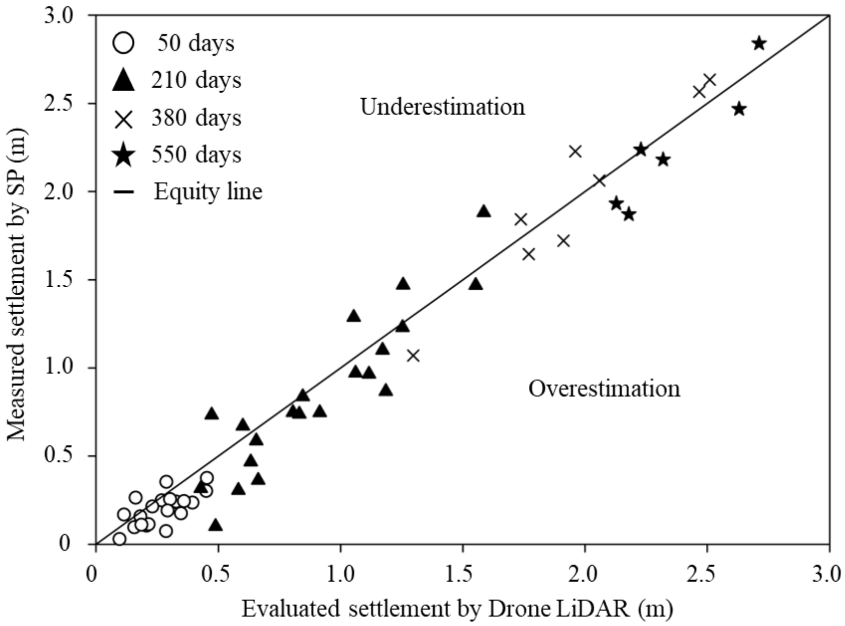
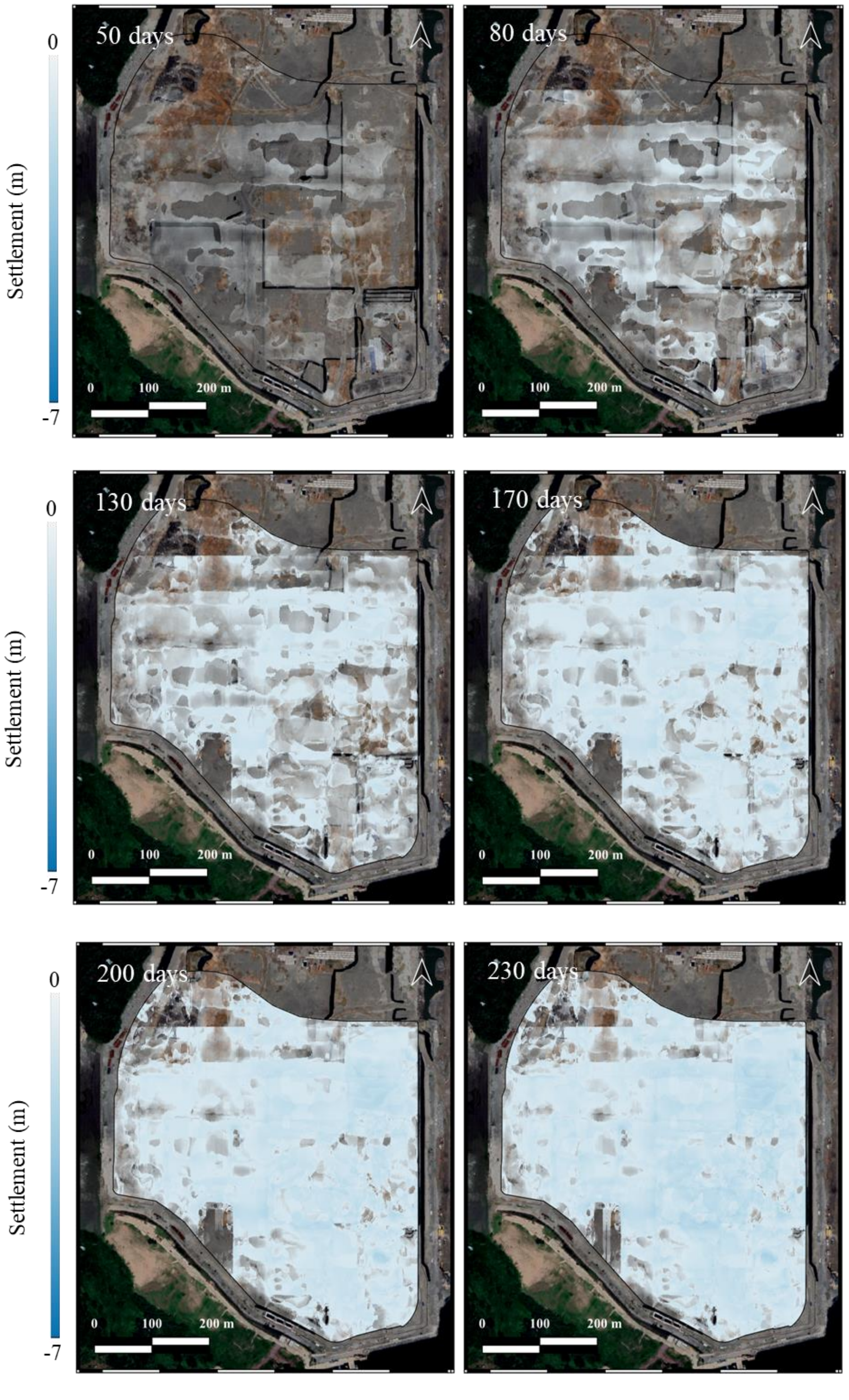
