Earthquake-induced slope instability: Data collection and management for future planning and development

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ABSTRACT: This paper examines the type of information collected, and the practicality of collecting and managing slope instability information following the 2010/11 Canterbury Earthquakes. Approaches and methods of improving preparedness for information collection following the next inevitable event in New Zealand are outlined.

The Canterbury Earthquakes of 2010/11 caused widespread rockfall, cliff collapses and landslides on the Port Hills. The initial task of collecting information to obtain a broad understanding of the extent and severity of slope instability was a significant undertaking mainly executed by local engineering geologists. Impacts and consequences of slope instability on key infrastructure were assessed in addition, many structures and residential properties required detailed inspections to assess public safety. On-going earthquake activity made this collection of relevant information increasingly complex and demanding on limited resources.

The slope instability information collected has been pivotal for assessing response and recovery life-safety risk and setting priorities to protect and repair key infrastructure; but this use of the information represents only part of its worth. Future risk reduction decisions including land use planning and development, and infrastructure design and location, will rely heavily on the information collected and the analysis completed over the last two years.

1 INTRODUCTION

1.1 Background

Christchurch City is on the east coast of New Zealand's South Island. The 2010/2011 Canterbury earthquakes began on 4 September 2010 with a M7.1 earthquake near Darfield, 40km west of the City. On 22 February 2011 a M6.3 earthquake occurred under the south of the City and a M6.4 earthquake on 13 June 2011 under the southeast of the City. A fourth earthquake, M6.0 on 22 December 2011 occurred 9km to the east of the City. The earthquakes are referred to in this paper as the 'September', 'February', 'June' and 'December' earthquakes.

There was minimal slope instability in the Port Hills from the September earthquake because the epicentre was 40km away, however widespread rockfall, cliff collapse and landslides occurred during the February and June earthquakes. The December earthquake caused limited further instability.

1.2 Geological Setting

Christchurch City is located on the Canterbury Plains, an area of glacio-fluvial gravels overlain with deep alluvial deposits laid down over the last 3Ma (Forsythe et al 2008). The greywacke bedrock is about 500m below Christchurch. The Port Hills, an area of about 120km^2 to the south of the City, is part of the eroded flanks of the extinct Lyttelton Volcano. The geology comprises interbedded basalt that has columnar jointing, ash layers, and layers of breccias and agglomerates. The columnar basalt is very strong, the ash, very weak, the breccia layers are variable in strength, and the overall rock mass dilated. Overlying the rock there are thick deposits of loess (wind blown silt) and these deposits generally thicken to the west. The topography of the Port Hills is generally more rugged to the east with steep slopes and numerous rock bluffs and cliffs.

1.3 **Land Use**

The Port Hills are a significant landscape feature forming the backdrop to the City. Most of the Port Hills is rocky open tussock land (public reserve) with some grazing. Residential development occupies about 15% of the Port Hills and is generally concentrated on north facing lower slopes, and selected ridges and spurs. The slopes above many residential areas, and particularly in the eastern part of the Port Hills, are steep with numerous rock outcrops.

2 DATA COLLECTION

2.1 **Background**

The February earthquake caused rockfall (boulder roll), cliff top failure, debris inundation (base of cliffs) and landslides. Rockfall was widespread with large but localised cliff collapses confined to three main areas. To determine the nature and extent of the slope stability hazards and risks to life, a methodical and consistent investigation was required. To help understand the scale of the hazards and determine the existing and potential risks information was needed by a range of organisations immediately after the February earthquake including Civil Defence Emergency Management (CDEM), Urban Search and Rescue (USAR), the Christchurch City Council (the Council) and emergency services. Life-safety risk was initially managed by evacuating people from their homes by issuing CDEM red placards to buildings. These were later replaced with Section 124 (s.124) notices issued under the Building Act 2004.

