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Structure-from-Motion Photogrammetry as a Tool for Slash Pile Volume Measurement

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Contents

Abstract

This work aims to evaluate the method of Structure-from-Motion (SfM) photogrammetry for determining the bulk volume of piled forestry slash. The issue of harvest residue management has been bought to the forefront of public knowledge after recent storms. Key to managing these residues is the ability to measure them in a repeatable manner, a task for which SfM photogrammetry is proposed. During the course of this work, a series of slash piles were surveyed using SfM methods, with both 3D models and Digital Elevation Models of the piles constructed for the measurement of volume.

It was found that the true dimensions of the piles were well preserved in the models, with most reproducing to within 0.1m of the actual dimension. The Digital elevation Models, from which volume was determined were produced with resolution ranging from 3.36cm/pixel to 1.51cm/pixel. The combination of these two factors indicated that the volumes determined were accurate representations of the actual pile volumes.

It was concluded that SfM photogrammetry is a reasonable method to be employed by forest managers looking to determine the volume of piled forestry slash. Due to the time involved in the application of the method, which ranges from 30 minutes to over 3 hours, it is likely only worthwhile on particularly tricky piles, to which access is either dangerous or restricted, or piles where there is a real risk of failure leading to damage.

Figure 1 - Structure-from-Motion model of a slash pile

Introduction

The impact of Cyclones Cook and Gita in 2017 and 2018 respectively, highlighted the issue of harvest residue management in New Zealand's commercial production forests. Both events resulted in large volumes of harvest residues being transported from hill country forest land, to coastal river flats, where damage was incurred on a significant number of infrastructure assets. The extensive media coverage following these events, as exemplified by articles appearing in newspapers and magazines, such as 'Tolaga Bay: A Beach Covered in Forestry Waste' (Black, 2019) and 'When the Rain Came For Tolaga Bay' (Naomi Arnold, 2019) has bought the issue to the public eye and added to pressure on the forestry industry to better manage its by-products and harvest practices.

Key to managing a problem is the ability to measure it in some quantifiable and repeatable manner. Currently, the method for obtaining volume measurement of piled forestry slash involves approximating the shape of the pile with a geometric solid. This method is capable of providing an estimate of the volume of a pile, but it is not accurate, due to the uneven nature of a pile of slash. Compounding the issue, there are a large number of landings and skid sites across the country, Peter Hall (Hall, 1998) noted that in 1996, there were over 860 hauler landings, with that number projected to exceed 1000 by 1998. Each of those landings would generate a slash pile. Due to the sheer number of piles across the country, it would not be economically feasible to employ LiDAR over all the piles, nor would it be practicable to manually survey each pile to obtain an exact volume of each pile.

It is here that I propose the emergent technology of Drone-Based Structure-from-Motion (SfM) Photogrammetry can be employed as a rapid, low cost alternative to the Geometric Method and LiDAR or professional surveys. Structure from motion photogrammetry utilises regular photographs captured with an unmanned aerial vehicle (Drone), and commercially available software to generate point clouds, similar to that obtainable from LiDAR surveys. SfM surveys can be completed at a fraction of the cost of a LiDAR survey, and by in-house personnel, with relatively little training and outlay costs.

This work will aim to determine whether it is possible to create models of piled forestry slash using a consumer grade drone, that are sufficiently accurate for the determination of the volume of the pile. The primary factors to be studied in order to determine the viability of this method will the resolution of the Digital Elevation Models produced during the SfM process, the volume of the piles, as determined from the DEM, and the ability of the process to preserve the physical measurements of the pile during the SfM process. Generally, the more images used to construct the SfM model, the better the quality of the model and resulting DEM.

An issue raised by members of industry is the time it would take to generate a model of sufficient quality, one that would model the volume of the pile to within 15% of its true volume. To address this concern, the number of images used in the models will be varied to determine the effect on the processing time required, volume measurement and the preservation of the dimensions of the pile.

Structure-from-Motion (SfM) is a photogrammetric process whereby it is possible to create three dimensional point clouds – similar to those obtainable through LiDAR sensing – from photographs taken by many common cameras. There are a number of software packages available both on commercial and recreational levels, including Agisoft Metashape and PIX4D Cloud. The Structure-from-Motion process involves the identification of common points between images, for instance the end of a log, visible in several images. The software is then capable of determining that point's location in space, based on the geometry of the sensor's lens, and the other points that are visible.

An **Unmanned Aerial Vehicle** refers to an airborne machine which is generally controlled from the ground by a human operator (Pilot). Unmanned Aerial Vehicles (UAVs) are colloquially referred to as drones, and are marketed as such to consumers. UAVs can be fitted with cameras that are capable of both photography and videography. Due to lowering entry price to the field, it is thought that there is over 175,000 drones in New Zealand (Hunt, 2020). With their increasing popularity, the potential uses for them is increasing likewise, with a number of civil works and mining entities around the world utilising imagery captured by UAVs for stockpile inventory (Chris H. Hugenholtz, 2015). UAVs are particularly useful in forestry, as they can quickly and safely obtain imagery from locations not easily, or safely accessible on foot.

Digital Elevation Models (DEMs) represent elevation data over a spatial area, and are commonly used for the representation of terrains in geographic information systems. They are particularly useful in hydrological modelling, and can be used for determination of volume. The resolution of large scale Digital Elevation Models, such as those available over large areas of the country are typically expressed in terms of meters per pixel with each pixel of the DEM representing a ground area of so many square meters. The required resolution of a DEM depends of the purpose for which it is to be used, and the scale it is to be used on (I.A. Thomas, 2017). The DEMs generated during this study will be expressed in terms of centimetres per pixel, due to the processes ability to produce fine scale DEM models, and the comparatively small scale on which they will be used – over tens of square metres, as opposed to square kilometres for large scale applications.

Literature Review

The present method for estimating the volume of piled slash was presented by Hardy (1996), and is known as the Geometric Method. This method involves approximating the volume of the pile, by representing it as one of a series of idealised geometric shapes, with basic physical measurements of length, width and height, as in Figure 2, below.

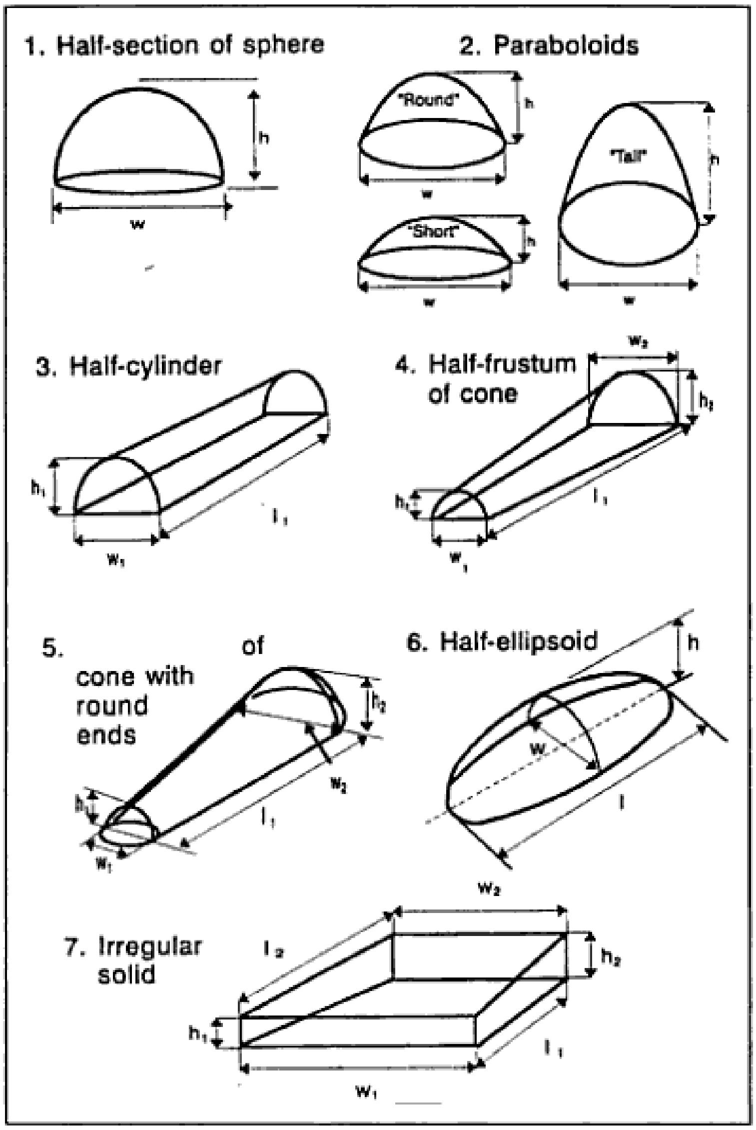

Figure 2 - Geometric shapes for estimating slash pile volume (Hardy, 1996)

Hardy's methodology has been included in subsequent studies for estimating slash pile volume. The accuracy of the Geometric Method has been assessed by Long and Boston in 2014 (Justin J. Long, 2014), where it was compared with LiDAR and a Laser Range-Finder. They found that the Geometric Method returned results with higher variability than LiDAR and laser range finder derived volumes did, and it was found to decrease in accuracy as pile size increased, as is shown below in Figure 3. The simplicity and low cost of the Geometric Method makes it still a reasonable option when conducting field investigations, as, while there is variability in the results, they are accurate enough for rough work.

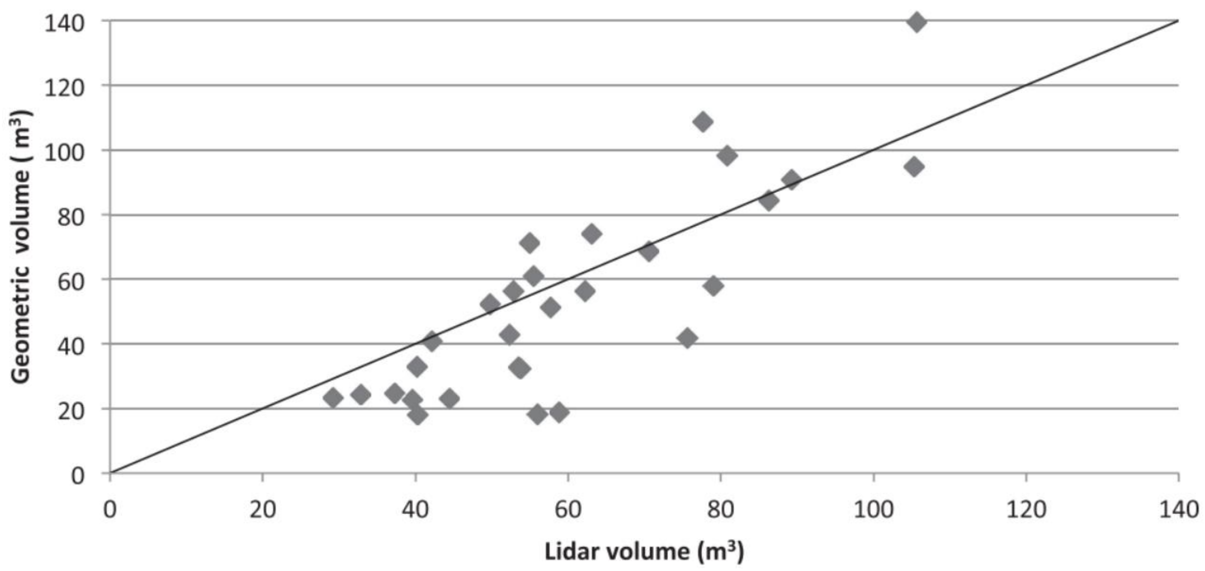

Figure 3 - Concordance correlation between the Geometric Method and LiDAR (Justin J. Long, 2014)

It was noted by Long and Boston that the cost of LiDAR analysis is prohibitive to implementing it on a regular basis, the use of a laser range finder was proposed as a viable alternative as a result of their study, but it would require at least three set-ups each time a pile was surveyed.

Photogrammetry is defined as the process of taking measurements from photographs, it was first developed in the 19th century, and the use of photographs in the creation of topographic maps was proposed around 1840. Standard photogrammetry can be used to estimate the location of points in 3D space from multiple photographs; this process is known as stereo-photogrammetry. Stereo-photogrammetry requires the 3D location of the camera to be known, so that the 3D location of objects in the imagery can be calculated.

