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UAV-Assisted Landslide Activity Monitoring: Applications and Open Issues

İrfan Zirek[1]
https://orcid.org/0000-0003-3593-0710

R. Cüneyt Erenoğlu[2]
https://orcid.org/0000-0002-8212-8379

[1] Çanakkale Provincial Disaster and Emergency Directorate - AFAD, Çanakkale, Turkey
[2] Çanakkale Onsekiz Mart University, Department of Geomatics Engineering, Çanakkale, Turkey

[*] Corresponding author: *ceren@comu.edu.tr*

Abstract

In this study, the principles, analyzes and results of landslide monitoring are presented by using aerial photographs obtained with the help of high-resolution cameras integrated with unmanned aerial vehicles. For this purpose, an active landslide near Sarıcaeli Village (Çanakkale, Turkey) was selected as the pilot study area. This landslide has been tried to be modeled using unmanned aerial vehicle photogrammetry and global positioning system. For this purpose, data were collected from the field for three periods: in May 2016, September 2016 and January 2017. These obtained data were evaluated during a series of photogrammetric workflows and final products such as digital surface models, digital terrain models, three-dimensional models and orthomosaics were produced. In addition, these products were processed in the geographic information system and the temporal development of the landslide was analyzed.

Key Words: Landslide, UAV, GPS/GNSS, Photogrammetry, DEM, DTM

İHA Destekli Heyelan Aktivitesi İzleme: Uygulamalar ve Açık Konular

Özet

Bu çalışmada, insansız hava araçlarına entegre olarak kullanılan yüksek çözünürlüklü kameralar yardımıyla elde edilen hava fotoğrafları kullanılarak heyelanların izlenmesine ilişkin esaslar, analizler ve sonuçları sunulmaktadır. Bu amaçla pilot çalışma bölgesi Sarıcaeli Köyü (Çanakkale, Türkiye) yakınındaki aktif heyelan seçilmiştir. Bu heyelan insansız hava aracı fotogrametrisi ve küresel konum belirleme sistemi kullanılarak modellenmeye çalışılmıştır. Bu amaçla Mayıs 2016, Eylül 2016 ve Ocak 2017'de olmak üzere üç periyot araziden veri toplanmıştır. Elde edilen bu veriler bir dizi fotogrametrik iş akışı yardımıyla değerlendirilerek sayısal yüzey modelleri, sayısal arazi modelleri, üç boyutlu modeller ve ortomozaikler gibi sonuç ürünler üretilmiştir. Ayrıca bu ürünler coğrafi bilgi sisteminde işlenerek heyelanın zamansal gelişimine ilişkin irdelemeler gerçekleştirilmiştir.

Anahtar Kelimeler: Heyelan, İHA, GPS/GNSS, Fotogrametri, SYM, SAM

Introduction

A landslide is the downward movement of material consisting of natural rock, soil, artificial fill or a combination of these in the direction of slope (Cruden and Varnes, 1996). Landslides, alone or together with earthquakes, volcanic eruptions, forest fires and major rainstorms that can trigger landslides, are the leading cause of loss of life, injury and property damage in natural disasters worldwide (WP/WLI, 1993). Landslides that can be seen in all continents, oceans and seas in the world can occur in different sizes, from a small landslide of a few square meters to large submarine landslides of hundreds of square kilometers covering the land and sea floor (Guzzetti, 2005). Landslides are natural events that are seen worldwide and have negative economic effects and sometimes result in loss of life. High slope, unstable ground, groundwater and human effects are some of the factors that cause landslides. With unmanned aerial vehicle (UAV) supported by digital cameras, data can be easily collected in difficult weather and terrain conditions at any time. The fact that data collection is fast and less costly is an important reason for using these tools. UAVs also enable rapid and high spatial resolution mapping of landslides.

In this study, global positioning system/global navigation satellite system (GPS/GNSS) and UAV studies were evaluated in the landslide area that occurred in 2016 and 2017 in the Sarıcaeli village of Çanakkale. The landslide was observed for a year and the aerial photographs of the landslide area were taken by UAV, with observations made in three different campaigns. Before the aerial photographs were taken, ground control points (GCPs) were established and the coordinates of the GCPs were measured with a geodetic GPS/GNSS receiver. The UAV photographs taken were processed using photogrammetry techniques.

Using the data obtained in different time epochs, the area and volume of the sliding mass, the direction of the landslide can be determined and its development can be followed. In addition, digital elevation model (DEM), digital terrain model (DTM), orthomosaic and three-dimensional models of the landslide area were created with the photogrammetry methods and software used. DTM derivatives such as surface slope and slope orientation were produced from the created DTMs and the global cell relations of the DTMs in GRID format were examined and the slip direction and accumulation area of the landslide were successfully determined.

Landslide Modeling using UAV Photogrammetry Approach

Studies in which the development of landslide areas, are analyzed by photogrammetric methods are becoming widespread. In these studies, using digital terrain models obtained at different times, landslide dynamics such as differences between produced digital terrain models, topographic profiles, volume calculations, three-dimensional displacement vectors are revealed. Complex analyzes such as tracking the development of landslide movement obtained by measuring from digital terrain models and orthophotos obtained at different times can be performed (Fernandez et al., 2015).

