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Short-term Slope Changes on Dokdo Island Identified from Ground-based 3D LiDAR Data

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Abstract

This study was designed to determine the slope changes on Dokdo Island, focusing on Seodo islet (slopes consisting of colluvial debris) and Dongdo islet (slopes consisting of large-scale tafoni). To do so, we obtained high-resolution 3D LiDAR data in May and November 2020 and calculated the changes in slope shape and volume over this period. Our results showed that during this time, approximately 136 m^3 of colluvial debris was removed from the slopes of Seodo islet and a boulder that had separated from the massive tuff breccia migrated approximately 5 cm downslope. The major causes of such rapid changes on the slopes of Seodo were sediment movement caused by heavy precipitation and load variation by slope-toe erosion due to high waves during typhoon events in September. On the contrary, no significant changes were observed on the slopes on Dongdo islet. While we predicted that weathering would cause major changes on the slopes, the measurement interval of this study was too short to observe such changes on the slopes consisting of tafoni. The 3D LiDAR data measures reflection intensity as well as 3D information on the surface of the earth. We measured the reflection intensity ranges of breccia, tuff, and vegetation, and subsequently ordered the intensity to increase from vegetation, breccia, and tuff. The reflection intensity ranges of the three different materials could be used to analyze the weathering rates according to the material types in future studies. In addition, the 3D scanning data on the Dokdo slopes could be used to monitor long-term slope changes and weathering rates.

Keywords

3D LiDAR, colluvial deposit, Dokdo, reflection intensity, tafoni

Acknowledgements

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1 INTRODUCTION

Dokdo, an island situated off the eastern coast of South Korea, is a stratovolcano that formed between approximately 2.5 Ma and 4.6 Ma from several volcanic eruptions 2,000 m under the sea. Dokdo consists of two islets, Dongdo and Seodo, as well as the circumjacent submerged rocks. The island consists of volcanic rocks and volcaniclastic sedimentary rocks. Various topographies such as debris deposits, tafoni and columnar joints are also observed.

The lithological composition of Dokdo has prompted several studies on its slope stability (Kang and Sung 2009; KIGAM 2006; KORDI 2000). The studies have focused on analyzing the ground stability of the island, the stability of major facilities, structures, pedestrian walkways, and areas subject to falling rocks of nearby rocky slopes and have evaluated the possibility of falling rocks (to increase the accessibility of Dokdo) (KORDI 2000). Since 2005, the Korea Institute of Geoscience and Mineral Resources (KIGAM) has performed field investigations and monitor soil stratum and topographic changes to ensure the sustainable use and preservation of the natural environment on the island (https://tinyurl.com/2p87fsdp). In terms of individual research, a 3D map of Dokdo has been established using elevation data obtained with airborne light detection and ranging (LiDAR) measurement equipment (Kang and Sung 2009). Moreover, ground classifications have also been established, and the slope stability of Dokdo has been determined using elevation, slope angle, and geological data from the island. Rapid changes resulting from mass movement on the slopes of Dokdo were detected and monitored using various measurement instruments such as a crack gauge, inclinometer and load cell. These instruments have mainly been used to provide warning signals of mass movements on the slopes, to mitigate natural disasters. Slope changes on Dokdo due to sediment movements are poorly understood. Weathering is also responsible for slope changes but is generally a slower process than the mass movement (Moses et al. 2014). While it is difficult to directly measure or analyze the weathering rate, Hwang and Park (2007) have shown that weathering caused by salt crystal formation is one of the significant factors shaping the slopes of Dokdo. The slopes of Dokdo are largely impacted by waves, especially because salty splashes may reach the top parts of both Dongdo and Seodo when typhoons cause high waves in the area. Empirical studies have used methods such as X-ray diffraction (XRD) and X-ray fluorescence (XRF) methods to analyze the chemical characteristics and rebound values, to determine rock strength of the weathering landforms (Kim et al. 2009; Kim 2013; Matsukura and Tanaka 2000; Trenhail 2002). These methods require either rock sampling or physical impact. Research on Dokdo has many limitations due to the low accessibility to the island, the time constraints of investigation, and research methods, particularly because Dokdo has been designated Korea's Natural Memorial No.336. Few empirical studies have quantified the exact changes to the slopes of Dokdo, despite the significance of such information (Choi and Seong 2021). Therefore, it is necessary to quantitatively analyze the slope changes on Dokdo and to clearly understand the conditions of the slopes.

Recently, 3D LiDAR has enabled the scanning of 3-dimensional spaces using a pulsed laser, and is widely used in construction, engineering, and environmental investigations for the production of digital surface model (DSM). DSM obtained using

3D LiDAR were first used to determine the hazards associated with landslides (Gritzner et al. 2001) and to investigate the surface processes occurring in mountainous areas (Bishop et al. 2003). In addition, this technique was used to investigate weathering rates and mechanisms (Emanuel and Levenson 2014). LiDAR simultaneously measures the spatial information and reflection intensity of the laser, which can be used to classify ground surfaces and objects (Burton et al. 2014; Scaioni et al. 2018). These analyses thus aid the investigations of landscapes without destroying the rocks through a non-contact-to-ground surface approach and can be applied to regions subject to slope changes on Dokdo.

This study examines slope changes on Dokdo, using 3D LiDAR data obtained at two different times. We analyze sediment movement on Seodo slopes, where colluvium is deposited, and the weathering characteristics of Dongdo slopes where tafoni is developed.

2 DATA AND ANALYSIS METHODS

2.1 Study Area

Dokdo is a volcanic island located in the East Sea of South Korea at 37°14'27.63" N and 131°52'02.16" E. The island was formed during volcanic activities and is primarily composed of two islets, Dongdo and Seodo, a peripheral sea stack, and a sea arch (Figure 1).