With increases in processing power in computers, the method of Structure-from-Motion photogrammetry (SfM) was introduced in the 1990's (M.J. Westoby, 2012). In SfM the geometry between the camera, its orientation and the objects in the scene is solved simultaneously with an iterative bundle adjustment procedure, which uses a database of features automatically identified in the input imagery. Essentially the software will identify common points visible in multiple images, and based on the geometry between these points and the camera's focal length, it will assign the points a location in 3D space, as illustrated in Figure 4, below.

Figure 4 - Diagram showing the identification of common points between photographs (Jonathan P. Dandois, 2012)

As the camera positions are calculated from the geometry of the photos and not from physical locations, the resulting model will not be located in real space, rather it will be given a project coordinate system, which is not related to the real location of the pile, but the dimensions of the pile will remain accurate. In situations where the imagery is captured with a GPS enabled drone, the input images contain GPS location data provided by the drone. This allows the model to be located in the real world, and to be saved and exported with its actual coordinates.

There are a number of SfM photogrammetry software packages available; Westoby (2012) utilised SFMToolkit3 (Astre, 2010), while Agisoft Photoscan, now Agisoft Metashape was utilised in a number of studies; (Casella, 2016), (Casella, 2019), (Sanz-Ablanedo, 2018). The Metashape platform allows the creation of 3D models from photographs that can be taken from any position through fully automated image alignment and 3D model reconstruction (Agisoft, 2019).

Aerial imagery has been utilised for forestry management since the 1920's. In recent years, there has been large growth in the number of remote sensing data sources that are available to foresters, including airborne laser scanning (ALS), satellite imagery, and more recently small unmanned aerial vehicles (UAV's) or drones. As mentioned previously, the use of drone-based photogrammetry has been widely used in the field of geoscience for evaluating large scale features, such as beaches.

SfM photogrammetry was used by Dandois and Ellis (2013) in their attempt to model the bio-physical properties of forests with drone-based SfM data. Their results were not consistent at all of their study locations, but reasonable correlations between the SfM data and variables of dominant height and above-ground biomass were observed. Further work in this area was completed by Puliti et al. in 2015. Their work used drone based SfM to evaluate common biophysical features used in forest management, including dominant height, stem density and basal area. The results for these features returned root mean square errors of 3.5%, 38.6% and 15.4% respectively. These errors are similar to those from Aerial Laser Scanning inventories (Jakob Iglhaut, 2019). SfM is only capable of representing what is directly visible to the sensor, so it is expected that more accurate values for canopy height were obtained, and less accurate for the sub-canopy features of stem density and basal area.

A 2016 study by Karl Forsman (Forsman, 2016) into the use of SfM photogrammetry for determining the volume of log stockpiles in a sawmill yard determined that SfM was a viable technology for evaluating the volume of the stockpiles. The study found that the total pile volume when determined with SfM ranged between 5 and 25% of the true value, which was determined with terrestrial laser scanning. The study comprised 4 log stacks, photographed with a Sony a500, with a 20mm fixed lens – to keep the focal length constant throughout the flight. The drone used was a Tarot 810 octocopter, which is a semi-customisable 'Pro-sumer' level UAV (Tarot).

Forsman captured the imagery at three altitudes, eye-level around the stacks, at 9m looking obliquely at the stacks at 45°, and from 48m altitude, directly above the stacks. The majority of the imagery was collected from the 9m oblique position.(Forsman, 2016) The photogrammetry software used in this study was Agisoft Photoscan (Now Agisoft Metashape)

The accuracy achieved with SfM photogrammetry is largely dependent on the overlap of the images collected, as the SfM process relies on the ability to identify common points between photographs. As such, the larger the number of common points between two photos, the higher the accuracy of the output model (Jakob Iglhaut, 2019). The weather conditions on the day of survey also contribute to the quality of the finished result, an overcast day, with little to no shadowing will provide more even lighting of the subject, and provide greater accuracy (Jakob Iglhaut, 2019).

Casella et al. (2016) utilised a DJI Phantom 2 drone, and GoPro Hero 4 camera to capture imagery of a coral reef that was underwater at the time of photography. The study surveyed an area of 8,380m², with 306 photos to obtain a bathymetric digital elevation model, which was accurate to 0.016±0.45m (A. C. Elisa Casella, Daniel Harris, Sebastian Ferse, Sonia Bejarano, Valeriano, James L. Hench, Alessio Rovere, 2016).

The use of smartphones for obtaining imagery for SfM analysis was examined by Jaud et al. in 2019. A Samsung Galaxy S9, Nokia Lumia 930 and Apple iPhone8 were used to capture imagery of a cliff face. To evaluate the accuracy of the models produced from the imagery, a Terrestrial Laser Scanner survey was also conducted on the cliff face. It was found that all of the cell phones were capable of producing imagery and subsequent 3D models with mean errors of less than 5cm. The study noted that to achieve better results it would be advantageous to obtain imagery from higher elevations (M. K. Marion Jaud, Christophe Delacourt, Stephane Bertin, 2019).

The accuracy of two DJI UAVs was evaluated by Peppa et al. in 2019, the DJI Phantom 4 Pro and DJI Phantom 4 RTK drones were used to capture 337 and 575 images respectively from oblique angles, with manual flight control. The models produced from the both sets of drone imagery were found to have planimetric accuracy of 14mm and vertical accuracy of 29mm (Maria V. Peppa, 2019). The study was conducted over a reasonably large scale area, at a quarry, hence the large number of images collected.

The accuracy of a SfM survey can be increased through the use of fixed Ground Control Points (GCP). These points are fixed to the ground around the survey subject, are visible to the camera and are able to be manually identified during the alignment of the imagery. GCP's can be constructed out of any readily visible material, in the case of Forsman (2016) the GCP's were spray painted X marks on the ground, that were measured with an RTK GNSS (Real Time Kinetic Global Navigation Satellite System). The GPS location of the GCP's is required if it is intended to complete multiple surveys of the site at different points in time, to aid the matching of the surveys to each other.

The application of structure-from-motion photogrammetry to the measurement of volume of large wood accumulations was investigated by Spreitzer et al. (2020), for the purpose of modelling accumulations of large wood in fluvial systems. The research utilised scale models of large wood accumulations in varying arrangements and PIX4DMapper photogrammetry software. The conclusion was drawn that SfM photogrammetry was well suited to this application, and could be considered a valuable tool for quantifying volumes of large wood accumulations, due to savings in both cost and time when compared to conventional surveying techniques.

It was proposed by Laporte-Fauret et al. in 2019 that drone based photogrammetry would be a viable option for large scale geographic modelling of coastal dunes. Their study utilised a consumer-grade DJI Phantom Pro 4 drone, and involved the aerial survey of 4km² of coastal dunes. It was found that the vertical root mean square error of the Digital Elevation Model produced from the survey was 0.05m. The study surveyed the dunes over the 6 months of winter, and was able to detect erosion to the seaward dunes, as well as wind-driven migration of the dunes. They concluded that drone based photogrammetry was well adapted to monitoring coastal changes (Quentin Laporte-Fauret, 2019).

The Environmental Code of Practice for New Zealand Forestry (NZFOA, 2007) includes in its Operational Rules for slash management that; slash piles need to be monitored to ensure they are always stable and fully utilise the available space, and that; monitoring and maintenance programmes applicable to the nature of the earthworks and structures, and their environmental risk should be instigated. This shows that there is a drive from our legislation that a repeatable and accurate method needs to be implemented in regards to slash management, particularly in areas that have a high risk to the environment. Additionally, in terms of managing fire risk, the generally accepted rule of thumb in the New Zealand forest industry is that spontaneous combustion of piled slash is a real risk when the pile height exceeds 3m above the ground surface. An accurate and repeatable method for determining height, as well as volume of the pile would therefore be advantageous in monitoring and assessing fire risk in our forests.

The National Environmental Standard for plantation Forestry states similarly to the ECoP that "Slash from harvesting that is on the edge of landing sites must be managed to avoid the collapse of slash piles" (MPI, 2018). This, in addition to the ECoP, as stated above, provides an opportunity for the application of drone-based SfM photogrammetry in our forests, in a capacity that is suited to a non-professional operator, such as a harvest manager, or engineer.

Statement of hypothesis

This work will aim to determine whether Drone-based Structure-from-Motion photogrammetry is useful as an everyday tool in the management of forest assets. It is hypothesised that it will be possible to achieve a suitable level of accuracy within an appropriate timeframe using the available technology. This will be assessed by the preservation of the dimensions of the pile into the model, the resolution of the output DEM and the time taken to complete the SfM workflow.

Furthermore, it is likely that the technology employed in the work can be used as part of an ongoing monitoring process, which will aid foresters in complying with the regulations set out in the Environmental Code of Practice and the National Environmental Standards for Plantation Forestry by providing a record of the structure of slash piles within the forest.

Methods

Samples

Slash piles used in this study were selected based primarily on their location, with those piles on flat ground being included in the study. As the volume of each pile was measured based on a plane drawn in around the base of the pile, the amount of native soil included in the volume measurement is minimised, as the flat ground underneath the pile is captured by the plane drawn in. Additionally, for safety reasons, the piles chosen had accessibility all the way around them, as I was doing some of the field work on my own, and did not want to accept the risk of walking over slash, or being exposed on steep slopes.

Piles were surveyed in two forests, the Tuhaitara Coastal Park (Te Kohaka o Tuhaitara Trust, 2020) and in the publically accessible part of the Hanmer Forest. Google earth imagery of the study sites is made available in Appendix 2. Potential piles were identified with Google Earth and then visited to determine their suitability for the study. Due to the flat terrain of the forests, harvests were ground-based, with residues in the cutover windrowed.

Sample Description

The piles used ranged in volume from 20 to 170m^3. Piles of this size were used in this study to allow comparison to the results obtained by Long in 2014, where the Geometric Method was evaluated against LiDAR measurement of pile volume. The validity of the results obtained in this study will be evaluated against those in Long's study, which are expected to provide more accurate volumes than will be achieved in this study. One of the piles used in the study is not piled forestry slash, but is a mechanically piled pile of sand, which was included due to its similar size to the slash piles, and its proximity to the Tuhaitara Coastal Park carpark.

The slash piles used in this study are generally representative of piles generated by ground based harvest operations. Located generally on the edge of the skid site, and shaped into a distinct pile by a machine with a clearly identifiable edge between the pile and ground. The piles used were not representative of cable extraction systems, or ground-based extraction on hill sites, where the slash pile is located on the edge of the landing, spilling down the hill to a bench cut below the landing. However, provided the measurements of the pile are preserved during the structure-from-motion process, the resulting model will be usable for determining volume of the pile, irrespective of its location. The difference will be in the process for identifying the ground surface beneath the pile for determination of the pile volume.

Measurement

To determine the viability of drone based structure from motion for slash pile volume measurement, the primary measurement collected will be that of volume, obtained through two methods – the volume derived from the SfM model, and a volume derived through the Geometric Method, Hardy

(1996). In using the Geometric Method, length, width and height measurements are taken in the field, to allow a check of the validity of the model; these measurements were checked in the model and compared to the physical measurements taken in the field. The assumption made here is that if the length, width and height of the actual pile are preserved in the SfM model, then the volume of the real pile will also be preserved.

The volume of the pile itself was measured using the measurement function in Agisoft Metashape, which allows the calculation of volume above a reference surface that you manually draw around the pile. There is variability introduced in this step, as without a shapefile of the true edge of the pile, the reference surface will be different each time it is drawn. To manage the impact of this, three volumes were determined for each model, and an average taken for use in the project.

The volume measurement is computed automatically in Agisoft Metashape once a polygon has been closed around the feature you want the volume of. As the volume is being calculated based on a DEM, the software knows the elevation of, and area of each pixel and with the known elevation of the polygon surface drawn in is capable of computing the volume between the polygon surface and the DEM surface. This volume computation feature is common across Structure-from-Motion software packages, including Virtual Surveyor ("Virtual Surveyor," 2019) and Pix4DCloud (PIX4D, 2020).

The volumes computed in this work are computed only as bulk volumes, and volumes, when mentioned in this report, unless otherwise stated refer to the bulk volume of the pile, which includes air voids. To determine a volume of woody biomass within the pile, packing ratios (m^3/m^3) can be applied to the bulk volume determined. Work by Hardy (1996) presented typical packing ratios for machine piles as ranging from 0.1 to 0.25, Clinton S. Wright (2010) found packing ratios for hand packed piles varied from 0.05 for shrubbery to 0.19 for conifers.

