2.0 DATA USED

The data and the sources of the data used in this report are listed in Table 2.

Table 3 Summary of the main data used in the analysis. LiDAR is Light Detecting and Ranging.

Data	Description	Data source	Date	Use in this report
Post-22 February 2011 earthquake digital aerial photographs	Aerial photographs were taken on 24 February 2011 by NZ Aerial Mapping and were orthorectified by GNS Science (10 cm ground resolution).	NZ Aerial Mapping	Last updated 24 February 2011	Used for base maps and to map extents of landslides and deformation triggered by the 22 February 2011 earthquakes.
Post-13 June 2011 earthquake digital aerial photographs	Aerial photographs were taken between 18 July and 26 August 2011, and orthorectified by NZ Aerial Mapping (0.5 m ground resolution).	NZ Aerial Mapping	18 July–26 August 2011	Used to map extents of landslides and deformation triggered by the 13 June 2011 earthquakes.
Historical aerial photographs	Photographs taken in 1940, 1946, 1975, 1975 and 1984 by multiple sources and orthorectifed by NZ Aerial Mapping and GNS Science (at variable ground resolutions).	NZ Aerial mapping and GNS Science	1946, 1975, 1975 and 1984	Used to assess the site history before the 2010/11 Canterbury earthquakes.
LiDAR digital elevation model (2003)	Digital Elevation Model derived from LiDAR survey carried out in 2003; resampled to a 1 m ground resolution.	AAM Hatch	2003	Used as the pre-22 February 2011 ground model.
LiDAR digital elevation model (2011a)	Digital Elevation Model derived from post-22 February 2011 earthquake LiDAR survey; re-sampled to 1 m ground resolution.	NZ Aerial Mapping	8–10 March 2011	To generate change models (between the 2003 and 2011a surveys) to determine the locations, extents and volumes of material leaving the cliffs and where it was deposited.
LiDAR digital elevation model (2011b)	Digital Elevation Model derived from LiDAR survey; resampled to a 1 m ground resolution.	AAM Hatch	May 2011	To generate a model of changes (between the 2011a and 2011b surveys) to determine the locations, extents and volumes of the material leaving the cliffs and where it was deposited.

Data	Description	Data source	Date	Use in this report
LiDAR digital elevation model (2011c)	Digital Elevation Model derived from post-13 June 2011 earthquake LiDAR survey; re-sampled to 1 m ground resolution.	NZ Aerial Mapping	18 July–26 August 2011	Used to generate contours and shade models for the maps and cross-sections used in the report.
Terrestrial laser scan (TLS) surveys	Multiple Digital Elevation Model's derived from surveys following the 22 February, 16 April and 13 June 2011 earthquakes.	GNS Science	Last survey carried out October 2013	To generate models of changes (between surveys) to determine the distribution and volume of material leaving the cliffs at selected areas where surveys were made.
Christchurch building footprints	Footprints are derived from aerial photographs. The data originate from 2006 but have been updated at the site by CCC using the post-earthquake aerial photos.	Christchurch City Council	Unknown	Used to identify the locations of residential buildings in the site.
GNS Science landslide database	Approximate location, date, and probably trigger of newsworthy landslides	GNS Science	Updated monthly	Used to estimate the likely numbers and volumes of pre earthquake landslides in the areas of interest.
Earthquake Commission claims database	Location, date and brief cause of claims made in the Port Hills of Christchurch since 1993.	Earthquake Commission	1993–August 2010	Used to estimate the likely numbers and volumes of pre earthquake landslides in the areas of interest.
Composite seismic hazard model	The increased level of seismicity in the Canterbury region since 4 September 2010 has been quantified using a modified form of the national seismic hazard model.	GNS Science	Updated December 2013	Used to estimate the frequency of occurrence of a given peak ground acceleration.
Synthetic earthquake time/ accelerations	Earthquake time acceleration histories for the four main 2011 earthquakes: 22 February, 16 April, 13 June and 23 December.	GNS Science	February 2014	Used as inputs for the seismic site response analysis.
Rainfall records for Christchurch	Rainfall records for Christchurch from various sources, extending back to 1873.	NIWA	1873–present	Used to assess the return periods of past storms triggering landslides of known magnitudes in the Port Hills.