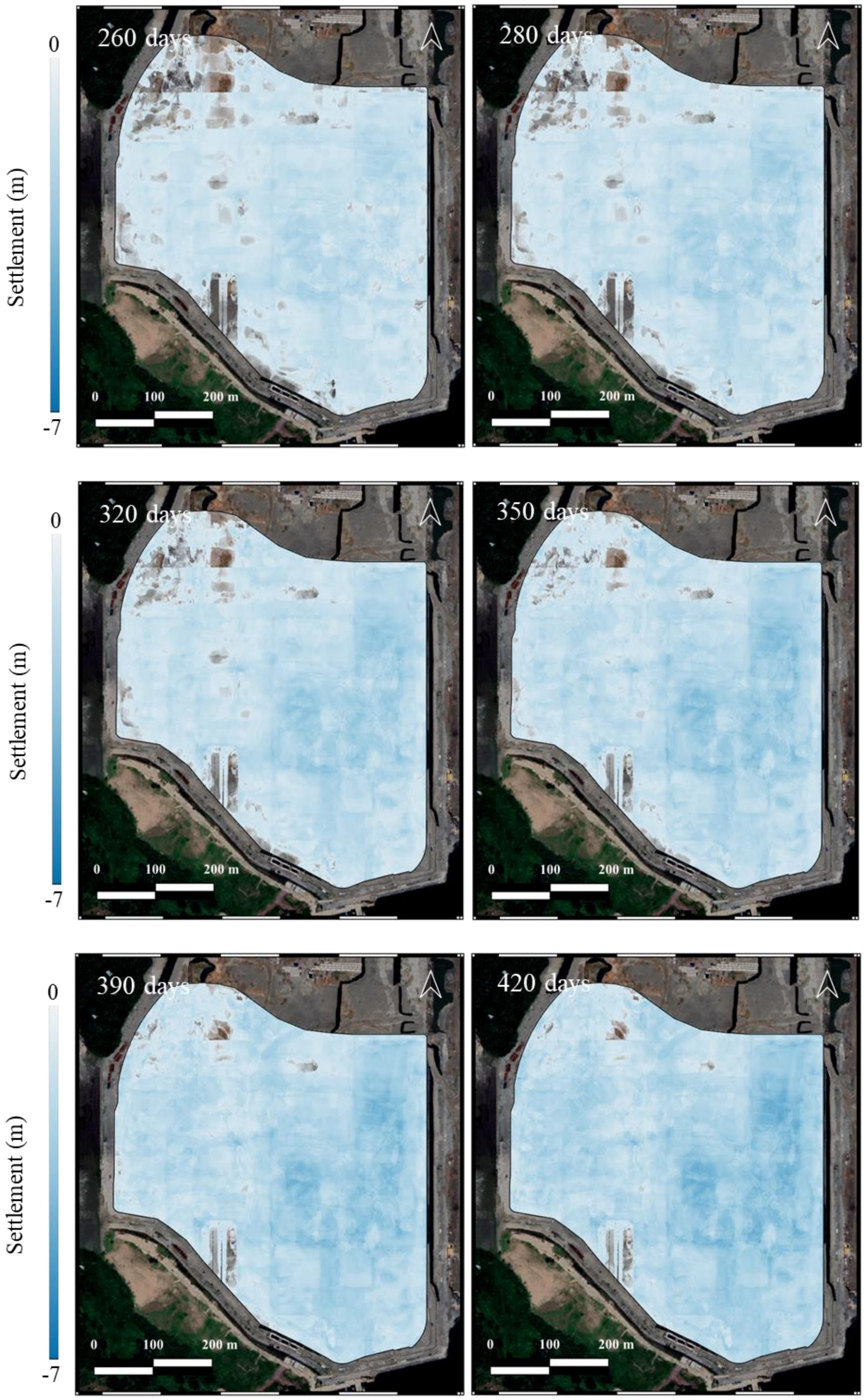