The quality of the model is assessed with the resolution of the Digital Elevation Model generated from the SfM process. The resolution of a DEM is given by Agisoft Metashape in terms of cm/pixel, which denotes the size of each pixel in the DEM, as being square, with edges of so many centimetres. A lower value of cm/pixel indicates a higher resolution DEM. This was used as an evaluation measure by Idrees and Abulrahman (2020) during their evaluation of UAV-based DEM generation for volume calculations.

The final measure used in this study is that of the processing time required by Agisoft Metashape to go from the set of input, un-aligned images through to a DEM of the pile. This measure has been included after notes from industry on the amount of time required for the generation of the models, and whether the gain in accuracy of the volume measurement is worth the increase in time required to arrive at the volume of the pile. This time will not include delays in processing due to the person running the analysis, as that depends on whether or not the person is sitting in front of the computer and setting off each processing step as soon as it is ready.

The procedure for collecting field data was consistent across all sites. The best geometric approximation of the shape of the pile for the Geometric Method was decided from visual inspection, and targets were placed at each end of the length and width measurements required for the Geometric Method. The height of the pile was estimated visually as the height between the average ground surface, and the average height of the pile. The targets used were circular, with two black quarters, on opposite sides of the circle, painted with black spray paint on 3mm MDF boards 600mm square, as in Figure 5, below. Agisoft Metashape is capable of identifying specific Coded Targets, which are printed with a certain set of shapes. The targets used in this work are Non-Coded Targets, as it was not necessary for the software to identify the targets (Agisoft, 2019).

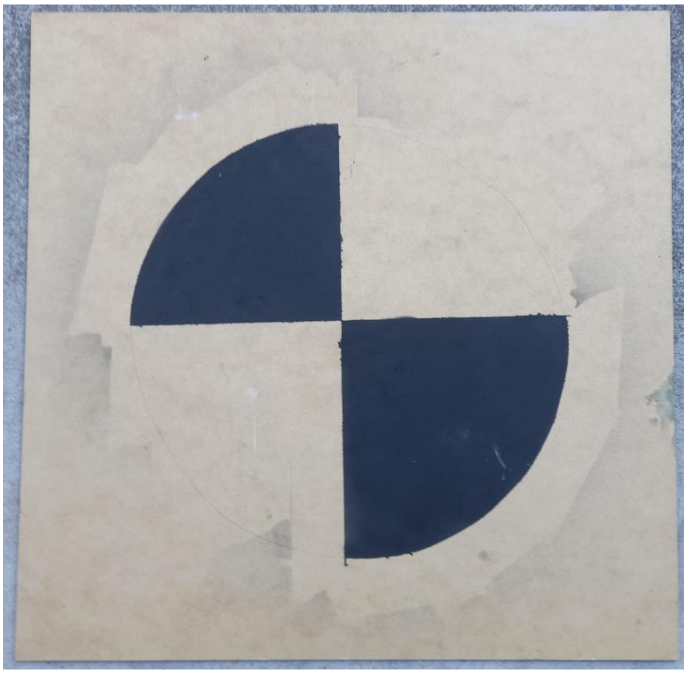

Figure 5 - Target used to mark the end of each length/width dimension

Photos of the pile were then captured with a DJI Mavic Pro unmanned aerial vehicle, flying first around the pile, taking photos at an oblique perspective at an elevation of 5-7m, depending on the size of the pile, and then at an elevation of 20m flying directly over the pile (Figure 6). Photos were taken on average every one metre around the pile, and every 5 meters when flying over the pile. Care was taken to ensure the targets placed on the ground were visible in the photos, and not out of the frame.

The drone was piloted by hand for all sites, it is more intuitive for people less experienced with drone based photogrammetry to fly and collect the data manually, as opposed to using software which controls the flight and collects the imagery for you. The likely application of this process is with forest managers on the ground, so it was decided that the best way to conduct this study was using the most basic of procedures, therefore if in practice, the procedures were improved on, the results would be of equal or better quality to those obtained in this work.

Field work was scheduled so as to make the most of fine days, with minimal cloud cover. This was decided on for two reasons, firstly, it would ensure consistency in the quality of the data collected between all sites, and it provided adequate lighting of the piles across all sites. It can be advantageous to complete photogrammetric surveys when conditions are overcast, as the cloud diffuses the light and minimises the extent of shadows around the pile (Jakob Iglhaut, 2019). It was decided to photograph during sunny conditions as the amount of light filtering provided by cloud cover would vary between days more than the sunlight would. To minimise the difference in lighting between the sunny and dark sides of the pile, the exposure of the camera was adjusted to maintain definition of pile features, and consistency of imagery.

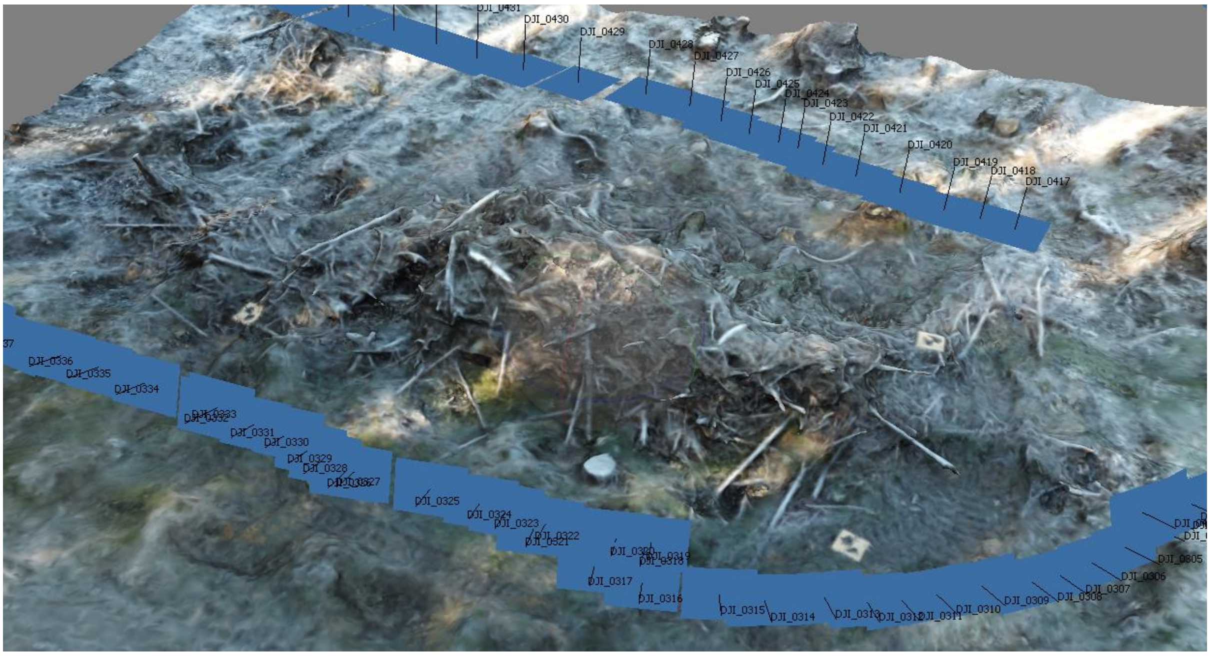

Figure 6 - Orientation of imagery used in this study, targets are visible at corners of the pile

Images taken by the drone were transferred into a separate file for each location photographed, and a field sheet for each site was filled out (an example of which is available in the Appendix). The imagery for each site was loaded into Agisoft Metashape on a School of Forestry computer, where it was taken through the structure from motion process, following guidance from the School of Earth and Environment (2019). This guidance uses the generic settings, as they are presented in the Agisoft Metashape workflow, beginning with image alignment, which was completed with 'Medium' accuracy which down-scales the input imagery, and limits of 40,000 and 4,000 on Key Points and Tie Points respectively, which sets an upper limit on the number of match points between images.

To achieve the varied number of images, three models were created of each individual pile in the study. One model would be constructed using all images collected, one would use half of the images collected, and the final used one quarter of the imagery collected. The imagery was selected during the image loading phase in Agisoft Metashape, for the model using half of the images, every second image was selected for import, for the model using a quarter of the imagery, every fourth image was selected.

Having aligned the imagery, a low resolution model of the slash pile is created with the points that were identified during the alignment process. Using the points from the alignment, a 'Dense Cloud' is constructed, with default settings for both Quality and Depth Filtering. This step consumes the most processing time of all the steps. The resulting 'Dense Cloud' looks like the model presented above in Figure 6.

Using the Dense Cloud, a Digital Elevation Model is constructed; this was done with all default settings as presented by Agisoft Metashape. The imagery collected by the UAV is geo-referenced with the GPS coordinates of the drone when it took the picture; this allows the DEM to be located in

3D space. To allow this, the projection for each DEM was set to the geographic NZGD2000 projection for all models. DEM creation is the fastest of all the steps in Agisoft Metashape, not taking more than thirty seconds to finish.

After generation of the DEM, it is possible to measure the volume of the pile. This was completed with the volume measurement capability in Agisoft Metashape. The pile was outlined with the Draw Polygon tool, using a best-guess estimate of the edge of the pile. The volume is determined once the polygon is closed around the pile, and presented as one of three components; Volume Above, Volume Below and Total Volume. Volume Above includes all volume above the level of the polygon, volume below is the volume beneath the polygon, in areas such as hollows or ruts, and Total Volume is the sum of volume above and below. For the purposes of this research, Volume Above is recorded, as this will most closely match the actual volume of the pile. The features described above can be seen in Figure 7, below.

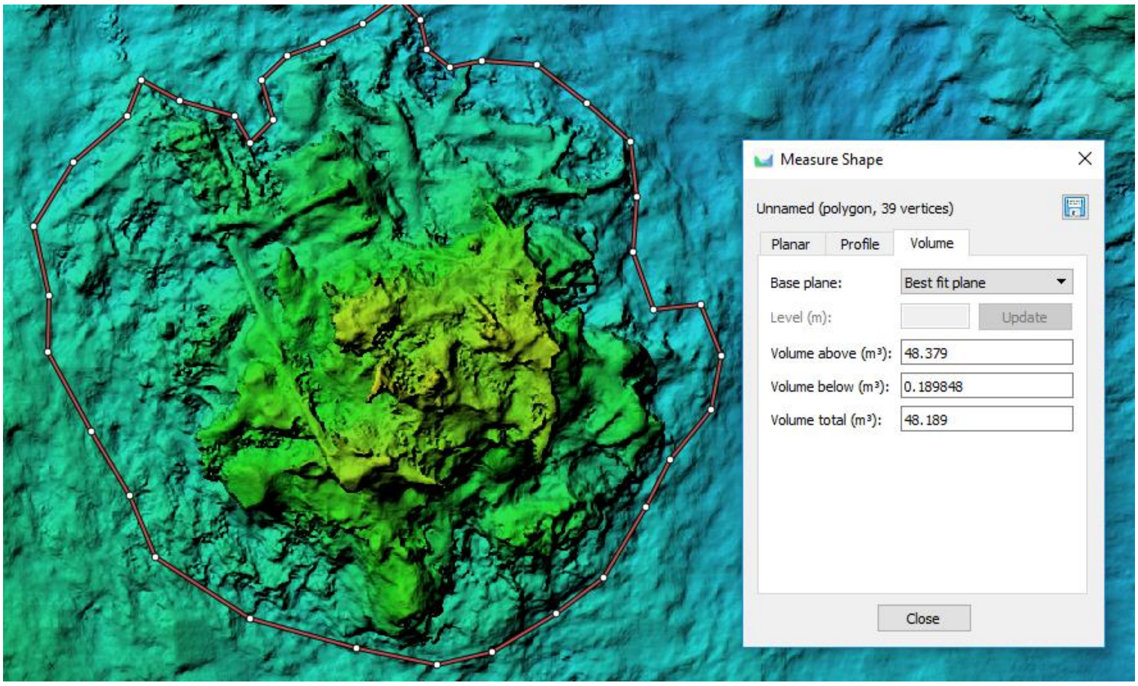

Figure 7 - Volume measurement in Agisoft Metashape. The polygon outlining the pile is shown in red, and the volume measurements in the pop-up window at right. 'Volume Above' is taken as the volume of the pile.