Erenoğlu et al. (2014) took aerial photographs of Adatepe Landslide, which was an active landslide in Çanakkale province on November 15, 2013, using low-cost UAVs and digital cameras in their study, in campaigns. By using the plane image correction method from the photographs taken, an orthomosaic with cm-level resolution covering the entire Adatepe Landslide slip area was created. In addition, displaced sections, regional differences on the surface, bumps, ridges, and grooves were modeled by scaling in the digital terrain model produced.

UAV-based photogrammetry has been proposed to be used for monitoring and analyzing active landslides. Peterman (2015) studied the Potosko Planina landslide that occurred near the village of Korosko Bela in the Karavanke Mountains in the west of Northwest Slovenia and presented a practical example of tracking landslides by UAV. As a result of previous geological researches in the region, it was seen that more than 10 cm displacement occurred per year. The data obtained as a result of periodic observations carried out twice a year have been processed and it has been determined that larger movements have occurred.

Niethammer et al. (2012), using UAV photographs of the Super Sauze landslide that occurred in France, a digital terrain model of many regions was produced with the high-resolution orthomosaic of the entire landslide. UAV capability to visualize cracks and displacements in the landslide surface was evaluated and image processing approaches were evaluated for appropriate georeferencing of data. As a result of the observations made between May 2007 and October 2008 in the landslide, it was observed that horizontal displacements from 7 m to 55 m occurred. In this study, it has been shown that radio-controlled low-cost unmanned aerial vehicles can provide high-resolution remote sensing data in landslides and the proposed UAV-based remote sensing approach has significant potential for the production of high-resolution orthomosaics and DTMs that enable analysis of cracks and surface coverage.

Fernandez et al. (2015) showed that mudflow in La Guardia (Jaen, Southern Spain) was measured by 4 UAV flights between 2012 and 2014. These measurements were also compared with data previously obtained from conventional aerial photogrammetry and light detection and ranging (LIDAR) measurements. DEM, which allows the estimation of the changes in the surface, and orthophotos, in which the horizontal and vertical displacements at the relevant points can be determined, were obtained in each measurement. Between some campaigns, significant displacements were observed in centimeters vertically and meters horizontally.

Rau et al. (2011) mapped the 21.3 km² test area with a fixed-wing unmanned aerial vehicle containing hundreds of landslides triggered by Typhoon Morakot. Air triangulation, orthophoto rendering and mosaicing were applied to the obtained images. An automatic landslide detection algorithm based on object-based image analysis (OBIA) technique is proposed. Color orthophoto and DEM were used. The orthophotos obtained before and after the typhoon were used to estimate the new landslide areas. Experimental results show that the developed algorithm has high accuracy and the feasibility of a fixed-wing UAV for landslide mapping.

In the studies by Farina et al. (2017), different landslides in Tuscany, Umbria and Sicily regions of Italy were investigated using the Saturn multicopter, an instrument developed at the University of Florence. It is aimed to show how fast a sensitive DTM can be produced by using aerial photographs obtained by UAV. As a result of the study, it has been seen that a detailed geomorphological map can be prepared by defining the main geomorphological features of the investigated area by obtaining high resolution point clouds data of the landslide area with UAV technology. It was also concluded that it is possible to measure surface deformations with a vertical accuracy of a few centimeters.

Turner et al. (2015) collected high-resolution images with UAV in 7 epochs for 4 years and used them to determine landslide dynamics. The DEM of the landslide was created with an accuracy of 4-5 cm horizontally and 3-4 cm vertically. Volumetric changes in certain areas of the landslide were measured over time series. The surface movement of the landslide was monitored and measured with the COSI-Corr image correlation algorithm without ground verification. Historical aerial photographs were used to construct the base digital surface model and the total displacement of the landslide was found to be approximately 6630 m³. In this study, a robust and reproducible algorithm is presented that enables UAV mapping and monitoring of landslide dynamics over a relatively long time series.

Eker and Aydın (2016) obtained digital images of the Hollenstein landslide that occurred in the YBBS Region of Lower Austria with UAV flights and used them for photogrammetric measurement. From these images, the orthophoto of the landslide and DEM with 6 cm error were produced with the Structure from Motion (SfM) algorithm. The deformation in the area was determined by comparing the DEM created with the 1 m resolution LIDAR image taken in 2009.

Lindner et al. (2015) used technologies such as geophysical methods (geoelectricity, inclinometer, soil moisture and soil temperature) and GPS/GNSS surveys to monitor and document a landslide. For this purpose, a large soil flow of several million cubic meters was successfully detected by modeling the landslide movement in a small village in Austria triggered by heavy rains in June 2013. Additionally, the UAV was also used for periodic assessment of the landslide process. In total, 9 flights were made by multicopter equipped with a digital single-lens reflex camera (DSLR) providing thousands of images. Based on these images and detailed GPS/GNSS surveys of the landslide area, DEMs with an accuracy of less than ±10 cm were produced as well as orthophotos. Crack tracing, flow direction and velocity and mass balance data were obtained from these datasets.