Figure 5.9 Comparison of cumulative settlement obtained from SPs and Drone-LiDAR

The results of evaluating the settlement across the study site using the proposed method are shown in Fig. 5.10. It is evident that the average settlement amount varies significantly at the boundary between the unloading and loading areas. Notably, the results at 550 days indicate that the difference in average settlement between the two zones is approximately 1.9m.


50 days
80 days
130 days
170 days
200 days
230 days
Settlement (m)
0
-7
0
100
200 m


260 days
280 days
320 days
350 days
390 days
420 days
0
Settlement (m)
-7
0 100 200 m

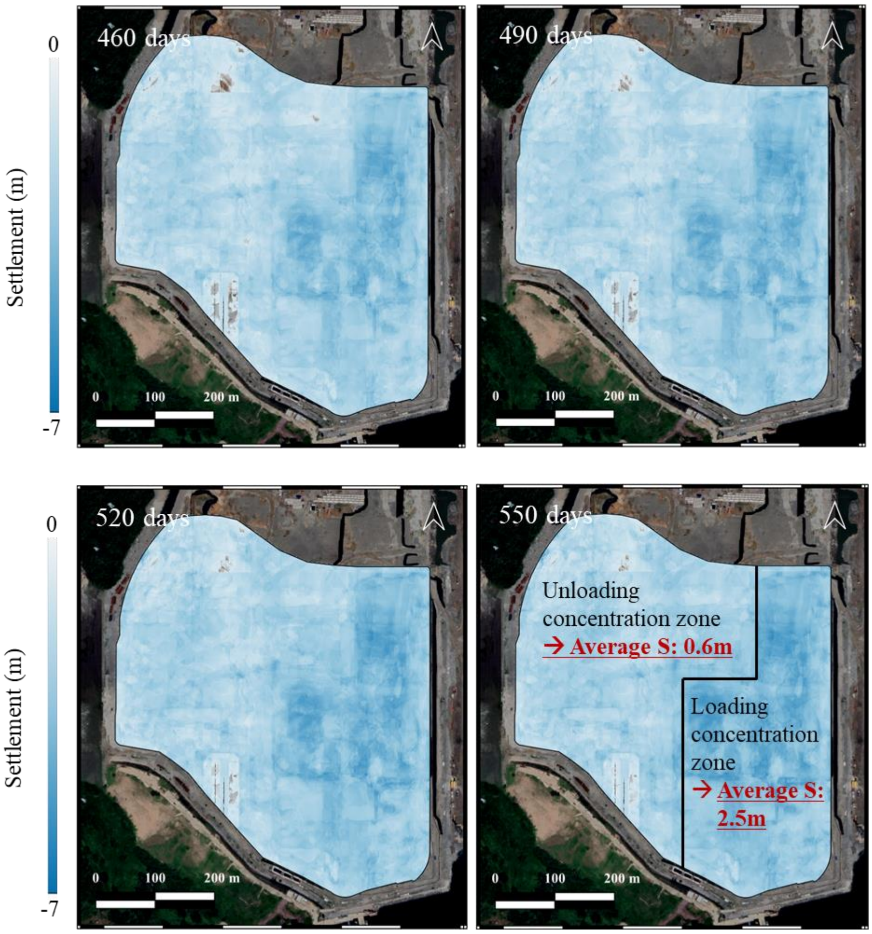


Figure 5.10 Settlement results in the study site over time

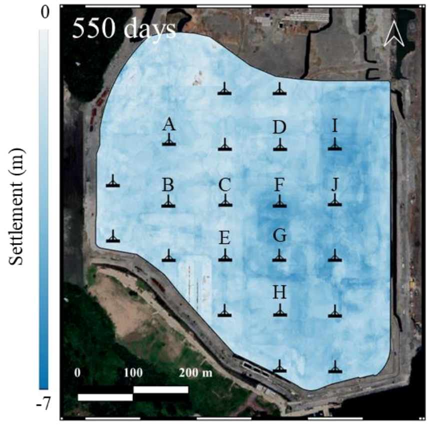


Figure 5.11 Settlement result in the study site at 550 days

Table 5.1 Measured settlement by SP and evaluated settlement by Drone-LiDAR

Settlement plate (SP)	Measured settlement by SP (m)	Evaluated settlement by Drone-LiDAR (m)
A	0.306	0.582
B	0.867	1.005
C	0.837	0.845
D	0.971	1.061
E	0.747	0.805
F	2.238	2.229
G	2.948	3.053
H	2.182	2.319
I	1.933	2.128
J	2.469	2.630

