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Controlling high hazard slope stability working environments by using digital tools

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ABSTRACT: Following the severe earthquake in Christchurch between 2010 and 2011 central government agencies working on earthquake recovery commissioned work to reduce the impact from rockfall and slippage from an 80m high near vertical cliff face onto a lifeline road. This paper is a case study and describes the journey developing a suite of digital tools for smarter and more efficient management of sites where geotechnical hazards require control to ensure safety for those affected by site activities. Drones were used for airborne image collection that was processed into point clouds. The point cloud data was used for visualisation and data change management, including volumetric earthworks control. Visualisation used augmented, mixed and virtual reality environments to engage with stakeholders and member of the public. The above process was then used following the Kaikoura Earthquake in 2016 to assess landslide dams blocking rivers and inform Civil Defence management.

1 INTRODUCTION

The Canterbury Earthquake Sequence started on 4 September 2010 with the Mw7.1 earthquake near Darfield, New Zealand, (GNS, 2015). Although this event caused wide spread liquefaction on the flatter parts of Christchurch, the Port Hills, volcanic hills up to 400m elevation to south and southwest of Christchurch were not greatly affected as the epicentre was about 50km away, (GNS Science, 2018). The second largest aftershock on 22 February 2011, however, was located underneath the Port Hills area. Ground accelerations, mainly due to epicentral proximity and ridge amplifications are estimated to be in excess of 2g, with significant vertical accelerations, (Bradley & Hughes 2012a) and (Bradley & Hughes 2012b). Several strong aftershocks continued to rock the Port Hills throughout 2011.

Strong to very strong earthquake shaking was observed on the eastern parts of the Port Hills, near the suburb if Sumner where rockfall affected hundreds of residential properties and roading infrastructure. This paper describes to work the authors undertook on a 350m long 85m high section of a former sea cliff to ensure that the road at the base is protected from ongoing rockfall and cliff collapse. The authors describe their journey to use conventional means to achieve their objective and the development of digital tools to provide a safer working environment. The tools developed, and lessons learned were vital in November 2016 to respond to the Kaikoura Earthquake.

2 BACKGROUND

The object site is 10km southeast of the Christchurch City Centre at the entrance to the beach suburb Sumner. Sumner can only be accessed by three roads, one was blocked and rendered un-serviceable by rockfall, the second is a narrow road over the tops of the volcanic peaks and

Figure 1. Peacocks Gallop shown after the 22 February 2011 earthquake.

the third goes past the 350m long and up to 80m high former sea cliff known as Peacock's Gallop. The cliff is made of fresh to highly weathered layers of volcanic rock, deposited in a chaotic fashion some 9Ma ago, refer to Figure 1. This geological setting is typical for the wider Banks Peninsula or which the Port Hills of Christchurch are part of (Brown & Weeber 1992).

Prior to the Canterbury Earthquake Sequence Peacocks Gallop featured the Shag Rock Reserve at the base of the cliff, a man made flat and level grassy park. After the September 2010 earthquake, an approximately 1:100a event, several large boulders were dislodged from the cliff face and the northern end featured a small area where multiple large boulders (1 to $3m^3$) fell. The recreational area was closed off to the public. In February 2011 earthquake, approximating an ULS event with some substantial seismic shaking, the majority of the cliff face retreated some 5 to 10m, and deposited approximately 35,000m3 of debris into Shag Rock Reserve, refer to Figure 2 below. The June 2011 earthquake featured slightly lesser shaking than the prior February 2011 event, dislodged a similar amount of debris. While fully ballasted shipping containers, stacked two high and secured with marine locks, provided some limited protection from fly rock, they provided little protection from a repeat debris mass inundation. The details for each earthquake are available on GNS web portal, (GNS Science, 2018).

Compounding the hazard was the presence of a large landslide body, estimated to comprise about $50,000m^3$ of material to the north of Peacocks Gallop, known as Deans Head landslide. The Deans Head landslide was activated by the strong seismic shaking and co-seismic deformation was estimated from cumulative crack mapping to be more than 3.5m. The landslide was able to be activated by heavy persistent rainfall, (Massey, et al., 2014) Although all residents left their homes, the main road to Sumner town-ship was at the base of this landslide and prone to inundation by landslide debris.