2.2 **Introduction**

The Port Hills Geotechnical Group (PHGG) "self-formed" immediately after the February earthquake under the auspices of the Council. The PHGG included eight local consultancy companies supported by the University of Canterbury and GNS Science. The PHGG divided the Port Hills into nine areas defined by the severity of observed slope instability, and other characteristic factors such as topography and land use. A sector leader was assigned to each area from the PHGG based on their local knowledge and experience. The PHGG rapidly grew with the spontaneous arrival of many field teams from around New Zealand.

Initial fieldwork comprised responding to a wide range of slope instability issues reported to the CDEM Operations Centre by the public. Property specific slope stability information was stored in a Microsoft Excel database. This format was useful initially for keeping a record of properties visited, however this was not an appropriate format to allow a full understanding of the nature and extent of the slope instability. A decision was therefore made by the Council to enter the data into a Geographical Information System (GIS). The GIS enabled efficient and consistent data management and allowed for an early and rapid preliminary overview of the extent and severity of the slope instability hazards.

The data collection initially focussed on all four mass movement types. However, because no landslides appeared to pose an imminent risk, the main focus of information collection was diverted to the rockfall and cliff collapse areas. (cliff top failure and debris inundation).

2.3 **Rockfall**

The aim of the rockfall mapping was to map the location of the boulders and to identify source areas. The initial focus was on boulders that were in precarious positions. Boulders that had reached slope toe areas were generally stable. Each boulder was assigned a unique number that was spray-painted on it. GPS co-ordinates of the boulders were recorded as well as size, shape, stability and how it was supported, an indication of what remediation may be required and an overall risk rating was assigned. The risk rating was based on the likelihood of the boulder moving downslope and what structures were at risk. With time, the amount and nature of the information collected by the PHGG became more targeted once the intended use of information became clearer. Significant time was spent uploading the information into the GIS because supplementary comments recorded on the field record sheets were difficult to translate into the GIS fields established by PHGG.

Within the first weeks after the February earthquake key roads for response and recovery purposes were identified and rockfall risk mitigation at source was carried out. This included scaling, blasting and temporary bolting. The purpose of the physical works was to reduce the risk to lifelines from rockfall. However, the June earthquake caused further significant rockfall (and cliff collapse) and extensive re-mapping was required.

Information in the GIS included location of houses with s.124 notices and other details such as the name of the person who had mapped each of the boulder locations. Photographs of the boulders were included and the data was divided into in-situ boulders and those that had fallen. Many other improvements were made to the GIS including the earthquake event the boulder could be attributed to, an important detail for the Council's insurance claims. With the ever increasing complexity of the data, a digital field data gathering system was developed by Aurecon NZ Ltd.

The digital field data gathering system used tablets synchronised to the GIS system in real-time and information such as GPS co-ordinates was automatically included. The system underwent several weeks of trials and improvements before being adopted by all the consultants of the PHGG. Unfortunately only about 20% of the information was recorded digitally as most had been mapped before the system was developed, however this system significantly reduced the time taken to input data into the GIS. Another benefit was being able to access the GIS data in the field via tablet computers, allowing rapid and accurate refinement of data already collected.

2.4 **Cliff Collapse**

During the February earthquake significant cliff collapses occurred and mapping was undertaken to determine whether areas of future failures could be defined. Detailed mapping along cliff tops showed a zone of cracking generally 10m to 40m back from the cliff edge. The data was recorded on high resolution post-earthquake aerial photographs which were digitised and included in the GIS. Simple crack monitoring devices were installed to show any displacement.

The majority of cliff collapses (by volume) occurred in the June earthquake where about 15m was lost from the top of one specific cliff. The mapping that had been done prior to the June earthquake was revised following the earthquake as new cracks had formed and many existing cracks had increased in size. The location of the current cliff edge is now where hair-line cracks were mapped following the February earthquake. This example emphasises the importance of carrying out field observations as soon after an event as possible.

2.5 **Landslides**

The initial work undertaken comprised a walkover survey of the most significant landslides where a rapid assessment was made of their stability. Crude monitoring devices were installed at this time. The most significant landslides were intensely monitored by surveyors for the first few days after the February earthquake. For example one area (1.3ha) had cracks up to 0.5m wide marking the scarp of a large landslide which threatened houses and a road, the only access to the eastern suburbs of the Port Hills.