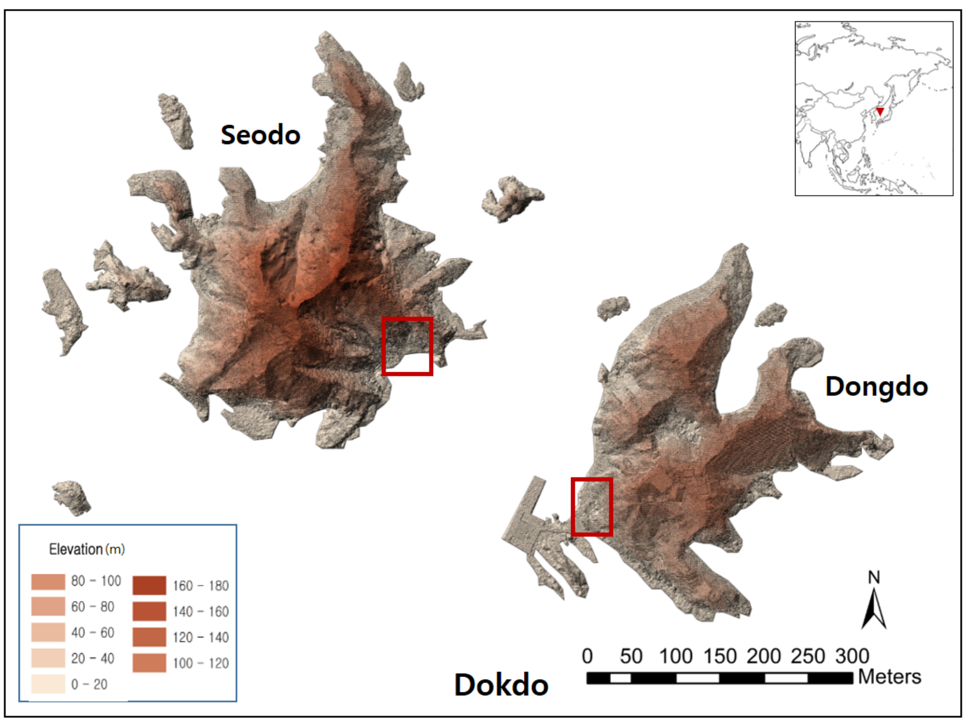

Figure 1 Elevation of Dongdo and Seodo islets, and peripheral sea stacks.

Dokdo was formed during several volcanic eruptions and displays various geological features resulting from different eruption periods and environments. According to a 1:2,500 scale geological map of Dokdo (KIGAM 2012), the surface geology is composed of Pliocene volcanic rocks that are classified into nine rock layer units, namely: massive tuff breccia, trachyandesite I, bedded lapilli tuff, bedded ash tuff, trachyandesite II, scoria-type bedded lapilli tuff, trachyandesite III, breccia, trachyte, and basic dyke.

Weather data accumulated during 2010–2019 from an automatic weather system (AWS) installed on Dokdo revealed dominant WSW and SE wind directions on the island (Figure 2). Tafoni formations, a weathering feature formed by the crystallization energy of moisture and salinity, occur on the back slope of the dock, which is located on the southwest side of the island and hence faces strong winds with high moisture and salinity content. Previous research has indicated that the weathering of the dock's back slope is closely related to the primary wind direction on Dokdo, and thus is an essential element of weathering on the island (Kang and Sung 2009). In 2020, when this study was performed, two typhoons, Maysak and Haishen, struck the Korean Peninsula in August and September, respectively, causing damage to the Ulleungdo and Dokdo islands. The torrential rain and strong winds associated with the typhoons resulted in a precipitation record of 86 mm in September, which is significantly higher than the annual average precipitation of 54.45 mm (Figure 3). In particular, when typhoon Maysak passed Ulleungdo and Dokdo on 3 September 2020, maximum wave heights reached 10.1 m, making it the highest recorded wave height that year (AWS data at Dokdo and buoy data at Ulleungdo from May to November, Meteorological Administration data).

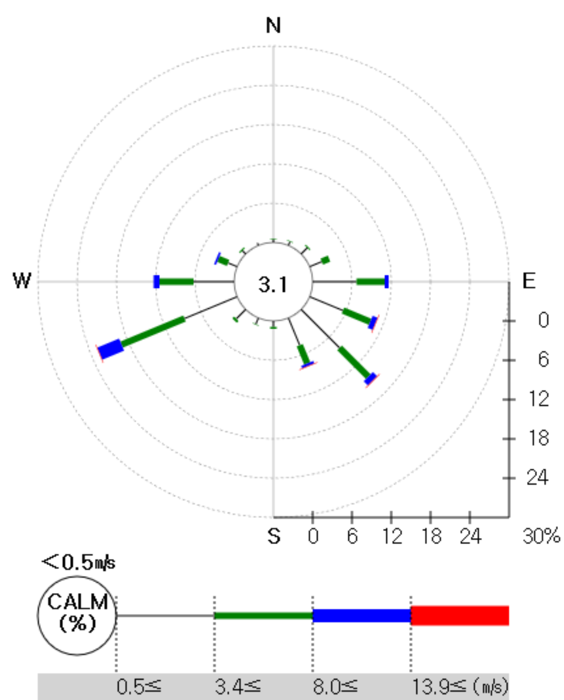

Figure 2. Wind directions and speeds recorded on Dokdo in 2020.