In summary, these findings demonstrate that the settlement evaluation method using Drone-LiDAR is effective in evaluating settlement under complex field conditions involving continuous unloading and loading. Furthermore, the proposed method provides relatively conservative settlement estimates. The high correlation and the relatively low RMSE and MAE values confirm the reliability of the method, highlighting its potential as a viable alternative to conventional settlement measurement techniques.

5.6 Summary

A method for evaluating settlement from DEMs was developed to overcome challenges in directly determining settlement from ground elevation changes, especially in areas with unloading and loading activities. The method uses a correction factor, derived from the ratio of calculated settlement to measured settlement, to account for increases in ground elevation. By comparing the settlement rates and distinguishing between unloading and settlement, the settlement across the entire site was evaluated. The accuracy of this method was validated against settlement plate measurements, enabling precise assessment of ground behavior.

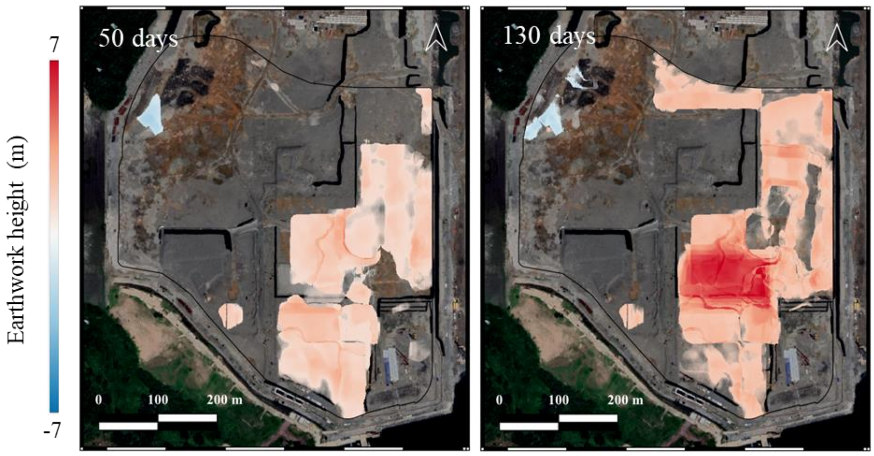
Chapter 6 Application of Settlement Evaluation Method