Study Area and Geological Setting

The study area is located at the coordinates of 40°07'14.48" N– 26°26'00.94" E, approximately 100 m above sea level of the Sarıcaeli Landslide, which occurred in the Sarıcaeli village of Çanakkale Province Central District (Figure 1). The landslide that occurred is a deep seated rotational type landslide and is approximately 1 km away from Sarıcaeli village center and approximately 7 km from Çanakkale city center. Some terrestrial photos visually verify that the width of the landslide is approximately 150 m and its length is approximately 45 m (Figure 2).

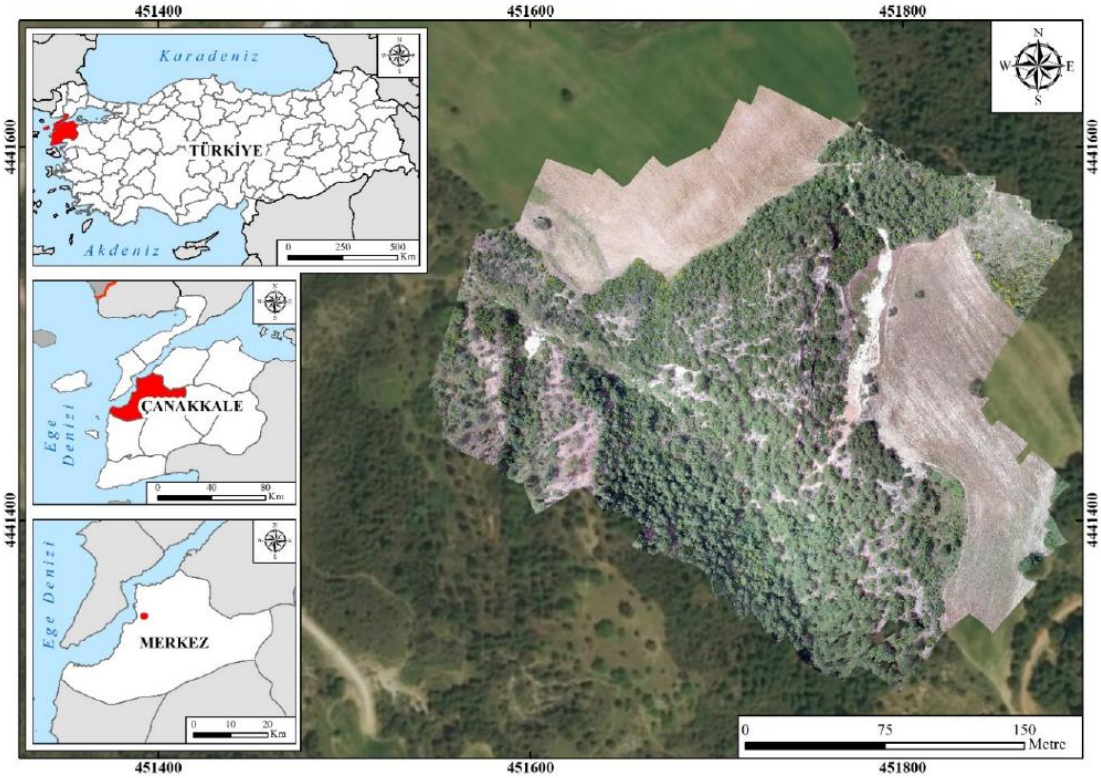

Figure 1. Location map of the study area

Figure 2. Terrestrial photos from the landslide site

Landslides where the surface of the slide is lower than the maximum rooting depth of the trees (more than 10 meters deep). Deep-floor landslides often involve deep regolith, weathered rock, and/or bedrock, and involve large cliff slides associated with translational, rotational, or complex motion. Such landslides, which move at a speed of up to a few meters per year, usually occur in tectonically active areas.

The geology of the study area is dominated by a marine unit consisting of small-coarse-grained sandstone and to a lesser extent pebble-pebbly conglomerate, siltstone and mudstone, which is located on the red colored conglomerate, sandstone and mudstone (Figure 3). The components of the sandstones are quartz and mica grains. The conglomerates, on the other hand, have well-developed planar parallel layers. All these sediments were affected by storm and tidal processes as well as the normal wave and current processes prevailing in the environment during deposition, and the sediments were processed depending on these processes (Ilgar et al., 2008).

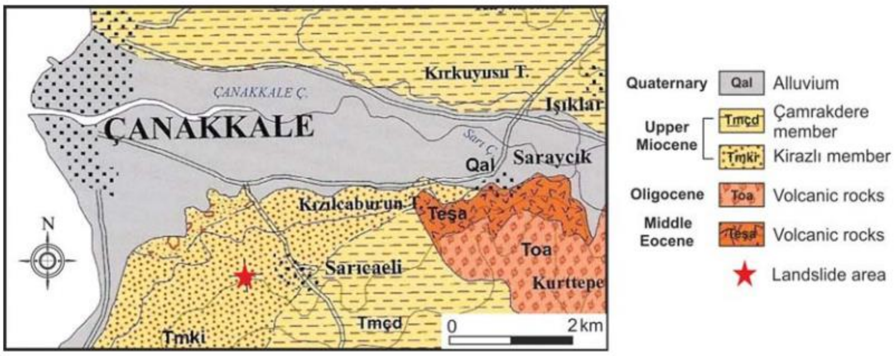

Figure 3. The geological map of study area

Material and Method

In the data collection stage, one DJI Inspire 1 brand UAV with four motors and one DJI Zenmuse X3 digital camera integrated into the UAV, a GPS/GNSS receiver and five GCPs were used. Field studies in the landslide area were repeated in three different epochs on 30 May 2016, 6 September 2016 and 27 January 2017. The data collection step is the same for all epochs. Therefore, in this section, only the GCP facility, coordinate measurement and image acquisition processes on May 30, 2016 will be explained.