As the polygon was drawn in manually around each slash pile, there is potential for variability. To minimise this, the volume was computed three times for each model, with the polygon being re-drawn each time. The final 'SfM Volume' as reported in results was taken as the average of the three volumes.

The measurements taken of the pile for the Geometric Method were taken between targets which could be positively identified in Agisoft Metashape so that the preservation of dimensions, from real life, into the model could be checked. To measure these dimensions in the model, the Measure tool in Metashape was used. When zoomed in close to each target it was possible to click in the centre to both start and end each measurement. A similar methodology was employed by Verma and Bourke in their 2019 study using high resolution DEMs for investigation of rock breakdown, albeit on a smaller scale, that of centimeters as opposed to meters as used in this study. The volume derived through the Geometric Method was computed using the appropriate equation from Table 1, below, for the shape selected for the approximation of the pile.

Table 1 - Volume equations for use with the Geometric Method (Clinton S. Wright, 2010) adapted from Hardy (1996)

Geometric shape	Volume formula
Half-sphere	$V = (\pi \times h \times w^2)/6$
Paraboloid	$V = (\pi \times h \times w^2)/8$
Half-cylinder	$V = (\pi \times w \times l \times h)/4$
Half-frustum of cone	$V = \{\pi \times l[h_1^2 + h_2^2 + (h_1 \times h_2)]\}/6$ or $V = \{\pi \times l[w_1^2 + w_2^2 + (w_1 \times w_2)]\}/24$
Half-frustum of cone with rounded ends	$V = \pi\{l[w_1^2 + w_2^2 + (w_1 \times w_2)] + w_1^3 + w_2^3\}/24$
Half-ellipsoid	$V = (\pi \times w \times l \times h)/6$
Irregular solid	$V = [(l_1 + l_2)(w_1 + w_2)(h_1 + h_2)]/8$

The time taken to process each model was retrieved from the Agisoft Metashape Processing Report, one of which was generated for each model. The processing time was taken to be the sum of the time taken for Image Matching, Image Alignment and Depth Map and Dense Cloud Processing. As these were the steps carried out during the SfM process. The time taken to construct the DEM was not included as it was always less than 30 seconds, and times were recorded to the nearest minute. All models were generated by the same computer, from the same file directories to eliminate the effect of different processing ability and file transfer rates.

The reliability of the field measurements done in this study is taken as being high, the measurements are relatively simple, and were executed in a repeatable manner. The only issues noted in regards to the collection of the physical measurements of length, width and height are those of collecting length and width measurements are right angles to each other, and the variability in estimation of the average height of the pile. If length and width measurements are not at right angles to each other, the accuracy of the Geometric Method is decreased, checking the preservation of dimensions in the SfM model is not affected. Locating the length and width measurements at right angles is due largely to 'operator error' and is exacerbated in situations where there is a large amount of undergrowth around the pile, obscuring vision when deciding on measurement location, as was exemplified at the Woodend Beach site, shown below in Figure 8.

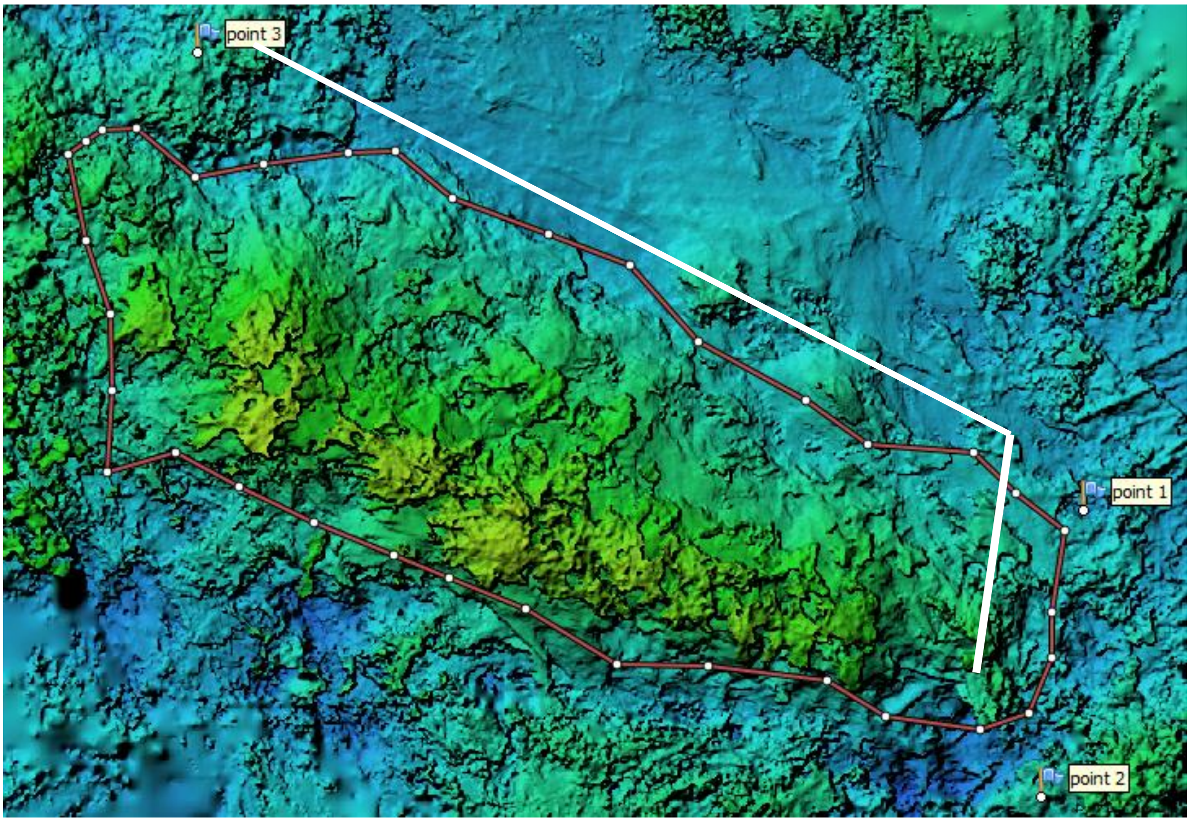

Figure 8 - Length and width measurements not collected at right angles to each other (Pile outlined in red)

The reliability of the volumes derived from the structure from motion process was assessed by comparing the volumes to those calculated by the Geometric Method. While the Geometric Method was expected to give volumes that were not accurate, they are a reasonable estimate of the actual volume of the pile, which generally overestimate the volume. Hence the volumes obtained through the SfM process were expected to be generally slightly lower than the volume derived through the Geometric Method.

To further evaluate the reliability and validity of the volume measurements, the results will be compared to work done by Justin Long in 2014 where the Geometric Method was compared to LiDAR measurement of the same piles. To enable this piles used in this study are of similar size to those used by Long. It was expected that the results obtained in this study should generally follow the results from Long, albeit showing more variability, due to my relative inexperience in applying the Geometric Method.

The length and width measurements on the SfM model are taken to be accurate, in terms of measuring from a point to a point. As the targets were readily visible on the Dense Point Cloud model, it was trivial to start and end each measurement in the centre of the corresponding targets. To evaluate whether the measurements are accurate in terms of what they represent in real life, the measurements were checked against the physical measurements taken between the same markers.

The height measurements of the piles were significantly less accurate than the length and width measurements, as the height was determined through visual inspection of the pile to determine an average height, then measuring that height as well as possible in the field. When measuring the height in the models, it was a matter of subtracting the elevation of the ground surface next to the pile from the average level of the top of the pile, using the measure tool on the Dense Point Cloud.

Design and Procedures

The number of piles used in this study was chosen so as to match the work by Long in 2014. Long's study consisted of 28 piles, with volume determined both by the Geometric Method, and with LiDAR. To achieve a similar number of models in this work, 9 piles were surveyed, and three models created of each pile to result in 27 models each with a unique volume that was determined through the SfM process. To assess the accuracy of the volume measurement, the difference between the SfM volume, and the volume determined by the Geometric Method will be compared to the difference in volume between LiDAR and the Geometric Method, as presented by Long.

The two differences will be assessed with a t-test to determine if there is a statistically significant difference in the volume differences. If the t-test returns a result indicating that there is no statistical difference between the two datasets (Differences between LiDAR and Geometric and SfM and Geometric) it will indicate that the SfM method will produce volumes similar to those produced by LiDAR. If there is a statistical difference, it will indicate that either the SfM volumes are different to those obtained through LiDAR, or there was inaccuracy introduced during the application of the Geometric Method. If the dimensions of the pile are preserved, but there is a statistical difference between the volume differences, it will indicate that there was an issue in the application of the Geometric Method, and if the dimensions are not preserved, it will indicate the model was not reproduced accurately, and the SfM volume was not accurate.

The internal validity of this study is preserved primarily through rigorously following a procedure determined at the start of the project, and then refined during the creation of the first model. The method was followed, as presented above, for all piles modelled during this work. It is expected that through this any variability potentially introduced between sites by following different methods will be eliminated. There is opportunity for variability to be introduced during measurement, particularly the measurement of volume, this was minimised through repetition of the volume measurement.

The selection of images for the creation of the three models of each pile was done by using all images for one model, then selecting every second image for the second model, and then for the third model selecting every fourth image, starting with the first image. This methodology was decided upon as all imagery was collected sequentially when flying around the pile, while taking more images than required to build the model. By skipping images, and selecting only every second or fourth, it simulates taking the imagery at longer intervals, or at greater spacing, while only conducting one flight. The possibility of randomly selecting the required number of images was considered, but was discarded as it had the potential to miss areas of imagery which would not happen during a manually controlled flight, where imagery is taken on a regular basis.

It should be noted that this point in the method was changed from what was stated in the Work Plan, as the method presented there for selecting the number of images for each model was too complex for what it needed to be, and introduced a problem in the selection of images. It would have given a number of images to use, but the selection of that number of images would have been difficult due to the issues mentioned above around random selection, as imagery is collected sequentially, not randomly.

To allow the different models to be compared to each other, particularly in the evaluation of the resolution of the DEM, the number of images used in the creation of the model per square area of the model was calculated. Square area was taken to be the measured length, multiplied by the measured width taken for the Geometric Method, essentially the area marked out with the targets around the pile.

To compare the volumes obtained in this work to those obtained by Long in 2014, a t-test assuming unequal variances was applied to the differences between SfM Volume and Geometric Volume obtained in this work, and the difference between LiDAR and the Geometric Method obtained from Long's work. The key value returned by this test was the Two Tail P Value, which, if less than 0.05 would indicate a statistically significant difference in the means of the two datasets, and vice versa if greater than 0.05.

The processing time required for the development of a model is determined by the number of images used in generating the model. To evaluate the effect of this in this study, the processing time was plotted against the number of images used in each model, and the resulting data series fitted with an appropriate trend line in Excel. To evaluate how well the trend line models the actual data, the R-squared value was included. A value of R-squared that approaches 1 indicates that the trend line accurately represents the change in the dependent variable bought about by the independent variable in question. In this case by converting the R-squared value to a percentage, by multiplying by 100, a measure of how much of the variance in processing time is accountable to the variance in the number of images used.

To determine how well the actual dimensions of the pile are represented in the SfM model, a concordance correlation between the measurements taken in real life and on the model was completed, using Lin's Concordance Correlation Coefficient (NCSS, 2020). The concordance correlation was completed in Excel one measurement at a time with results over 0.95 indicating that the measurements taken In the SfM model are in agreement with those taken in the field, taken in this case to be the 'Gold Standard'. This measure is applicable to small sample sizes, such as the size of the sample in this work (n=27).

Results

Piles Surveyed

This work, as mentioned in previous sections, involved the photogrammetric survey of nine piles of forestry slash, and the subsequent image processing with Structure-from-Motion software to create point cloud models of the piles. The nine piles were located across two publically accessible forests in the Canterbury region, in Hanmer Springs and coastal North Canterbury. Table 2 below sets out the basic dimensions of the piles, along with the geometric solid used to approximate their shape in the Geometric Method. It should be noted that in this instance, while effort was made to vary the size and orientation of the piles, the majority all conformed to the same shape, that of a half ellipsoid. Other notable features in Table 2 are HAN01, which was comprised of stumps and root balls, rather than slash in the form of branches. PEG01_V2 was a repeat of PEG01; that was surveyed under different conditions on a different day, and PEG03, which was a pile of sand, as opposed to a pile of slash, however as this project is only concerned with the bulk volume of the pile; this was considered a reasonable addition, especially as it allowed the evaluation of the impact of water next to a pile, which could reasonably occur on a landing – in this case the water did not affect the construction of the model.