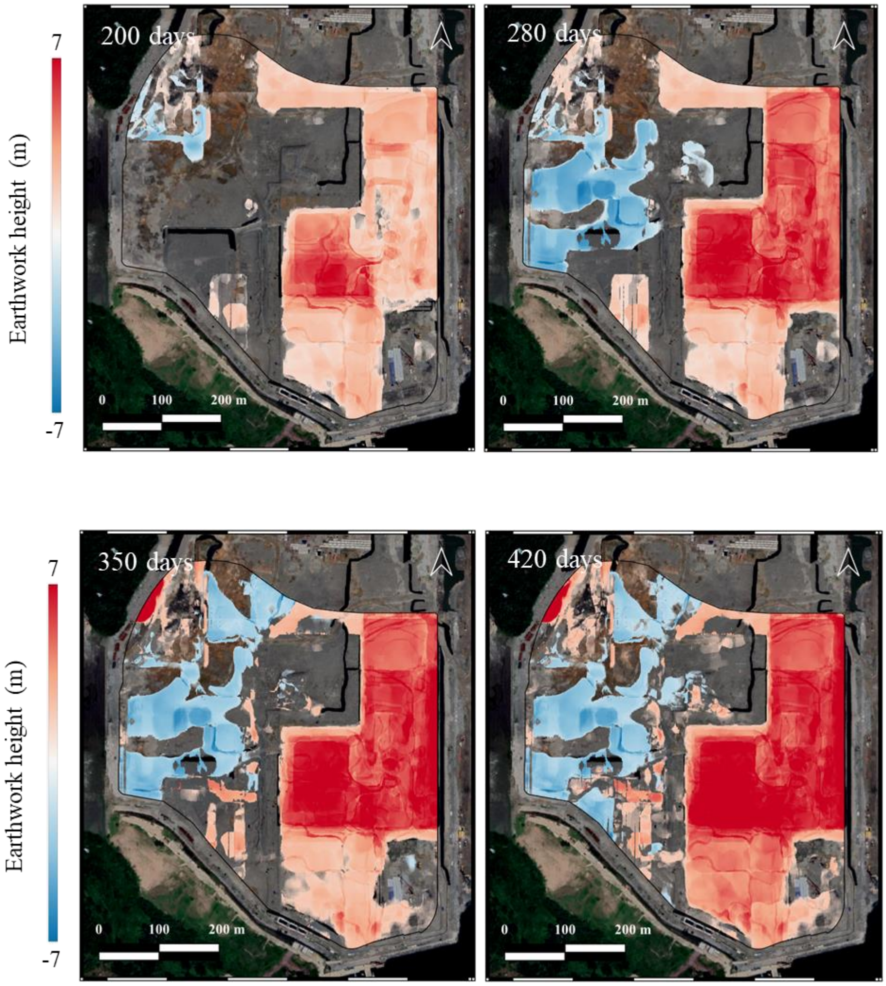
6.1 Introduction

The settlement across the entire site was evaluated using the proposed settlement evaluation method, enabling additional applications to be performed. First, the total volume of earthwork volumes across the site can be estimated. The settlement evaluation method also made it possible to distinguish unloading from settlement. Furthermore, this evaluation identified areas requiring careful settlement management. These analyses provide valuable insights for managing settlement in complex soft ground conditions.

6.2 Estimation of Earthwork Volume

Evaluating the settlement across the study site was reliably performed by the proposed method. Additionally, this method was utilized to estimate the earthwork volume, including loading and unloading for the entire site. The fill height was corrected by incorporating the evaluated settlement during periods of ground elevation increase. Specifically, the fill height was determined by adding the evaluated settlement during ground elevation increases to the observed increase in ground elevation. Using this approach, the total amount of fill for the study site was obtained. For cases where the ground elevation decreased, if the measured settlement rate increased in sections where the calculated settlement rate decreased, the decrease was classified as unloading. This enabled the estimation of the total amount of unloading for the study site. Through prior data preprocessing in Chapter 4, the optimal DEM grid size for this study was determined to be 0.5m. The loading and unloading heights calculated for each grid cell were then multiplied by the grid area to determine the earthwork volume for the study site. Figs. 6.1 and 6.2 present both the earthwork volume and the cumulative earthwork volume for the study site over time. At 550 days, the total cumulative loading and unloading volumes are estimated to be 1,114,071m^3 and 468,342m^3, respectively. Additionally, the maximum loading and unloading volumes per measurement are 77,152m^3 and 57,606m^3, while the minimum loading and unloading volumes are 5,243m^3 and 9,100m^3. Compared to the ground elevation changes shown in Fig. 8, it is evident that the amount of earthwork significantly varies in areas with rapid elevation changes. In Fig. 3.6, the settlement plate location at the end of the settlement measurement on day 200 corresponds to the unloading concentration zone. Furthermore, Figs. 6.1 and 6.2 show that the amount of unloading increases rapidly after 200 days, with the unloading occurring within the unloading concentration zone. This observation demonstrates the effectiveness of using Drone-LiDAR for calculating earthwork volumes.