Data	Description	Data source	Date	Use in this report
Drillhole logs	Results from the logging of three drillholes and three scala penetrometers carried out at the site.	Tonkin and Taylor Ltd. (Tonkin and Taylor, 2012a)	2012	Used to generate the engineering geological map and cross-sections.
Drillhole logs	Results from the logging of two drillholes carried out at the site	Aurecon NZ Ltd. (Pletz and Revell, 2013)	September 2013	Used to generate the engineering geological map and cross-sections.
Downhole shear wave surveys	Downhole (in drillhole) shear wave velocity surveys.	Southern Geophysical Ltd. (2013)	February 2014	Used to determine the dynamic properties of the materials in the slope for the seismic site response analysis.
Geotechnical laboratory data	Geotechnical strength parameters for selected soil and rocks in the Port Hills.	GNS Science (Carey et al., 2014)	February 2014	Used for static and dynamic slope stability analysis.
Field work	Field mapping of slope cracking and engineering geology and ground truthing of the risk analyses.	GNS Science and the Port Hills Geotechnical group	22 February 2011–present	Used in generating the engineering geological models of the site. Results from field checks used to update risk maps.
Traffic counts for Main Road (Causeway, Ferrymead/Main Rd junction and Sumner Surf Life Saving club data available for recent years)	Detailed motor vehicle counts at 2-year intervals, by hour of day and day of week, are available for several locations. Data for Redcliffs were taken as the average of figures used for Dean's Head and those used below Quarry Road	Christchurch City Council	2008, 2010 and 2012 surveys	Used to assess total numbers of road users, and to model likely average extent and frequency of delays (and hence extended average time at risk) on Main Road.

3.0 SITE ASSESSMENT RESULTS

The site assessment results and engineering geological conceptual models developed for the site by GNS Science are summarised below.

3.1 SITE HISTORY

3.1.1 Aerial photograph interpretation

Aerial photographs of the site are available for various dates since 1940. Table 4 summarises the photograph details and main features noted.

Table 4 Summary of observations from aerial photographs used to assess the site history at Redcliffs.

Date/scale of photo	Resolution	Comments
1940 1:10,000 (approx.)	Poor resolution	Several large arcuate features – possible relict landslide scars – are apparent in the cliff face. Below these features are what appear to be corresponding accumulations of talus. These features are labelled 1–5 on Appendix 2 Map 1. No dwellings are present at the cliff crest. The area behind the cliff crest appears to be farmland. Several dwellings are apparent at the cliff toe, outside the extent of the pre-2003 talus (Figure 10). Several brighter areas are apparent on the cliff face, these may relate to recent failure of material from the cliff.
30/05/1946 1:5,500 (approx.)	Good resolution	At the northern end of the site there appears to be an area of "hummocky" ground within a subtle concave depression behind the cliff crest. This appears to be consistent with the location of the 2011 loess slump (Figure 10). A possible recent collapse of the cliff edge is apparent in the north east corner of the site (Figure 10). Several relict and recent loess failures, at the cliff crest, are apparent. No dwellings are present at the cliff crest. The area behind the cliff crest still appears to be farmland. A few possible recent boulders are apparent on the surface at the cliff toe.
1973, 1:10,000 (approx.)	Poor resolution	A few dwellings have now been constructed at the cliff crest in the central part of the site. Several possible recent rockfalls are present at the bottom of the cliff (Figure 10). Several brighter areas are apparent on the cliff face, these may relate to recent failure of material from the cliff.
1975, 1:10,000 (approx.)	Poor resolution	No obvious change. Much of the cliff face and toe is in shadow. A few more buildings have been constructed at the cliff crest.
1984, 1:6,000 (approx.)	Good resolution	A few more dwellings have now been constructed at the cliff crest in the central and northern part of the site. Several possible recent rockfalls are present at the bottom of the cliff (Figure 10).