The GCPs to be used in the image processing phase were installed at the upper limit of the landslide (Figure 4, left). The GCPs and their locations were chosen so that they can be easily seen on the images taken by the UAV (Figure 4, right). The coordinates of the installed GCPs were measured in millimeters with the GPS/GNSS receiver. YCPs are used in georeferencing and datum transformations of DEMs and orthomosaics to be produced. The coordinates of the GCPs were measured in the Universal Transverse Mercator 3° (UTM) Projection System, Datum of the International Terrestrial Reference Frame 1996 (ITRF96). The slice number is 27.

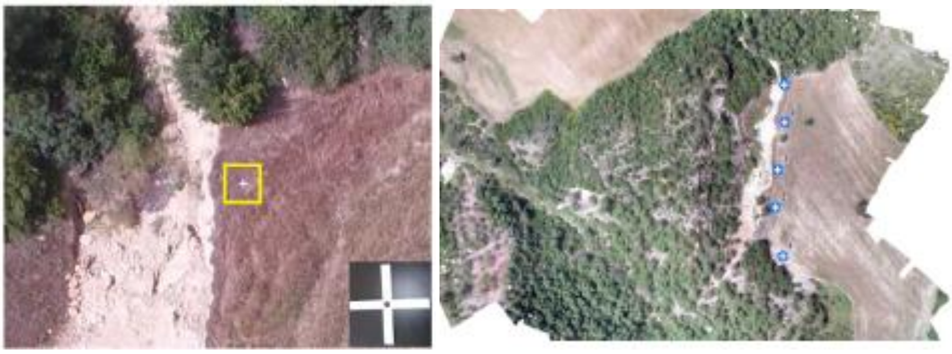

Figure 4. Ground control point and locations of ground control points used in the study (30 May 2016)

UAV-based UA studies have been carried out for many years. For UAV photogrammetry, the first fixed-wing, remotely controllable aircraft were produced in the late 1970s. A quarter century later, unmanned helicopters were developed to produce high resolution DEMs. Today, many other UAV systems are also used (Niethammer et al., 2010).

UAVs are very useful due to their low cost compared to satellite images, when images cannot be obtained from satellites due to weather conditions and data can be obtained at any time. Orthophoto and DEM of the desired area can be produced in a short time.

Determining the area where the image will be taken and preparing the flight plan is sufficient for the use of UAVs for photogrammetric purposes. The easy use of UAVs, their light weight, their ability to be used in adverse weather conditions, and the ability to obtain fast data compared to satellite systems have made the use of these vehicles widespread in land surveying and orthophoto production. Orthophotos, three-dimensional models, digital terrain and elevation models, point clouds can be easily produced with photogrammetric approaches from the data obtained with UAVs (Türk, 2013). One of the biggest advantages of UAV-based UA applications is that it provides the opportunity to collect information about hazardous areas such as landslides and rockfall areas where direct measurements cannot be made (Niethammer et al., 2010).

Monitoring and analysis of active landslides includes both spatial and temporal measurements. In addition, landslide conditions (changes in surface topography, including the rate and extent of displacements) need to be evaluated continuously. Displacements are of great importance and are obtained by comparing DEMs and orthophotos created on different dates. These measurements can be made manually or automatically. UAV-based orthophotos allow large-scale analysis of landslide material and crack structures. Fracture structures can be clearly identified and associated with the fracture process in the landslide material. In addition, high resolution textural information in UAV-derived orthophotos also allows the analysis of soil moisture on the landslide surface. DEM derivatives such as slope, aspect, curvature of the landslide area and landslide accumulation area data can also be produced using UAV-based DEMs (Niethammer et al., 2010).

Data Processing and Results

After the data collection process was completed, the data processing phase was started. At this stage, point cloud, DEM, SAM and orthomosaic were produced with Structure from Motion (SfM) Algorithm using Agisoft PhotoScan Professional Edition Version 1.2.4 software. After aligning the photographs with the software, sparse and dense point clouds, 3D polygonal model, DEM, SAM and orthomosaics were produced, respectively. The operations have been completed according to the general workflow and explanations in the Agisoft PhotoScan User's Guide (Figure 5). These processes are described in turn below. The data processing step is the same for all epochs. Therefore, in this section, only the studies based on aerial photographs obtained on 30 May 2016 will be explained.

