Appendix A.20:

1/19 Chardale St – VsVp 57320

Table 1: Site Description for 1/19 Chardale St ($v_s v_p$ 57320).

Attribute	Yes/No			Description/Date	Symbol in Figure 1
	10-m Buffer	20-m Buffer	50-m Buffer		
Near a body of surface water or other free face features?	No	No	No	The center of the site is 75 meters away from the Avon River. The direction of the nearest free face is roughly NE-SW, while its height is approximately 1.25 m.	NA
Lateral spreading observed during the CES?	Yes	Yes	Yes	No lateral spreading was observed for the September 2010 earthquake but the February 2011 earthquake.[1,*]	NA
Nearby buildings or structures?	Yes	Yes	Yes	Building coverage of the 10-m, 20-m, and 50-m buffers is 56, 39, and 32%, respectively. They are in all quadrants of the buffers.	White Fill + Brown Outline
Sloping land?	No	No	No	Flat land, residential area.	NA
Step changes in the ground surface?	No	No	No	NA	NA
Retaining walls?	No	No	No	NA	NA
Vegetation?	Yes	Yes	Yes	Trees and bushes cover 19, 21, and 16% of the 10-, 20-, and 50-m buffer, respectively. They are in all quadrants of the buffers.	White Fill + Green Outline
Anthropogenic changes to the site between the LiDAR surveys?	No	No	No	NA	NA
Other important factors?	No	No	Yes	Low-motor-vehicle-volume, two-way roadway (street) occupies 13% of the 50-m buffer and stretches throughout the NE, SE, and SW quadrants.	Road: Gray Fill + Red Outline

Notes: Buffer is the area within a circle of a specified radius with CPT investigations done at its center (172.694632°, -43.502797°); * indicates that the settlement analysis was conducted only for the September 2011 earthquake due to lateral spreading observed for the February 2011 earthquake (the anthropogenic changes description pertains to the period between Dec 2004 and Feb 2011 only).

[1] Canterbury Geotechnical Database. (2012). "Observed Ground Crack Locations", Map Layer CGD0400 - 23 July 2012, retrieved July 09, 2018 from https://canterburygeotechnicaldatabase.projectorbit.com/

Figure 1: Site plan with areas where ejecta-induced settlement is considered.

Note 1: Three patches (outlined in red) in free field were initially selected for settlement assessment as areas free of vegetation and structures. Further analyses such as proximity of a patch to a CPT, proximity of a patch to a property subjected to addition and/or demolition of a structure, front yard/backyard alterations (e.g., ploughing, rubble, scrap), and aerial distribution of sediment ejecta, resulted in Patches A and B being selected for detailed settlement assessment and Patch C being discarded in detailed settlement assessment. In addition, the entire portion of the road within the 50-m buffer was considered for settlement assessment. The ejecta-induced settlement analyses were not performed for the Feb-11, Jun-11, and Dec-11 EQs due to lateral spreading. The LiDAR-based settlement analysis for the Sep-10 EQ was not performed due to the evident absence of ejecta from Patch A and uncertainties listed in Table 2.

Table 2: LiDAR flight error adjustments, global adjustments for the difference between average LiDAR point elevations and benchmark survey elevations, and vertical tectonic movement adjustments.

	Adjustments (mm)		
Earthquake Event(s)	LiDAR Flight Error	Global Offset[2]	Tectonic Vertical Movement
Sep-10	-50	-3	0
Feb-11	0	16	-40
Jun-11	0	38	-50
Dec-11	0	-65	0
CES	-50	-14	-90
Any LiDAR survey affected by ejecta?			Yes*

Notes: The negative sign indicates the subtraction from the ground surface subsidence, while the positive sign indicates the addition to the ground surface subsidence; * Ejecta were not removed from Patch B and Road at the time of the Sep-10 LiDAR survey which requires the addition of ~30 mm to the ground surface subsidence for the Sep-10 EQ.

Table 3: LiDAR Measurement Error for Patch B and Road.