Approximately four years after the main earthquake academic, engineering and scientific work indicated that the risk to road users is unacceptable, both from cliff collapse along Peacocks Gallop and land sliding from Deans Head, (Massey, et at. 2014a & 2014b). The authors were commissioned by the New Zealand Central Government agency for earthquake recovery, CERA, to attempt to demolish the residential structures on the Deans Head land-slide and reduce the risk to road users along Peacocks Gallop and Deans Head.

Access to both sites was challenging. Top access to Deans Head was limited to machinery of less than 10t due to narrow roading. Access to the bottom of Peacocks Gallop was limited

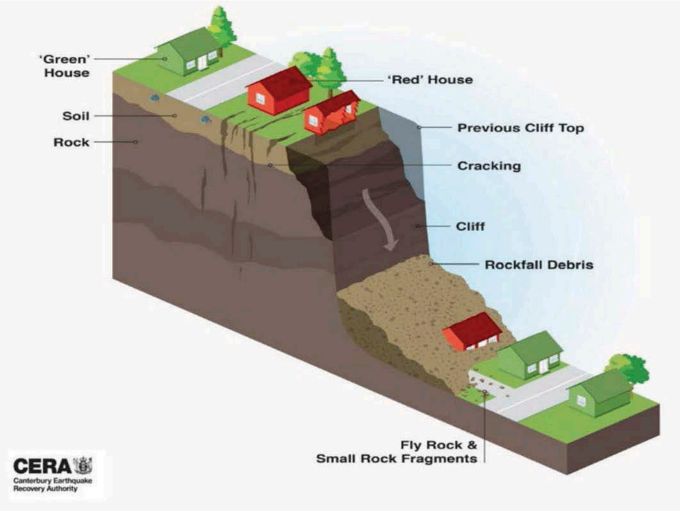

Figure 2. Schematic cliff collapse, after (CERA, 2011).

due to the proximity to rock slope and active roading environment. The project concept involved excavation of 45,000m^3 of debris within the talus and forming a 13m high protection bund, followed by creating of steep haul road to Deans Head and excision of the landslide mass of about 50,000m^3.

The urgency for the project derived from the need to prevent the Deans Head landslide from activating as this would not only block the sole viable roading access to the township, but would, according to several debris run out modelling studies, block the estuary of the Avon and Heathcote Rivers and cause wide spread flooding of the lower lying parts of Christchurch, (Massey, et al. 2014a). Protection of road users from ongoing rockfall from Shag Rock Reserve was equally essential as the road to Sumner is considered a lifeline route.

3 DIGITAL JOURNEY

The primary design constrain was the protection of construction and engineering staff working on the landslide and below the near vertical 80m high rockface. Execution of the proposed protection design had the potential to significantly impact on the community as the sole access to the township was alongside the construction areas. The authors carefully considered the available resources and tools available to undertake the project and widely research past project examples in roading and mining, few exist that would compare to the complexity of the terrain and environment.

The main drivers for the project were provision of rockfall protection and removal of landslide material above the main access road to the Sumner Township, essentially ensuring that the community can live and work in their township. The design of the physical works aimed at reducing the disruption of the community and providing a safe working environment. This posed restrictions on road closures and available construction methodology. The below featured monitoring and digital tools were used to achieve the project objectives and keep work force safe. The project duration, i.e. physical works, was in excess of 18 months.

3.1 *Geotechnical and survey monitoring*

At the very onset of the project continuous geotechnical monitoring and early warning systems were installed on Deans Head landslide. Borehole drilling using helicopter portable rigs

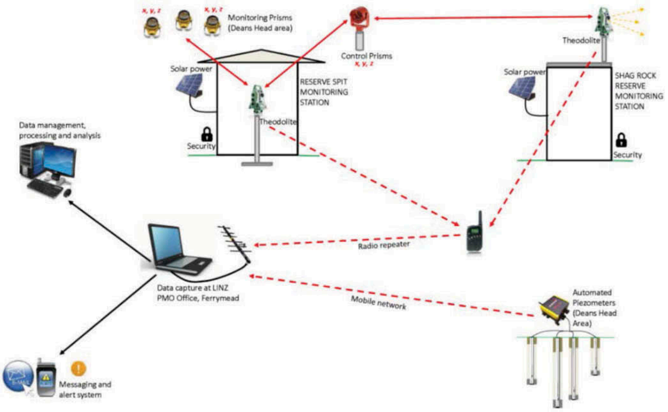

Figure 3. Geotechnical and survey monitoring.