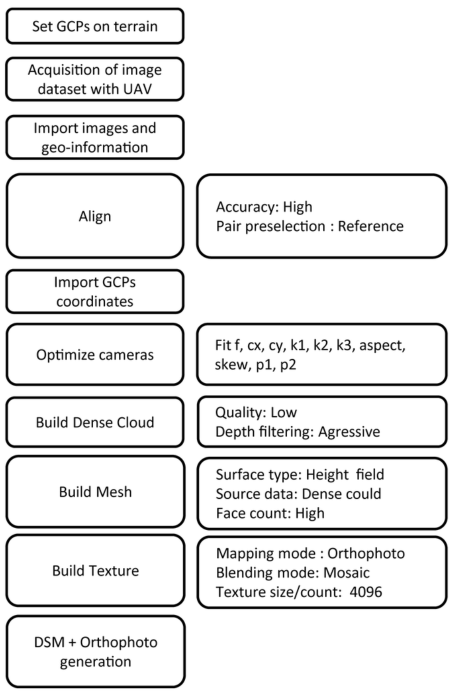

Figure 5. Schematic diagram of the digital (digital) photogrammetry environment (Schenk, 2005)

The SfM process begins with the acquisition of relevant object photographs from multiple positions and/or angles with sufficient overlay (eg 80-90%) (Figure 6). Characteristic image objects can be automatically detected, identified and matched between photos. Beam compensation is then applied on the matching features. Thus, the 3D positions of the details, camera rotations and XYZ positions in the photos are determined. As a result, a sparse point cloud is produced. The condensation technique can be used to produce very dense 3D models with multi-image stereopsis (MVS) or depth mapping techniques. The use of GCPs and/or the inclusion of camera locations allows the 3D model to be located in a real-world coordinate system. Finally, the model can be exported as a grid-based DEM and orthomosaics can be produced based on the photographs taken (Lucieer et al., 2014).

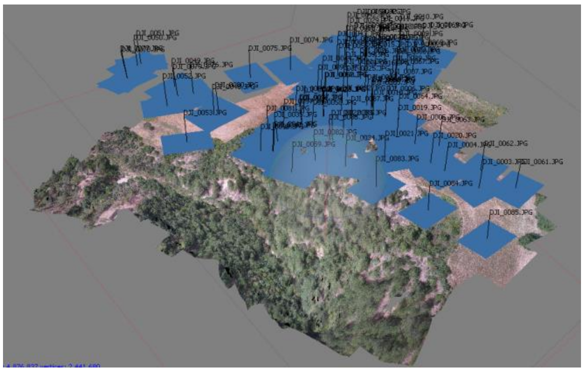

Figure 6. The position of the aerial images

DEMs are models in which the earth's surface is shown numerically, natural objects such as vegetation, man-made objects such as buildings and other objects rising above the bare earth, together with the location information of the surface. DEM can be generated from sparse point cloud, mesh (3D polygonal model) and dense point cloud with PhotoScan software. However, the most accurate result is the data produced from the dense point cloud (PhotoScan UM, 2018). With the "Build DEM" command under the "Workflow" menu, the SYM with a resolution of approximately 6 cm was produced in GRID format. Dense point cloud was used as surface data and DEM was generated in World Geodetic System 1984 (WGS84) datum (Figure 7, left).

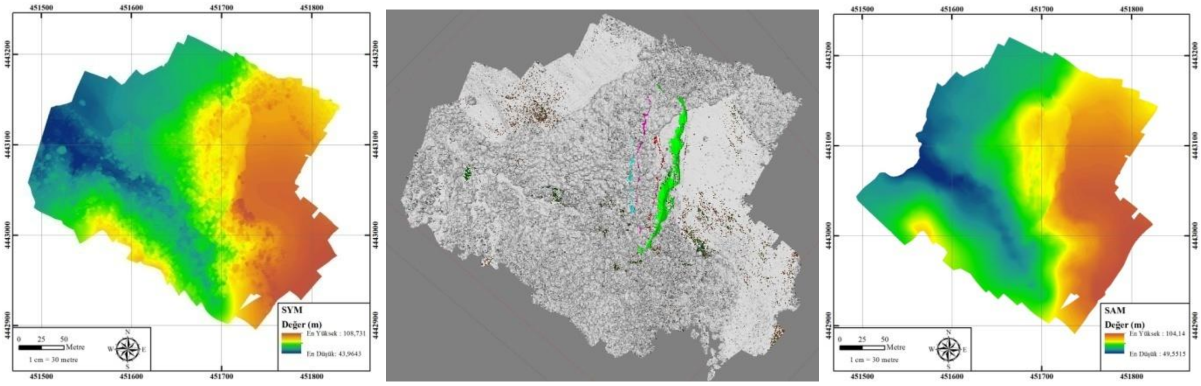

Figure 7. Digital surface model, classification of ground points and digital terrain model (30 May 2016)

DTM can be defined as a three-dimensional representation of the land surface consisting of X, Y, Z coordinates held in numerical format. It includes not only heights, but also other geographical elements and natural details such as rivers and ridge lines. The DEM produced in the previous step will show the current status of the landslide area and its surroundings, and the vegetation on this area will also be represented on this data. Since data such as slope, aspect, landslide flow direction to be produced using this model will not provide accurate information about the area, DTM was produced by classifying the points belonging to the ground and analyzes were carried out using this model (Figure 7, middle).