3.1.2 Before the 2010/11 Canterbury earthquakes

- The Redcliffs slopes are part of an abandoned pre-historic coastal cliff. Erosion of the base of the cliff probably ceased 3,500–3,700 years ago (McFadgen and Goff, 2005).
- Several relict (apparent in the 1940 aerial photographs) possible landslide source areas are identified in the slope face with corresponding debris deposited beneath them.
- Using the 2003 LiDAR survey digital elevation model of these slopes, and by projecting the rockslope face at the toe of the slope through the talus to intersect an assumed pre-talus ground surface, it was possible to estimate likely volumes of talus present before the 2010/11 Canterbury earthquakes (Appendix 2). At Redcliffs, the talus totals about 30,000 (±10,000) m^3, but some of this debris may be wind-blown sand. Some middens excavated from beneath rockfall debris were abandoned some 600 years ago (Trotter, 1975).
- The likely age of the coastal beach surfaces on which this material was deposited may be about 3,500–3,700 calibrated radiocarbon years (McFadgen and Goff, 2005), suggesting rockfall accumulation rates averaging 8.1–8.6 m^3/year. If it is assumed that dune sand is largely filling interstices between fallen boulders, the proportion of dune sand may be ignored.
- Estimated debris volumes per possible landslide scar range from 2,400 to 7,300 m^3, each of which we assume fell as a result of a single landslide rather than as the accumulation from several smaller landslides (this assumption is justified only as a more conservative option).
- There is no evidence in the aerial photographs (1940, 1946, 1973, 1975, 1984 and 2011) of past quarrying at the site. It appears that none of the rock mass exposed in the cliff has been judged durable enough to be quarried, even as base course for roading, or rip-rap for mitigation of coastal erosion.
- Bell (1992) reports on two failures of the rock slope at Redcliffs, one in 1968 and the other in 1992; both are reported to have been about 50 m^3 in volume with rainfall as the trigger.
- There are several possible rockfalls visible in historical aerial photographs (Figure 10).
- A rockfall bund (a barrier constructed of rock fill to prevent rockfalls from passing it) was constructed in 2010 behind the Redcliff School hall (Figure 10).

