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LANDSLIDES CAUSED BY THE MW7.8 KAIKŌURA EARTHQUAKE AND THE IMMEDIATE RESPONSE

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ABSTRACT

Tens of thousands of landslides were generated over 10,000 km^2 of North Canterbury and Marlborough as a consequence of the 14 November 2016, MW7.8 Kaikōura Earthquake. The most intense landslide damage was concentrated in 3500 km2 around the areas of fault rupture. Given the sparsely populated area affected by landslides, only a few homes were impacted and there were no recorded deaths due to landslides. Landslides caused major disruption with all road and rail links with Kaikōura being severed. The landslides affecting State Highway 1 (the main road link in the South Island of New Zealand) and the South Island main trunk railway extended from Ward in Marlborough all the way to the south of Oaro in North Canterbury.

The majority of landslides occurred in two geological and geotechnically distinct materials reflective of the dominant rock types in the affected area. In the Neogene sedimentary rocks (sandstones, limestones and siltstones) of the Hurunui District, North Canterbury and around Cape Campbell in Marlborough, first-time and reactivated rock-slides and rock-block slides were the dominant landslide type. These rocks also tend to have rock material strength values in the range of 5-20 MPa. In the Torlesse ‘basement’ rocks (greywacke sandstones and argillite) of the Kaikōura Ranges, first-time rock and debris avalanches were the dominant landslide type. These rocks tend to have material strength values in the range of 20-50 MPa.

A feature of this earthquake is the large number (more than 200) of valley 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 largest landslide dam has an approximate volume of 12(±2) M m^3 and the debris from this travelled about 2.7 km^2 downslope where it formed a dam blocking the Hapuku River. The long-term stability of cracked slopes

and landslide dams from future strong earthquakes and large rainstorms are an ongoing concern to central and local government agencies responsible for rebuilding homes and infrastructure. A particular concern is the potential for debris floods to affect downstream assets and infrastructure should some of the landslide dams breach catastrophically.

At least twenty-one faults ruptured to the ground surface or sea floor, with these surface ruptures extending from the Emu Plain in North Canterbury to offshore of Cape Campbell in Marlborough. The mapped landslide distribution reflects the complexity of the earthquake rupture. Landslides are distributed across a broad area of intense ground shaking reflective of the elongate area affected by fault rupture, and are not clustered around the earthquake epicentre. The largest landslides triggered by the earthquake are located either on or adjacent to faults that ruptured to the ground surface. Surface faults may provide a plane of weakness or hydrological discontinuity and adversely oriented surface faults may be indicative of the location of future large landslides. Their location appears to have a strong structural geological control. Initial results from our landslide investigations suggest predictive models relying only on ground-shaking estimates underestimate the number and size of the largest landslides that occurred.

INTRODUCTION

At 12.03 am local time on 14th November 2016 (UTC: 11.03 am 13th November 2016) a shallow (15 km^2) magnitude 7.8 earthquake (Mw), with an epicentre located near Waiau in North Canterbury, struck 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 run by GNS and funded by EQC, has a requirement to respond to major landslide events in New Zealand using a set of wellestablished criteria [1,2]. The MW7.8 Kaikōura earthquake met several of these criteria, including the presence of consequential hazards in the form of landslide dams, direct damage in excess of $1 M, indirect damage in excess of $10 M and significant scientific interest. The landslide response initially involved capturing a picture of what had happened in terms of landslides during the first week and quickly evolved into two work-streams. One work-stream focussed on developing the processes and acquiring data in order to compile a world-class landslide inventory. The other workstream focussed on landslide dams (landslides blocking rivers and streams and impounding bodies of water) and again evolved from a search task, to a rapid assessment of hazard and examining high hazard dams for consequent risks, and then undertaking more detailed

work to survey the dangerous dams so the consequences of a very rapid (catastrophic) failure could be modelled and used by authorities to manage the risks.