Surveys	Buffer	Area Averaged Difference Indicating Repeat Measurement Error (mm)	σ* individual LiDAR points (mm)	%Reduction in σ due to Area Averaging of LiDAR Points
Post Feb 2011: Mar 2011 and May 2011	10-m	NA	59	[ND,ND]
	20-m	NA		
	50-m	ND		
Post Dec 2011: Feb 2012 and Oct 2015	10-m	NA	70	[ND,ND]
	20-m	NA		
	50-m	ND		

*Standard deviation; NA = Not available; ND = Not determined.

[2] Russell, J., & van Ballegooy, S. (2015). *Canterbury Earthquake Sequence: Increased liquefaction vulnerability assessment methodology*. New Zealand: Tonkin & Taylor Ltd.

Table 4: Ground surface subsidence adjustments due to LiDAR measurement error for Patch B and Road.

Earthquake Event(s)	$\sigma_{\text{pre-EQ LiDAR survey}}$ (mm)	$\sigma_{\text{post-EQ LiDAR survey}}$ (mm)	σ_{total} (mm)	Area Average Adjusted σ (mm) **
Sep-10	158	56	134	ND
Feb-11	56	59	59	ND
Jun-11	59	61	62	ND
Dec-11	61	70	87	ND
CES	158	70	124	ND

**Based on the highest %Reduction in Table 3a; ND = Not determined.

Table 5: Raw liquefaction-related ground surface subsidence using original LiDAR points for Patch B and Road.

	Average Ground Surface Subsidence (mm)		
Earthquake Event(s)	10-m Buffer	20-m Buffer	50-m Buffer
Sep-10	NA	NA	ND
Feb-11	NA	NA	ND
Jun-11	NA	NA	ND
Dec-11	NA	NA	ND
CES	NA	NA	ND

Table 6: Corrected liquefaction-related ground surface subsidence using original LiDAR points for Patch B and Road with the calculated adjustments in Table 2.

	Average Calculated Ground Surface Subsidence (mm)		
Earthquake Event(s)	10-m Buffer	20-m Buffer	50-m Buffer
Sep-10	NA	NA	ND
Feb-11	NA	NA	ND
Jun-11	NA	NA	ND
Dec-11	NA	NA	ND
CES	NA	NA	ND

Notes: Plus/minus values are same as those in Table 4a, but rounded to the nearest 25; Positive overall values indicate ground surface subsidence, while negative overall values indicate ground surface uplift; NA = Not available; ND = Not determined.

Table 7a: Corrected liquefaction-related ground surface subsidence for Patch A using LiDAR DEMs.

	Estimated Ground Surface Subsidence (mm)								
	10-m Buffer			20-m Buffer			50-m Buffer		
Earthquake Event(s)	16th %ile	50th %ile	84th %ile	16th %ile	50th %ile	84th %ile	16th %ile	50th %ile	84th %ile
Sep-10	<50	<50	50	<50	50	50	<50	50	50
Feb-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
Jun-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dec-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
CES	ND	ND	ND	ND	ND	ND	ND	ND	ND

Note: These percentiles are not the exact statistical measures; they indicate the spatial variability of ground surface subsidence.

Table 7b: Corrected liquefaction-related ground surface subsidence for Patch B using LiDAR DEMs.

	Estimated Ground Surface Subsidence (mm)								
	10-m Buffer			20-m Buffer			50-m Buffer		
Earthquake Event(s)	16th %ile	50th %ile	84th %ile	16th %ile	50th %ile	84th %ile	16th %ile	50th %ile	84th %ile
Sep-10	NA	NA	NA	NA	NA	NA	100	100	100
Feb-11	NA	NA	NA	NA	NA	NA	ND	ND	ND
Jun-11	NA	NA	NA	NA	NA	NA	ND	ND	ND
Dec-11	NA	NA	NA	NA	NA	NA	ND	ND	ND
CES	NA	NA	NA	NA	NA	NA	ND	ND	ND

Note: These percentiles are not the exact statistical measures; they indicate the spatial variability of ground surface subsidence.

Table 7c: Corrected liquefaction-related ground surface subsidence for Road using LiDAR DEMs.

