Response and initial risk management of landslide dams caused by the 14 November 2016 Kaikoura earthquake, South Island, New Zealand

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ABSTRACT

At 12.03 am local time on 14th November 2016 (UTC: 11.03 am 13th November 2016) a shallow magnitude 7.8 earthquake, with an epicentre located near Waiau in North Canterbury, struck the North Canterbury and Marlborough regions of NZ. The most visible consequence of the strong ground shaking was widespread landslides. A feature of the landslides from this earthquake is the large number (196) of drainage blocking landslides it generated. This was partly due to the steep and confined slopes in the area and the widely distributed strong ground shaking.

The majority of the landslide dams occurred in two geological and geotechnically distinct materials: weak sedimentary rocks (sandstones and siltstones) where first-time and reactivated rock-slides were the dominant landslide type, and; strong sedimentary rocks (greywacke and limestones) where first-time rock and debris avalanches dominated. This gave rise to two quite distinct end-member landslide dam types, large rock block slides comprised a few large blocks, and rock and debris avalanches comprised of coarse angular gravels.

Identifying the location and size of landslide dams was a priority in the post-earthquake response because of the potential public safety risks. Once dams had been located the hazard of catastrophic failure (likelihood) was assessed. Those with a higher likelihood of catastrophic failure had the consequences (risks) from failure identified. Those with a higher likelihood of failure and substantive risks were examined in more detail using field mapping and terrestrial laser scanning. These data were used to model the catastrophic failure scenarios to determine the scale of the risk so that appropriate countermeasures could be put in place to alleviate the risks.

1 INTRODUCTION

The Kaikoura Mw7.8 earthquake struck at 12.03 am local time on 14th November 2016 (UTC: 11.03 am 13th November 2016) - a shallow (15 km) magnitude 7.8 earthquake (Mw), with an epicentre located near Waiau in North Canterbury (Kaiser et al, 2017), and strongly shook the North Canterbury and Marlborough regions of NZ (Figure 1). The strong ground shaking caused widespread damage to buildings and infrastructure across the sparsely populated areas of the northeast of the South Island. The most visible consequence of the strong ground shaking was widespread landslides (Figure 1). Given the sparsely populated area affected by landslides, only a few homes were impacted and there were no recorded deaths due to landslides.

GeoNet, the geohazards monitoring programme funded by the New Zealand Earthquake Commission and run by GNS Science, has a requirement to respond to major landslide events in New Zealand using a set of established criteria (Dellow 2001, McSaveney et al. 2010). The M_W7.8 Kaikoura earthquake met several of these criteria, including the presence of consequential hazard in the form of landslide dams and direct damage in excess of $1M. The landslide reconnaissance effort the first day after the earthquake quickly determined that landslide dams represented on ongoing hazard and risk to earthquake response activities. Immediate plans were made to search for, photograph and attribute all the landslide dams. Following on from this, a process for evaluating the hazard of dam failure and the risks or consequences of failure was developed. This process quickly identified landslide dams with the highest hazards and greatest risks allowing emergency managers to focus efforts to develop mitigation plans. The dams with the greatest risks, to people or road networks, were selected for additional work to acquire survey-quality data to model rapid dam failure to further inform mitigation strategies.