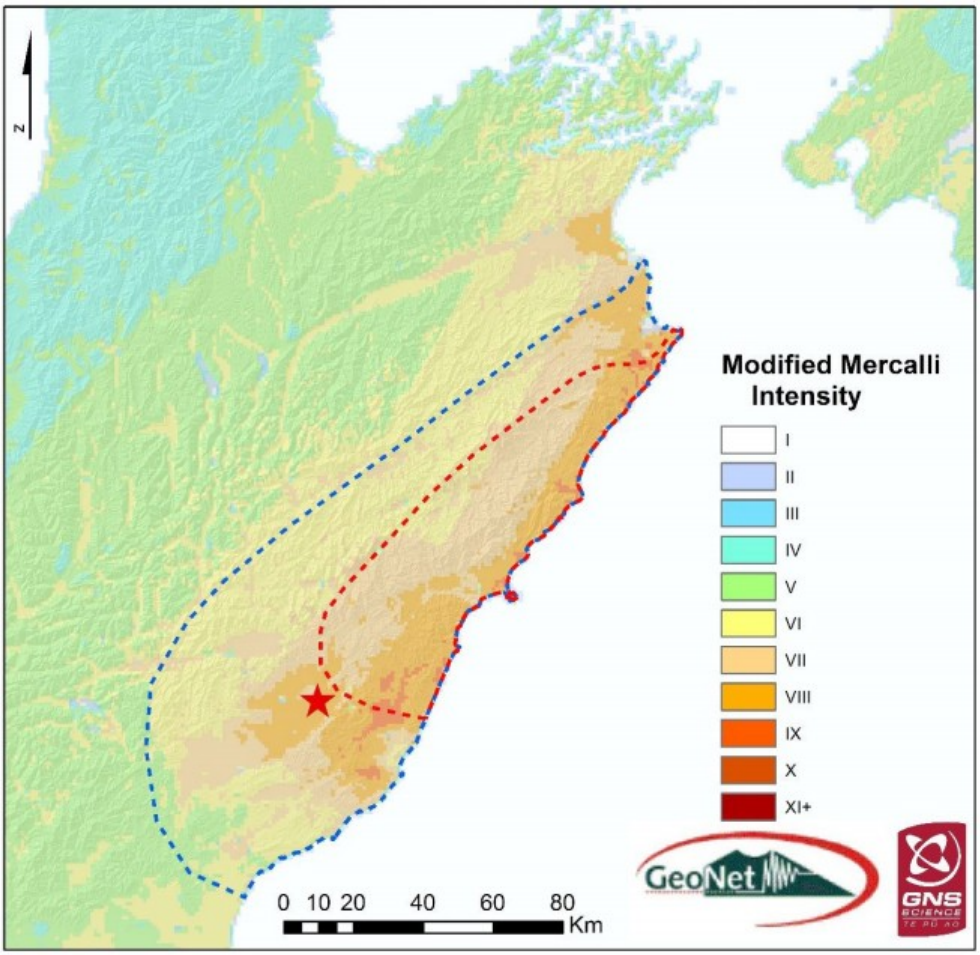

Figure 1: The 14th November 2016 M_W7.8 Kaikōura Earthquake. The epicentre is shown by the red star in the south of the map. The colours depict the Modified Mercalli Shaking Intensity, with MM VIII in the worst affected areas with isolated pockets of MM IX where deep soils are present. The areas of no landslide damage; light to moderate landslide damage (blue dash), and severe landslide damage (red dash) are shown. The severity of the landslide damage corresponds well with the strength of ground shaking in areas of hills and mountains. (Map credits: MMI - Nick Horspool; Landslide observations - Dougal Townsend).

LANDSLIDE RESPONSE

Response to events that generate thousands to tens of thousands of landslides has evolved over the last sixteen years through the GeoNet Project run by GNS Science and funded by EQC. Landslide response activities for events that generate multiple landslides are focussed on two strands of work. The first strand deals with the immediate risks, particularly if no other agency has the responsibility or resources to assess and inform the relevant authorities of actions that can be taken to reduce the risks, in the first instance to people and subsequently to property. For example, NZTA has the responsibility and resources to assess and inform decision making around landslide risks to road users, and can take appropriate steps to reduce the risks. In contrast, the Department of Conservation does not have the

resources to assess landslide hazard but can implement actions to reduce the risk if supplied with good quality information. If a state of emergency is declared, then the landslide team at GNS Science can provide specialist advice to the agencies with statutory authority to implement risk reduction measures (e.g. emergency services with respect to evacuations).

The second strand of work is compiling an inventory of the landslides with as much information as possible (e.g. location (polygon preferred), size (area and volume if possible), source area, and debris trail). This ensures any subsequent work to understand and mitigate future hazards and risks from landslides has a good empirical evidence base. This work is important because it provides the basis for providing advice on longer term measures to manage the risks from landslide hazards, such as rules and regulations in district plans implementing risk reduction measures.

LANDSLIDE RECONNAISSANCE

The MW7.8 Kaikōura earthquake occurred at 12.02 am on Monday morning 14th November 2016. Because the earthquake occurred in the middle of the night little attention could be paid until daylight arrived. Aerial reconnaissance leaving from Wellington at daybreak (6.00 am) identified the first indications of slope failure attributable to the earthquake on the western side of Cape Campbell. Also identified were small rock and soil falls along cut slopes adjacent to SH1 south of Ward along with associated slumped fills.

Between Waipapa Bay and Mangmaunu at the Mouth of the Clarence River in the north, to the mouth of the Hapuku River in the south, State Highway 1 and the main trunk railway line was completely inundated by debris from large landslides in several places (Figure 2). After stopping briefly in Kaikōura the reconnaissance continued, travelling south and observing State Highway 1 and the main trunk railway line again being blocked in several places by large landslides between Peketa and Oaro. Continuing south along the coast, landslides were prominent on the coastal cliffs as far south as Goose Bay (Figure 3).

Figure 2: Landslide blocking the railway line and State Highway 1 north of Kaikōura. The landslide has broken the railway line and dragged the tracks across the road on the right hand side of the photo. The coastal uplift at this site is also visible in the exposed shoreline covered with sub-tidal seaweed. (Photo: S. Dellow 14/11/2016).