Table 2 - Data captured in the field for all study sites

Pile ID	Shape Approximation	Length (m)	Width (m)	Height (m)	Notes
HAN01	Round Paraboloid	7.5	6.5	3	Mostly stumps
HAN02	Half Ellipsoid	15	6	2.5	
HAN03	Half Ellipsoid	9	6.9	4	
HAN04	Half Ellipsoid	8.9	3.7	1.5	
PEG01	Half Ellipsoid	45.2	7.7	1	
PEG01_V2	Half Ellipsoid	45.2	7.7	1	Repeat of PEG01
PEG02	Half Ellipsoid	23	6.2	1.2	
PEG03	Half Ellipsoid	21.5	7	1.8	Sand pile
WOOD01	Half Ellipsoid	24.3	7	2.5	

SfM Models Created

Of the 27 SfM models created (Three of each pile) two were not able to match and align a large enough number of input images so as to successfully create the model, and one model, generated using 37 images (1/4 of total number of images captured), generated in such a way that it was not possible to measure the volume. All of the remaining 24 models generated properly, and all measurements were able to be collected from the models. Some models, when created with one quarter of the input images on three occasions returned an error message alerting that some images had not aligned, this was only one, two or three images in each case. These images were removed, and the alignment process was run again, with the images aligning properly on the re-run. These images were typically of the very edge or the corner of a pile, and tended to include more background than they did pile, so it was not unexpected that they failed to align.

From an initial visual inspection of the models created, it was noted that the piles were generally reproduced with a good level of quality; many of the intricate features of the piles were captured, as evidenced in Figure 9 below, showing the DEM for pile HAN03. Attention should be drawn to the centre of Figure 9, where the end of a protruding branch can be clearly seen, and immediately above that, areas of red, which represent bits of foliage on the end of the branch that was sticking out of the pile.

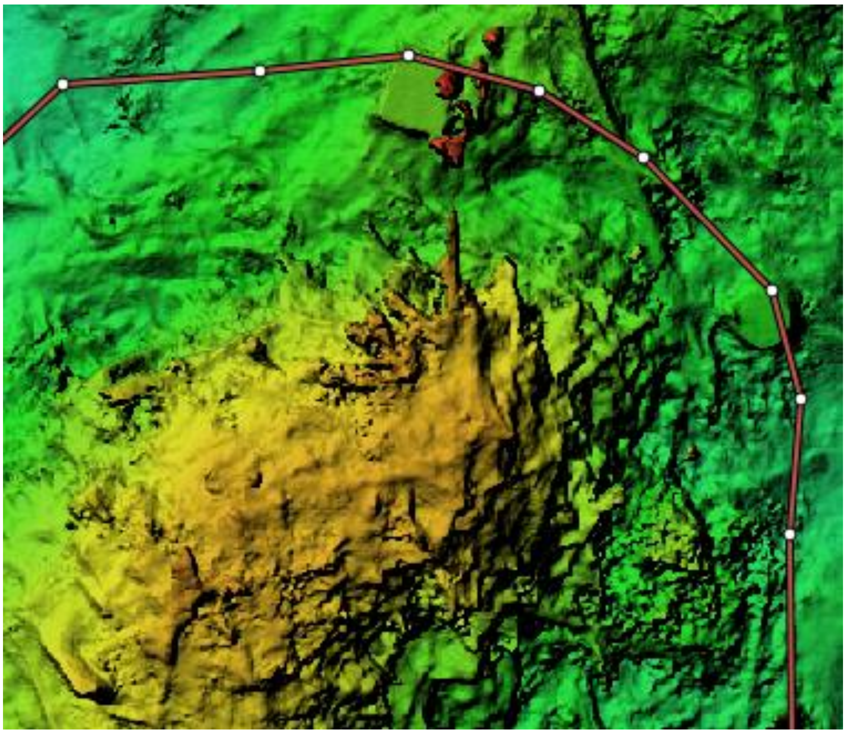

Figure 9 - DEM of pile HAN03. Protruding branch can be seen in centre of image

The potential for high quality reproduction of slash piles as point clouds is exemplified by the PEG01 pile, shown in Figure 10, below. The pile itself is reproduced very well, in terms of both resolution and colour correctness, allowing inspection of the make-up of the pile. Due to the method of photography, collecting oblique imagery of the pile, the area surrounding the pile loses definition quickly and reproduction of features is not as crisp, nor as accurate as features on the pile. At the ends of the pile, where it merges into the surrounding scrub, it is possible to positively identify the extents of the pile in the SfM model, where it is inaccessible in the real world. This provides scope for exact measurement of the pile, both for length and volume, in areas where it is not possible to do so in real life, due to the inaccessibility of the end(s) of a pile.

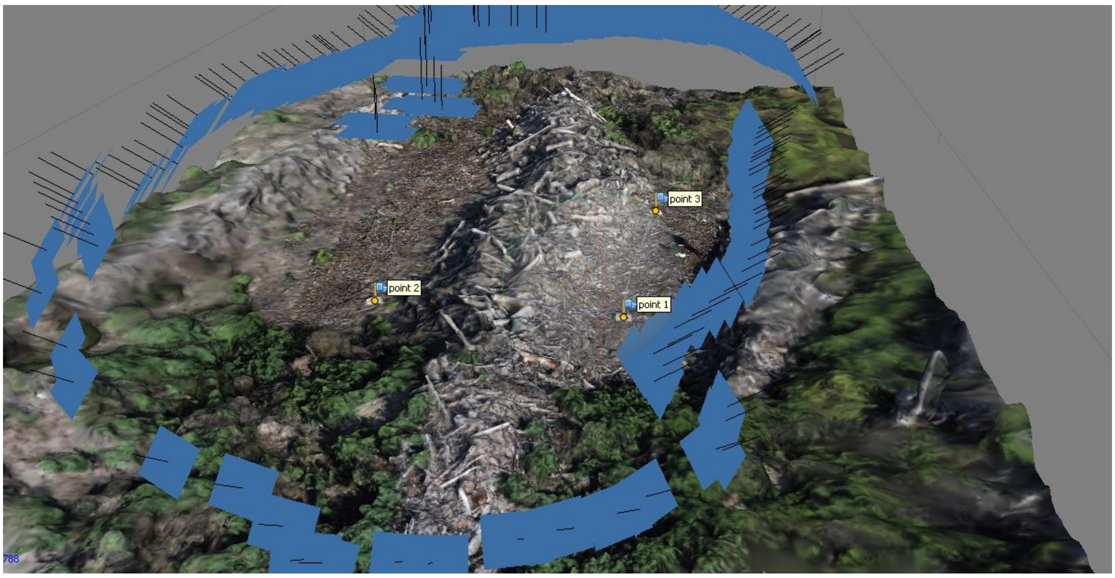

Figure 10 - Dense Point cloud of PEG01 pile, showing image capture locations

Dimension Preservation

The preservation of the dimensions of the slash piles from the real world, into the SfM model was checked by comparing the measurements of length, width and height from the actual pile, to the same measurements in the model. It was noted that the length and width measurements were preserved particularly well in all cases, while the height measurements showed greater variability. This variability however is more likely attributable to the difficulty in estimating the average height of a pile in the field, than it is to an inaccurate reproduction of height in the SfM model. The dimensions recorded are displayed in Table 3, below.

Table 3 - Pile measurements recorded for all piles surveyed

	Actual Dimensions (m)			Model Dimensions (m)		
Pile ID	**L**	**W**	**H**	**L**	**W**	**H**
HAN01	7.5	6.5	3	7.5	6.6	2.5
HAN02	15	6	2.5	15.0	5.9	1.9
HAN03	9	6.9	4	9.1	6.9	3.1
HAN04	8.9	3.7	1.5	9.1	3.7	1.1
PEG01	12.3	9.5	1.7	12.2	10.1	1.0
PEG01_V2	15.6	4.5	1.7	15.5	4.3	1.4
PEG02	23	6.2	1.2	22.9	6.1	1.4
PEG03	21.5	7	1.8	21.5	7.2	1.3
WOOD01	24.3	7	2.5	23.9	7.1	2.2

To quantify how well the dimensions were preserved between real life and the SfM models, a concordance correlation was completed, using Lin's Concordance Correlation Coefficient in Excel. This was completed for each measurement (length, width and height) separately, using measurements from all models.

The length measurements showed high levels of correlation between real and SfM model measurements, returning a correlation coefficient of 0.9997, indicating very strong, positive correlation. This is visible in Figure 11 below, where all measurements fall either on, or very close to the 1 to 1 line indicating a perfect correlation. From this, it can be seen that the length measurement of all piles is especially well preserved in the construction of the SfM models of slash piles, using this methodology.

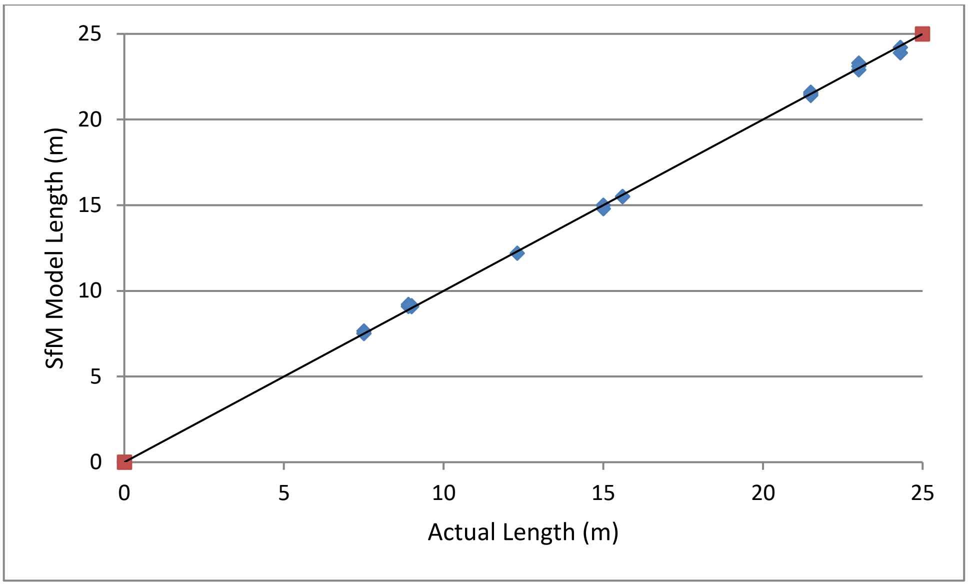

Figure 11 - Concordance correlation for pile length

As with the length, the width measurement also exhibited a high level of correlation, returning a correlation coefficient of 0.9953, which, although less than the length measurement achieved, still indicates a very strong positive correlation. This is backed up by Figure 12 below, which shows almost all measurements falling on the 1 to 1 line of perfect correlation. The outlier observed at around 10m is due to experimental error caused by taking a measurement across the top of a windrowed slash pile on my own, it was kept in the results as it was determined to not be so significant as to have a large impact on the results.