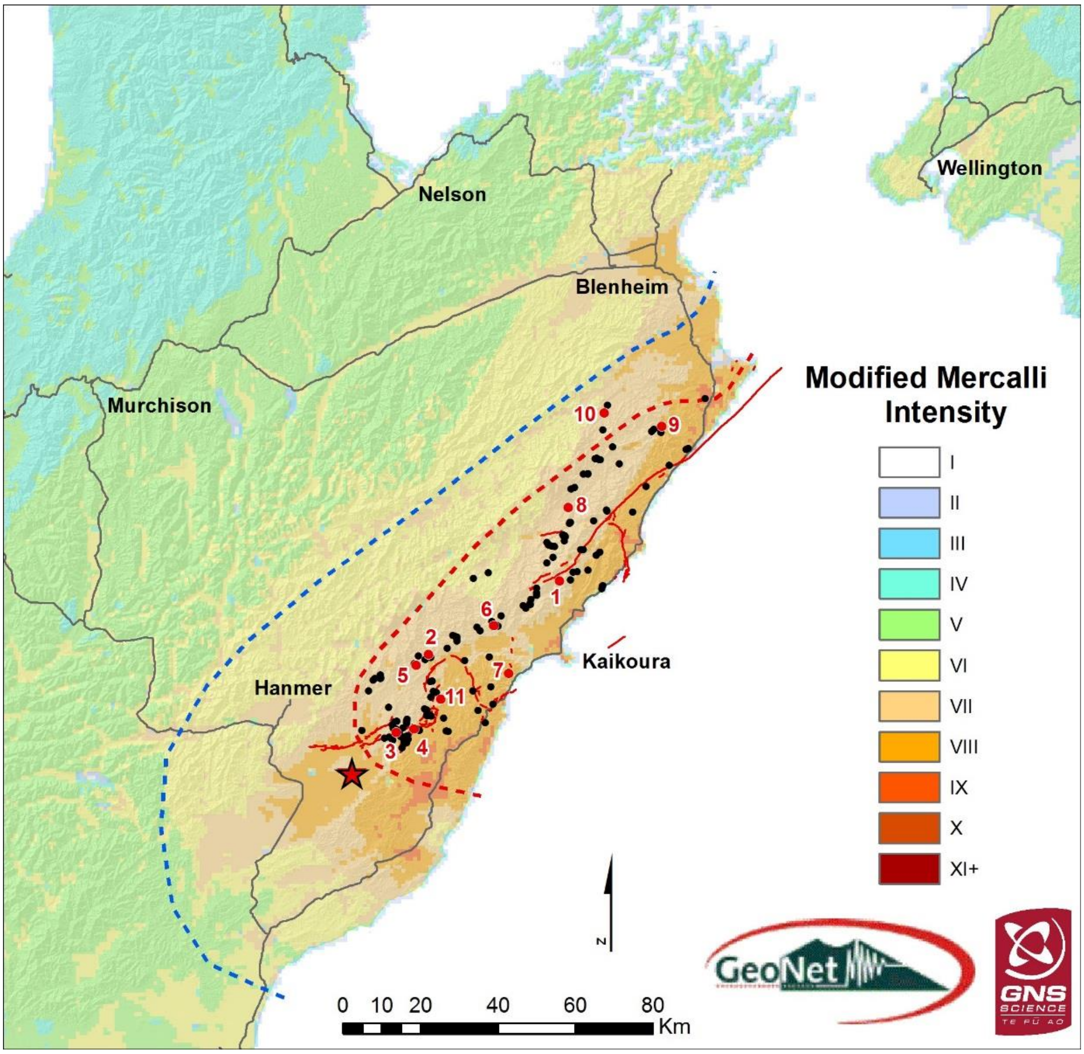

Figure 1: The 14th November 2016 M_W7.8 Kaikoura Earthquake. The epicentre is shown by the red star. The colours depict the MM Shaking Intensity, with MM VIII in the worst affected areas with isolated pockets of MM IX where deep soils are present. The areas of light to moderate landslide damage (area between the blue dashed and red dashed lines), and severe landslide damage (area inside the red dashed line) are shown. Fault rupture during the earthquake is shown as solid red lines (Litchfield et al, 2017). The landslide dams are by a black dot, or for the dams assessed having the highest failure hazard and consequential risks a numbered red dot: 1: Hapuku; 2: Conway; 3: Stanton; 4. Leader; 5. Towy; 6. Linton; 7. Ote Makura (Goose Bay); 8. Clarence; 9. Waima/Ure; 10: Medway; 11. Gelt. (Map credits: MMI: Nick Horspool).

2 LANDSLIDE RECONNAISSANCE

As the Kaikoura earthquake occurred in the middle of the night, aerial reconnaissance of the damage could not start until daylight. The first helicopter from Wellington left at daybreak (6.00 am) and identified the first slope failures caused by the earthquake on the western side of Cape Campbell. Further south the large landslides completely blocking State Highway 1 and the railway line were seen. While flying along the Hope Fault, which is at the southeast foot of the Seaward Kaikoura Range, several of the rivers crossing the range front were flown upstream, particularly if river flows were absent or the water was discoloured. This revealed landslide damming in several river valleys with water slowly impounding behind the landslide dams.