provide an indication of the local geology and enabled the installation of inclinometers and piezometers. Crack gauges were installed across prominent cracks. The surface was surveyed and monitored in real time using an extensive terrestrial survey network refer to Figure 3 below. Due to the size of the site and its location on a steep slope, the main monitoring station was located several hundred metres away across the estuary. Remote data loggers provided real time information on three axis deformations, groundwater levels, precipitation. The cycle time was approximately 15 minutes and the network was monitored continuously. The network was sensitive enough to capture landslide mobilisation of several tens of millimetres after each major aftershock. The main aim and benefit were information on the porewater pressures and deformations indicating impeding failure of the slope. The monitoring provided an early warning system and informed Civil Defence, emergency services and local authorities.

3.2 *Laser scanner*

GNS, a Crown research organisation, completed several laser scans of the Peacocks Gallop cliff face to monitor changes from a scientific perspective, (Massey, et al., 2014). Based on the GNS work the authors adopted a laser scan approach to see any rockface deformations that could indicate impeding failure of individual blocks or bulging of large areas indicating potential for cliff collapse or mass movement. A terrestrial laser scanner was located into a specially modified shipping container, located centrally underneath the cliff near the road side. The scan area encompassed most of the cliff face. A detailed scan of the entire 350m long and 80m high face took about one hour, plus one hour post processing. The output was visual representation of the cliff face showing deformations as a heatmap. Difference plots were generated as shown in Figure 4 below.

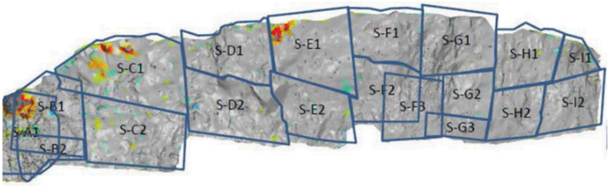

Figure 4. Differential laser scan results showing cliff retreat as a heat map over one month period (warm colours show loss of land up to 1m; cold colours indicate bulging up to 500mm).

Although, this system was not able to provide real time information, as the data capture and post processing created a lag which had to be factored in, it did provide useful information where material was lost out of the cliff face and where bulging of areas occurred. At a later stage of the construction process smaller areas above individual worksites were surveyed only which significantly reduced the turnaround time to few tens of minutes. The spatial resolution was sufficiently high to monitor deformations of few tens of millimetres. The main benefit of this system was to be able to monitor changes in the cliff face while incurring only a small time delay. Although, similar systems are adopted in mining, using laser light or radar waves, their costs are significantly higher than the commercially available laser scanner which was equipped with remote access and data connections to suit our purpose. The system performed very well over the 18-month long construction period with only few minor shutdowns due to environmental effects, often dense sea fog that in anyway prevented work on the site.

3.3 *Aerial surveys*

The site topography and setting, combined with the high rockfall risk, prevent close access to the cliff side or top of the landslide area. Vantage points were often hundreds of metres away. Aerial surveys using helicopters were the only viable means to determine changes in site conditions. A process was established to compare data from the terrestrial survey network monitoring and helicopter surveys. The relatively high cost, inclement weather and restrictions for prolonged flight operations above residential areas meant that helicopter surveys of the main geotechnical hazards were only conducted once every two months.

3.4 *UAV/RPAS surveys*

In early 2014 Canadian Discovery Channel brought an octocopter drone to film a documentary of the Christchurch earthquake damage. We were fortunate to be able to work with their team and get access to their film footage. Encouraged by the early results, the engineering team purchased in 2015 several Unmanned Aerial Vehicles (UAV) or Remote Piloted Aerial Systems (RPAS) for use on the Deans Head project, as this reduced the use of helicopters and avoided people being close to high hazard areas. Initially the UAVs were solely used as high resolution aerial cameras.