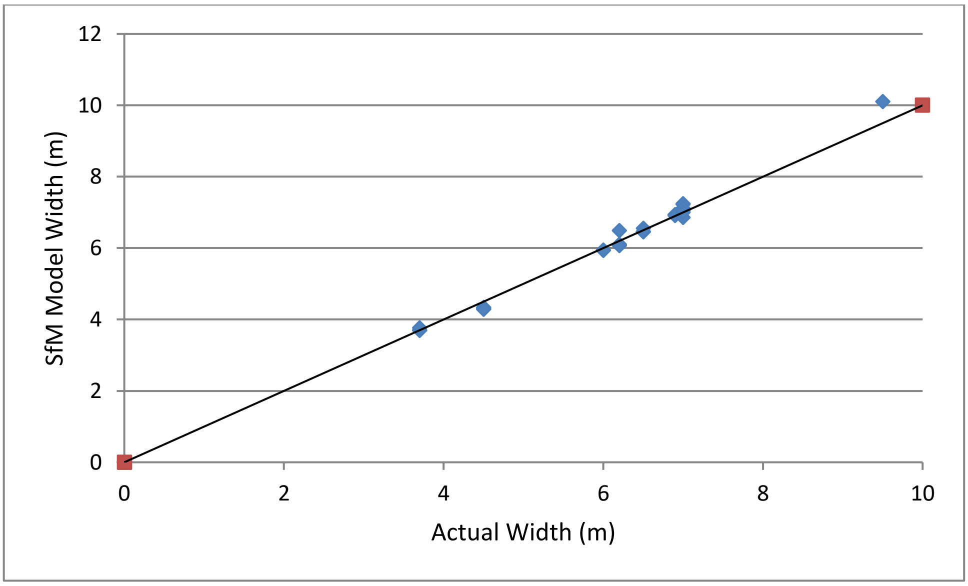

Figure 12 - Concordance correlation for pile width

The preservation of the height measurement between real life and the SfM model was not as complete as it was for the length and width measurements. This is evidenced by the correlation coefficient for height, which was found to be 0.9420. While this value is less than the values observed for length and width, it still indicates a reasonable positive correlation, as can be seen in Figure 13 below. The variation between the real life and SfM model heights is likely attributable to the difficulty encountered in correctly estimating the actual height of the slash piles in the field. As can be seen below, the height measured typically overestimated the height of the pile from 0.5 to 1m which is almost entirely attributable to operator error. Further inaccuracy was introduced in the determination of an average pile height to estimate, when measuring height from the DEM it was possible to reasonably accurately decide on an average height of the pile, which was not always possible in the field.

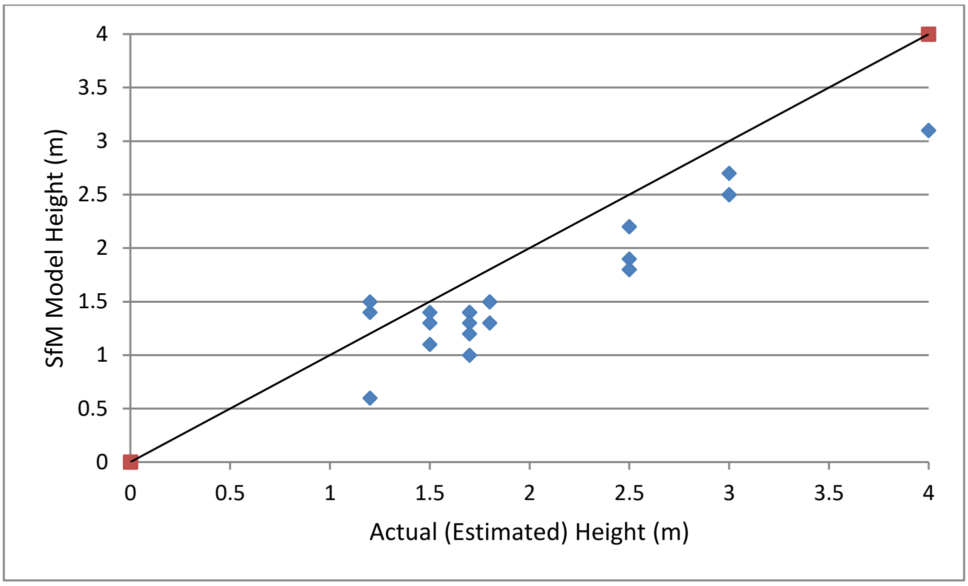

Figure 13 - Concordance correlation for pile height

Volume Measurements

The volumes obtained during the course of this work have been obtained through either Hardy's Geometric Method or through volume measurement on a SfM derived DEM. The Geometric Method is generally not considered an accurate measure of pile volume, due to its approximation of the pile as a geometric solid. In this work the Geometric Method was used both as a basis volume measurement, to allow comparison, as while it is not accurate, it provides a not unreasonable estimate of volume , and as a method of 'common sense' checking the volume derived from the DEM.

Previous work by Long in 2014 compared the Geometric Method to LiDAR derived volume measurement, and it is to these results that the work done here is compared. The figure below displays both Long's results, and those obtained in this work. The graph also includes black lines indicating ±15% volume from the 1 to 1 line in the middle of the graph. This ±15% threshold was proposed by members of industry as what would constitute a reasonable level of accuracy for volume measurements – i.e. being within 15% of the true value.

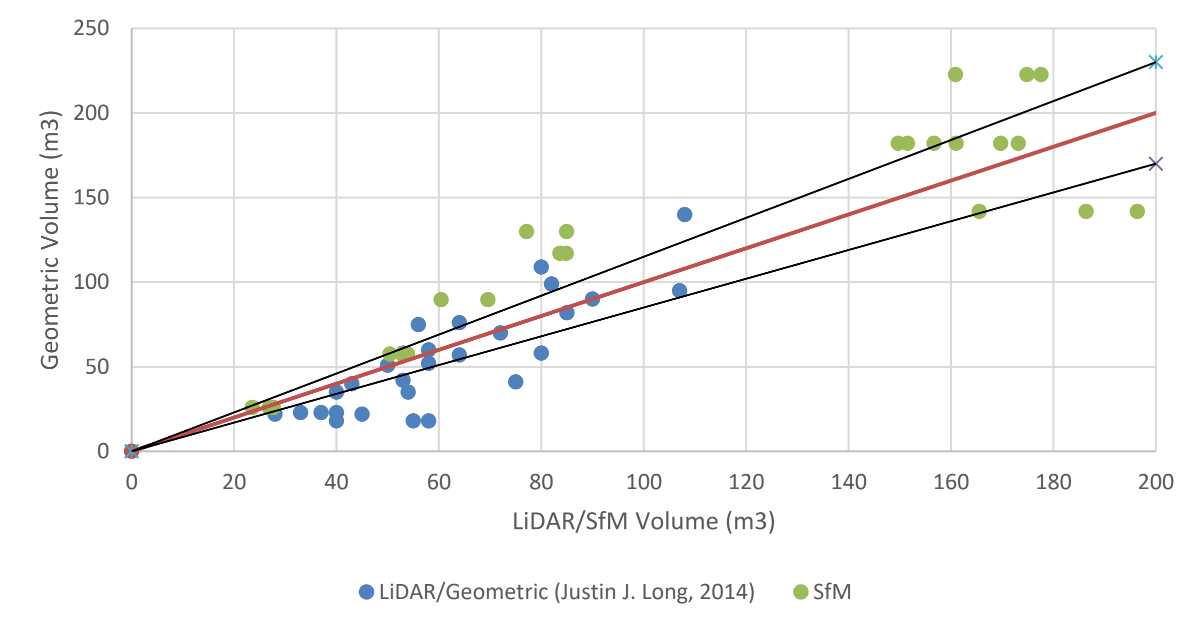

Figure 14 - Pile volumes as determined by SfM (Green) and LiDAR (Blue) against the volume computed with the Geometric Method

A paired t-test, assuming unequal variances was conducted on the differences between LiDAR and Geometric (Long, 2014) and SfM and Geometric to determine whether there was any similarity in the differences observed between the methods. This returned a P value of 0.02859, which given it was less than the 0.05 alpha value; indicates that there was a statistically significant difference between the means of the difference between measurements in the two studies. This value however is not significantly less than 0.05, indicating that while there is a statistically significant difference, the difference is not so large that the data, when viewed visually, are not majorly different from each other.

As the dimensions of the piles were preserved particularly well in the generation of the models, this would suggest that the application of the Geometric Method is the likely cause for the difference observed in the means of the differences. This is reasonable to assume due to the difficulty observed in estimating the height of the piles for the application of the Geometric Method. All piles were approximated with shapes which require a height measurement for the Geometric Method, this will have inflated the volume of the piles, which can be seen in Figure 14 above, with a significant number of the green dots appearing above the 1 to 1 line indicating overestimation of volume from the Geometric Method, assuming the SfM volume was accurate. This was the case in 20 of 27 models, of which 24 volumes were measureable, resulting in 83% of Geometric Method volumes overestimating the true volume.

From a visual inspection of the graph in Figure 14 above it can be seen that largely, the results obtained in this work are similar to those obtained by Justin Long at low volumes, particularly when the effect of overestimating pile height is taken into account. At these small volumes (20 to 100m^3), assuming that the Geometric Method will have similar levels of error in both Long's work and in my own, then the SfM derived volumes are reasonably similar to the volumes obtained by LiDAR in Long's work. At large volumes, it is expected that the Geometric Method will produce inaccurate volumes that would tend to overestimate the volume of the pile, and that has been the case here, with three of the four large piles falling above the 1 to 1 line. Based on the measurement preservation, as discussed earlier, there is no reason to suspect that the increase in pile volume would lead to a decrease in the accuracy of the volume measurement. However, to fully check the validity of SfM derived volumes, it would be necessary to complete a professional survey of the pile or fly LiDAR over it.

Resolution of DEMs

For a measure of the quality of each model, the resolution of the Digital Elevation Model that was created from the Dense Point Cloud was recorded, and used as this measure. To enable an objective view of the impact of the number of images used, the rebased number of images per square metre was used to evaluate the changes in resolution between models without influence from the size of the pile. The resulting chart is shown below in Figure 15.

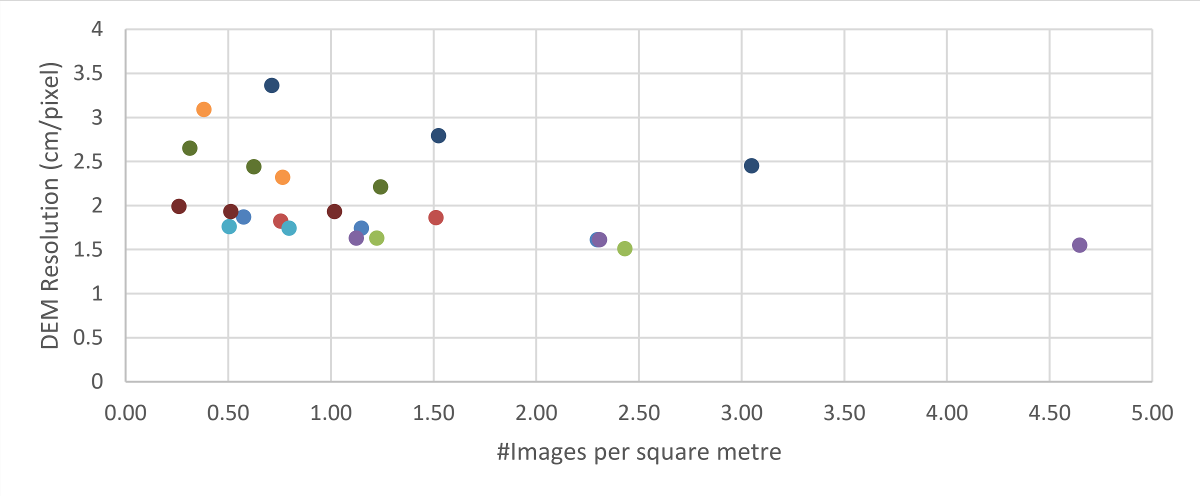

Figure 15 - Output DEM resolution for all models as a function of the number of images per square metre of pile (Same colour dots indicate different models of the same pile generated with a different number of images)

It can be seen that a high resolution has been achieved across all piles, with the coarsest resolution of 3.36cm/pixel. Generally, the more images captured per square metre, the higher the resolution will be, up to what appears to be a maximum resolution of 1.5cm/pixel, which was not exceeded by any model. The variation between models here can be attributed to the variation in the number of input images used, which in turn will affect the number of tie points the SfM software is capable of identifying, from which the Dense Cloud and then the DEM are constructed, resulting in varying DEM resolution. The asymptote observed is potentially due to the resolution of the sensor used for collection of imagery, in this case an 11MP camera mounted on the drone. This will limit the amount of information gathered at the start of the process, which will flow on to the subsequent stages of the process. Further work in this area could evaluate the impact of sensor resolution on DEM resolution.

Processing Time

Processing time was included as a dependent variable in this study due to comments from industry around the time required for the generation of the point clouds and digital elevation models created during the process just to arrive at a volume. To this end, the total processing time required by Agisoft Metashape for each model was recorded, and is presented in Figure 16, against the number of images used in each model. The total processing time, as it is presented here, is taken as the total time taken to Match and Align the imagery and to generate the Depth Map and Dense Cloud. The time taken to generate the DEM was omitted, as it was less than thirty seconds in all cases.

