Use of UAVs and photogrammetry to reduce uncertainty in bulk earthwork calculations

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ABSTRACT

The application of Unmanned Aerial Vehicles (UAVs) and photogrammetry for bulk earthwork calculations is a recent development for ground engineering in New Zealand. The approach developed on the Deans Head Land Remediation Project has proven to be an innovative solution increasing workflow efficiency to calculate and reduce uncertainty during bulk earthworks.

Following the 2010-2011 Christchurch Earthquake Sequence, Deans Head and Shag Rock Reserve, located near the suburb of Sumner, Christchurch, suffered significant land damage. Subsequently, Shag Rock Reserve was inaccessible to the public and Deans Head was assessed as being in the highest relative landslide hazard category with a potential risk to life and/or cause significant lifeline damage.

This paper presents the application of UAV and photogrammetry technology, outlining the 'Fly-Model-Analyse' workflow to generate accurate change models on the Deans Head Land Remediation Project. UAV and photogrammetry methods are compared with traditional methods for volumetric calculations, such as LiDAR, ground surveys and truck count estimates. The associated emerging technologies to enhance its application for ground engineering and some of these progressions and future uses are explored.

1 INTRODUCTION

1.1 Outline

The recent advancement of UAVs and photogrammetry applications has enabled the project team to develop a workflow process to reduce the uncertainty in bulk earthwork calculations. Traditional methods including truck count for volume estimates and ground surveys were taken into account during project establishment however considered time consuming and labour intensive and more importantly placed staff into high risk areas. An alternative method that is safer, quicker and allowed third party verification was required by key stakeholders to meet their regular reporting requirements.

A proficient workflow system was created using UAVs and photogrammetry to calculate key volumes that were required every fortnight on the project. Increasing project efficiency reduced personnel working in high risk and complex, steeply inclined slope with heavy earthworks machinery.

1.2 Background

Following the 2010-2011 Canterbury Earthquake Sequences, significant land, property and infrastructure damage was observed south of Christchurch at the foot hills of the Port Hills (GNS Science, 2013). Located near the suburb of Sumner, Deans Head and Shag Rock Reserve were badly affected by the severe ground shaking, resulting in collapse of the 80m high volcanic cliffs above Shag Rock Reserve and dense ground cracking across the steep Deans Head hillside area.

Following the Canterbury earthquakes, GNS Science (Massey et al., 2014) identified numerous mass movement areas in the Port Hills. Identified as a Class I mass movement area, the Deans Head area extends approximately 8,300m2 in size and contained an estimated 53,300m3 of soil (loess) material that could be mobilised as an earth/debris flow likely to have debris runouts which could cause damage to critical infrastructure, lead to loss or disruption of services and/or loss of life. Based on recorded surface movements and slope displacements across the site area, the landslide direction has been modelled in a northwest direction in relation to the site with trigger mechanisms rain related. Located on a steep sloping hillside, Deans Head has an average slope angle between 25° to 30°. Deans Head and Shag Rock Reserve site locations are presented in Figure 1 including the Deans Head indicative landslide direction.

Figure 1: Deans Head and Shag Rock Reserve site areas in relation to Main Road. Indicative movement direction shown in red arrows (LINZ, 2011 and Aurecon, 2015).

Deemed as an unacceptable risk to road users, local and central government agencies aimed to remove all the mass movement hazard material (soil) to rock level, with a portion of material placed in Shag Rock Reserve to construct a rockfall protection bund. Bulk earthworks removal formed part of the overall Deans Head Land Remediation Project (New Zealand Government, 2016a, 2016b).

Tracking key milestones and earthwork progress during the project was a critical requirement for stakeholders in the early detection of potential cost overruns. With a limited number of historical ground investigations completed across the site area, final volume values deviating from initial estimates could have had financial implications for the overall project. Although allowed for in project contingencies, if overruns can be foreseen earlier, the better.