No reports of people trapped or missing were received (a priority for emergency services) indicating that it was unlikely any potential victims had been buried by rock falls and slides along State Highway 1 north and south of Kaikoura. This allowed the response to shift focus to potential public safety risks. The key concern with respect to public safety was finding and assessing the landslide dams because of the potential for rapid failure of the dams resulting in a flood wave travelling down the river valleys without warning and presenting a risk to life and property. This was further highlighted by Environment Canterbury reporting on and dealing with the landslide dam in the Clarence River that failed about 4.00 pm on the afternoon of the 14 November 2016, some 16 hours after the earthquake.

A plan to systematically search for, and assess landslide dams was developed and implemented. The first task of the landslide reconnaissance effort was to determine the extent of the area to be searched for landslide dams. Within three days of the earthquake it was determined that the approximate bounds of the landslide damage extended from the Waiau River in the south, from the coast to inland at Hanmer Springs, and from Hanmer Springs to the Clarence Acheron confluence, north along the Acheron until Wards Pass before following the Awatere River to the coast (the area within the red dashed line on Figure 1).

3 LANDSLIDE DAMS

The assessment of, landslide dams after the 14th November 2016 M_W7.8 Kaikoura Earthquake is still in progress (as of July 2017). The process started with delineating the area that needed to be searched to find landslides that had blocked river and stream valleys, forming landslide dams. This first step required defining the search area (Figure 1). Once the search area had been defined, and in reality this was an iterative process, a systematic search was undertaken starting with the areas where the strongest shaking was reported and where lives and/or property might be at risk from rapid failure of the landslide dams.

On the 14 November 2016 a landslide dam blocking the Clarence River was quickly identified. By 4.00 pm on the 14 November 2016 this landslide dam had overtopped and breached, sending a rapidly attenuating flood-wave down the Clarence River. The early identification and reporting of this dam to Environment Canterbury, the government agency responsible for managing floods in Canterbury's rivers, allowed a warning to be issued to residents of the Clarence Valley. As more landslide dams were recognised in the first week after the earthquake a general warning to the public was issued to stay away from rivers and streams because of the possible risk of rapid failure of landslide dams sending a flood-wave down valleys without warning. The systematic search for landslide dams eventually identified 196 drainage blocking or drainage constricting landslides in the area affected by landslides (Figure 1). This figure includes landslides that diverted river and stream courses over low-lying river terraces as well as landslides that completely blocked valleys to a depth of sometimes tens of metres. The rational was that areas of identified instability could potentially fail again during strong aftershocks or high intensity rainfall events, and having a list of sites where the exiting instability could result in a more substantial blockage was deemed prudent.

Initially all catchments were searched systematically by helicopter reconnaissance flights and any constrictions located by GPS, photographed and recorded in a GIS. At the start we reported daily observations to MCDEM using map coordinates, but these had potential for misunderstanding and miscommunication. Once the nearest altitude contour was adopted with the catchment name, we had a unique identifier that enabled consistent reporting, communication, classification of photographs and follow-up investigations. Landslides were initially triaged daily, with their hazard classified into high, medium, low, unlikely and yet to develop. For those involved in the first week this typically involved 6-8 hours of flying per day, followed by 5-6 hours of data plotting and photo assessment, then 1-2 hours writing reports and recommendations for MCDEM. It was an intensive phase of work that utilised many people and left all weary.

Using the estimated values for the key variables for each dam, the hazard of the dam failing suddenly and sending a flood-wave downstream was made. This included identifying rivers and streams where multiple dams were present and where the flood could become a cumulative event. From this exercise a list of about thirty landslide dams was compiled where a breach hazard was present. This list of dams was then assessed for potential downstream risks, i.e. where people or property were potentially at risk from the rapid failure of a dam, taking into account the likely rapid attenuation of the flood-wave. This initially reduced the list to 12 dams (the process is a fluid one and remains so – some dams have overtopped and breached, some have breached by piping failure, others have been added to or removed from the list as better data has come to hand). Where the hazard or risk was assessed as high, either because of a large volume of impounded water, or people or critical assets (e.g. road bridges) in the path of a flood caused by rapid failure of the landslide dam further work was undertaken. A team of geologists and geomorphologists from the United States Geological Survey, including landslide specialists was then asked to review the landslide dam assessments and visited the key dams in the field. This peer review of the initial work carried out by the GeoNet landslide reconnaissance team confirmed the initial field assessments.