	Estimated Ground Surface Subsidence (mm)								
	10-m Buffer			20-m Buffer			50-m Buffer		
Earthquake Event(s)	16th %ile	50th %ile	84th %ile	16th %ile	50th %ile	84th %ile	16th %ile	50th %ile	84th %ile
Sep-10	NA	NA	NA	NA	NA	NA	<50	50	100
Feb-11	NA	NA	NA	NA	NA	NA	ND	ND	ND
Jun-11	NA	NA	NA	NA	NA	NA	ND	ND	ND
Dec-11	NA	NA	NA	NA	NA	NA	ND	ND	ND
CES	NA	NA	NA	NA	NA	NA	ND	ND	ND

Note: These percentiles are not the exact statistical measures; they indicate the spatial variability of ground surface subsidence.

Table 8a: Ejecta-Induced settlement for the top 20 m of the soil profile for Patch A (20-m buffer) for the 50th %ile PGA, P_L=50%, and C_{FC}=0.13 using BI-2014, ZRB-2002, and I_C cutoff of 2.6.

Earthquake Event(s)	M_W	PGA (g)	Depth to Groundwater (m)	S_T (mm)	S_{V1D} (mm)	$S_{E,L}$ (mm)
Sep-10	7.1	0.17	2.2	ND	2±20	ND
Feb-11	6.2	0.34	2.0	ND	ND	ND
Jun-11	6.2	0.25	1.2	ND	ND	ND
Dec-11	6.1	0.30	1.5	ND	ND	ND

Notes: S_T = Total settlement (Table 6); S_{V1D} = Average vertical settlement due to volumetric compression using Boulanger and Idriss (2014) (BI-2014), Zhang et al. (2002) (ZRB-2002) procedures and de Greef and Lengkeek (2018) thin-layer correction; $S_{E,L}$ = Ejecta-induced settlement as the difference between the LiDAR-based S_T and S_{V1D}; ND = Not determined.

Table 8b: Ejecta-Induced settlement for the top 20 m of the soil profile for Patch B (50-m buffer) for the 50th %ile PGA, P_L=50%, and C_{FC}=0.13 using BI-2014, ZRB-2002, and I_C cutoff of 2.6.

Earthquake Event(s)	M_W	PGA (g)	Depth to Groundwater (m)	S_T (mm)	S_{V1D} (mm)	$S_{E,L}$ (mm)
Sep-10	7.1	0.17	2.2	ND	7±20	ND
Feb-11	6.2	0.34	2.0	ND	ND	ND
Jun-11	6.2	0.25	1.2	ND	ND	ND
Dec-11	6.1	0.30	1.5	ND	ND	ND

Notes: S_T = Total settlement (Table 6); S_{V1D} = Average vertical settlement due to volumetric compression using Boulanger and Idriss (2014) (BI-2014), Zhang et al. (2002) (ZRB-2002) procedures and de Greef and Lengkeek (2018) thin-layer correction; $S_{E,L}$ = Ejecta-induced settlement as the difference between the LiDAR-based S_T and S_{V1D}; ND = Not determined.

Table 8c: Ejecta-Induced settlement for the top 20 m of the soil profile for Road (50-m buffer) for the 50th %ile PGA, P_L=50%, and C_{FC}=0.13 using BI-2014, ZRB-2002, and I_C cutoff of 2.6.

Earthquake Event(s)	M_W	PGA (g)	Depth to Groundwater (m)	S_T (mm)	S_{V1D} (mm)	$S_{E,L}$ (mm)
Sep-10	7.1	0.17	2.2	ND	15±20	ND
Feb-11	6.2	0.34	2.0	ND	ND	ND
Jun-11	6.2	0.25	1.2	ND	ND	ND
Dec-11	6.1	0.30	1.5	ND	ND	ND

Notes: S_T = Total settlement (Table 6); S_{V1D} = Average vertical settlement due to volumetric compression using Boulanger and Idriss (2014) (BI-2014), Zhang et al. (2002) (ZRB-2002) procedures and de Greef and Lengkeek (2018) thin-layer correction; $S_{E,L}$ = Ejecta-induced settlement as the difference between the LiDAR-based S_T and S_{V1D}; ND = Not determined.