In a challenging site setting, developing UAV applications and workflows improved project efficiencies during the Deans Head Land Remediation Project. The ability to obtain aerial imagery quickly, reduced personnel and heavy earthmoving machinery interaction while operating in a common work area on the ground. Undertaking repeat surveys regularly allowed the project team to track contractor progress claims for bulk earthworks on a site with geological uncertainties.

2 APPLICATION OF UAVS

2.1 Previous Use

The applications of UAVs has significantly grown in recent years, driven by the availability and affordability of recreational and pro-consumer UAVs. The improvements in camera specifications fitted to UAVs has enabled visual imagery to be collected from a different perspective and at a fraction of the cost of a commercial helicopter. The terminology for "drones" is plentiful including; Unmanned Aerial Vehicles (UAV), Remotely Piloted Aerial Systems (RPAS), and Unmanned Aerial Systems (UAS). For continuity throughout this paper we use the term 'UAV' to cover all aerial systems.

Initially UAVs were used in the Port Hills for visual inspections using the high resolution photographs and high-definition video. These inspections focused on cliff edge deterioration and unstable boulder inspections, where access was limited and/or hazardous.

We developed this visual monitoring to incorporate the simple technique of cliff edge tell-tales or extensometers. During cliff face scaling works, abseil teams installed wooden stakes positioned horizontally across significant ground cracks, see Figure 2. These tell-tales could then be observed periodically using UAVs to visually compare imagery and detect ground movement. This technique reduced personnel accessing close to the cliff edge. Combining UAV technology and tell-tale monitoring simplified work streams and increased monitoring frequency in hazardous locations.

Figure 2: Comparison from UAV images of tell-tale monitoring at Shag Rock Reserve (Aurecon, 2016a).

2.2 UAV Volumetric Measurements

Identified during project establishment, volumetric calculations were required fortnightly during the 9 month earthworks programme to track milestones and verify contractor claims. To accurately calculate material removed and remaining on site, a unique and innovative workflow was developed using UAV and photogrammetry capabilities which was termed 'FMA' (Fly-Model-Analyse). From start to finish, the FMA process could be completed in approximately 24 hours.

This workflow comprises three key steps;

1. ***Fly*** **-** A UAV is flown over the site to capture high-resolution images. The flights were flown manually as flight automation is unable to account for complex 3D environment and gradual slope changes. The images were captured using a single camera and variations in flight altitude,

flight direction and camera angle, which enabled the the project team to obtain the required overlap and array of images for detailed photogrammetry modelling.

2. ***Model*** – The images captured are processed through multiple photogrammetry software, including Autodesk ReCap360, which transforms the 2D images into a 3D point cloud. Ground Control Points (GCPs) are included during the modelling phase. These points are captured using RTK-GPS survey.

3. ***Analyse*** – The 3D point cloud is then converted into a Digital Terrain Model (DTM), using software such as Autodesk ReMake. This data can then be used for a number of analysis functions including rockfall simulations, slope stability analysis and volumetric calculations.

The FMA workflow produced a DTM (3D model) that could be compared to previous models to identify topography changes, see Figure 3. With each new DTM the team were able to compare the mesh layers and calculate the difference between the current excavated surface and the previous ground surface to estimate the volume of material that has been removed between DTMs. Earth removal rates could then be calculated and tracked for project management purposes.

In addition, by comparing the latest DTM with the design surface the project team were able to forecast the amount of remaining soil to be removed. This was critical in key milestone decisions and sequencing works with site won material for the construction of mitigation works in Shag Rock Reserve.