The later adopted UAVs were commercially available ‘hobby’ products that were extensively modified with 3D printed gimbals, high definition cameras and other accessories. As RPAS are much cheaper to deploy, compared to helicopter surveys, the survey frequency increased from once every two months to twice weekly fly overs, thus improving the ability to recognise changes on the landslide mass and cliff faces. The UAV were able to monitor conventional survey markers, stakes in the ground monitoring ground deformation, located close to the cliff edges, thus avoiding sending abseil crews to do this work, refer to Figure 5 below.

Figure 5. Typical deformation markers on the cliff edge as monitored by UAVs, combining established geotechnical monitoring tools with state-of-the-art remote sensing and survey tools. Note the large cracking of the 80m high cliff edge.

In summary, UAVs were able to capture photos from previously difficult to access locations, monitor areas where previously technicians had to abseil and generally provide a clearer view of the project area. The introduction of UAVs coincided with the changes in NZ legislation related to Health and Safety that required a much greater standard of care, (WorkSafe NZ, 2014).

3.5 *3D model development*

The project team and client quickly realised the potential to generate high resolution 3D photo- grammetry models from the captured 2D images. 3D photogrammetry modelling was used from mid-2015 to generate highly accurate change models. This was particularly useful to record changes in the cliff face after strong aftershock activity, as well as, look at individual areas on the cliff edge, refer to Figure 6 below.

3.6 *Volumetric control*

The 3D photogrammetry models were used to compare weekly changes on the site. This was particularly important at the work area on the landslide mass on Deans Head. The work area was affected by multiple hazards, such as steep to near vertical faces, slippery ground, large earth mowing plant. etc. Getting accurate survey and volumetric measurements would have entailed stopping work, marking no-go areas and allowing a survey crew to access the site to collect their data. Due to programme and Health & Safety requirements while working on the landslide this was not a desired approach. An alternative was provided via remote data capture using UAVs which converted 2D photos into a high-resolution 3D model, refer to Figure 7 above. This model was georeferenced by survey marks provided by the surveyors. The models achieved an accuracy of +/- 50mm which was deemed sufficiently accurate for the bulk earthworks purposes. Both the client and contractor agreed that the basis for intermediate payment claims would be the UAV photogrammetry model. Final surveys, comparing UAV models and conventional terrestrial survey, found a difference of less than 1%, or 500m^3 over 50,000m^3.

3.7 *Visualisation*

The ability to view a 3D model was important for stakeholder information. The project team often worked with national media, updating them on construction progress. As access to the site was restricted we extensively used 3D models. The use of both Mixed and Virtual Reality environments was greatly beneficial to communicate key points to the media and wider public. Figure 8 shows a 3D model projection used for a press conference and media briefing.

Further use of 3D model visualisation was the overlay of complex engineering analysis, such as rock fall trajectories. The ‘waterfalls’ as shown in Figure 9 are rockfall trajectories superimposed over a 3D site model enabling non-experts to visualise the rockfall risk at various areas on the site.

Figure 6. 3D photogrammetry model of the Shag Rock Reserve showing talus debris removal works.

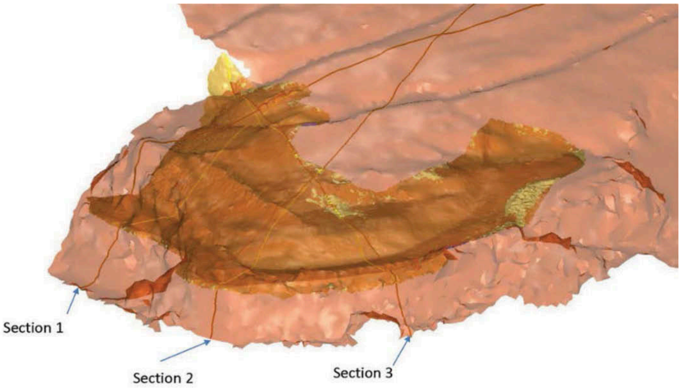

Figure 7. Cut surfaces on the Deans Head landslide, showing in light brown soil material removed from the pink rock surface.

Figure 8. Mixed reality model using Microsoft HoloLens showing as a holographic projection.