Note 2: The uncertainty for volumetric settlement was derived based on the sensitivity of volumetric settlement to PGA, C_{FC}, and P_L for each earthquake event for VsVp 57203 *Shirley Intermediate School* and CC LIQ 1 – CPT 5586 – *Vivian St* sites. Taking the 50th percentile as the baseline case, the minimum and maximum values corresponding to the difference between the 25th percentile and the 50th percentile and the 75th percentile and the 50th percentile were determined. The arithmetic mean of the range of the minimum and maximum difference was evaluated for each patch at the two sites. The maximum arithmetic mean for each earthquake event was rounded to the nearest five and used as the uncertainty value. Accordingly, the 1-D volumetric settlement uncertainties of ±20, ±50, ±25, and ±50 mm for the Sep-10, Feb-11, Jun-11, and Dec-11 earthquake events, respectively, were used for all sites in this study.

Table 9a: Coverage area and height of ejecta estimates for Patch A (10-, 20-, and 50-m buffers) using photographs.

Earthquake Event	$A_{E,thick}$ (m^2)	$H_{E,thick}$ (mm)	$A_{E,thin}$ (m^2)	$H_{E,thin}$ (mm)	A_T (m^2)
Sep-10	0	0	0	0	56.5
Feb-11	ND	ND	ND	ND	56.5
Jun-11	ND	ND	ND	ND	56.5
Dec-11	ND	ND	ND	ND	56.5

Notes: $A_{E,thick/thin}$ = Coverage area of thick/thin ejecta layers; $H_{E,thick/thin}$ = Lower-upper estimate of height of thick/thin ejecta layers; A_T = Total assessment area of a buffer being considered; Thin and thick layers correspond to light gray and dark gray colors of ejecta observed in aerial photographs; ND = Not determined.

Table 9b: Coverage area and height of ejecta estimates for Patch B (50-m buffer) using photographs.

Earthquake Event	$A_{E,thick}$ (m^2)	$H_{E,thick}$ (mm)	$A_{E,thin}$ (m^2)	$H_{E,thin}$ (mm)	A_T (m^2)
Sep-10	12.7	30-60	14.3	20-40	39.1
Feb-11	ND	ND	ND	ND	39.1
Jun-11	ND	ND	ND	ND	39.1
Dec-11	ND	ND	ND	ND	39.1

Notes: $A_{E,thick/thin}$ = Coverage area of thick/thin ejecta layers; $H_{E,thick/thin}$ = Lower-upper estimate of height of thick/thin ejecta layers; A_T = Total assessment area of a buffer being considered; Thin and thick layers correspond to light gray and dark gray colors of ejecta observed in aerial photographs; ND = Not determined.

Table 9c: Coverage area and height of ejecta estimates for Road (50-m buffer) using photographs.

EQ Event	$H_{E,thin1}$ (mm)	$A_{E,thin1}$ (m²)	$H_{E,thin2}$ (mm)	$A_{E,thin2}$ (m²)	$H_{E,prism/pyr}$ (mm)	$V_{E,prism+pyr}$ (m³)	A_T (m²)
Sep-10	5-10	150	2-6	5.5	17-180	2.05-3.40	1009*
Feb-11	ND	ND	ND	ND	ND	ND	1019
Jun-11	ND	ND	ND	ND	ND	ND	1019
Dec-11	ND	ND	ND	ND	ND	ND	1019

Notes: $A_{E,thin}$ = Coverage area of thin ejecta layers; $H_{E,\,thin}$ = Lower-upper estimate of height of thin ejecta layers; * indicates uncertainty in the place of origin of the ejecta; $H_{E,prism/pyr}$ = Lower-upper estimate of ejecta height near the curb based on 2-4% cross slope of normal crown; $V_{E,prism+pyr}$ = Lower-upper estimate of total volume of prismatic- and pyramidal-shape ejecta; A_T= Total assessment area of a buffer being considered; * indicates reduction in A_T due to the presence of objects/shadows; ND = Not determined.