A process was then started to survey the dams in priority order based on risk, with life safety issues given the highest priority. The life safety issues identified included both occupied buildings (including a campground) and risks to road-users. Seven dams were identified as posing potential life safety risks, and additional data was collected so that rapid or catastrophic failure of the landslide dam could be modelled and the results used to inform those agencies tasked with managing public safety. Initially this started with experienced engineering geologists and geotechnical engineers providing visual estimation of the key parameters. However, it quickly became apparent there was variation in the way people interpreted observations and interpreted risk, so a process to obtain more rigorous data by surveying the dams and acquiring good topographic data for the potential flow-paths downstream of the dams was instigated. A terrestrial laser scanner was used to acquire initial scans of the landslides. However, it has taken longer to get LiDAR topographic data which is the preferred dataset for modelling the flow-paths. As each dataset has been acquired, the models have been re-run. This has consistently shown the initial visual estimates were conservative.

Two types of landslide dams are recognised based on the geological source material as mapped by Rattenbury et al (2006), namely: weak (5-20 MPa) Neogene sedimentary rocks (sandstones and siltstones), and moderately strong to very strong (20-100 MPa) Carboniferous to Cretaceous Torlesse ‘basement’ greywacke (sandstone) and argillite (mudstone) rock, but also includes some Neogene limestones. The most frequently occurring landslide types, adopting the scheme of Hungr et al. (2014), correlate to these materials, where reactivated rock planar and rotational slides tend to be the dominant landslide type in the Neogene sedimentary rocks. First time rock and debris avalanches with strong structural geological controls, were the dominant landslide type in the basement materials. This led to two quite distinct types of landslide dam. The weak rocks failed as large block slides and slumps and, compared to the strong rock dams, were relatively impervious (Figure 2). In contrast, the landslide dams formed from strong source rocks were effectively piles of porous angular gravels where piping of water flows through the dam is readily apparent (Figure 3). The source material for these landslides is Torlesse Greywacke which typically forms disrupted rock slides because of the closely jointed and fractured nature of the source rock mass. The resulting debris can be described as an angular gravel and is highly permeable. As a result, the large greywacke-derived landslide dams developed flows through the permeable material forming the dam under normal flow conditions. On the 6 April 2017, ex-Tropical Cyclone Debbie passed over the area dumping 100-150 mm of rain in 24-hours for the first time since the earthquake. As a consequence of this rainfall several of the greywacke dams finally overtopped and breached, effectively removing the landslide barrier and potential hazard.

How these two very different styles of landslide dam perform over the coming months and years is of interest as it will inform landslide dam assessment after future earthquakes. As of the 12th July 2017 only one of the large, strong source rock dams remain (on the Hapuku), the others having breached during annual flood flows generated by heavy rainfall in early April 2017. The large weak rock dams on the Stanton and Leader rivers are either still intact (Stanton River) or partially intact (Leader River).

Figure 2: Landslide dam on the Leader River shortly after the earthquake. The landslide is a slump/block slide in a siltstone and is typical of the large landslides in weak Neogene rocks. The dam overtopped and partially breached in February 2017 (Photo credit: Environment Canterbury).

In one case, the landslide dam in the upper reaches of the Hapuku River, the terrestrial laser scanning process has been repeated three times. The change model was derived from two scans, the first taken on 15 December 2016 and the second on 28 March 2017 (Figure 4) and shows the landslide dam was slowly deforming. The crest of the dam was lowered by a nearly one metre over a period of nearly four months, and the front of the dam shows erosion and scour from piping flows with deposition downslope. Subsequent to the second scan, the dam overtopped on 6 April 2017 with the formation of an overflow channel and further erosion of the downstream face.

4 DISCUSSION

A noticeable feature of this earthquake is the number of drainage blocking landslides it generated, which was partly due to the steep and confined slopes in the area and to the widely distributed strong ground shaking. 196 drainage blocking landslides triggered by this event have been mapped. The largest has an approximate volume of 12(±2) M m^3 and the debris from this travelled about 2.7 km down slope where it formed a dam blocking the Hapuku River. There are at least three other mapped drainage blocking landslides with volumes ranging from 2M to 8M m^3.