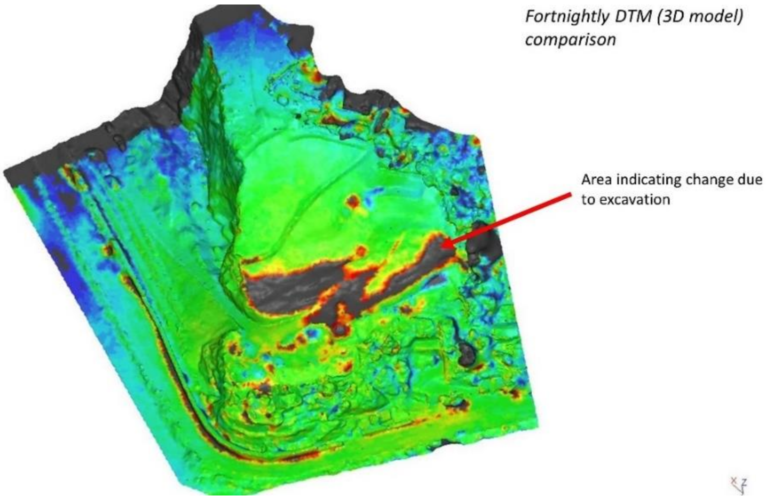

Figure 3: Fortnightly 3D terrain model comparison of Deans Head, green and blue signifying no significant change and black signifying vertical change due to excavation (Aurecon, 2016b).

Reducing DTM uncertainty or margin of error improves model reliability. We defined our error or uncertainty through the measurement of accuracy and resolution.

The level of accuracy is measured as the distance between the identified control points within the DTM to the corresponding known ground control points (GCPs) to provide difference in the x,y,z planes. During baseline establishment, this measurement started at 300mm, but was reduced to less than 50mm with the improvement of flight paths, ground control point locations and camera angles.

The resolution indicates the level of detail that is captured in relation to the ground surface. The ground sampling distance measures the distance between each pixel, which is represented as a point within the 3D point cloud. This measurement also relates to the amount of ground that each point (or pixel) represents. This measurement started at around 25mm and was reduced to less than 10mm using improved camera sensors and flight paths.

Increasing the level of accuracy and resolution decreased the margin of error or uncertainty for each DTM. On a larger site, such as Deans Head with an area of 8,300m2, reducing the margin of error was crucial in reducing potential volume errors. With the improvements in model accuracy and resolution, the uncertainties for earthwork volumes reduced from approximately ±2,300m³ to ±500m³ (Aurecon, 2016c).

3 DISCUSSION

3.1 Comparison between UAV and traditional methods

Traditional methods for earthwork volume calculations were investigated during project establishment and comprised of three main categories;

1. ***LiDAR*** – an aerial based system that provides accurate and high resolution data. The system normally requires piloted aircraft to fly-over the area, which can be expensive and challenging dependent on the size of the site. Capture of LiDAR data was impractical to achieve on a fortnightly basis.

2. ***Ground Survey*** – this includes laser scanning, theodolites and RTK GPS. These data capture techniques provide highly detailed and very accurate measurements. However GPS units and theodolites can be restricted in the number of total points captured across the site, which reduces the overall resolution. Laser scanning can be expensive and with complex terrain requires several set-up locations to achieve appropriate view angles, this become impractical across a working site with moving plant. Data capture with theodolite and GPS systems would need to consist of a grid style pattern (such as 0.5m by 0.5m) across the site and this was impractical due to the scale of the site and the resolution required to pick up the extremely variable terrain.

3. ***Contractor Estimations*** – a method most commonly used to calculate volume removed for bulk earthwork projects. The contractor provides the material that is excavated and/or trucked off-site. These estimated quantities are calculated based on the number of trucks, and the approximate known load of each truck. This form of volume calculation can have errors associated with larger volumes such as there may be one to two excavator buckets difference per load; generally the greater the number of trucks, the larger the error. Truck volume counts are difficult to verify and a weigh station would be costly to install.

On review at the beginning of the project, the above methods were deemed to be time consuming and labour intensive, and an alternative method using UAVs combined with photogrammetry was selected. Through recent advances in UAV and photogrammetry technology, good coverage and resolution was achieved on the project. Accuracy was improved by incorporating an increased number of ground control points to improve data quality.

The repeated collection of UAV derived photogrammetry models which formed our DTMs reduced the overall uncertainty of the underlying design (rock) surface, and enabled the project team to forecast and refine estimates of the remaining material to be removed. By building in these forecasted models along with refining the original estimates, the comparison between our forecasted removal estimates and actual volume removed calculation was on target and within ±110m3 of the 53,300 m³ to be removed (Aurecon, 2016c).