Note 3: The values in Table 9 correspond to the coverage area of ejecta outlined in the aerial photograph (Figure 30) and the lower and upper estimates of ejecta height based on geometrical approximations. The ejecta-induced settlement using photographs and engineering judgment, $S_{E,P}$, is estimated as

$$S_{E,P} = \frac{\sum_{i=1}^{a} A_{E,thick,i} * H_{E,thick,i} + \sum_{j=1}^{b} A_{E,thin,j} * H_{E,thin,j}}{A_T} + \frac{\frac{1}{2}\sum_{n=1}^{f} W_{E,prism,n} * H_{E,prism,n} * L_{E,prism,n}}{A_T} + \frac{\frac{1}{3}\sum_{p=1}^{g} W_{E,pyramid,p} * H_{E,pyramid} * L_{E,pyramid}}{A_T} = \frac{\sum_{i=1}^{a} V_{E,thick,i} + \sum_{j=1}^{b} V_{E,thin,j} + \sum_{n=1}^{f} V_{E,prism,n} + \sum_{p=1}^{g} V_{E,pyramid,p}}{A_T}$$

where

- $A_{E,thick,i}$ and $H_{E,thick,i}$ are the area and the height of a thick ejecta layer, respectively;
- $A_{E,thin,j}$ and $H_{E,thin,j}$ are the area and the height of a thin ejecta layer, respectively;
- $W_{E,prism,n}$ and $L_{E,prism,n}$ are the width and the length of the coverage area of a prismatically shaped ejecta layer, respectively, and $H_{E,prism,n}$ is the height of the prism-like ejecta layer;
- $W_{E,pyr,p}$ and $L_{E,pyr,p}$ are the width and the length, respectively, of the coverage area of a pyramid-like ejecta layer, and $H_{E,pyr,p}$ is the height of the pyramid-like ejecta layer;
- A_T is the total assessment area for a buffer being considered (Figure 1).

Table 10: Ejecta-induced settlement estimates for Patches A, B, and Road based on photographs.

Earthquake Event	Patch A (10-, 20-, and 50-m buffers)		Patch B (50-m buffer)		Road (50-m buffer)	
	$S_{E,P,lower}$ (mm)	$S_{E,P,upper}$ (mm)	$S_{E,P,lower}$ (mm)	$S_{E,P,upper}$ (mm)	$S_{E,P,lower}$ (mm)	$S_{E,P,upper}$ (mm)
Sep-10	0	0	17	34	3	5
Feb-11	ND	ND	ND	ND	ND	ND
Jun-11	ND	ND	ND	ND	ND	ND
Dec-11	ND	ND	ND	ND	ND	ND

Note: $S_{E,P,lower}$ and $S_{E,P,upper}$ correspond to lower and upper estimates of $S_{E,P}$, respectively; ND = Not determined.

Table 11: Best final estimates of ejecta-induced settlement for Patches A, B, and Road.

EQ Event	Patch A (10-, 20-, and 50-m buffers)			Patch B (50-m buffer)			Road (50-m buffer)		
	$S_{E,L}$ (mm)	$S_{E,P}$ (mm)	$S_{E,final}$ (mm)	$S_{E,L}$ (mm)	$S_{E,P}$ (mm)	$S_{E,final}$ (mm)	$S_{E,L}$ (mm)	$S_{E,P}$ (mm)	$S_{E,final}$ (mm)
Sep-10	ND	0	0	ND	26±8	25±10	ND	4±1	5±5
Feb-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
Jun-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dec-11	ND	ND	ND	ND	ND	ND	ND	ND	ND

Notes: $S_{E,L}$ = Ejecta-induced settlement based on LiDAR data reported in Table 8; $S_{E,P}$ = Median ejecta-induced settlement for the range of values reported in Table 10; $S_{E,final}$ = Best final estimate of ejecta-induced settlement rounded to the nearest 5; Final plus/minus values are also rounded to the nearest 5; ND = Not determined.

Note 4:

- $S_{E,final}$ is based solely on $S_{E,P}$ for the Sep-10 EQ due to the evident absence of ejecta from Patch A and LiDAR-related uncertainties explained in Table 2 for Patch B and Road. $S_{E,L}$, $S_{E,P}$, and $S_{E,final}$ for the Feb-11, Jun-11, and Dec-11 EQ are not estimated due to lateral spreading following the Feb-11 EQ.
- The 1/19 Chardale St site is in the apparent zone of higher ground surface subsidence for the Sep-10 EQ (i.e., the overestimate of the ground surface elevation by the Jul-03 LiDAR survey). The site is in the zone of accurate LPI prediction of liquefaction severity for the Sep-10 EQ (Maurer et al. 2014[3]). The LDAT property inspection reports or ground photographs are not available for any property within the 50-m buffer for the Sep-10 EQ.