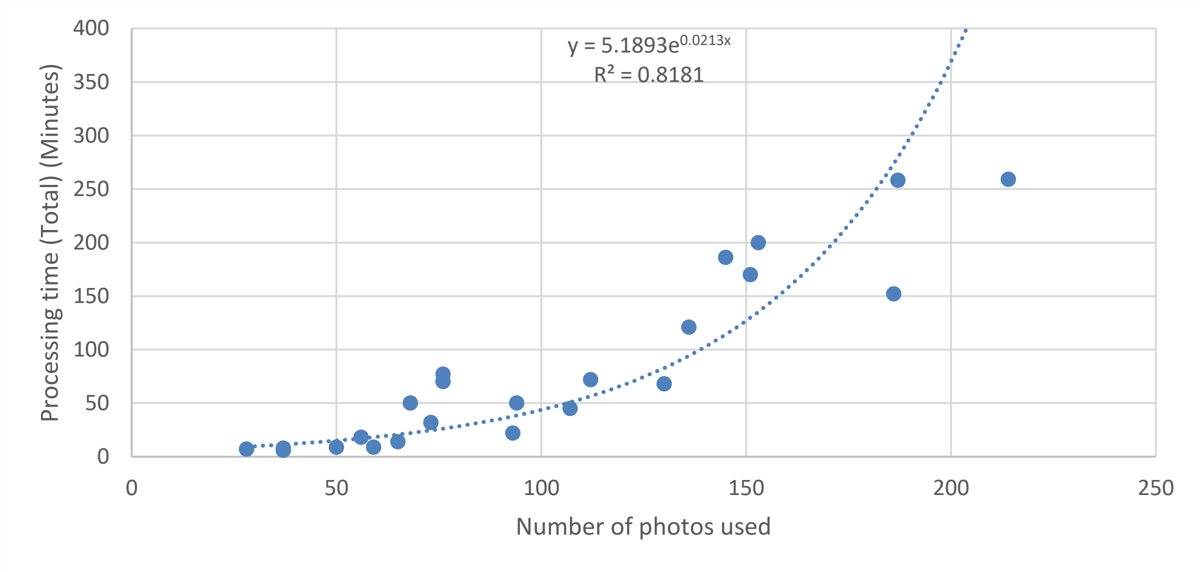

Figure 16 - Effect of number of images used on the processing time required

It can be seen that the processing time is highly dependent on the number of images used in the creation of the dense point cloud. This is to be expected, as more images used will result in a larger number of tie points, which in turn will create a dense point cloud of higher resolution than if fewer images were used. What can also be identified from this is that the processing time will increase exponentially with a linearly increasing number of input images, and this increase can be modelled to an extent by the equation;

$$Processing\ Time = 5.1893e^{0.0213(\#Images\ Used)}$$

This equation provides a reasonable fit, with an R^2 value of 0.8181, which indicates a reasonable, if not perfect fit. Combining this with the results obtained in regards to the resolution of the DEM, it is apparent that a large number of images are not required to obtain a model of reasonable definition, and the preservation of measurements; as seen previously; does not appear to change significantly with a change in the number of images used. This indicates that models of suitable quality can be produced with less than two images per square metre of pile, and a total processing time of less than 60 minutes.

Issues Encountered

Model Generation Issues

During the alignment of images in two of the models, Agisoft Metashape was unable to complete an alignment, due to an insufficient number of Tie Points. This was due to not enough images being included in the model generation, the models for which it failed were constructed with 34, and 37 images respectively. These models also had among the lowest number of images per square metre, of 0.38 and 0.60, respectively. It is a useful feature of Agisoft Metashape that it will notify the operator reasonably quickly (Within 5 minutes for models with approximately 30 images) if the alignment has failed, so the amount of time wasted is not significant.

One model, generated with 37 images was successfully aligned, but experienced construction issues, with the terrain surface not generating properly, with some of the surface appearing several metres above the rest of the model, making a volume measurement impossible to obtain. This model was only used to check the preservation of dimensions, which were reproduced satisfactorily. In all, of the 27 models constructed, only 2 failed, and three were unusable for volume measurement (Including the two that failed)

Being able to create three models of each pile, as a result of over-imaging the piles proved beneficial to this research, and would likely be a useful practice to employ going forward. The time required to capture double the imagery required for each pile (e.g. 140 as opposed to 70 images) was approximately 10 minutes per pile, and is outweighed by the time saving achieved from only using half the collected imagery in the generation of the model. In the event that the model doesn't generate, or is of insufficient resolution, there is the ability to increase the number of images used without having to go back into the field to collect more imagery.

Applying the Geometric Method

Applying the Geometric Method in the measurement of slash pile volume was found to be highly dependent on the person applying it and the way in which you approached the pile. It is possible to slip in to a manner of assuming one shape for all piles, as they all seem to adequately fit that shape, without considering the other shapes. Measuring length and width was relatively trivial, provided time was taken to positively identify the start and end points of each measurement, and ensure they were at right angles to each other. Height measurement was the most inaccurate measurement taken, as it was determined by approximation, both by me, and the assistant I had for several of the piles.

Orienting Targets

As mentioned previously, it was necessary to orientate the length and width measurements at right angles to each other to maximise the accuracy of the Geometric Method. This was not always possible at all sites, particularly the bigger piles, where it was easy to mis-align the targets due to the scale of the pile. In hindsight, the drone could have been used, flying directly above the pile to aid in target placement by providing an aerial view of the geometry between the pile and the targets.

In addition to orientation of targets, they had to be visible in the imagery taken, this was realised after the first survey at Woodend Beach, where the targets were not visible in as many photos as they should have been, making them difficult, although not impossible to identify. This was caused by the drone being too close to the pile, and not capturing enough of the ground around the pile, where the targets were placed. This was noted, taken on-board and in the subsequent surveys, it was endeavoured to capture the targets in as many of the images as possible when flying around the pile.

External Factors

During the survey of the Woodend Beach pile, it was noted that the wind was pushing the drone around and overcoming the ability of the drone to hold its position in the air. This resulted in flying an erratic line around the pile, as is evident in the below Figure 17. In this case it did not appear to impact on the quality of the model generated, however in stronger winds or with a lower number of images captured, at greater spacing it may affect the model quality. With this in mind, subsequent surveys were completed on reasonably calm days, with wind speed less than 10 knots.

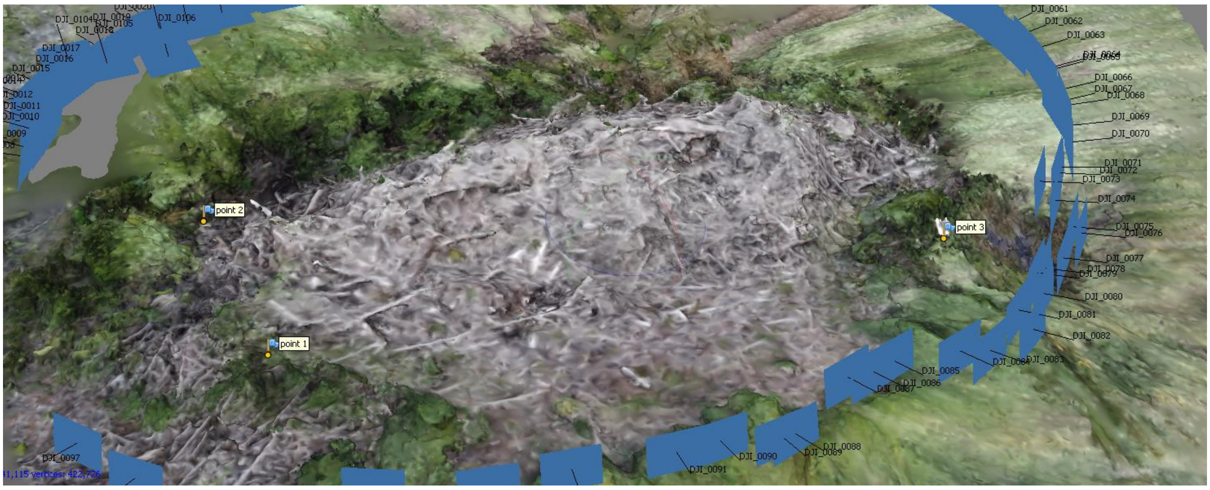

Figure 17 - Woodend Beach pile, erratic line of flight visible at right of image

It should be noted that a very real threat to safety during a drone survey is that of the New Zealand Falcon - Karearea, which often find a home in our clear felled production forests (NZ Birds Online, 2013). The Falcon, viewing the drone as a threat will swoop in and make out as if it will attack the drone, in such a situation, it is best to land the drone, and wait for the falcon to move off. During the course of the field work for this project, one falcon incident was experienced in the Hanmer Forest while surveying HAN03. The effect of landing the drone and re-commencing the survey from where it stopped was not noticeable on the SfM model, and shouldn't be expected to be an issue, provided the survey re-commences from the vicinity of where it stops.

Conclusions

This work has aimed to determine whether the Structure-from-Motion process, applied using basic methods is a viable method for determining the volume of piled forestry slash. To evaluate this, nine slash piles were surveyed, with three Structure-from-Motion models constructed of each pile to obtain 27 models. By measuring the length and width of the piles in real life, and in the SfM model, it was concluded that the measurements of the piles were well preserved in the generation of the model, reproducing to within 0.1m, with correlation coefficients of 0.9997 for length, 0.9953 for width and 0.9420 for height, which indicated the volume of the pile, as measured from the SfM model was an accurate representation of the actual volume.

The results obtained were reasonably similar to results obtained by Long in 2014, where the Geometric Method was compared to LiDAR, indicating that while not as accurate as LiDAR, the SfM method presented was capable of producing reasonable results. The Digital Elevation Models constructed during the scope of this project were constructed with resolutions not exceeding 3.36cm/pixel, and a maximum resolution of 1.51cm/pixel was achieved. This high resolution, combined with the good level of dimension preservation in the model leads to the conclusion that the volumes computed are accurate to the actual volumes of the piles.

While the SfM process is capable of generating reasonable quality models of slash piles, from which volume measurements can be taken, it is not, in my opinion, a viable technology for determining the volume of every slash pile within a harvest area, particularly if there is no environmental risk from the slash piles, or they are only going to be left, and not utilised for bio-energy. The time required, even to produce a model with a low number of images is simply too great, compared to the application of the Geometric Method, which would be sufficient in many cases.

If the slash piles were located in tricky to access areas, or their actual volume needed to be known for environmental management purposes, or for bio-mass sale, then SfM photogrammetry would be a useful tool in the management of the piles, providing both accurate bulk volumes, and a record of the pile, if it is re-surveyed over a long time period. This would allow for proactive management of slash pile, particularly those located in vulnerable areas, which would have a high impact on downstream stakeholders if they were to fail.

The key limitation of this study is the reliance on the preservation of measurements and the resolution of the DEM for assessing the accuracy of the volume measurement. The assumption made is that if the dimensions of the pile are the same in the model as they are in real life, and the resolution of the DEM is reasonable, the volume of the pile will be generally accurate. Ideally, the SfM method, as it is presented here would be compared to LiDAR surveys of the same piles, taking the LiDAR volume to be the true volume, and assessing the differences. It was decided that that was outside the realm of potential for this work, and the measurement preservation method would be used. A potential improvement on what was done could have been to construct a solid of known volume, such as a cube, with 1m sides, and place several around the pile to provide a check for volume preservation, in addition to providing a measurement point.

Potential Applications

As alluded to in the Literature review, there is potential for the process used in this project to be used as a method for 4D monitoring of slash piles. 4D monitoring in this case refers to the creation of a number of 3D models of a slash pile over some temporal scale – monthly, or on a biannual basis for example. This would allow the forest manager to monitor any changes to the volume or dimensions of the pile which could indicate a potential failure of the ground underneath the pile, and be able to arrange to remedy any issues that could occur.

If the survey was conducted with fixed ground control points, it would be possible to align the subsequent models with each other, and determine a difference in volume between the two models, allowing for determination of the rate of decay, as well as any signs of potential failure.