200 days
280 days
350 days
420 days
Earthwork height (m)
7
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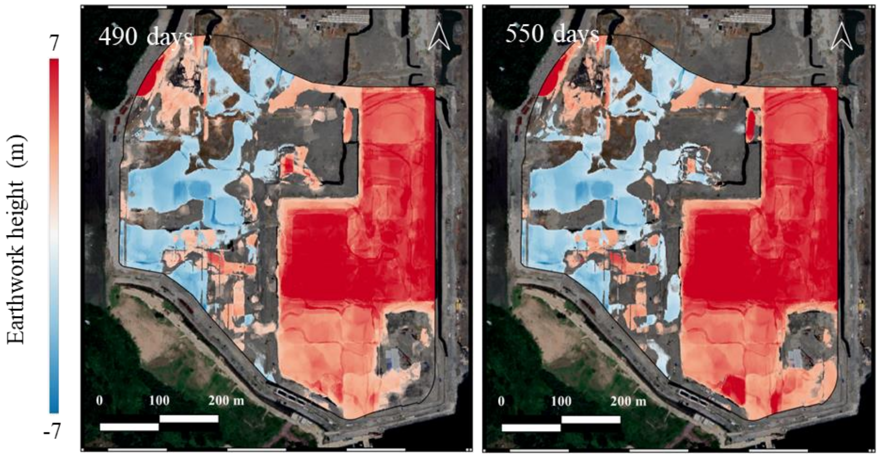

Figure 6.1 Earthwork volume results in the study site over time

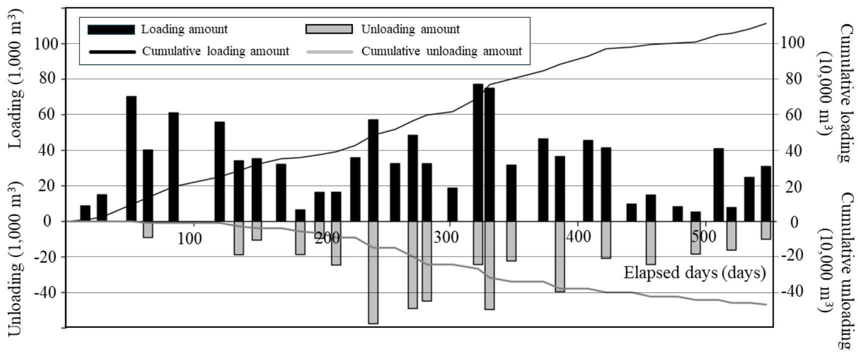

Figure 6.2 Cumulative loading and unloading amounts over time

6.3 Estimation of Settlement Risk Areas

Settlement plates are installed across the site to divide the study site into sections and measure settlement, considering factors such as construction methods, sequences, and strata characteristics. These plates measure the settlement over time, with the goal of reaching the target residual settlement. Each settlement plate measurement represents the settlement of the corresponding section, covering an area of approximately 100m×100m. The proposed method can be used to verify the representativeness of settlement plate measurements for their respective areas.

In this study, the degree of consolidation for final settlement was calculated using the hyperbolic method for each grid within the sections represented by the settlement plates. Two sections (Section A and B), located in unloading concentration zone, where settlement was expected to have reached the target residual settlement, were selected for analysis. Additionally, two sections (Section C and D) in loading concentration zone, where settlement was less likely to have reached the target residual settlement, were also analyzed. These sections were chosen to allow a comprehensive comparison of settlement behavior under varying construction conditions.

First, the degree of consolidation derived from the measured settlement at the settlement plates exceeded 95% in all cases, indicating that settlement had largely stabilized. In parallel, the degree of consolidation for each 0.5m grid within each section was calculated using the settlement based on the proposed method. Fig. 6.3 presents the degree of consolidation distribution for each section. It shows that section A and B, located in unloading concentration zone, exhibit stable settlement and high-density distributions. In contrast, section C and D, in loading concentration zone, display relatively lower density distributions compared to section A and B.

It can be also observed that in section A and B, 98% and 96% of the area, respectively, show degree of consolidation exceeding 95%, aligning closely with the degree of consolidation derived from the settlement plates. On the other hand, section C and D demonstrate a slightly lower degree of consolidation, with 91% and 93% of their respective areas exceeding 95%.

Most areas in section A and B exhibit a degree of consolidation greater than 95% in Fig. 6.3. On the other hand, in section C and D, as shown in Figs. 6.3 (d) and 6.3 (e), there are areas where the target degree of consolidation has not been achieved, particularly away from the vicinity of the settlement plates. These areas indicate the potential for additional settlement.

The identification and calculation of these settlement risk zones can significantly enhance the ability to predict and maintain settlement stability, thereby contributing to more effective long-term settlement management.