[3] Maurer, B. W., Green, R. A., Cubrinovski, M., & Bradley, B. A. (2014). Evaluation of the Liquefaction Potential Index for Assessing Liquefaction Hazard in Christchurch, New Zealand. *Journal of Geotechnical and Geoenvironmental Engineering*, 140(7), 04014032-1-11. doi:10.1061/(asce)gt.1943-5606.0001117

<u>Summary 1</u>:

- **The best estimate of the ejecta-induced free-field ground settlement at the 1/19 Chardale St site for the SEP 2010 earthquake is 25±10 mm for properties with ejecta (<5% of the site, within the 50-m buffer). The ejecta-induced free-field ground settlement for the FEB 2011, JUN 2011, and DEC 2011 earthquake is not estimated due to lateral spreading following the FEB 2011 earthquake.**
- **The best estimate of the ejecta-induced settlement of the road at the 1/19 Chardale St site for the SEP 2010 earthquake is 5±5 mm. The ejecta-induced free-field ground settlement for the FEB 2011, JUN 2011, and DEC 2011 earthquake is not estimated due to lateral spreading following the FEB 2011 earthquake.**

Figure 2: Location of the site.

Figure 3: Position of the site relative to nearby buildings, vegetation, and free-face features.

Figure 4: Street view of the flat land.

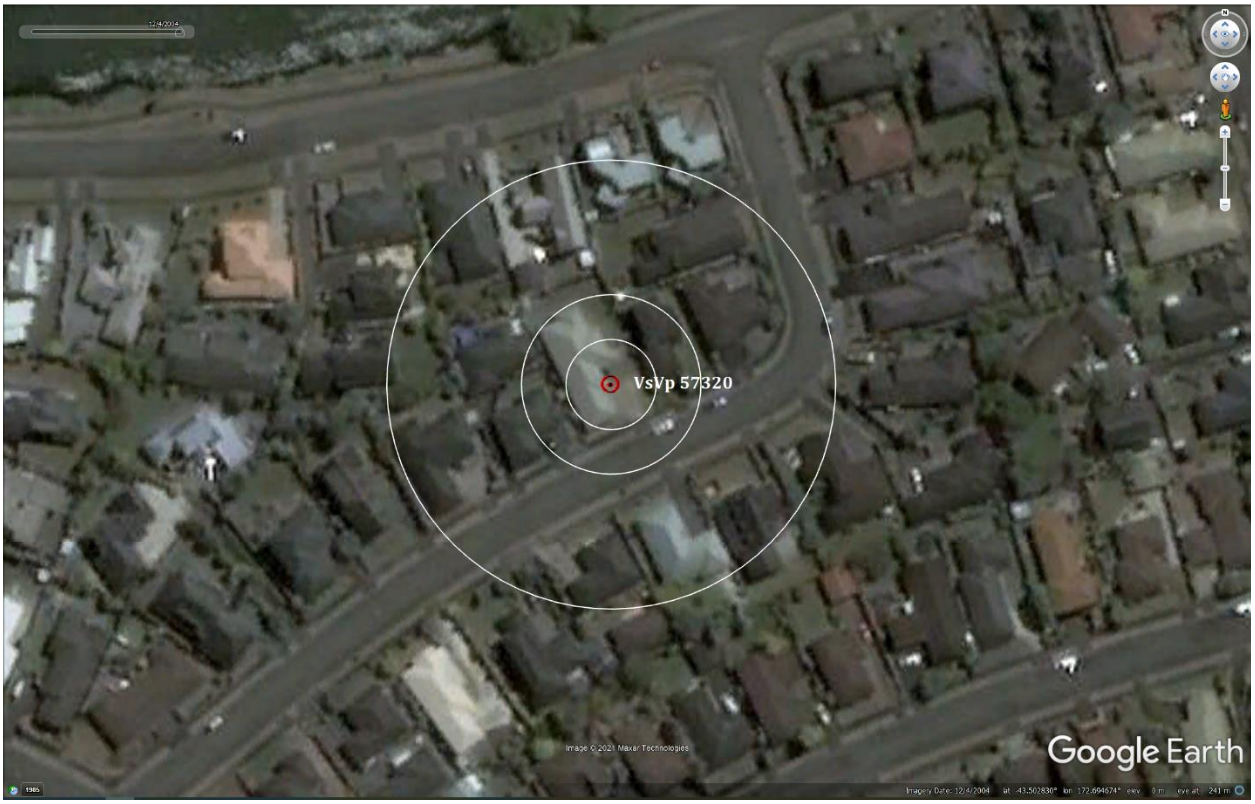

Figure 5: Satellite image of the site taken in Dec 2004.