The largest landslides triggered by the Kaikoura earthquake are located either on or adjacent to faults that ruptured to the ground surface, are distributed across a broad area of intense ground shaking are not clustered around the earthquake epicentre, and their location appears to have a strong structural geological control (Figure 1). The mapped landslide distribution from the M_W7.8 Kaikoura earthquake, therefore suggests a complex interaction among earthquake ground shaking, geology, and topographic slope angle, which drives the occurrence of the largest landslides generated by this event. Many of the very large landslides that formed drainage blocking dams are also associated with fault rupture through or close to the source area. It is the potential for these large landslide dams to fail rapidly that represents the longer-term hazard after an earthquake. The large landslide dams on the Leader River, Stanton River and Hapuku River were identified as potential hazards in November 2016 and remain hazardous as of July 2017.

Figure 3: The greywacke-derived landslide dam in the upper reaches of the Conway River in the Seaward Kaikoura Ranges. This large dam developed flows through the permeable material of the dam under normal flow conditions (Photo 3A: J. Mitchell, 22/11/2016). On the 6 April 2017, 100-150 mm of rain fell in 24-hours and as a consequence this dam overtopped and breached, removing the landslide barrier and potential hazard. (Photo 3B: D. Townsend, 7/4/2017).

Monitoring and observations of landslide dams over a period of several months shows these features change. The change can be gradual as in the case of the settlement of the debris forming the dam across the Hapuku River or rapid as in the case of dams breaching. Rainstorms are an obvious driver of rapid change to landslide dams. A hazard that has slowly emerged is where large landslides occurred high in catchments. The inflow of water has been very slow and it has taken several months for lake filling to reach a point where it needs to be monitored regularly. An example is the landslide dam on the Bourne Stream, a tributary of the Waiau River, 5 km east of Waiau. This lake was still 4 metres below crest level as of July 2017.

The long-term stability of the cracked slopes and the drainage blocking landslide 'dams' during future strong earthquakes and significant rain events are an ongoing concern to the central and local government agencies responsible for rebuilding homes and infrastructure. A particular concern are the debris flood hazards that occur when some of the landslide dams breach. Several of these dams are located upstream from people and critical infrastructure such as road bridges, which might be at risk if the hazard were to occur. However, the number of dams that are of concern is reducing with rainstorm events (particularly in early April) resulting in breaching of four of the dams of greatest concern. Although the direct threat of debris flood hazards from rapid dam breaching is reducing the longer-term effects of sediment aggradation as the debris moves downstream from the steeper in-land slopes to the sea is another 'cascading' hazard that could pose a risk to agriculture, aquaculture and infrastructure. For example, these cascading hazards will increase river aggradation which will widen river beds, increase bank erosion and consequently increase both the magnitude and frequency of flooding.