Turning inland at Goose Bay to refuel at Cheviot before travelling through to the Hanmer Springs turn-off the landslide observations were sparse, in part a reflection of the gentler topography and the directivity of the shaking that became apparent in the days and weeks that followed. From Hanmer Springs the Hope Fault was picked up and flown along back to the coast, north of Kaikōura. While flying along the Hope Fault, which is at the southeast foot of the Seaward Kaikōura 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 (Figure 4).

Figure 3: Landslides on either side of the Paratatahi Tunnels, State Highway 1, south of Kaikōura. The railway line at this location is enclosed in a rock shelter, and so was not directly affected. (Photo: S. Cox, 20/11/2016).

The final leg of the initial reconnaissance flight was almost directly north from Half Moon Bay, where the Hope Fault crosses the coastline, through to Omaka. This leg of the flight revealed reasonably severe landslide damage in both the Seaward and Inland Kaikōura Ranges but very little north of the Awatere River.

The reconnaissance carried out on the 14th November 2016 by GNS Science staff using the GeoNet programme and observations reported in the media and by others (ECAN reported on and dealt with the landslide dam in the Clarence River that failed some 16 hours after the earthquake) gave a picture that could be used going forward. 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 between the coast and the red dashed line on Figure 1).

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 Kaikōura. 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. A plan to systematically search for, identify and carry out an initial assessment of landslide dams was developed and implemented.

Figure 4: Landslide dams in the upper reaches of the Conway River in the Seaward Kaikōura Ranges. Two landslide dams are visible in the photo with water still impounding behind both. The source material for the 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, none of the large greywacke derived landslides overtopped under non-flood conditions, but developed flows through the permeable material forming the dam. (Photo: D. Townsend, 16/11/2016).

LANDSLIDE DAMS

The search for, and assessment of, landslide dams after the 14th November 2016 MW7.8 Kaikōura Earthquake is a process that is still in progress (as of April 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 over 200 valley blocking 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 with a unique identifier relating to the catchment name and altitude (in m) above sea level. Landslides were triaged daily, with their hazard classified into high, medium, low, unlikely and yet to develop. 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 (Figure 5). Initially this started with experienced engineering geologists and geotechnical engineers

providing visual estimation of the key parameters. However, it quickly became apparent that this was unreliable from the variation in estimates made by different people and a process to survey the dams and acquire good topographic data for the potential flow-paths downstream of the dams was instigated. Again this task is ongoing. 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 shown fairly consistently that the initial visual estimates were highly conservative.

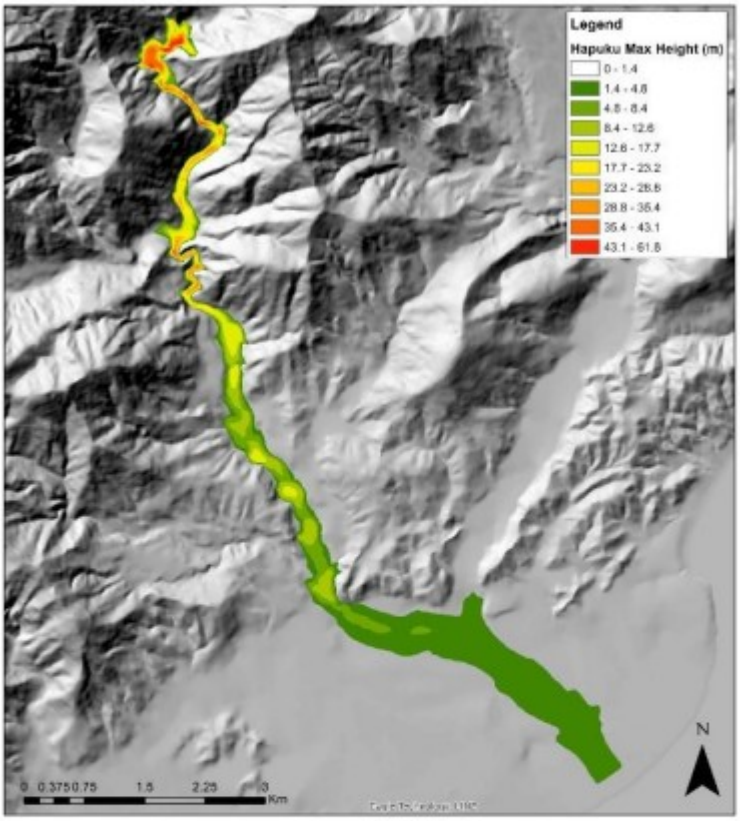

Figure 5: RAMMS modelling of the flow heights from rapid failure of the Hapuku landslide dam. Model parameters include a dam height of 80 m, dam width of 230 m; total volume of flow of 3 x 10^6 m^3; and a maximum discharge of 13,000 m^3/s. Even with good data a range of scenarios is possible. This model run depicted the maximum credible flow height from rapid dam failure.