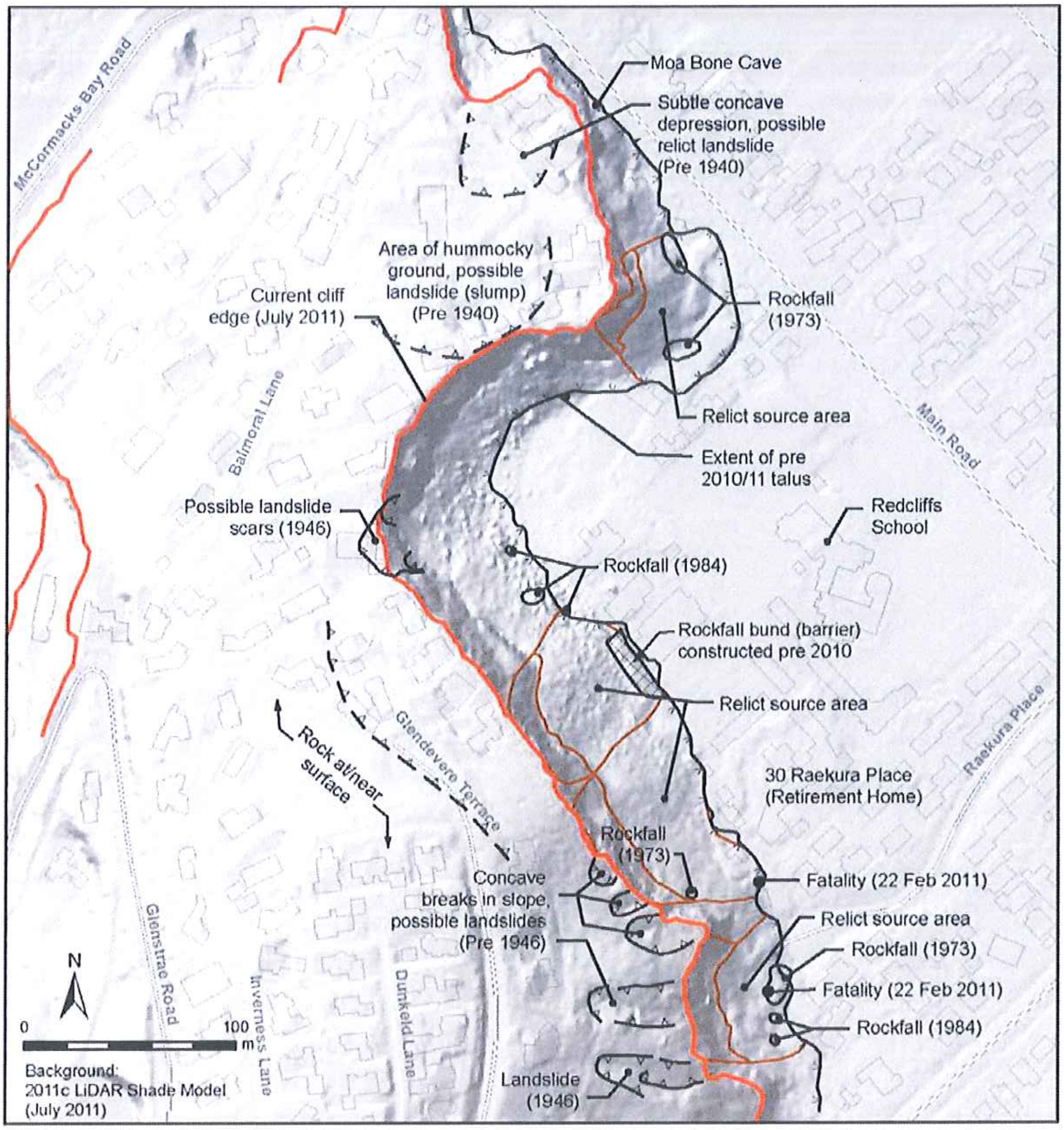

Figure 10 Main features identified at the site from field mapping and the interpretation of historical aerial photographs.

3.1.3 During the 2010/11 Canterbury earthquakes

Summaries of the cliff-top displacements in response to the earthquakes, inferred from crack apertures and limited surveying of cadastral marks, are contained in Tables 5–7. A summary of the volumes leaving the cliffs during the largest 2010/11 Canterbury earthquakes derived from airborne LiDAR and terrestrial laser scan surveys is contained in Table 8.

Assessment results from: 1) airborne LiDAR survey change models are presented in Appendix 2; 2) terrestrial laser scan survey change models in Appendix 3; and 3) surveying of cadastral and monitoring marks in Appendix 4. Results of crack mapping between the main earthquakes, carried out by Yetton (Geotech Ltd.), are contained in Appendix 5.

The main results from these field-based assessments are summarised below:

- *4 September 2010 (Darfield) earthquake:* no mapped displacement of the cliff face or cracking of the cliff top was identified; about 60 m^3 of debris fell from the cliff face.
- *22 February 2011 earthquakes* – the cracks, mainly in loess at the cliff crest (shown on the maps in the Stage 1 report and displacements summarised in Tables 5–7), were mainly generated on 22 February 2011 by one or more earthquakes that occurred on this day. Permanent total displacement of the area, inferred from the results of mapping of cracks and measurement of their apertures was between 0.03 and 1.7 m (Table 7). Surveying of cadastral marks, was carried out by GNS Science to allow before and after (the 2010/11 Canterbury earthquakes) measurements to be made (results are presented in Appendix 4). Many of the identified cadastral survey marks were outside the main areas of inferred movement. The displacements of the two survey marks, only marginally within the inferred areas of movement, were about 0.2–0.3 m, and represent lower bound estimates of the total displacement during the earthquakes. During these earthquakes approximately 23,900 (±6,600) m^3 of rock fell from the slope (Table 8 and shown graphically in Appendix 2), onto residential and commercial properties at the toe of the slope, killing two people. In some locations the cliff edge receded up to six metres. Many cracks were visible in the cliff face after these events (Massey et al., 2012a). The area behind the rockfall bund, constructed behind the Redcliffs School hall, was completely filled in by debris, and is now incorporated in the debris.
- *16 April 2011 earthquake* – No displacement of the cliff top or opening of the mapped cracks was reported or detected by GNS Science. About 1,180 (±110) m^3 of rock fell from the cliff; some of it fell onto vacant dwellings at the cliff toe (Table 8 and Appendix 3).
- *13 June 2011 earthquakes* – Some new cracks, and the reactivation (further opening) of existing cracks, were recorded (in loess) at the cliff crest following these earthquakes (Appendix 5). Horizontal permanent displacement of the cliff crest in response to these earthquakes (inferred from crack apertures) ranged between 0.2 and 0.7 m; vertical displacements were not measured. During this earthquake, about 11,800 (±3,500) m^3 of rock fell from the cliff, some onto dwellings and other buildings at the cliff toe, which were unoccupied following the 22 February 2011 earthquake (Table 8 and Appendix 2). The cliff edge locally receded by up to seven metres (Massey et al., 2012a) and many more cracks appeared on the cliff face.
- *23 December 2011 earthquake* – During this earthquake about 1,180 (±130) m^3 fell from the cliff, on to unoccupied dwellings at the cliff toe (Table 8 and Appendix 4).
- No survey monitoring marks were installed at the cliff top to record permanent ground movements during these earthquakes.