In order to create the DTM to be used in the analysis, first of all, it is necessary to determine the ground points by classifying the dense point cloud. For this, ground points were determined by automatically classifying the dense point cloud. As a result, the points of vegetation on the land were removed. After the classification process was completed, the classified dense point cloud was used as the surface data, similar to the DEM generation, and the DTM was generated in the WGS84 datum. As a result, a digital terrain model was produced in GRID format. The resolution of the digital terrain model created is approximately 6 cm. (Figure 7, right).

Discussion and Conclusion

The produced DTM and orthomosaics were opened using ArcMap software included in the ArcGIS Desktop 10.5 package, which is a GIS software. Before starting the analysis, artificial gaps on the SAMs were removed with the "fill sink" function. The resolution of the DTMs was then resampled. The global cell relationships were examined and the slip direction and accumulation area of the landslide were determined by using the gap-filling function and resampled DTM in GRID format. In addition, slope and slope orientation data of the landslide area and its surroundings, which are derivatives of DTM, were also produced in GRID format. In order to make comparisons between DTM and orthomosaics based on the data collected and produced in different epochs, a grid mesh of the same width and cell size as the DTM was created. The data analysis step is the same for all epochs. Therefore, in this section, only the analyzes made on the data produced on the basis of aerial photographs obtained on 30 May 2016 will be explained.

In order to eliminate the gap errors on the SAM in GRID format, the "fill sinks" function has been applied on the data. If a cell has less height than the other 8 cells around it, as shown in Figure 8, first two sub-figures, surface flow will not be achieved. For this reason, these gaps should be filled by rearranging the height values.

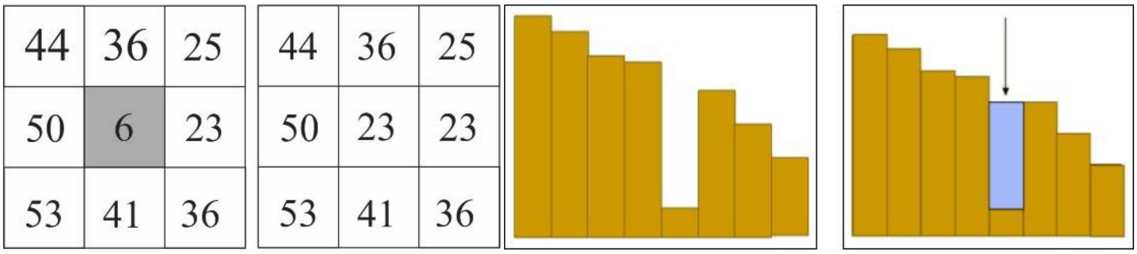

Figure 8. Fill in the gaps (Güreşçi, 2012)

These defects on the DTM opened with Arcmap software have been fixed with Spatial Analyst Tools > Hydrology > Fill function in the Arctoolbox toolbox, which includes many data management, transformation and analysis geoprocessing functions (Figure 8, second two sub-figures).

The resolution of DTM, which was approximately 6 cm before starting the analysis, was rearranged to 50 cm by resampling. It was observed that the analyzes made without this correction did not yield healthy results. It was resampled with the Data Management Tools > Raster > Raster Processing >Resample function in the Arctoolbox toolbox.

The flow direction of the landslide was determined by applying the "flow direction" function to the gap-corrected DTM data. In this function, the height of the cell is compared with the 8 cells around it. The flow will be towards the cell with a height lower than its height value (Figure 9).

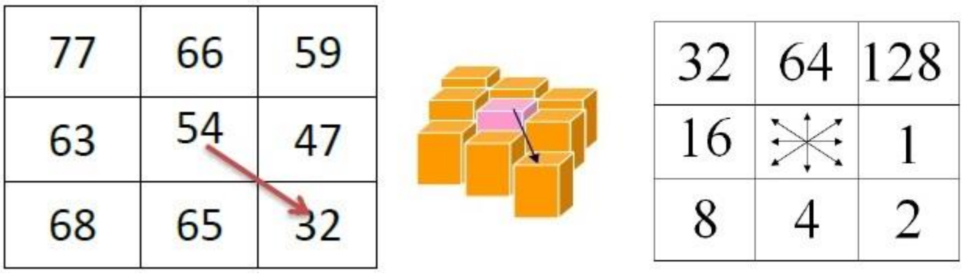

Figure 9. Flow directions (Güreşçi, 2012)

Flow direction data was produced with the Spatial Analyst Tools > Hydrology > Flow Direction function in the Arctoolbox toolbox. The flow direction is expressed in the digital environment with the "8-way flow model". Flow directions are represented by the numerical values shown in Figure 10, left.