Two types of landslide dams are recognised based on the source material, namely: weak (5-20 MPa) Neogene sedimentary rocks (sandstones and siltstones), and moderately strong to very strong (20-100 MPa) Carboniferous to Cretaceous Torlesse ‘basemen’ rocks (greywacke (sandstone) and argillite (mudstone), but also includes some Neogene

limestones). The most frequently occurring landslide types, adopting the scheme of [4], correlate to these materials, where reactivated rock planar and rotational slides tend to be the dominant landslide type in the Neogene sedimentary rocks (Figure 6). First time rock and debris avalanches with strong structural geological controls, were the dominant landslide type in the basement materials (Figure 7). 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. 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. How these two very different styles of landslide dam perform over the coming months and years is of interest because of the ability this has to inform landslide dam assessment after future earthquakes. As of the 12th May 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. Both of the large weak rock dams on the Stanton and Leader rivers are still intact (Stanton River) or partially intact (Leader River).

In one case, the largest landslide dam in the upper reaches of the Hapuku River (Figure 7), the terrestrial laser scanning process has been repeated three times. This showed that the landslide dam itself was slowly deforming (lowering at the crest by a nearly one metre over a period of nearly four months and bulging at the toe, again by a nearly one metre).

KAIKŌURA LANDSLIDE INVENTORY

A landslide inventory is being compiled to capture the spatial distribution of landslides triggered by the 14 November 2016, MW7.8 Kaikōura earthquake, to provide information for recovery activities and to provide a high quality dataset for future research (Figures 8 and 9). The inventory captures information on: landslide type (material and style of movement); landslide magnitude (areal size, and volume where possible); runout (distance the debris travels down slope); connection and/or interaction with rivers (e.g. occlusions, blockages, buffered); surface deformation such as evidence of potential/incipient landslides (e.g. areas of cracking or incomplete failures where landslide debris may still be present in the source and has potential to remobilize).

The data will be useful for recognizing immediate hazards (potential for failures/reactivations; Figure 8), outburst floods (dam breaches), short- to longer-term potential for debris flow and valley floor aggradation impacts, sediment budgets for catchments, and for assessing landslide causes (i.e. relationships with topography, geology, fault structures, shaking; Figure 9). One of the main uses of this data will be to assess how slopes performed in particular rock and soil (material) types during the earthquake. This data will be especially useful for those similar-sized slopes in Wellington, where much of the city is formed in similar materials (greywacke sandstones and

argillites) to those forming the slopes in the, albeit more mountainous, Kaikōura region. Such data will allow us to better constrain the response of the Wellington slopes to strong shaking e.g. a Wellington Fault earthquake.

Capturing the landslide data is an ongoing process as new information becomes available (e.g. satellite images, LiDAR survey data). Once the inventory has been completed it will be uploaded to the NZ landslide database maintained by GNS Science (http://data.gns.cri.nz/landslides).

Figure 6: Landslide dam on the Leader River shortly after the earthquake. The landslide is a slump/block slide in a siltstone unit and is characteristic of the large landslides in weak Neogene rocks. The landslide dam overtopped and partially breached on the 13-14 February 2017 (Environment Canterbury).