3.1.4 After the 2010/11 Canterbury earthquakes

- Analysis of survey results for some parts of the cliff top adjacent to Moa Bone cave shows that the cliff edge locally has advanced outward 30 mm since the 2010/11 earthquakes; vertical displacements were not measured. In this area, possible break-out of a shear surface through basalt breccia has been located on the cliff face at the cliff toe. Displacements occurred during the winter of 2013.
- About 460 (±160) m^3 of rock fell from the slope face between January 2012 and December 2012 (about 475 m^3/year). About 81 (±47) m^3 of rock fell from the slope face between December 2012 and November 2013 (about 90 m^3/year). No large ground

accelerations were recorded during this interval in the local area. Most of these failures comprised relatively frequent discrete failures that were small in volume (mean volume of about 0.1 m^3).

- Many earthquake-induced cracks are apparent on the cliff. Many of these extend from cliff top to cliff bottom and were formed mainly by the 22 February and 13 June 2011 earthquakes.

3.2 SITE INVESTIGATIONS

3.2.1 Geomorphological mapping

The results from field mapping of slope morphology, interpreted surface materials and their genesis, surface deformation mapping and other relevant information are shown in Figure 11.

The site consists of an asymmetric north-tending spur with a very steep eastern flank (cliff face) and a gentler sloping western flank. The width and height of the spur is about 300 m and 80 m respectively. The cliff on the eastern side is about 70 m high, 500 m long with a slope angle ranging from 60° to overhanging in places. The cliff has three main sections based on slope aspect: 1) a southern, northeast-facing cliff; 2) a central, southeast-facing cliff; and 3) a northern north east-facing cliff. The southern and central parts of the cliff are the steepest. Main Road is located at the toe of the northern cliff.

3.2.2 Subsurface trenching and drilling

The ground investigation details are summarised in Table 8 and shown on Figure 12. Geological logs and equipment installation details are contained in the reports by Aurecon NZ Ltd. (Pletz and Revell, 2013; Tonkin and Taylor Ltd., 2012a).

Based on this work the main slope-forming materials and groundwater conditions are summarised below.

Table 5 Summary of the ground investigations carried out at the site by Aurecon NZ Ltd. (Pletz and Revell, 2013) and Tonkin and Taylor Ltd. (Tonkin and Taylor, 2012a).

ID	Source	Type	Depth (m below ground level)	Instrumentation
BH-MB-01	Aurecon NZ Ltd.	Cored hole	35.2	Inclinometer
BH-MB-02	Aurecon NZ Ltd.	Cored hole	41.1	Inclinometer
BH-MB-03	Aurecon NZ Ltd.	Open hole	41.0	Seismometer
BH-BAL-03	Tonkin and Taylor Ltd.	Cored hole (inclined 45°)	35 m	None
BH-GDV-01	Tonkin and Taylor Ltd.	Cored hole	10.0	Inclinometer and standpipe
BH-GDV-02	Tonkin and Taylor Ltd.	Cored hole (inclined 45°)	40.5	None
CPT-GDV-01	Tonkin and Taylor Ltd.	Cone penetration	2.9	Standpipe
CPT-GDV-02	Tonkin and Taylor Ltd.	Cone penetration	4.0	Standpipe
TPB01-02, TPG01-05 and TPY01-04	Tonkin and Taylor Ltd.	Test pits	Variable 2–3.5 m	N/A