The technology is not limited to 3D models and volume measurement; the point cloud can be exported from Agisoft Metashape in .las format, which can then be input to the Roadeng software suite, and the drone survey can be used for small scale road design projects, without the need to commission a professional LiDAR or SfM survey. This functionality could become particularly useful with the increasing prevalence of small-scale woodlot harvesting, allowing for small scale, detailed design in sensitive areas.

This work has focused solely on slash piles located on flat terrain, these are not representative of piles located in hill country, where they will tend to 'spill' over the edge of the landing and be caught by a bench beneath. What this project does show is that the measurements of a pile surveyed by SfM will be preserved, and from that volumes calculated will be reasonable. Due to the different geometry of the pile, a different method of determining the ground surface under the pile will be needed, and it will need to be tailored to each situation. Using subsequent survey software, such as Virtual Surveyor ("Virtual Surveyor," 2019) it is possible to calculate the volume of a pile in segments; volume above the plane of the landing, and then volume on the slope below the landing. In both cases, the ground surface beneath the pile needs to be approximated.

There are a range of software packages available on all positions of the consumer spectrum, from DIY use through to commercial packages. The software used for this project, Agisoft Metashape is targeted toward the commercial end of the spectrum, and has been used in a large number of studies into the use of Structure-from-Motion. Consequently, Agisoft Metashape is priced accordingly, making it uneconomic for a significant segment of the market. Alternative software is that of PIX4D Cloud, which is available as a web-based service, which costs $165 (USD) per month, and allows fully cloud-based models to be generated. This software was trialled on the HAN01 and PEG01 piles, and found to be reasonably intuitive to use, with comparable results to those obtained in Agisoft Metashape (Figure 18).

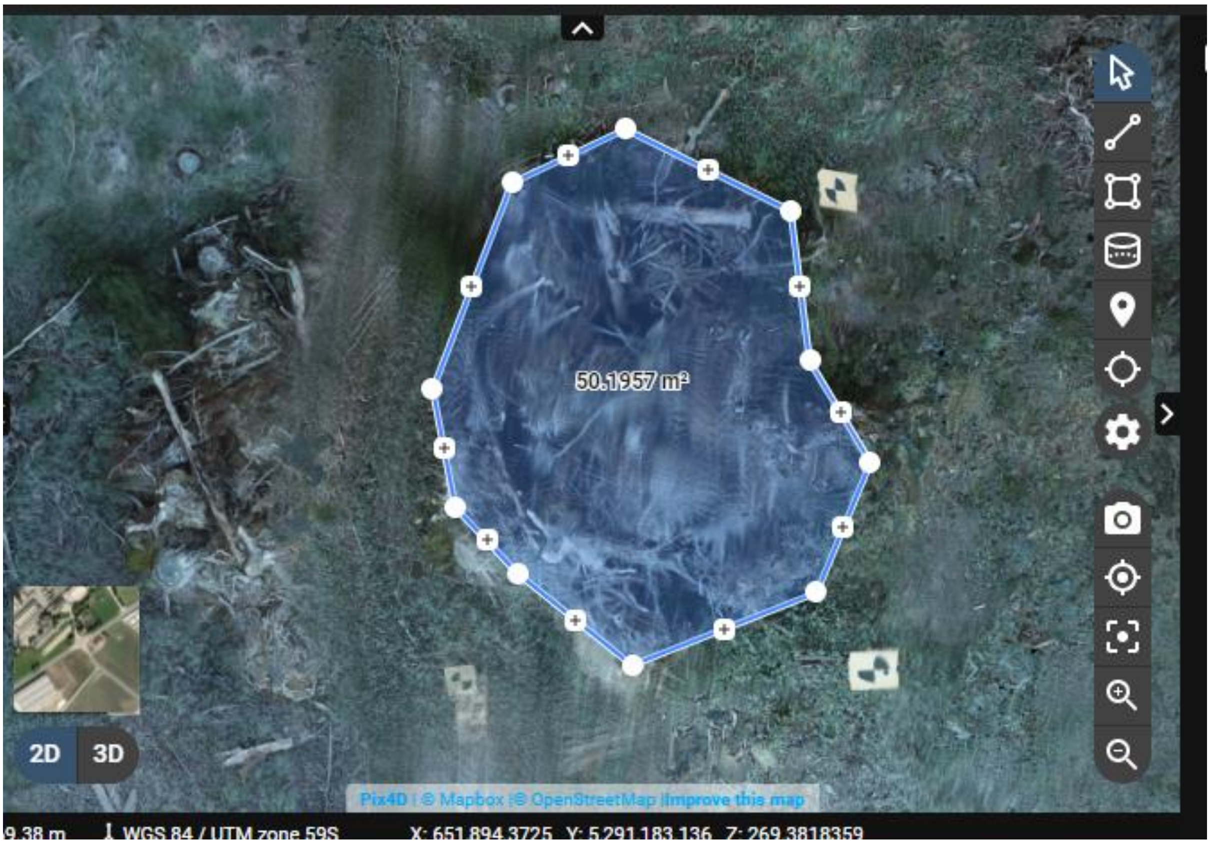

Figure 18 - SfM model of the HAN01 pile generated in PIX4D Cloud. The volume is comparable to the volume determined with Agisoft Metashape (50m³)

PIX4d Cloud will locate your model on a map, based on the coordinates embedded in the images captured by the drone, as shown below in Figure 19. Agisoft Metashape can give the DEM coordinates in real space, based on the same coordinate information, but cannot output that on a map, and in some instances the coordinates are not accurate, for instance, locating a Pegasus Beach pile in the hills behind the Balmoral Forest.

Figure 19 - PEG01 Survey area, as located on a map by PIX4D Cloud

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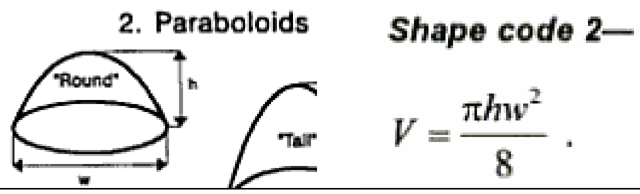
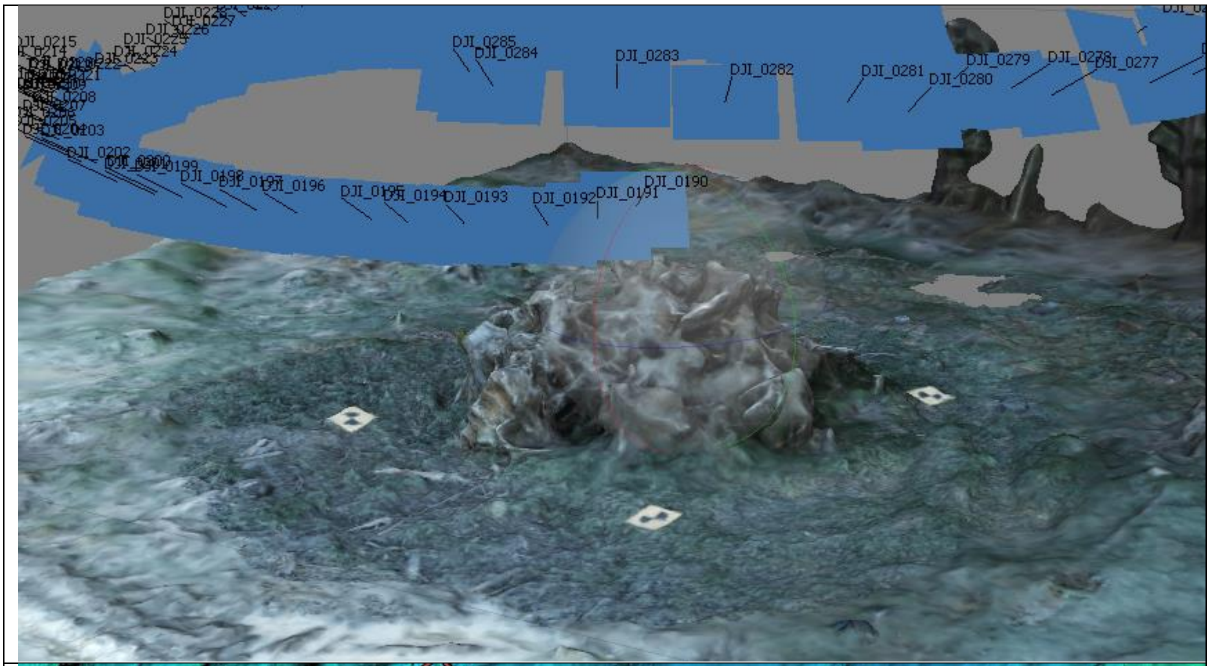
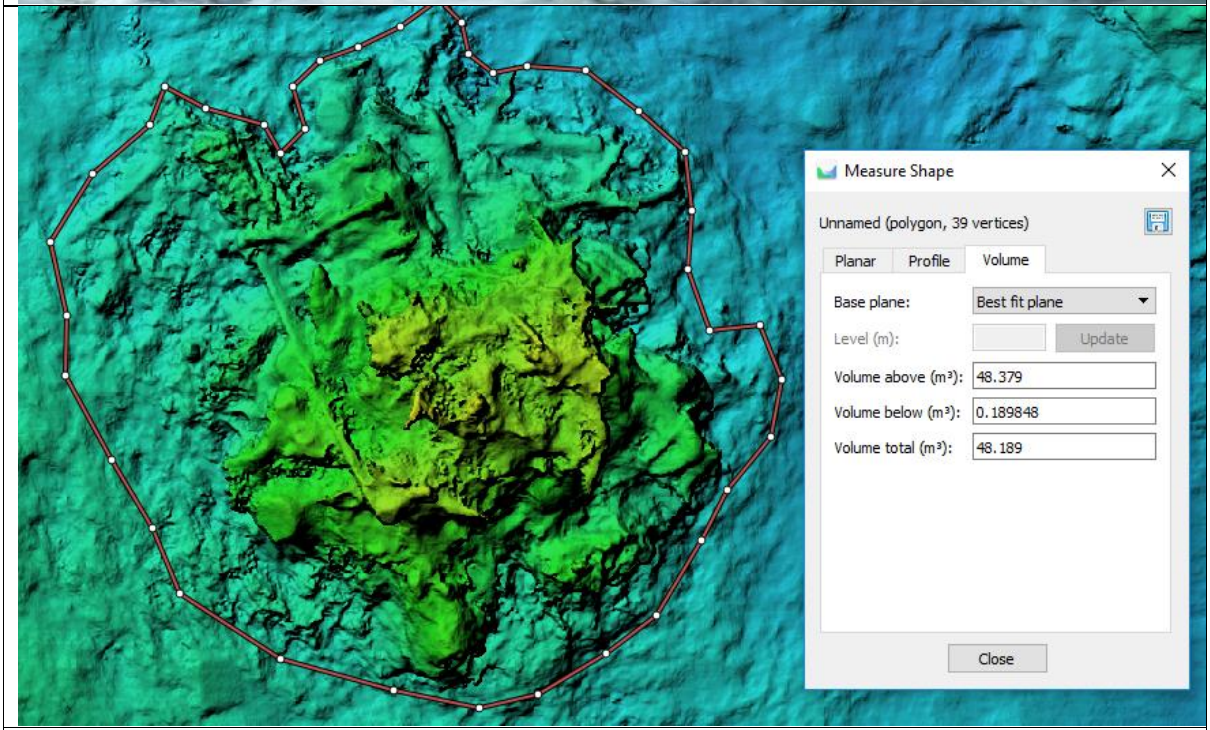
Appendices

Appendix 1 – Field Sheet

Location: Hanmer Forest	Pile Id. HAN01
Primary Road Access: Jollies Pass Road	Date of Survey: 26 July
Harvest Detail: Ground Based, Flat Terrain	Stand Characteristics: Radiata
	
Geometric Solid Approximation: 	L=6.5m W=7.5m H=3m V=49-66m^3 (Using L or W) V_{SfM}=48m^3
#Photos Taken: 112 Conditions: Sunny (Pile in shade) Time of Survey: 10.00am	





Notes

- This was a pile of stumps
- Length and width measurements were extremely well preserved in the model(L=7.5, W=6.55)

Appendix 2 – Study Locations

Figure 20 - Study locations in the Tuhaitara Coastal Park

Figure 21 - Study locations in the Hanmer Forest