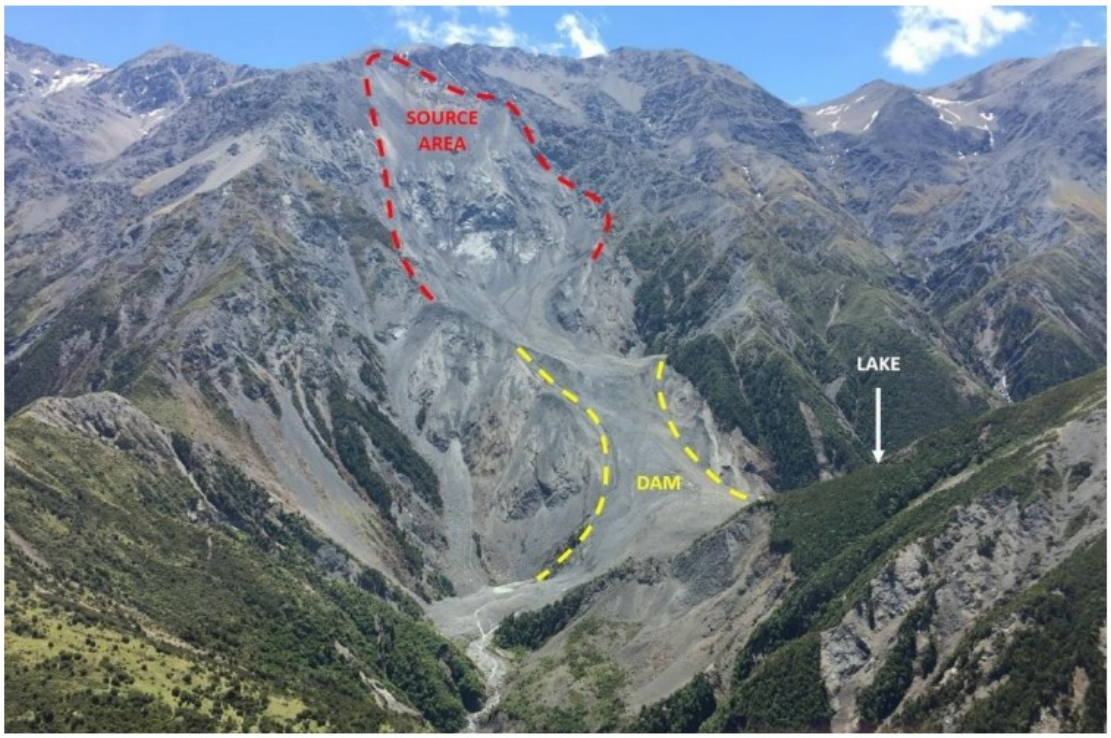

Figure 7: Hapuku River Landslide dam showing source area, landslide dam and valley downstream of dam. The landslide is a rock avalanche with a horizontal distance between top of the source area and the toe of the debris of 2.7 km. The volume of material in the landslide dam is estimated at 12 (±2) x 10^6 m^3. This is an example of a greywacke dam with internal flows readily apparent as seepage discharges near the toe of the dam on the downstream face.

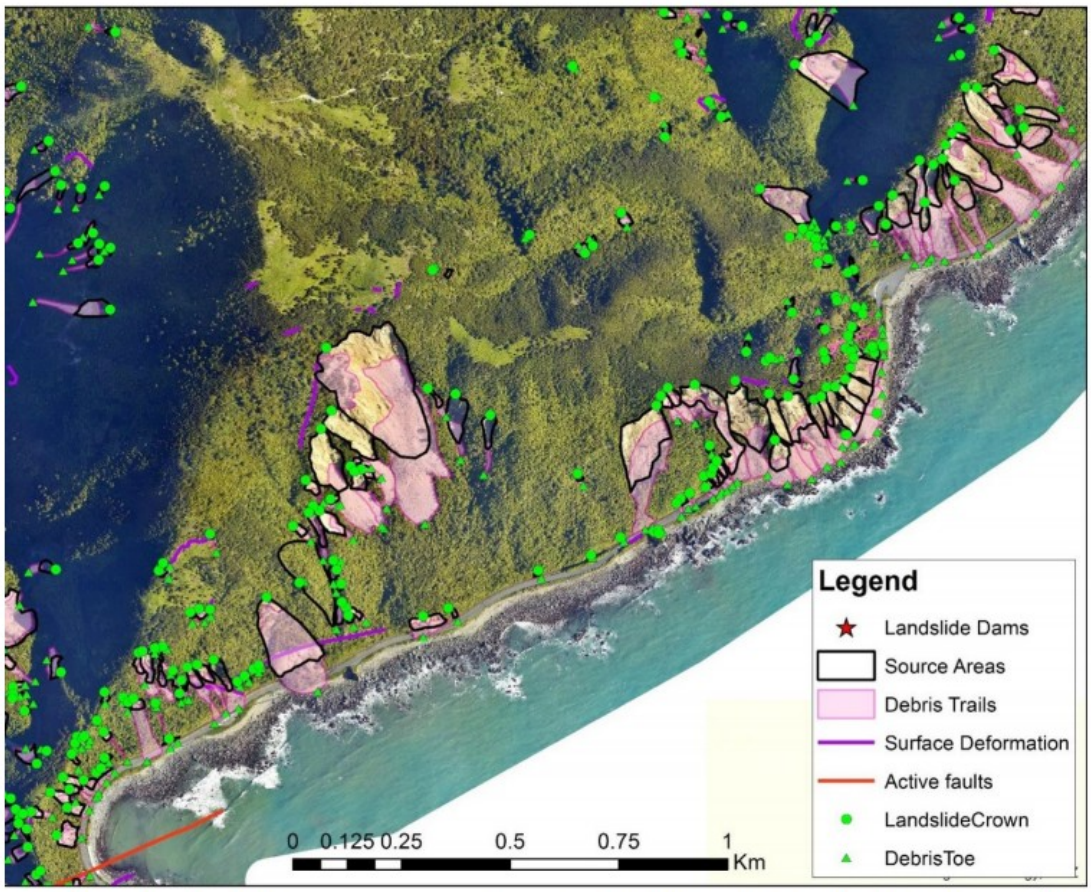

Figure 8: An example of landslide inventory mapping on the coast north of Kaikōura. The large landslides in the centre left of the photo did not reach the foot of the slope and the debris is a hazard that could remobilize in an aftershock or rainstorm and will present an ongoing risk to road and rail users if mitigation measures are not determined and implemented.

The compilation of the landslide inventory will utilize the following data sources:

- Satellite imagery including: WorldView- 2 (WV2) 2.4 m resolution (multispectral bands). Imagery date: 22 November 2016; WorldView- 3 (WV3) is 1.4 m resolution (multispectral bands). Imagery date: 25 November 2016; GeoEye (GE) 2 m resolution. Imagery date: 15 November 2016.
- Low level aerial oblique photographs are also being used to help define the landslides. These photographs (many thousands) have been captured by the landslide reconnaissance team and others post-earthquake, mainly from helicopters. The photographs are georeferenced, and they cover most of the area affected by landslides.
- Pre- and post-earthquake orthorectified aerial photographs (captured by Aerial Surveys Limited and commissioned by LINZ), 0.3 m resolution.
- Post-earthquake digital elevation models derived from airborne LIDAR.