Once it was known that the risk of imminent failure was low, PHGG resources were diverted to hazards posing greater life-safety risks, however monitoring of the significant landslides continued albeit less frequently.

Mapping was undertaken at variable levels of detail. The maps were digitised and included in the GIS. There was no systematic approach by PHGG to gather landslide data beyond basic geomorphological mapping, and consequently many significant landslide related features were likely to have been missed.

3 **MODELLING**

Two models were developed to define the rockfall hazard. GNS developed a two-dimensional (2-D) probabilistic model based on source area and run-out information. The other model was a three-dimensional (3-D) model used by Geovert Ltd. The 3-D model defined the likely trajectories of the boulders, bounce heights and energies. The two methods complimented each other and reached similar conclusions on identifying areas with high life-safety risks. The 3-D model however was a preliminary model that was not developed further (Avery 2012). The GNS model was fully developed through several iterations including pilot study assessments (Massey et al 2012b 2012c 2012e) and the wider area (Massey et al 2012a 2012d).

The GNS model expresses risk as the Annual Individual Fatality Risk (AIFR), also referred to as life-safety risk, to describe the likelihood of an individual in a house being killed by either cliff collapse or rockfall in any one year.

GNS modelled a range of scenarios using input parameters such as varying seismicity over time, non-seismic triggers and occupancy rates of houses. Specific modelling parameters and scenarios need to be carefully considered by Council for policy development for future residential development on the Port Hills.

The modelling will allow the Council to define acceptable, tolerable and intolerable levels of risk, expressed as AIFR. For a risk to be acceptable, the consequences and likelihood of it occurring are low. A tolerable risk has a slightly higher level of risk than acceptable risk, but the benefits of living with the risk make the risk tolerable. An intolerable level of risk occurs when the level of risk becomes unacceptable.

A large part of the modelled risk can be attributed directly to the current elevated seismic hazard. As the seismic hazard decreases over time the risk from earthquake triggered cliff collapse and rockfall also decreases. In some locations on the Port Hills there are also properties exposed to risk levels of about 10^{-3} from non-earthquake triggered rockfall and cliff collapse (e.g. those triggered by rainfall and weathering).

GNS has also developed a model to determine the life-safety risk from cliff collapse which considered both cliff top failure and debris inundation. The models allowed ‘retreat zones’ to be defined at the cliff tops for future earthquake events and AIFR zones to be defined at the cliff toe (debris inundation areas).

4 MODEL APPLICATION FOR PLANNING AND DEVELOPMENT

The GNS models were used initially by the Canterbury Earthquake Recovery Authority (CERA) to help inform the Port Hills residential zoning decisions. Following this the models were, and continue to be, used by the Council to inform its statutory responsibilities under the Building Act 2004 (e.g. s.124 notices and building consent applications), the Civil Defence Emergency Management Act 2002, Local Government Act 2002 and the Resource Management Act 1991 (e.g. processing resource consent applications). The GNS models will also inform the Council’s proposed District Plan Review planned for 2014.

The district plans administered by the Council include objectives, policies and some rules to address natural hazards. Since the Canterbury earthquakes some of these provisions are inadequate and do not appropriately address the heightened seismicity, and changes to slope stability hazards and the associated risks. The Council analysis of the GNS information suggests that in addition to the CERA zoning there are other areas on the Port Hills at potentially similar levels of risk from slope instability. A future earthquake in a new location is likely to cause fresh instability as the location of earthquake induced slope instability is directly related to earthquake epicentres. The modelling has taken this into account however for the immediate Port Hills area.