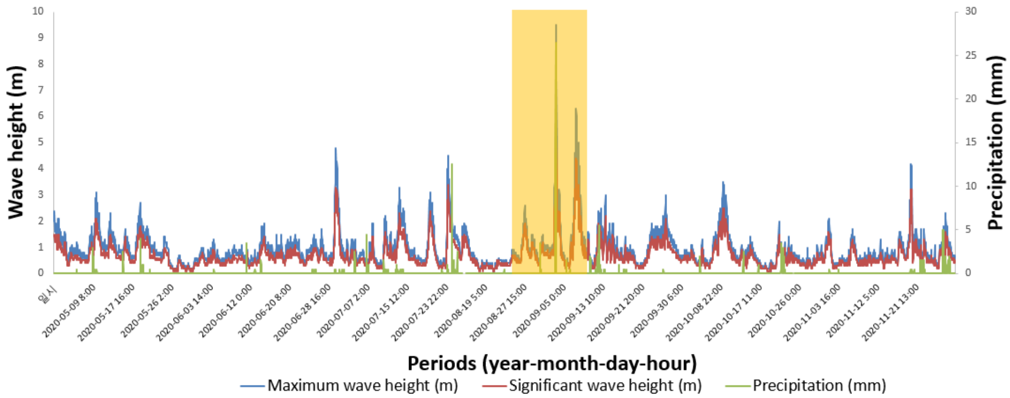

Figure 3. The maximum and significant wave height at Ulleungdo and precipitation on Dokdo (2020.5.–2020.11.).

To analyze slope changes, we obtained 3D data for selected sections of slopes (red boxes in Figure 1 and yellow boxes in Figure 4). We identified areas where slope changes were likely to occur in the field. The first area covers the slope at the back of the fisherman's lodging on Seodo and consists of a massive tuff breccia and trachyte dyke, with colluvium deposits developed on the slope (Figure 4 (A) w-a). We also selected the boulders in front of massive tuff breccia layers (Figure 4(A) w-b). To determine the weathering processes on the slopes, we examined the tafoni on the layer of massive tuff breccias behind the dock on Dongdo. We also examined a WSW-facing slope characterized by a large-scale tafoni (Figure 4 (B) e-a) and a WNW-facing slope with a relatively small-scale tafoni (Figure 4 (B) e-b).

2.2 Data Collection and Analysis

To obtain high-resolution 3D LiDAR data of the Dokdo slopes, we conducted LiDAR scans in May and November 2020 using a terrestrial LiDAR sensor. The filming equipment included a TX8 laser scanner from Trimble. The scanner has a wavelength of 1.5 mm, can measure from 0.6 to 340 m, and features a scan rate of 1,000,000 points/sec and a <2 mm resolution (below 1 mm for the high-precision scan mode). The TX8 device must be fixed on the ground to perform measurements. Therefore, we chose the dock in front of the fisherman's lodge, the shingle beach on Seodo, the dock on Dongdo, the shingle beach on Dongdo, and the deck at the back of the Dongdo dock as location for equipment installation. Scanning was conducted at a total of 17 stations in May and 13 stations in November, and the data were merged into a single datasheet. The Trimble RealWorks v11.0 software was used for the point processing and analysis. This data was used to create cross-sections of the ground surface on Seodo, and any changes in height and volume were used to characterize the sediment movement on the slope of Seodo. We conducted a morphological comparison of Dongdo slopes containing the tafoni using the two sets of 3D LiDAR data, and an analysis of reflection intensity data to characterize the weathering slope. The reflection intensity variation of 3D LiDAR data is defined as the ratio of the strength of reflected light to that of emitted light and is influenced mainly by the

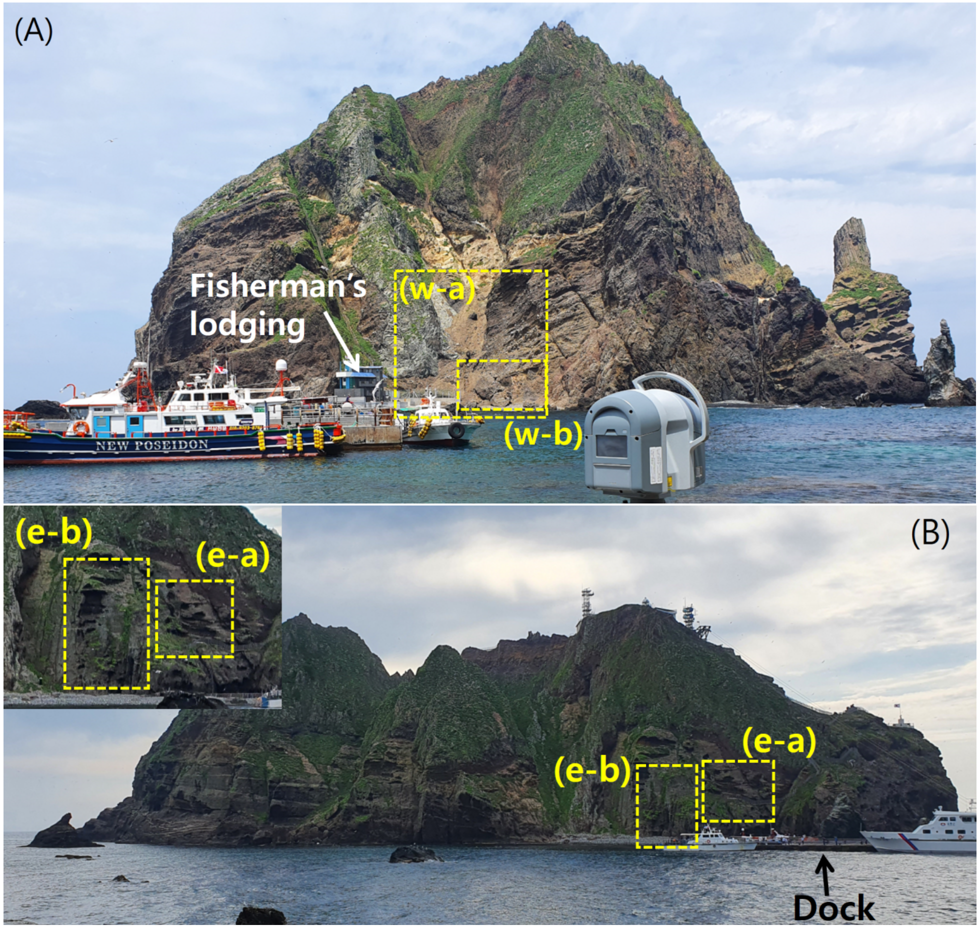

Figure 4. Survey areas. (A) is Seodo and (B) is Dongdo; slope (w-a) with valleys formed between massive tuff breccias and a trachyte dyke (Seodo islet), slope (w-b) loose boulder broken off massive tuff breccia, slope (e-a) with tafoni developed on the massive tuff breccias, and slope (e-b) with plants growing on the massive tuff breccias, Dongdo islet.