Figure 9. Rockfall trajectories, determined using industry standard 2D analysis, superimposed over the 3D site model.

4 FURTHER DEVELOPMENT

Development work on digital photogrammetry continued. UAV are now capturing photo realistic imagery (4k or better), which allows development of complex 3D models georeferenced to 10mm ground resolution. These models can be viewed in virtual environments. Engineers and geologist can work on slopes and cliffs without the need to be physically present. This is useful to share work internationally and seek expert advice from abroad. Further it allows mapping of slopes without the need for abseiling or scaffolding steep slopes and cliff faces.

Further developments, more recently, use combined photogrammetry and laser scans to derive models that can be computationally manipulated using machine learning and artificial intelligence to extract data such as rock mass information on jointing orientations and identify failure planes in rock cliff faces to assess the risk of failure (publications are pending). The data collected has been compared with traditional field methods and found to be highly reliable. This approach has since been prototyped in Christchurch, New Zealand and applied internationally. Given the high accuracy of these models', 3D slope stability analyses are becoming common practice, thus avoiding over simplification common to 2D analysis.

5 DISCUSSION AND CONCLUSIONS

The above-mentioned digital tools were effective communicating complex engineering issues to various stakeholders. For example, the visualisation of rockfall trajectories superimposed on 3D model can be easily understood by lay people. This in turn raises the awareness of complex safety issues on site and shows areas that are at lower seismically triggered rockfall risk. Being able to look at a site from a bird's eye view provides a much better situational awareness. This was particularly useful for site inductions and communicating construction progress. On this project the high hazard work was able to be completed without any major H&S incidents, despite significant aftershock activity. Lessons learned were taken to solve complex engineering problems that arose after the 2016 Kaikoura Earthquake, where more than three dozen very large slopes failed (>1Mm$_3$ landslides) and blocked rivers. These slopes were flown using helicopters and UAVs. 3D models were developed to complete a rapid dam breach analysis with visualisation showing the failed slopes and mobilised material. The geotechnical work on landslide dams, including 3D models, informed Civil Defence and allowed for rapid evacuation of affected communities. Using experience from above described work, the process took less than two days to quantify dam breach risk without the need to physically access the failed slopes. Minimising time spent on site or reducing the need in its entirety has significant health and safety benefits, especially in a seismic environment where aftershock activity can trigger substantial rock falls and slope instability.

REFERENCES

Bradley, B.A. & Hughes, H. (2012a). Conditional Peak Ground Accelerations in the Canterbury Earthquakes for Conventional Liquefaction Assessment. Wellington: Ministry of Business, Innovation and Employment.

Bradley, B.A. & Hughes, H. (2012b). Conditional Peak Ground Accelerations in the Canterbury Earthquakes for Conventional Liquefaction Assessment: Part 2. Wellington: Ministry of Business, Innovation and Employment.

Brown, L. J. & Weeber, J. H. (1992). Geology of the Christchurch urban area. Scale 1:25,000. Institute of Geological & Nuclear Sciences, map 1.

CERA. (2011). Illustrations of geotechnical hazard on the Port Hills for Public Meetings. Canterbury Earthquake Recovery Authority.

GNS. (2015, July 19). Canterbury Earthquake. Retrieved from Institute of Geological and Nuclear Sciences Limited: http://www.gns.cri.nz/Home/Our-Science/Natural-Hazards/Recent-Events/Canterbury-quake

GNS Science. (2018). New Zealand Geological Web Map. Retrieved from http://data.gns.cri.nz/geology/

Massey, C. I., Della Pasqua, F., Taig, T., Lukovic, B., Ries, W., & Herron, D. (2014a). Canterbury Earthquakes 2010/2011 Port Hills Slope Stability: Risk Assessment for Deans Head. Wellington: GNS Science.

Massey, C. I., McSaveney, M. J., Tait, T., Richards, L., Litchfield, N. J., Rhoades, D. A., van Dissen, R. J. (2014b). Determining rockfall risk in Christchurch using rockfalls triggered by the 2010/2011 Canterbury Earthquake Sequence, New Zealand. Wellington: GNS Science.

WorkSafe NZ. (2014). Health and Safety at Work Act. Wellington: New Zealand Government.