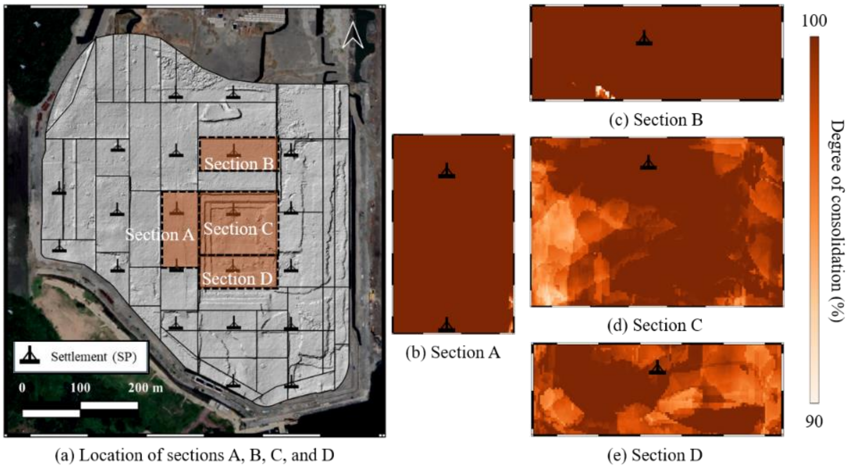

Figure 6.3 Distribution of degree of consolidation results based on Drone-LiDAR in Section A, B, C, and D

6.4 Summary

The settlement evaluation method was applied to evaluate the settlement across the entire site, enabling additional analyses. One key application was estimating the earthwork volumes by correcting the fill height through evaluated settlement and distinguishing between unloading and settlement. Furthermore, the method identified areas requiring careful settlement management, ensuring targeted interventions for complex soft ground. These applications highlight the method's practicality in supporting effective settlement monitoring and management for large-scale construction sites.

Chapter 7 Conclusion

In this study, a method to evaluate settlement using Drone-LiDAR was proposed. First, ground elevations were derived from Drone-LiDAR measurements of the study site. Next, settlement evaluation method was suggested based on the derived ground elevation data. The effectiveness of the proposed method was then verified by comparing the measured settlement with settlement plate measurements. Finally, additional application analyses were conducted, demonstrating the broader utility of the settlement evaluation method. This led to the following conclusion.

(1) In the processing of Drone-LiDAR measurement data, outliers were removed using the SOR, and ground elevations were extracted through the CSF. To construct the DEM, an optimal grid size of 50cm×50cm was determined through analysis. Using this optimal grid, time-series ground elevation DEMs for the entire site were constructed. However, the results revealed limitations in directly evaluating settlement from ground elevation data alone.

(2) A settlement evaluation method was proposed based on the time-series DEMs of ground elevation across the entire site. When the ground elevation increases, a correction factor (ϕ) is determined by comparing the calculated settlement with the measured settlement, which is then applied during loading. Conversely, when the ground elevation decreases, the calculated settlement rate is compared with the measured settlement rate to differentiate between unloading and settlement. Using this approach, the settlement over time for the entire site was effectively evaluated.

(3) The settlement evaluated using the proposed method was validated by comparing it with the measurement results from 21 settlement plates. The final measurement yielded an average RMSE of 0.134m, an MAE of 0.119m, and a coefficient of determination (R^2) of 0.956. The method slightly overestimated settlement due to the assumption that settlement during unloading followed the previous settlement

rate. The method's accuracy was higher in unloading concentration zone compared to loading concentration zone, where site complexity introduced additional challenges. On average, the settlement in loading concentration zone was 1.9m higher than that in unloading concentration zone, demonstrating the method's reliability across varying site conditions.

(4) Additional application analyses were conducted using the settlement evaluation method. The actual loading amount was adjusted based on the evaluated settlement, and when ground elevation decreased, settlement and unloading were differentiated to estimate the unloading amount. The total earthwork over time for the entire site was estimated, with 1,114,071m^3 of loading and 468,642m^3 of unloading determined from the final measurements. Degree of consolidation analysis identified areas requiring careful settlement management. Most unloading concentration zones achieved the target settlement, while many loading concentration zone did not. Furthermore, grids that failed to meet the target settlement in unloading concentration zone were clustered. This analysis allowed the identification of high-risk settlement areas within the site, enabling targeted settlement efforts.