reflectance of the reflecting object (Song, et al. 2002). The variation in reflection intensity can be used to map various attributes, such as land cover and bio/geophysical parameters (Scaioni et al. 2018). In addition, Burton et al. (2011) proposed that the intensity increases with the increasing weight ratio of quartz, plagioclase, and K-feldspar, and decreases with the increasing weight ratio of clay minerals. Moreover, the degree of weathering and moisture content can affect the reflection intensity of an outcrop, with less advanced weathering and a lower moisture content resulting in a higher intensity. Therefore, in this study, we began by classifying the reflection intensity according to the rock types on the slopes of Dokdo. The Trimble RealWorks software used in this study uses a 0 to 255 grayscale intensity, with 0 denoting a low reflection intensity and 255 denoting a high reflection intensity.

3 RESULTS

3.1 Slope Processes

The slope changes between May and November 2020 were determined by analyzing the data collected at the fisherman's lodge on Seodo and the dock on Dongdo. The results indicated that the slope area experiencing the most rapid changes was the back slope of the fisherman's lodge on Seodo. The colluvium of this region is composed of cobble- and pebble-sized rock fragments with a low roundness, including pyroclastic material in bedded lapilli tuff and plaster rock exfoliated from massive tuff breccia bedrock. In addition, field observation showed that the particle sizes tended to increase from the upper to the lower part of the slope, although the slope material was mixed and exhibited a low degree of sorting. Figure 5 (B) shows the change in colluvium height on the slopes of Seodo between May and November, within the boundary located in Figure 5 (A). This change indicates sediment transport on the surface of the colluvial sediment. Moreover, the transported sediment that accumulated to a depth of approximately 30-50 cm depth at the foot of the valley slope is indicated in yellow and yellowish-green in Figure 5 (B). In May, a large amount of colluvium had accumulated at the upper part of the protective fence where a mass movement flow was halted. In November, this deposit was found to be eroded. As shown in the yellow dotted circle in Figure 6, the uppermost part of the cross-section a-a' exposes the massive tuff breccia bedrock and bedded lapilli tuff, and no difference in slope was evident between May and November. However, in the central part of the slope, colluvium deposits (yellow circle in Figure 6) reached a maximum thickness of 0.64 m. A significant amount of sediment was eroded from the slope between the protective fence and the boulder that was separated from the massive tuff breccias, and colluvium of approximately 2 m was found to have been eroded (blue region in Figure 5 (B); Figure 6).

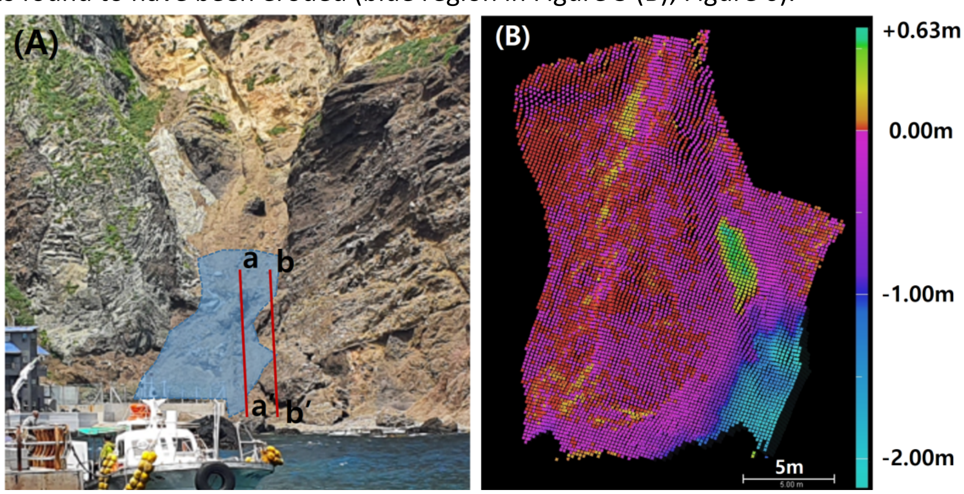

Figure 5. (A) Boundary for analysis of sediment movement (in blue). (B) Change in elevation on the Seodo slope between May and November. In (A), section lines for analyzing the colluvium height changes are indicated. (B) The height changes. In the legend, "+" indicates the accumulation of colluvium, while "-" denotes erosion.