4 EMERGING TECHNOLOGIES

There are a number of emerging technologies that can be used to improve image capture and accuracy and resolution of the photogrammetry derived digital terrain models. These emerging technologies include;

- ***Operating Applications*** - There are several operation applications that have the ability to automate flight paths. Currently many of these applications do not allow for sloping and complex terrain. Automated flight path applications that adjust for variation in altitude would be beneficial, and improve efficiencies by removing the need to "over-fly" an area to ensure consistent data. Current automated volume calculation applications appear to struggle with complex terrain, as they are focused on stockpile estimates on flat surfaces compared to variations within complex terrain models.

- ***GPS Improvement*** – Continuing improvements in the on-board GPS technology for UAVs will improve the accuracy of the known location of each image captured. This improved accuracy will feed into improved accuracy of the 3D point clouds to create the DTMs. Improvement in GPS will also allow more accurate refinement of predefined automated flight paths for improved consistency between models.

- ***LiDAR*** – Current UAV LiDAR is available for a high cost, and the weight of the attachment requires a larger UAV requiring more restrictive operating procedures. As the LiDAR attachments develop and reduce in cost and size, they will become more applicable to smaller UAVs. This will allow for better resolution and accuracy of the digital terrain models, with the advantage of a reduction in "noise" from vegetation.

An advancing stream of emerging technologies is currently being developed that focuses on the stakeholders interaction with the DTMs using virtual reality (VR) and augmented reality (AR). Virtual Reality includes the use of headsets such as the Oculus Rift or HTC Vive to immerse the user into a virtual model of the DTM, enabling them to interact and explore the virtual environment. Augmented Reality requires devices such as the Microsoft HoloLens, which merges the digital terrain model with the real world, enabling users to view a blend of virtual and real world environments, see Figure 4.

During the Deans Head project, the team harnessed both VR and AR technologies to enable clients, contractors and engineers to discuss particular hurdles during the earthworks phase and logistical problems as well as final design. The AR technology provided project engineers with an opportunity to refine and visually check the proposed design surface. Health and safety hazards could be clearly communicated to stakeholders on an interactive level, facilitating engaging discussions prior to site visits.

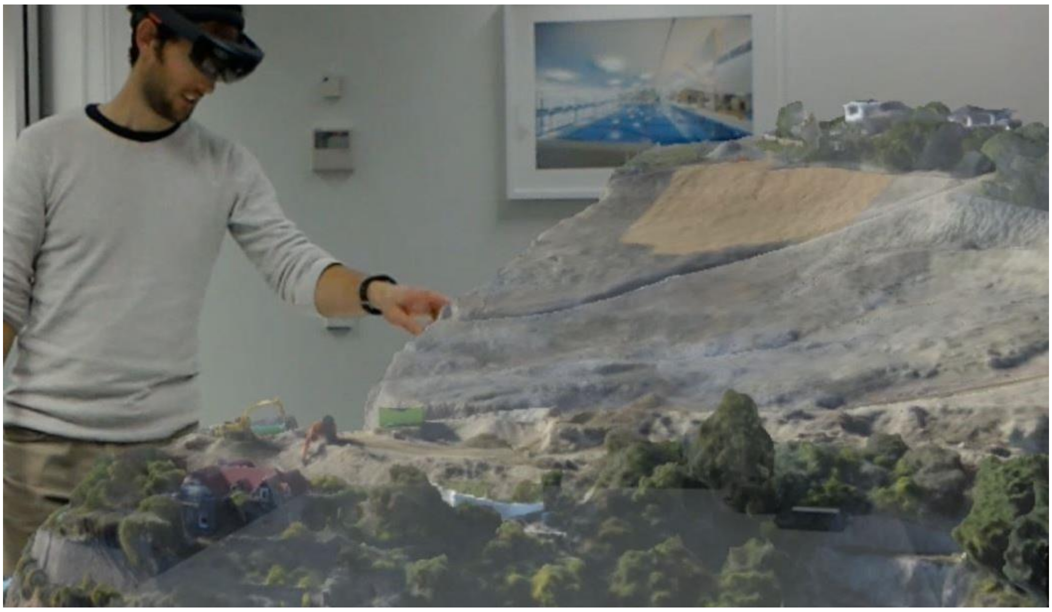

Figure 4: Deans Head viewed through the Microsoft HoloLens (Aurecon, 2016b).