- Post-earthquake digital surface models derived from stereo satellite imagery (NSF RAPID project).
- Pre- and post-earthquake digital surface models derived from the aerial photographs.

The WV2 and WV3 images (provided by Digital Globe) have been processed by GNS Science. These have moderate positional quality (X, Y and Z) and in some mountainous areas the images have been poorly stretched (relief stretch). The same images have been processed by EAGLE Technology. These have better relief stretch but poor positional quality. The images from the different data sources do not cover the entire area affected by landslides, but together they do cover all of the main area affected by landslides.

In addition to the satellite imagery, low level aerial oblique photographs are also being used to help define the landslides. They are made available to the mappers via a geodatabase structure in ESRI ArcMap.

The national LINZ 8 m by 8 m digital elevation model (DEM) covers the entire area affected by landslides. This is also being used for the mapping. In addition to this, there is also a 1 m by 1 m DEM generated from pre-earthquake LIDAR, however, this is confined to a small coastal strip, but is still useful.

The USGS landslide program team and members of the Landslide GEER team have also contributed their field data. Some of this information comprises a preliminary landslide inventory based on LandSat imagery (carried out by the University of Texas), which covers some of the main area affected by landslides. These data are also being used to generate the initial landslide inventory.

To ensure a consistent methodology for capturing landslide information, several feature classes in an ArcGIS geodatabase have been set up, with fields containing drop down (restricted) lists for capturing the key landslide information (discussed below).

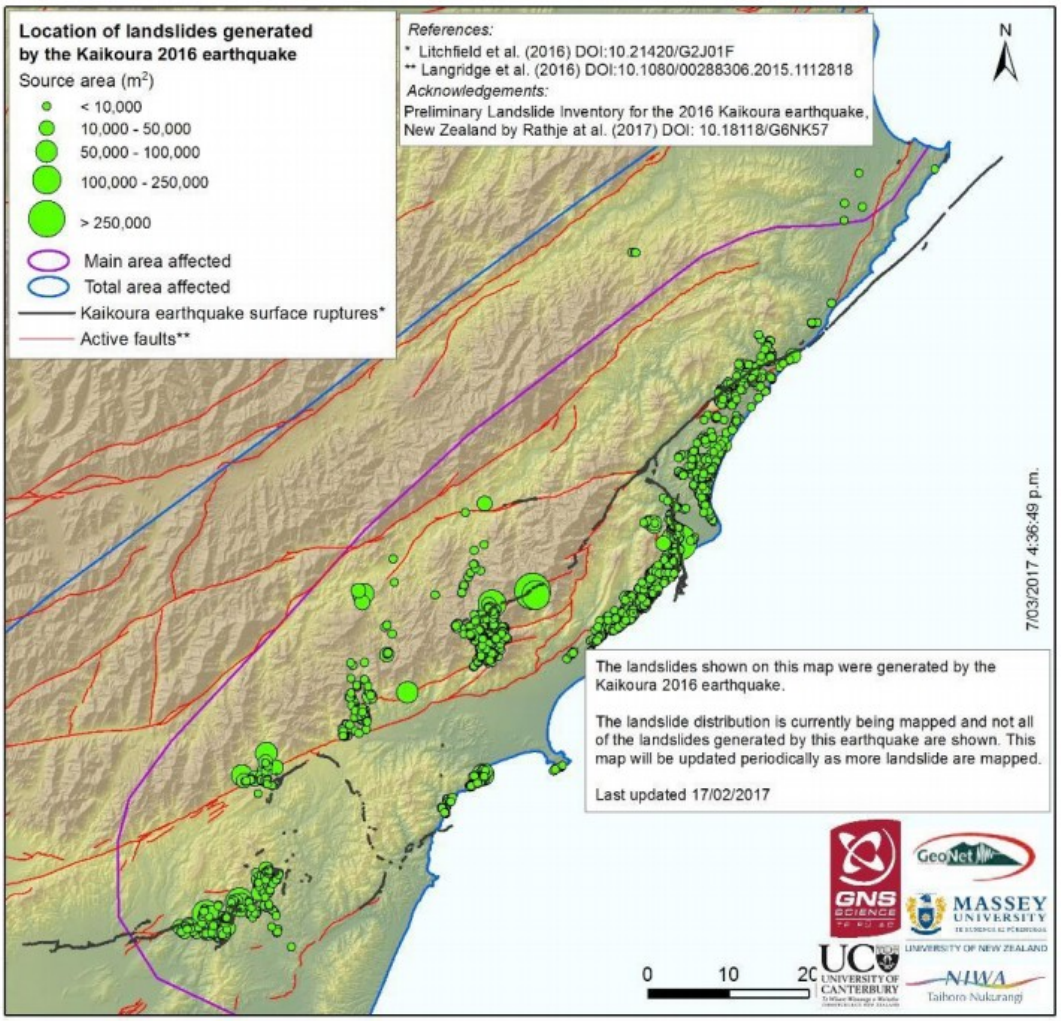

Figure 9: The landslide inventory for the 14 November 2016 M_W7.8 Kaikōura earthquake as at 17 February 2017 (estimate 30% complete). The active fault ruptures cause by the earthquake are shown as black lines on the map. The landslides, and particularly the largest landslides cluster around the fault ruptures.