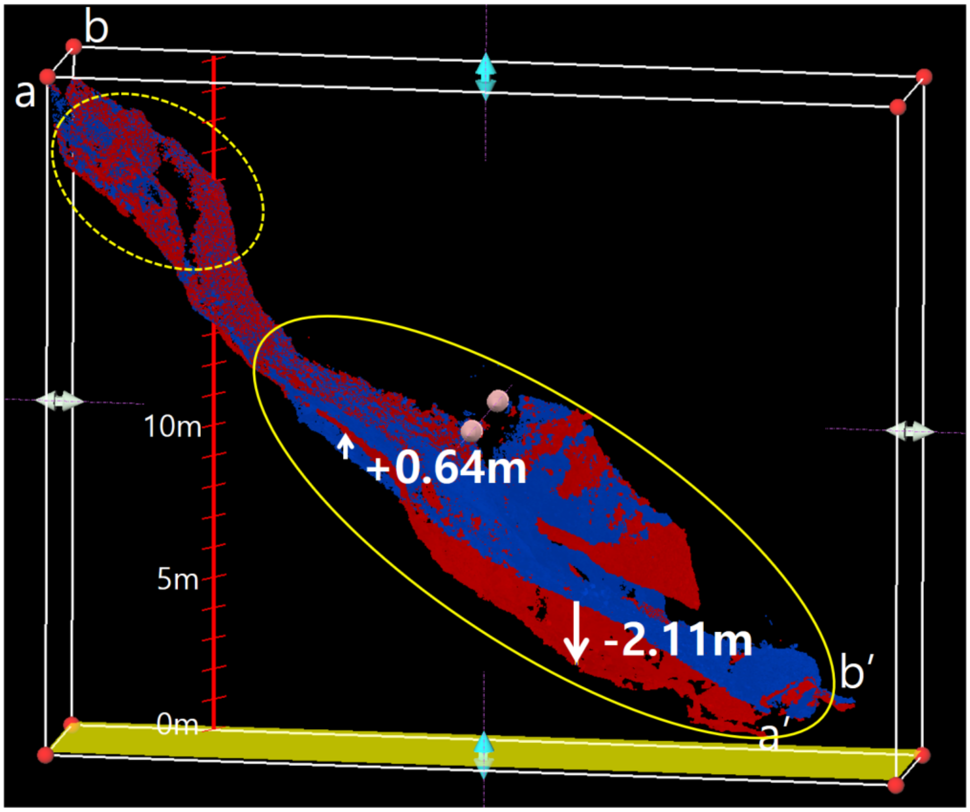

Figure 6. Comparison of the 3D LiDAR data on cross-sections, between May (blue) and November (red) (the lines a-a' and b-b' are identical to those in Figure 5(A)).

A collapsed boulder from the massive tuff breccias was identified at the lower part of the massive tuff breccia slope (Figure 4(A). w-b). Pebble sized sediment around the boulder in May had decreased by approximately 2 m in November (Figure 7). Along with sediment removal, the boulder appeared to have shifted by approximately 5 cm downslope in November, compared to May (Figure 8).

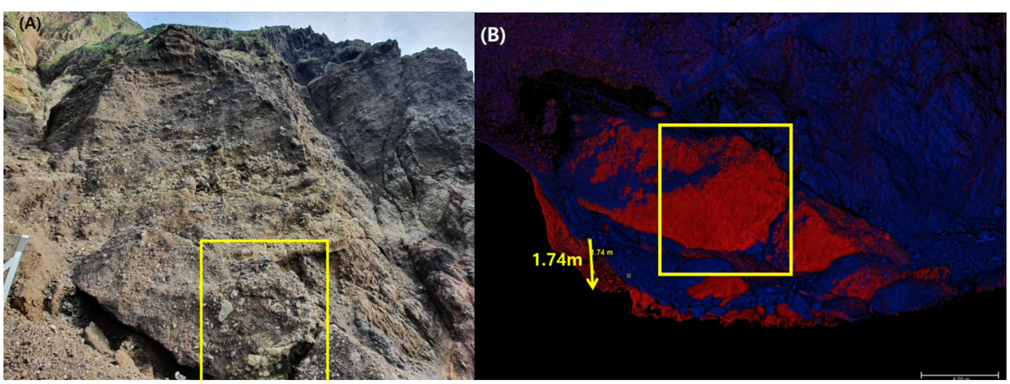

Figure 7. Pebble sized sediment movement near the boulder (Photo and 3D LiDAR data) and increase in slope angle due to sediment removal around the lower part of the boulder (In (B), blue represents May measurement while red indicates November measurement. The yellow boxes indicate the same location).

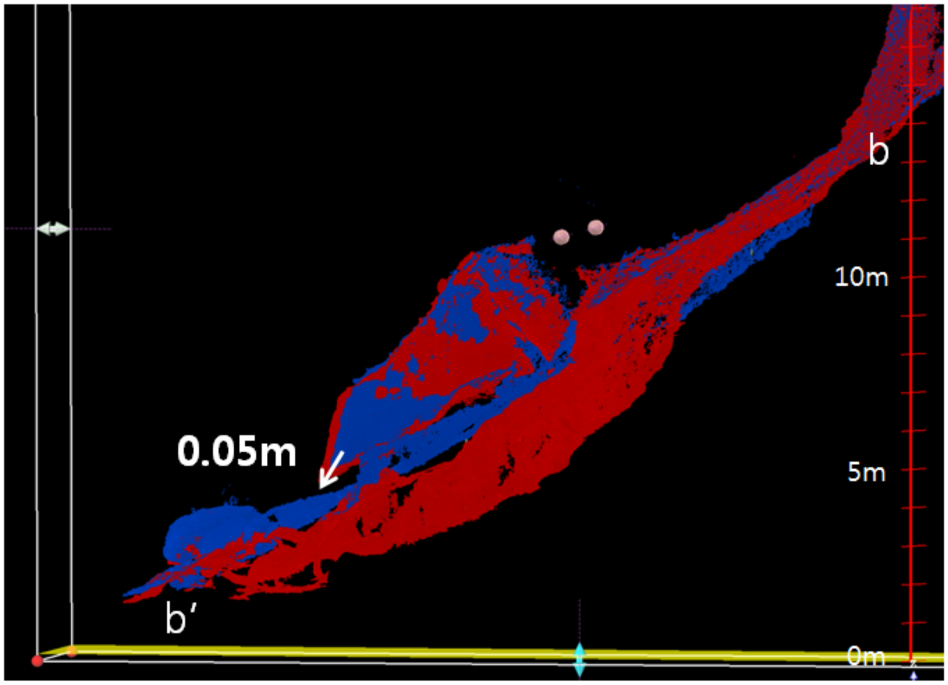

Figure 8. The boulder migrated downwards along the slope. The boulder in the yellow box in Figure 7 moved 0.05m in the direction of the white arrow (blue image: May, red image: November).