Policy is being developed by the Council to address slope stability hazards and the associated risk to life, property and infrastructure on the Port Hills. The approach addresses the slope stability hazards consistent with specific levels of risk. This approach involves identification of four management areas which include:

- Cliff-top Recession Management Area - the area of the cliff top at high risk of collapse (AIFR >10-4);
- High Life-safety Risk Management Area - land that is at high risk from rockfall and debris-inundation (AIFR $>10^{-4}$);

- Moderate Life-safety Risk Management Area - land that is at moderate to high risk from rockfall (AIFR 10^{-4} to 10^{-5}); and
- Land Damage Management Area - land that has been identified as potentially subject to mass movement and includes failures in loess, fill and bedrock, as well as areas of cliff-top deformation.

The principle underlying this ‘precautionary’ approach is that the financial loss from the Canterbury earthquakes has been high, and the Council needs to avoid increasing the number of people living, working or congregating in areas of high risk. This approach will help to ensure that the risk to individual property owners, communities, local and central government is minimised. As part of the policies under development, new rules are proposed to control land use and development for existing developed and undeveloped urban zoned land and rural zones, as these may be considered for future greenfield urban development. The approach is consistent with the natural hazard provisions of the Canterbury Regional Policy Statement (2012).

5 DISCUSSION

5.1 Data Collection

Fieldwork was extensive and large amounts of data were collected. When the data collection process started, it was not entirely clear what the information would be used for. Those undertaking the work primarily considered the immediate emergency and response needs, and the associated life safety risks. The future use of the data for planning and recovery development was generally not considered. The PHGG understood that the information would be required for modelling purposes but at that time the type of modelling and specific inputs required were unknown. Previous experience from non-seismic rockfall work therefore influenced the type of information recorded.

The information recorded provided adequate information for CDEM to undertake its response roles and responsibilities. As the data was interrogated further and GNS started to develop their probabilistic model, additional information was required and field teams had to re-visit many areas to gather additional information. For example the initial focus on the high risk and unstable boulders distorted the statistics of the boulder data by indicating a high percentage were at high risk. Additional mapping later, where boulders at the toe of the slope were included, created a more valid data set. Also other information like the number of houses that were impacted by boulders was needed and this again required additional site visits, the same occurred with the size of the boulders and many field teams did not map anything less that about $0.5m^3$, this was prudent due to the number of boulders. However, this again distorted the statistics of the range of boulder sizes, and additional discussions and some additional fieldwork were required for GNS to develop their model. As the required inputs to the modelling are now known, the information could be gathered in fewer visits for any future events.

The risk rating of individual boulders was difficult to record consistently across the Port Hills because individual PHGG members had different reference points for interpreting risk levels. This occurred because the PHGG members worked predominantly in one area and did not have an appreciation of the wider risk. To address this, the PHGG collectively discussed typical examples for each risk category and undertook site visits to areas on the Port Hills managed by other sector leaders. Additionally, field workers that had never experienced a large magnitude earthquake or were in Christchurch in February 2011 had difficulty in appreciating the high levels of shaking that occurred and that could occur again.

The mapping of mass movement areas was not a priority for PHGG immediately following the earthquakes. This was the appropriate decision at the time because resources were limited and the high life-safety risks associated with rockfalls/cliff collapse. However, this has meant a significant delay in developing an understanding of the individual failure mechanisms and the associated risk. The consequence of this, amongst other matters, is a delay in repairing some infrastructure, uncertainty in issuing building consents, and general uncertainty for recovery (e.g. insurance payouts and house repairs)

The fieldwork phase could have been completed earlier if additional resources had been available, however this may have increased the likelihood of inconsistency in date collection.

There was no consistent recording of completed mitigation works. Many of the boulders had been mapped and had unique numbers, however the current data does not definitively indicate whether the boulder remains untouched, whether it was scaled, blasted or secured in place. This information would have been effortless to record at the time however the aim of the emergency mitigation was to reduce the risk in an area and recording treatment of individual boulders was not initially considered. Within a few weeks of the earthquakes this information started to be recorded, however the dataset is not reliable due to these uncertainties.