The proposed settlement evaluation method, along with its application, offers a reliable and efficient framework for monitoring and managing settlement in soft ground sites. By leveraging Drone-LiDAR, this method improves accuracy and efficiency, providing critical insights for infrastructure projects in challenging geotechnical environments. Further studies could refine the method by exploring additional preprocessing techniques and applying it to other geotechnical conditions to broaden its applicability.

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초 록

대심도 연약지반 현장에서는 침하를 관리하는 것이 중요하다. 침하에 관련한 많은 연구들이 수행되었지만, 대부분 지표침하판과 토탈 스테이션을 이용한 기존 계측 방법으로 얻은 데이터에 의존하고 있다. 기존 계측 방법은 넓은 현장에 비해 상대적으로 소수의 계측 지점을 갖는다는 한계가 있다. 이는 미계측 구역의 신뢰성을 떨어뜨려 복잡한 침하 거동을 파악하기 어렵게 한다. 최근 전체 현장을 계측할 수 있는 다양한 원격 탐사 기술에 대한 연구가 수행되고 있으며, 그 중 드론 라이다는 다양한 분야에서 정확하고 효율적인 결과를 보여주고 있어 복잡한 연약지반 현장에 적용하기에 적절할 것으로 기대된다. 드론 라이다 계측 데이터에는 이상치와 표면 위의 물체를 포함하고 있으며, 방대한 데이터 양을 갖고 있기에 적절한 전처리 과정을 수행하여 효율적인 지표고 정보를 추출해야 한다. 하지만, 지표고 정보로 연약지반 현장의 직접적인 침하를 산정하는 것은 한계가 있다.

따라서 본 연구에서는 드론 라이다 계측 데이터를 전처리하여 얻은 지표고 정보로부터 침하를 산정하는 방법을 제안하였다. 우선, 대상 현장에 대한 드론 라이다 계측 데이터의 전처리 과정을 수행하였다. 통계적 기법인 SOR 을 적용하여 이상치를 제거하였고 지표고 정보를 얻기 위해 CSF 를 적용하였다. 다음으로 지표고 정보에 대한 DEM 을 생성하기 위하여, 포인트가 포함되지 않은 격자가 존재하지 않는 최소 격자인 50cm × 50cm 를 최적 격자로 선정하였다. 다음으로, 대상 현장 전체의 지표고 정보를 담은 DEM 을 기반으로 침하를 산정하는 방법을 제안하였다. 지표고가 증가하는 경우에는 성토 중 발생하는 침하량을 추정해야 하며, 지표고가 감소하는 경우에는 절토와 침하를 구분해야 한다. 지표고가 증가할 경우, 계산 침하량과 계측 침하량을 비교하여

보정계수, ϕ 를 산정하여 성토 시 발생하는 침하를 보정하였다. 지표고가 감소할 경우, 계산 침하율과 계측 침하율을 비교하여 절토와 침하를 구분하였다.

제안된 침하 산정법으로 산정된 침하는 대상 현장의 지표침하판에서 계측된 결과와 비교하여 정확도를 검증하였다. 최종 계측 기준 평균 RMSE 는 0.134m, MAE 는 0.119m, 결정계수 R^2은 0.956 으로 나타났다. 또한 제안된 방법으로 산정된 침하는 침하를 약간 과대평가하는 경향을 보이는데, 이는 절토 시 침하량을 이전 침하율로 가정해서 발생한 것임을 알 수 있었다. 또한 제안된 침하 산정법을 통해 수행할 수 있는 추가적인 적용을 분석하였다. 제안된 방법은 전체 현장의 침하량 산정을 통해 신뢰성 있는 성토량을 추정할 수 있으며, 절토와 침하의 구분을 통해 절토량을 추정할 수 있다. 이를 통해 대상 현장 전체의 시간에 따른 토공량을 추정하였다. 또한, 시간에 따른 대상 현장 전체의 침하를 통해 압밀도 평가를 수행하여 침하 위험 구역을 추정하였다. 절토가 집중적으로 이루어졌던 구역은 대체로 목표 침하량에 도달했으며, 성토가 집중적으로 이루어졌던 구역은 목표 침하량에 도달하지 못한 격자들이 상대적으로 많이 존재하였다. 이를 통해 주의를 기울여야 할 침하 위험 구역을 추정할 수 있었다. 제안된 침하 산정법과 적용 방법들은 신뢰성 있는 침하 유지 관리 방법으로써 적용될 수 있다.

주요어 : 드론 라이다, 연약지반 침하, 지표고 결정, 침하 산정법

학번 : 2023-27027

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