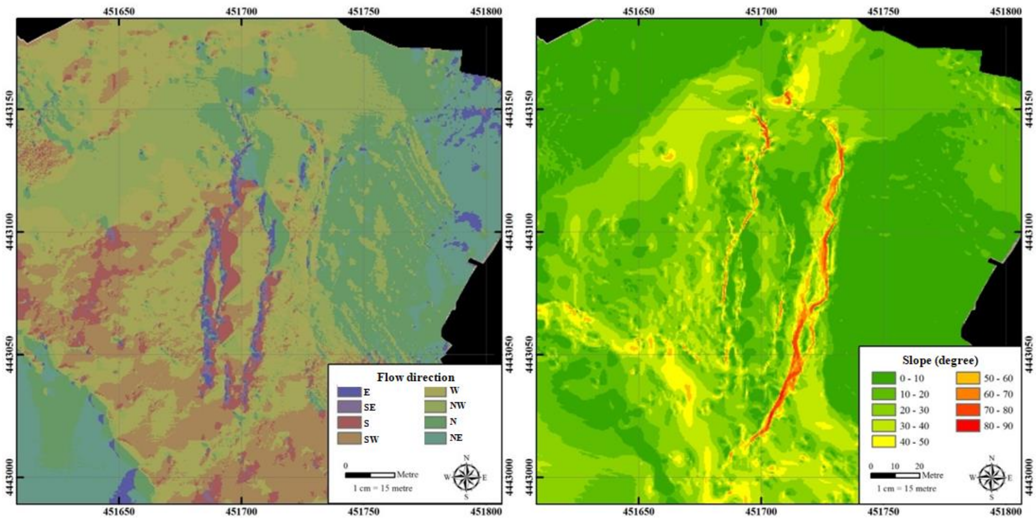

Figure 10. Landslide flow direction and slope map (30 May 2016)

The slope is the rate of change in the maximum z-value from each cell. Slope can be expressed as percent slope or degree slope (Chang, 2007). Slope in percent is the percentage expression of the ratio of the vertical distance to the horizontal distance. The slope in degrees is the tangent of the ratio of the vertical distance to the horizontal distance (Küpçü, 2015). The slope data (slope), which is a DTM derivative, was produced in GRID format and in degrees with the Spatial Analyst Tools >Surface >Slope function in the Arctoolbox toolbox. SAM was used as input data. The pixel size, number of columns and rows of the generated data are the same as the SAM data. The resolution of the slope data produced in GRID format of the landslide area and its surroundings is 50 cm, just like the DTM data (Figure 10, right).

Aspect is a measure of the direction of the slope. Aspect starts at 0 degrees in the north, moves clockwise and ends at 360 degrees in the north (Chang, 2007). It corresponds to 90 degrees east, 180 degrees south, and 270 degrees west. Flat areas are expressed with the value of -1 (Küpçü, 2015). Aspect, a SAM derivative, was produced in GRID format with the Spatial Analyst Tools>Surface>Aspect function in the Arctoolbox toolbox. DTM was used as input data. The pixel size, number of columns and rows of the generated data are the same as the DTM data. The resolution of the slope orientation data produced in GRID format of the landslide area and its surroundings is 50 cm like the DTM data (Figure 11, left).

Hillshades are shadows drawn on the map to simulate the effect of sun rays on the terrain. It is the hypothetical illumination of a surface for a certain azimuth and altitude relative to the sun (Wade, 2006). The relief data of the landslide area and its surroundings were produced in GRID format with Spatial Analyst Tools >Surface >Hillshade function (Figure 11, right).

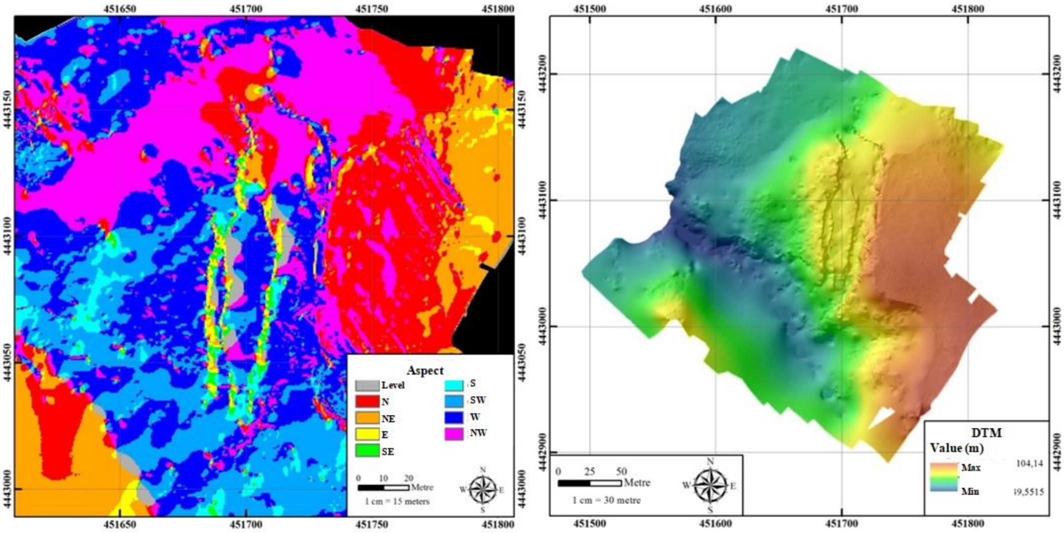

Figure 11. Aspect map and DTM with hillshade map

One of the main purposes of this study is to analyze and interpret the development of landslides using UAV photogrammetry. Based on the generated grid network, the frames where the changes on the landslide (natural objects, etc.) can be followed and examined were created as shown in Figure 12. It is clear that the ruptures from the upper boundary of the landslide increased, one of the bushes in the frame in the orthomosaic obtained in the 1st epoch was not included in the orthomosaic obtained in the 3rd epoch as a result of the progression of the landslide.