3.2 Weathering

The slopes of Dokdo are highly exposed and continually affected by waves and strong winds. Although this weathering process is slower than the mass movement occurring on slopes, it is thought to be the primary factor causing the disassembling of volcanic rocks on Dokdo (Hwang and Park 2007). The tafoni situated on the massive tuff breccias that lack vegetation were formed by cavity generation from the extraction of boulders by saline water and the joining of cavities. Although among the slopes (e-a) and (e-b) comprise the same massive tuff breccia, the slope (e-a) is more exposed to the predominant wind direction of Dokdo, and thus have developed large-scale tafoni. A comparison of the two datasets obtained in May and November showed no significant changes in slope. In the 3D LiDAR data, shown in Figure 9, the blue color indicates the dataset collected in May and the red color indicates the dataset collected in November. When the two datasets are merged, if the slope color is blue, it indicates slope exfoliation, while if the slope color is red, it indicates that either there was no change in the slope, or that sediment was deposited. Although the blue predominates on the slope shown in Figure 9 (A), the difference on both surfaces has been shown to be less than 2 mm. The degree of variation was below the resolution of the equipment used in this study. Therefore, it was not possible to determine whether our results were due to weathering of the slope or the resolution of the equipment. This was similarly shown on another slope, in Figure 9 (B). Nevertheless, Figure 9 (B) displays significant differences in several regions, and these differences were visible in the DSM

simulations because the regions covered with vegetation in May had less vegetation cover in November.

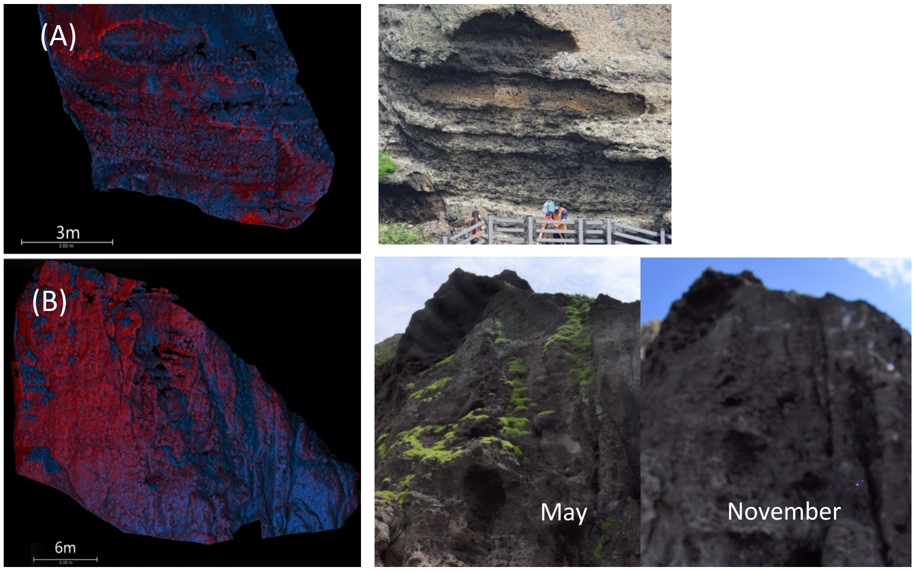

Figure 9. Overlapping of 3D scan data from May and November, and photographs of Dongdo slopes (e-a) and (e-b). (A) 3D scan data and the photographs indicating the development of tafoni on the slope featuring massive tuff breccias (e-a). (B) The opposite slope (e-b), some parts which were covered in vegetation May.

Figures 10 (A) and 11 (A) show the reflection intensity obtained from the 3D LiDAR data measured in May. In Figures 10 (B) and 11 (B), the reflection intensity of the breccia and vegetation is denoted with a red color, respectively. The reflection intensity was expressed from 0 to 255, and the difference in its value depending on the slope materials was identified in Figure 12. Figures 10 (B), 12 (A) and (B) present the reflection intensity distribution of the tafoni behind the Dongdo dock (slope e-a). The reflection intensity of the slope containing the tafoni varies from 0 to 255 and is distributed throughout the entire section. The value with the highest frequency was 56. The reflection intensity differed with material characteristics: breccia and tuff had intensities of below 60 and over 70, respectively, suggesting that the reflection intensity of the breccia included in the massive tuff breccia is lower than that of tuff. In Figure 12 (C), the reflection intensity of slope (e-b) ranges from 0 to 186, and the value with the highest frequency was 57. In May, herbaceous vegetation covered the slope (e-b), and the reflection intensity of the vegetation-covered slope was below 35, a lower intensity than that of the breccia (Figure 12 C).

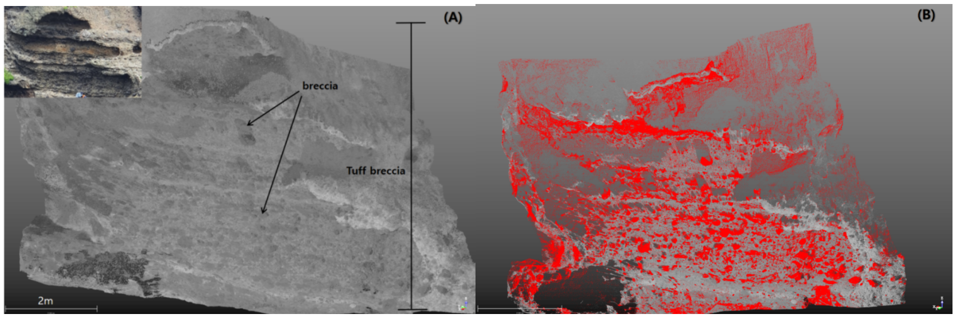

Figure 10. (A) Reflection intensity inside the tafoni of the slope (e-a) on Dongdo. (B) Reflection intensity of the breccia (red), which appears lower than that of the tuff.