When the June earthquake occurred, the Port Hills had to be re-assessed for all the slope stability hazards. The GIS quickly produced maps with all field observations to date, and this significantly increased the rate of reassessments. During the June earthquake many boulders fell down some slopes that had previously been assessed as being "low" risk. This emphasises the importance of the modelling results to inform the policy and zoning decisions as it does not rely on human judgement. It also highlights the importance of the timescale in which the modelling needs to be completed.

5.2 Modelling

The modelling undertaken relied on the field data having been collected. However the GNS modelling process was being developed in parallel to the fieldwork being undertaken. The development of the model relied on a good understanding of the accuracy and reliability of the data being collected, but it was not until the model was developed that the data inputs were fully understood. This circular process resulted in repeated field visits. There was no model available and ready to apply because the magnitude of the event had been considered unlikely. Part way through the GNS modelling process it was determined that a large number of 2-D models were needed to determine the expected run-out distances of the boulders in all the areas covered by the GNS model. The results of these individual models fed into the overall model. This element of the modelling was undertaken by the PHGG and could have been run in parallel with some of the fieldwork, accelerating the overall process, however again, at the time the specific requirements were unknown.

The 3-D model used the same input dataset used by GNS. In early 2012 CERA commissioned Geovert Ltd. to provide a preliminary assessment of the rockfall hazard. The assessment was completed quickly, however, more detailed input information and further verification was required for the model results to be useful for broader recovery and zoning decisions.

The GNS model was tailored to provide the Council and CERA with the specific information they required for policy development and planning, and zoning decisions. The model as it is now has wide applicability to other regions in New Zealand, however there will be specific aspects that would be relevant only to the Port Hills, such as the geology. Despite this, the model is likely to be easily adapted to other parts of New Zealand.

5.3 Model application

In the short term, the initial use of the model results was to confirm the application of the s.124 notices. The initial placing of these notices relied on the experience and judgement of the PHGG members and the model provided the required supporting evidence to justify these decisions. The modelling results were then primarily used by CERA to inform the policies around the land zoning. These decisions relied on the modelling results to provide the supporting evidence, however it was about 18 months before the results of the modelling were finalised. This delay was frustrating for residents but unavoidable. With prior planning, if a similar situation were to happen again, the results of modelling may be obtained more quickly and recovery may be quicker.

Some of the slope stability information collected immediately showed how high the risk was to properties. Despite this, significant time was taken to make decisions on the future of these properties. There are several reasons for these delays including the need to gain a thorough appreciation of all areas or properties and risk before a decision could be made, and the uncertainty and possible consequences of making a wrong decision.

Information on life-safety, following the completion of GNS modelling, was used to reassess the appropriateness of some s.124 notices. Original decisions on the need for s.124 notices for some houses were based on walk-over surveys. Although these decisions were considered by some to be conservative most of the houses with s.124 notices retained the notices. This highlights the importance of having highly trained and experienced people making the early decisions on the issuing of s.124 notices.

The detail of the information available on rockfall, cliff collapse and landslides will allow the Council and other organisations to make robust and defensible decisions on a wide variety of planning and development, and emergency management matters, both in the mid-term and longer term. Use of GIS will allow rapid and easy access to both the factual field data and the hazard assessment information. It is generally considered that the information collected for immediate recovery was adequate in quality and quantity, and that all essential factual data was collected.

6 CONCLUSION

Under the circumstances, the initial and on-going geotechnical response has been exceptional. The data that was collected initially was not complete but through close collaboration of PHGG and GNS, this was rectified as the specific requirements for the information became clear. With hindsight, and now that the specific requirements of the modelling are known, the efficiency and timeliness of the information collection process could have been improved. The GIS significantly improved the efficiency and availability of the data for use by a wide rang of stakeholders. The GNS models were tailored to provide the specific information required by policy advisors for both the immediate policy development and decisions such as the CERA zoning, but also the longer term input for district planning matters.

The Canterbury Earthquake response and recovery processes developed in the City since the earthquakes can be used to inform future emergency planning in other parts of New Zealand. As this paper describes, the initial hazard identification, data gathering and subsequent modelling processes were developed iteratively.

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