Figure 12. Landslide development (Aerial view of locations a and b at the 1st, 2nd and 3rd epochs)

Meteorological data obtained from Çanakkale Meteorology Directorate shows the amount of precipitation between May 2016 and January 2017 (Table 1). The amount of precipitation is particularly high in the period between November 2016 and January 2017.

Table 1. Monthly precipitation (kg/m²) in 2016 and 2017

Month	Precipitation in 2016 (kg/m²)	Precipitation in 2017 (kg/m²)
January	110.2	174.3
February	88.4	56.8
March	53.6	22.1
April	15.0	14.9
May	26.8	20.9
June	39.9	36.8
July	-	17.2
August	-	-
September	1.8	-
October	8.6	-
November	209.0	-
December	28.6	-

The volumetric changes in the amount of soil in the area of the landslide among the measurement epochs performed using UAV photogrammetry are given in Table 2.

Table 2. Volumetric change (m^3)

Epoch #	Volume (m^3)	Difference between 1st and 2nd Epochs (m^3)	Difference between 2nd and 3rd Epochs (m^3)
1	169918,843	2740,585	3904,147
2	172659,428		
3	176563,575		

The elevation changes between consecutive epochs were determined by differentiating the DTMs obtained in 3 epochs of the landslide area. Depending on the progress of the landslide, changes related to the amount of material displaced occurred (Figure 13).

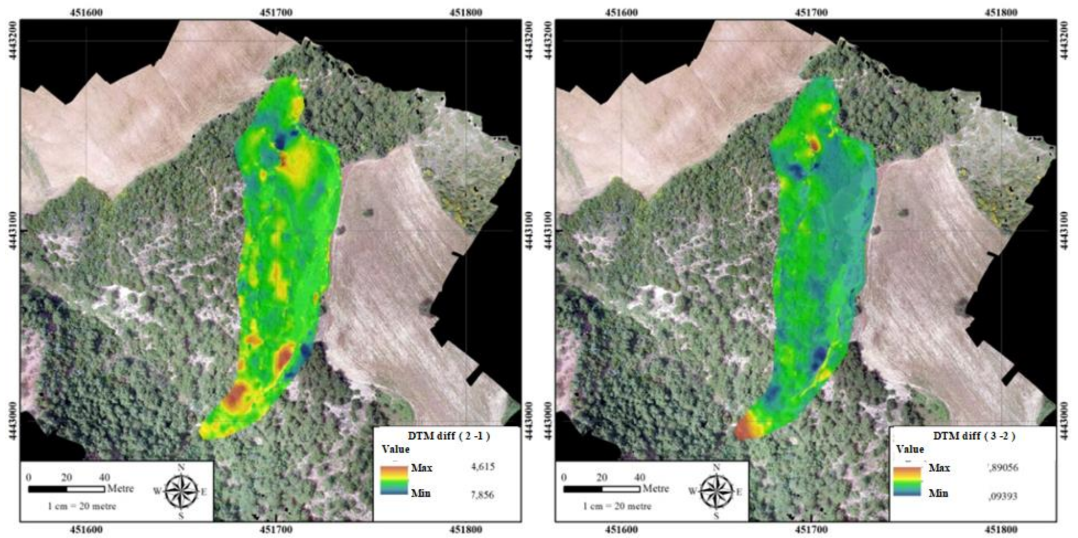

Figure 13. DTM difference (epoch 2 – epoch 1) and DTM difference (epoch 3 – epoch 2)

The soil in the study area is wet, the structure of the rocks consisting of conglomerate-sandstone-mudstone alternation observed in the area, and that the structure of the ground and surface water permeable and impermeable units, together with the high slope factor, creates a suitable environment for landslide development. From the detailed analysis of orthomosaics, it has been determined that the landslide grows continuously depending on the structural and environmental factors in the landslide area. It is thought that following the landslide development with economical and fast methods such as unmanned aerial vehicles will make a difference especially in disaster management. This method is also very effective in tracking landslides in areas that may create danger or where there is no access. In particular, possible loss of life and economic losses will be prevented by observing and monitoring the landslide areas in or near the settlements. When necessary, the settlement area will be evacuated, and the risk of loss of life in these areas will be prevented. The widespread use of this method in all "Provincial Disaster and Emergency Directorates", making predictions about the direction of disasters such as landslides in the future, identifying possible eligible disaster victims, new settlement areas, housing, public facilities, infrastructure projects, social facilities, etc. will be effective in choosing the areas where the structures will be built. The data to be obtained with this study can be used as base data within the scope of the projects for the preparation of hazard and risk maps using geographic information systems.

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Conflicts of Interest

The authors declareno conflict of interest.

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