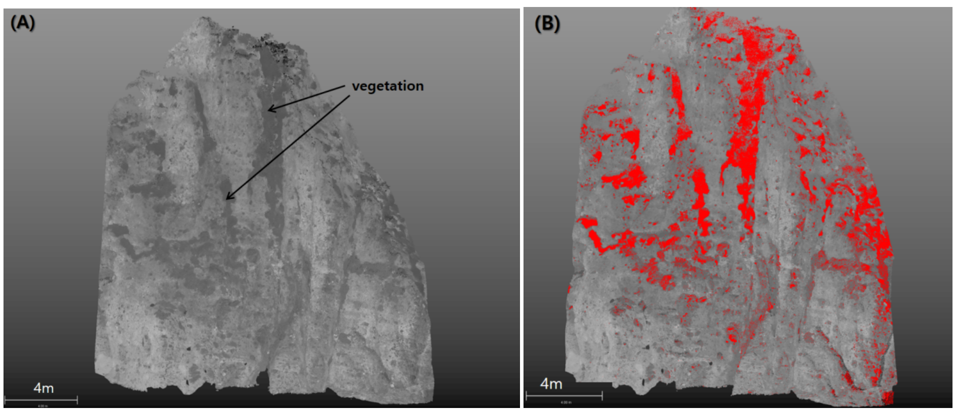

Figure 11. (A) Reflection intensity of Dongdo slope (e-b) comprising massive tuff breccia. (B) Reflection intensity of vegetation (red); which appears to be lower than that of the other materials.

4 DISCUSSIONS

We would like to discuss two issues here. The first is related to the factors and processes causing changes on the slopes of Seodo islet. The second is related to the weathering rate on Dongdo islet, determined from 3D scan data and reflection intensity data.

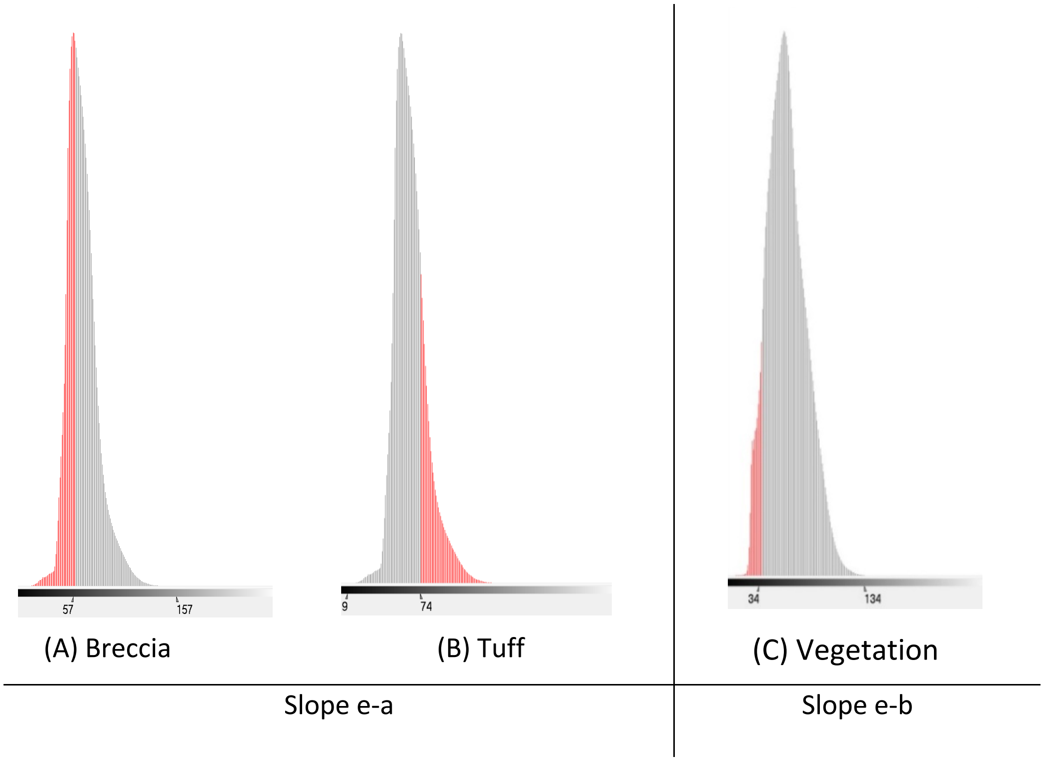

Figure 12. Reflection intensity histogram for different matrices (horizontal axis is reflection intensity, vertical axis is frequency of the reflection intensity value). (A) is the intensity of breccia, (B) is that of tuff, and (C) is that of vegetation (May 2020). The histogram shows the reflection intensity distribution of the entire slope, and red indicates the reflection intensity range of the breccia, tuff, and vegetation.

In early September 2020, typhoon Myssak passed the eastern part of the Korean peninsula, causing major damage to Dokdo. The highest precipitation measured by the Dokdo AWS, of 26.5 mm per hour and 49 mm per day, was recorded on September 3. This rainfall value represents approximately 10% of Dokdo’s annual average rainfall of 497 mm. Olivia (1994) reported that landslides can occur if the 24-hour precipitation exceeds 20% of the annual average rainfall. The rainfall in Dokdo during this period was not sufficient to cause a landslide. However, the weather conditions were sufficient to induce sediment movement on the steep slope. In addition, the sediment was unconsolidated and not covered by vegetation. This sediment movement was accelerated because the sediment quickly became saturated due to its shallow depth. Gullies and rills were observed in the upper part of the Seodo slope. These are the primary slope processes in soil layers or sediment layers not covered by vegetation. A large amount of sediment was eroded from the lower part of the Seodo slope within 8 m above sea level. At the bottom of the slope, the space between the concrete wall and cliff narrows abruptly, forming a bottle neck and causing water flowing from the upper slope to be concentrated at this location. Such high-velocity and concentrated runoff was able to transport large amounts of sediment (Figure 13). At the same time, the coast was affected by high waves with a maximum height of 4.2 m and an average wave height of 2.9 m. The high wave energy in the swash zone caused topographic