5 FUTURE USES

There are a number of opportunities for the use of complex terrain photogrammetry models built from UAV derived imagery. The majority of industries are using UAVs to improve the efficiency of their operations, monitor sites and improve health and safety. The engineering industry is now forging ahead with the use of photogrammetry. Based on the recent developments in emerging technologies the use of workflows such as the FMA will likely develop several different work streams including;

- ***Environmental Management*** – The FMA process enables volume calculations to be used in a variety of ways, and due to the short turnaround period for the process, derived change models can be used for short and long term predications for erosion or sediment accumulation of rivers, beaches, slopes and exposed cliff faces. The UAV enables the FMA process to be used in inaccessible areas, using remotely placed ground control points, which could enable the monitoring of forests for their progressive growth and density increase. The information collected and recorded can be used to anticipate areas prone to erosion and enable decision makers to prioritise areas that may require additional remediation and slope stabilisation.

- ***Natural Disasters Response –*** following an earthquake or significant rainfall event, the FMA process could be used in an initial response to quantify the volume of debris flows or landslide material transported downslope and potentially covering road or rail infrastructure. This can provide emergency response crews with information critical to identifying the extent of the damage and enable recovery teams to repair the infrastructure.

- ***Infrastructure*** – The DTMs created through the FMA process can be used to measure any movement or settlement along road, rail and bridge embankments. As the FMA process can be undertaken within 24 hours, the process could be used on a scheduled type basis during construction and life cycle of the asset to improve the performance and safety for asset users.

- ***Underground engineering –*** Tunnelling and mining operations are associated with varying levels of geological uncertainty dependent on the stage and scale of the project. Comprehensive survey techniques are normally undertaken during the established and monitoring phase, these techniques include InSAR, Laser Scanning and prism based monitoring. The UAV-based FMA process can be beneficial in the concept phase and provide the initial information which detailed DTMs for planning purposes. The DTMs can be coupled with geological models to create 3D complex terrain models for planning and concept design. The low cost and timeliness of the FMA process makes it efficient to complete during the pre-feasibility stage of a project.

There are a number of future uses that are being developed outside of the engineering sector, and as these develop they may become transferrable for use. As the applications are explored and technologies improve the uses of UAVs and process such as the FMA will expand.

6 CONCLUSIONS

The application of UAV and photogrammetry technology through the Fly-Model-Analyse (FMA) workflow has been successful in the volumetric calculation of bulk earthworks during the Deans Head Land Remediation Project. UAV and photogrammetry methods have generated accurate models which are cost effective, timely and repeatable. These methods are comparable to traditional methods such as LiDAR, ground surveys and truck count estimates. UAV technology has reduced personnel working in high risk rockfall areas and interacting on the ground with heavy earth moving machinery.

UAV and photogrammetry is a new and evolving technology for ground engineering. There are a number of emerging technologies under development to improve image capture and the accuracy and resolution of photogrammetry derived digital terrain models. Some of these technologies include the development of automated flight paths, improved on-board GPS and low cost LiDAR which will allow UAV and photogrammetry applications to become more affordable and practical. The inclusion of VR and AR developments into this workflow process enables the data to be interrogated in a more immersive environment, and can facilitate stakeholder and contractors collaboration.

There are a number of applications for UAV and photogrammetry technology. UAV surveys are repeatable and can be compared for periodic monitoring and erosional surface management such as around lakes, beaches and slopes. Other future uses include quantify damage extent caused by landslides and earth debris flows and assessments following natural disaster events.

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