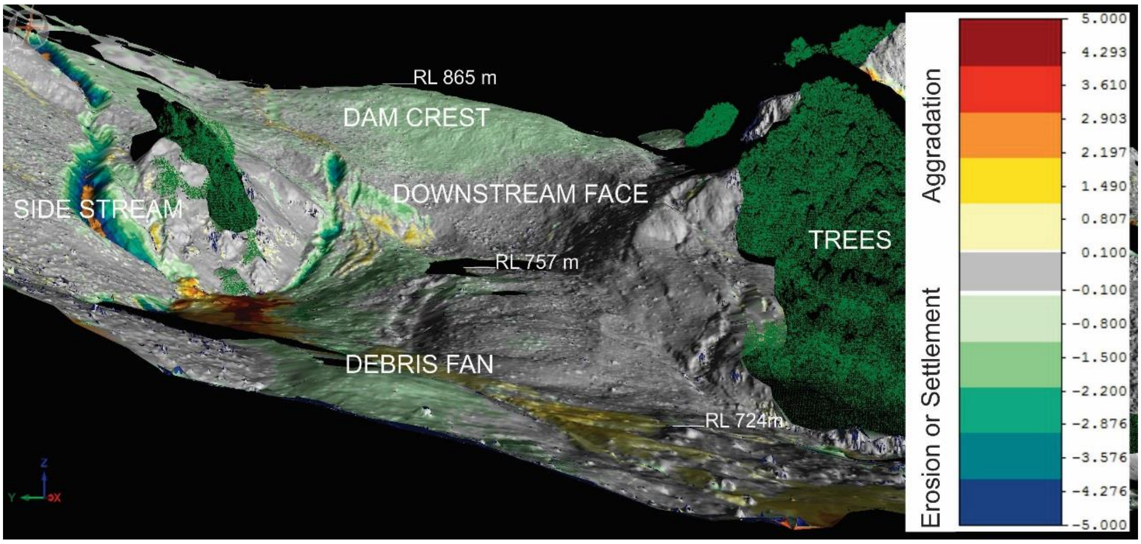

Figure 4: A change model of the downstream face of the Hapuku landslide dam. It shows cool colours in areas of settlement and erosion (greens and blues) and warm colours (oranges and yellows) in areas of aggradation. Dark green is woody vegetation. (Image processing carried out by Garth Archibald, GNS Science).

5 CONCLUSIONS

196 landslide dams or significant drainage constrictions were created as a result of this earthquake. Most have been assessed as having a low probability of failing in a way that will cause a hazard or present a risk to people or property as a consequence of rapid failure. However, at least a dozen, were identified as potentially hazardous with seven having clearly identified risks to people and property should they fail rapidly. Work to monitor and revise landslide dam hazard and risk assessments was ongoing for many months after the earthquake and in some cases continues (as of July 2017). The assessment of hazards and risks posed by the landslide dams informed the development of long-term management plans to mitigate the hazards and manage the residual risk. However, natural events have also played a hand with four of the seven dams assessed as having the highest risk having already breached before or during rainstorms in April 2017. These breached dams no longer pose a direct risk, but the longer term behaviour of the landslide source areas and the large volume of landslide debris now in the river systems still needs to be determined.

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REFERENCES

Dellow G.D. 2001 GeoNet landslide response. New Zealand Geomechanics News 62: 31-35.

Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update. Review article. *Landslides*. April 2014. Volume 11. Issue 2, pp 167-194.

Kaiser, A.E.; Balfour, N.; Fry, B.; Holden, C.; Litchfield, N.J.; Gerstenberger, M.C.; D'Anastasio, E.; Horspool, N.A.; McVerry, G.H.; Ristau, J.; Bannister, S.C.; Christophersen, A.; Clark, K.J.; Power, W.L.; Rhoades, D.A.; Massey, C.I.; Hamling, I.J.; Wallace, L.M.; Mountjoy, J.; Kaneko, Y.; Benites, R.A.; Van Houtte, C.; Dellow, G.D.; Wotherspoon, L.; Elwood, K.; Gledhill, K.R. 2017 The 2016 Kaikoura, New Zealand, earthquake: preliminary seismological report. *Seismological Research Letters, 88(3):* 1-13; doi: 10.1785/0220170018

Litchfield, N., Villamor, P., Van Dissen, R.J., Nicol, A., Pettinga, J., Barnes, P., Langridge, R., Little, T., Barrell, D., Mountjoy,J., Ries, W., Rowland, J., Fenton, C., Stirling, M., Cochran, U., and the surface rupture mapping team. Submitted. Surface fault ruptures of the Mw 7.8 2016 Kaikōura Earthquake demonstrate complexity at a plate boundary transition zone. Geology.

McSaveney MJ, Massey CI, Dellow GD 2010 Landslide response and monitoring: The New Zealand GeoNet experience. p. 443-450 (paper 053) IN: Williams, A.L.; Pinches, G.M.; Chin, C.Y.; McMorran, T.J.; Massey, C.I. (eds) Geologically active: delegate papers *11th Congress of the International Association for Engineering Geology and the Environment*, Auckland, Aotearoa, 5-10 September 2010. Boca Raton, Fla: CRC Press.

Rattenbury, M.S.; Townsend, D.; Johnston, M.R. (compilers) 2006: Geology of the Kaikoura area: scale 1:250,000 geological map. Lower Hutt: GNS Science. Institute of Geological & Nuclear Sciences 1:250,000 geological map 13. 70 p. + 1 folded map.