changes through coastal erosion processes (Leont'yev 1996). Such storm waves could easily erode the colluvium deposited near the coast of Seodo, so that the sediment on the middle part of the slope collapsed and moved due to the erosion of sediment lower down the slope. We speculate that coastal erosion of Seodo caused the collapse of the boulder from the massive tuff breccias. As shown in Figures 7 and 13, approximately 1 m or more of sediment below the boulder was removed. In addition, the boulder moved 5 cm towards the coast. It is presumed that the slope changes on Seodo were caused by rill and gully during heavy rainfall on the upper slopes, coastal erosion by storm waves, and the movement of sediment and the boulder due to a change in load. On slope (w-a), the sediment and erosion amount were approximately 38 m^3 and 176 m^3, respectively, and the total amount of eroded colluvium was determined to be approximately 136 m^3. Dokdo has shallow soil depth comprising sandy loam. Although there is no data on the amount of soil developed on Dokdo, the amount of soil on Seodo can be estimated as approximately 6,340 m^3 using soil developed area and soil depth examined on Seodo by Sohn et al. (2011). The total erosion on Seodo (136 m3) accounts for 2% of the soil in this islet and occurred over only six months. However, this analysis of the sediment movement rate on Seodo is limited by several factors. The typhoon was the major factor explaining the slope change, but this study was not a comparison of before and after the typhoon. Various weather conditions between May and November may have affected the slope changes. Therefore, information is required regarding slope change under normal weather conditions, and slope changes affected by specific events should be analyzed separately from those affected by normal weather conditions.

Figure 13. Sediment erosion between the concrete wall and boulder.

Weathering occurs continuously at the tafoni formed at the back of the Dongdo dock (Hwang and Park 2007). However, in this study, the weathering rate of the tafoni and pyroclastic rocks could not be determined. Because the weathering process takes place over an extended time period, it was difficult to analyze the slope changes using two datasets obtained with such a short interval. According to previous research, the weathering rate of tafoni on the granitic layer is 0.125 mm/y at Mount Deoksoong (Matsukura and Tanaka 2000) and 1 mm/y at Jumunjin (Kwon 2002) in South Korea. Choi and Seong (2021) determined the long-term lowering rate of shore platforms on Dokdo from cosmogenic 36Cl as 0.68 mm/yr. Considering that this lowering rate is

directly affected by wave erosion, it can be estimated that the weathering rate by salinity will be even lower. The weathering rates reported in previous studies are too low to be detected by our 3D scan equipment, which will not detect changes below 2 mm/y. Thus, when the rates suggested in previous studies were applied in this study, significant weathering would only be detected after at least two years had passed. However, the weathering rate cannot be applied uniformly across the surfaces of all slopes. The same rock type could have a different weathering rate depending on the moisture effect, number of joints, and level of vegetation development, hence quantitatively analyzing the weathering rate remains a challenge (Matsukura and Tanaka 2000; Hill 1996; Matsuoka 1995). The massive tuff breccia layer associated with tafoni development on Dokdo is composed of various rock fragments such as light brown or light gray coarse sand-sized tuff and gravel. In particular, the tafoni is primarily developed on the slope at the back of the dock, with a high density of vertical and horizontal joints. The tafoni are developed predominately alongside joints, due to the mechanical weathering reaction of salinity associated with waves and splashes. NIE (2015) conducted a survey of the weathering features of the Dokdo ecosystem in 2015 and measured and analyzed their physical rebound strength and chemical properties using X-ray Fluorescence (XRF). In that survey, censuses were conducted at eight points, including the (e-a) slope of this study, featuring the massive tuff breccia tafoni. The (e-a) slope exhibited a rebound strength of 19.28, which was the second-lowest rebound strength among the eight points selected. Low rebound strength indicates a weak rock. Furthermore, in the XRF analysis conducted to investigate the level of rock weathering, the Na2O concentration was 4.55%, which was higher than the average value of the earth's crust (3.1%) (Campbell 1999). This means that the rocks on slopes (e-a) are more weathered than those on other Dokdo slopes which have higher rebound strength and lower Na2O concentrations. Therefore, the slopes (e-a) consisting of large tafoni should be monitored on a regular basis.

The 3D LiDAR data provides information on the reflection intensity of various materials, in addition to the spatial information. Such information can be used to identify slopes experiencing a fast weathering rate. Smith (2006), Davis (2015), and Flubert et al. (2005) calculated the tafoni growth rate as an average value over the whole slope. However, the weathering rate varies with the rock type, joint density, surface moisture content, and vegetation distribution. The slope examined in this study contained weathering features such as tafoni, joints, and exfoliated rocks with high moisture contents (Park and Shin 2019). Our research found that the reflection intensity data obtained from 3D LiDAR scanning vary according to the rock type and vegetation distribution. It is possible to analyze the weathering rate using spatial change data coupled with intensity value data. For combinatorial research into material properties and reflection intensities, it is necessary to measure the reflection intensity of various rock types on the slopes of Dokdo, along with their moisture content.

5 CONCLUSIONS

This study investigated slope changes on Dokdo Island between May and November of 2020 using 3D LiDAR data. The results indicate that colluvium movement occurs rapidly on the slopes and is driven by rill erosion due to heavy rain, and beach erosion due to storm waves associated with typhoons. In particular, the colluvium on the Seodo islet consists of pyroclastic debris with large particle sizes, and lacks vegetation cover, making it particularly prone to transport. Extreme weather events as well as normal precipitation can affect sediment transport. Therefore, long-term seasonal monitoring with regular high-resolution 3D LiDAR scans is essential for analyzing average slope changes on Dokdo. In addition, prolonged monitoring will allow for the determination of weathering rates of both the unconsolidated and consolidated geological layers on the island. In this short-term study, no significant weathering-induced slope changes could be identified form the 3D LiDAR data. However, data measured over several years or decades will allow for a more accurate determination of the weathering rate on the weathered slopes. In particular, if the relationship between the geological features and weathering rate is analyzed using the reflection intensity of the 3D data, the weathering rates of the slopes experiencing preferential weathering can be determined. As slope change is closely related to slope stability, the results of this study can be used as a reference for the management of Dokdo, which is a slope change-sensitive region.

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