After mapping the respective areas (and weekly updates during mapping), the data is collated and sent to various parties. A sample of each area is checked by another mapper. Following this, further samples of the mapped data have been targeted for field verification.

For each landslide, the following is being collected:

Polygons:

1. Extent of source area (polygon). Note that as best as possible, this should define the whole source area (not just the exposed source area), and may therefore overlap with the landslide debris.

2. Extent of landslide debris. If debris trails from multiple source areas merge, then the polygons also need to merge. Points:

3. Landslide crown: A point at the top of the landslide crown/headscarp (highest point).

4. Debris Toe: A point at the distal end of debris tail (lowest down slope point).

Lines:

5. Slope deformation: evidence of surficial cracking (scarps), bulging or other deformation indicating mass movement not captured within the landslide polygon areas. These are potential sites of water ingress during later rainstorm events that may destabilize the slope.

Each of these features is linked by a common feature ID, in the 'SourceID' field within each feature class. If there are multiple source areas linked to one debris trail, each Source ID number is added into the 'SourceID' field in the landslide debris attribute table.

For each landslide **source area** polygon, as much information as possible is entered into the attribute table (Table 1). There are drop down lists for landslide type information (material type and movement style/mechanism), which are based on the [4] classification. There are potentially other terms that can be added later that are not included in the classification. There are also a few landslide types that we are unlikely to observe (such as peat failures) but that have been included for completeness. Below are the fields for the source area feature class, with an explanation and example of each.

For the **debris trail** polygon feature class, and the crown and debris toe points, only the SourceID is used to link to the landslide source area.

In addition to discrete landslides, linear slope deformation indicators (i.e. evidence of incipient failures, such as scarps, antiscarps, or cracks that occur outside of the landslide polygons), can be mapped using a Surface Deformation feature class. The information to add to the attribute table is the type of surface deformation (from the 'Type' dropdown list).

Work areas that cannot be mapped (e.g. due to cloud cover or very poor quality imagery) are also identified. For these areas, a polygon shapefile is created (e.g. named 'obscured areas') that outlines the obscured areas. These may be mapped at a later date if suitable imagery becomes available.

DISCUSSION

The 14 November 2016 MW7.8 Kaikōura earthquake generated tens of thousands of landslides and more than 200 significant landslide dams. Landslides affected a total area of about 10,000 km^2 with the majority concentrated in smaller area of about 3,500 km^2. During the Kaikōura earthquake at least 21 faults ruptured to the ground surface or sea floor [5, 7] through two geologically and geotechnically distinct materials: Neogene sedimentary rocks, and Carboniferous to Cretaceous Torlesse greywacke. Although the observed landslide types correlate to these materials, the largest landslides triggered by the 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 and not clustered around the earthquake epicentre, and their location appears to have a strong structural geological control [6]. These results suggest that event-triggered populations of large landslides could be used to map surface-fault rupture for previous historical earthquakes in New Zealand (e.g. 17 June 1929 M7.8 Murchison earthquake; [3]).

Table 1: Landslide source area attribute table.

Fields	Explanation	Examples
ObjectID	Auto	
Source ID	A unique number for your copy of the database. Each source area should have a unique number. Number does not have to be unique to the whole database, as 'Originator' field will be used to differentiate duplicate id numbers.	1000
Primary material	The main material type that failed. This is not the geology or description of the origin of the material, but rather related to the material properties and their genesis (origin) which influence the failure and runout behavior. If it cannot be easily assessed use the 'undifferentiated' term.	Rock, clay, mud, coarse clastic (e.g. non-plastic silt, sand, gravel and boulders), peat, ice, undifferentiated.
Secondary material	If there is a second material type involved which appears to have had a significant influence on the failure or runout mechanics, then can include a second material type. If only one major material type, just leave this field as 'Null'.	Same options as primary material.
Landslide style	The movement mechanism	Fall, topple, slide (can differentiate into rotational, planar, wedge), flow (can differentiate into avalanche, dry flow, flowslide, earthflow), slope deformation, or creep. Use 'undifferentiated' if you cannot tell which style of movement.
Activity/history	Indicated whether landslide appears to be a first-time failure or a reactivation of a previous movement.	
Connectivity	This describes the relationship of the landslide debris to streams/rivers or major drainage lines.	Uncoupled (i.e. sediment has remained on the slope); Coupled (at least some of the sediment has entered a drainage line (including active floodplain, but not including well-vegetated terraces); Blocked (any evidence of blockage even if blockage has since breached).
Comment	Additional notes or clarifications.	
Method & Confidence	Initial mapping method (i.e. imagery etc.) used to digitize the landslide, and confidence in the mapping.	For each of the methods (Satellite, Orthophoto, Oblique photo, Ground visit, or Multiple [i.e. some combination of these methods]), specify the confidence of the mapping by either 'High' or 'Low'. 'Low' confidence may indicate strong uncertainty in the landslide boundary, uncertainty in the type of landslide mapped, or uncertainty in co-seismic occurrence (in Kaikōura EQ sequence). 'High' confidence can be used if you are fairly confident on the mapping.
Shape Area	Auto generated	
Length	Auto generated	
Geology	Will auto generate from QMAP data later.	
Originator	Who digitized the landslide.	C. Massey

The majority of landslides occurred predominantly in two geologically and geotechnically distinct materials, namely: weak to moderately strong (5-50 MPa) Neogene sedimentary rocks (limestones, sandstones and siltstones), and moderately strong to very strong (20-100 MPa) Carboniferous to Cretaceous Torlesse "basement" rocks (sandstones and argillite). The most

frequently occurring landslide types, adopting the scheme of [4], correlate to these materials, where reactivated rock planar and rotational slides tend to be the dominant landslide type in the Neogene sedimentary rocks, and first time rock and debris avalanches with strong structural geological controls, were the dominant landslide type in the basement materials.

A noticeable feature of this earthquake is the number of valley 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. More than 200 significant valley 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 valley blocking landslides with volumes ranging from 2M to 8M m^3. Another noticeable aspect of this event is the large number of landslides that occurred on the steep coastal cliffs south of Ward in southern Marlborough and extending to Oaro, north of Christchurch.

The area affected by landslides is relatively remote with few people living there, and so only a few homes were impacted by landslides and there were no recorded deaths due to landslides. Landslides along the coast, however, caused the closure of State Highway (SH) 1 and the North Line of the South Island Main Trunk Railway, preventing people and goods from entering or leaving the town of Kaikōura, which had a permanent population of about 3,550 people (and seasonally expands due to tourists). These closures led the responsible government agencies to prioritise opening the'Inland Route 70' to Kaikōura to allow the passage of people, food and water. At the time of writing, the northern section of SH1 from Kaikōura and the North Line of the South Island Main Trunk Railway are both still closed, six months after the earthquake. The long-term stability of the cracked slopes and the valley 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 might occur should 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.

The largest landslides triggered by the Kaikōura 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. The mapped landslide distribution from the MW7.8 Kaikōura 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.

Past efforts to explain the spatial variability in co-seismic landslide size and concentration typically rely on comparisons with earthquake magnitude and mechanism, epicentral distance, seismic observations such as peak ground acceleration, peak ground velocity, and engineering parameters such as Arias Intensity and other proxies for ground shaking intensity such as proximity to mapped faults. These factors are then combined with topographic slope angle and geologic information to generate event-based statistical or deterministic models used to explain the distribution of landslide frequency and area or volume. However, most eventbased models fail to adequately describe the occurrence of the few relatively large volume landslides generated by a given earthquake, and in plots of landslide frequency and volume, these landslides are typically outliers. This limits the usefulness of such models for assessing the hazard and geomorphic impacts associated with large co-seismic landslides. A high quality landslide inventory and detailed engineering geological mapping of the largest landslides will allow the interaction between large landslide occurrence and surface fault rupture to be investigated and how the localised release of energy, along with structural geological and material controls and slope morphology interact to initiate large landslides.

SUMMARY

Tens of thousands of landslides were generated over 10,000 km^2 of North Canterbury and Marlborough as a consequence of the 14 November 2016, MW7.8 Kaikōura Earthquake. The most intense landslide damage concentrated in 3500 km^2 around the areas of fault rupture. Given the sparsely populated area affected by landslides, only a few homes were impacted and there were no recorded deaths due to landslides. Landslides caused major disruption with all road and rail links with Kaikōura being severed. The landslides affecting State Highway 1 (the main road link in the South Island of New Zealand) and the South Island main trunk railway extended from Ward in Marlborough all the way to the south of Oaro in North Canterbury.

Over 200 landslide dams 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. However, at least a dozen, have been identified as potentially hazardous with seven having clearly identified risks to people and

property should they fail rapidly. Work is ongoing to assess the hazard and risk posed by these dams to inform the development of long-term management plans to mitigate the hazards and manage the residual risks. However, natural events have also played a hand with four of the seven dams assessed as having the highest risk having already breached during rainstorms in April. 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.

The landslide inventory work continues. The creation of a high-quality empirical landslide inventory for this earthquake will underpin the development of plans and policies to mitigate and manage the risks from slope instability in this area. Quantifying the changing hazard as rainstorms and aftershocks return the landscape to equilibrium will also provide for some understanding of the longer-term impacts of this earthquakes as sediment cascades from slopes and through fluvial systems where bridges and flood protection schemes are at risk of being overwhelmed.

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