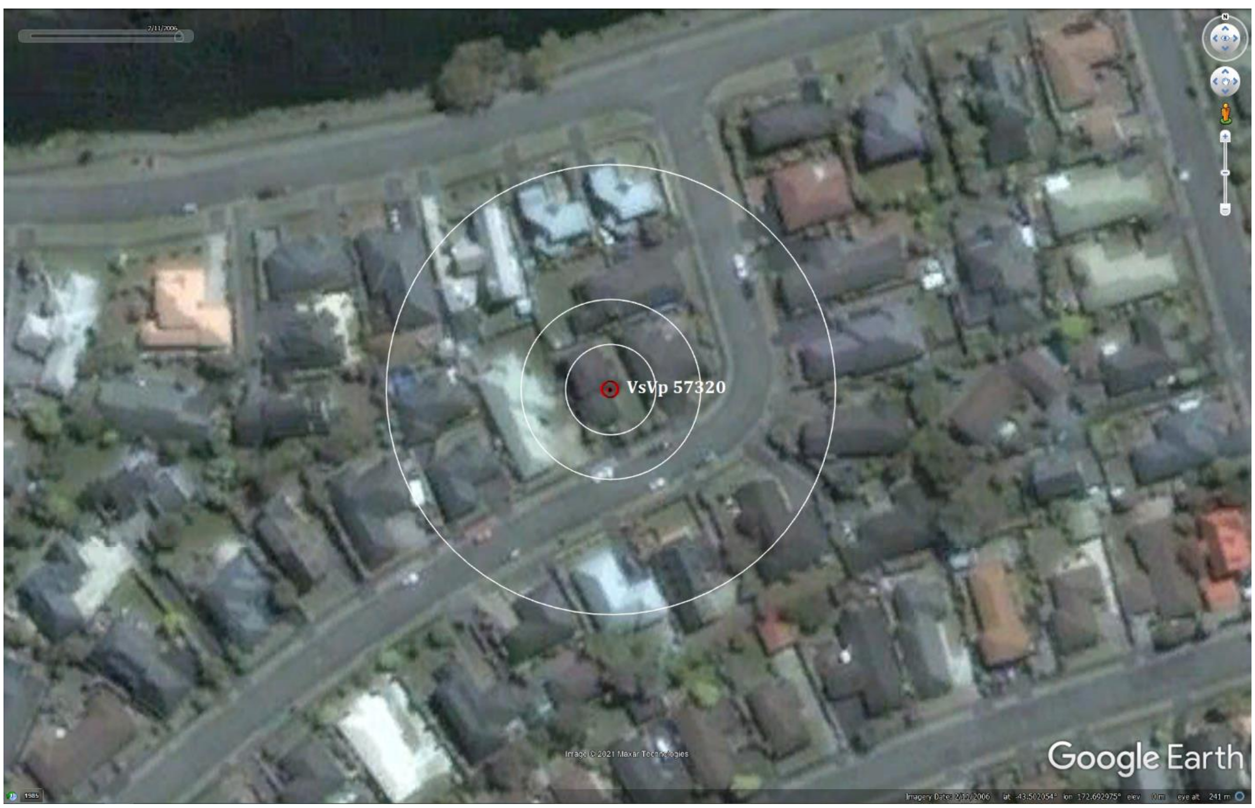

Figure 6: Satellite image of the site taken in Feb 2006.

Figure 7: Satellite image of the site taken in Mar 2009.

Figure 8: Satellite image of the site taken in Sep 2010.

Figure 9: Satellite image of the site taken acquired just days before the Feb-2011 EQ.

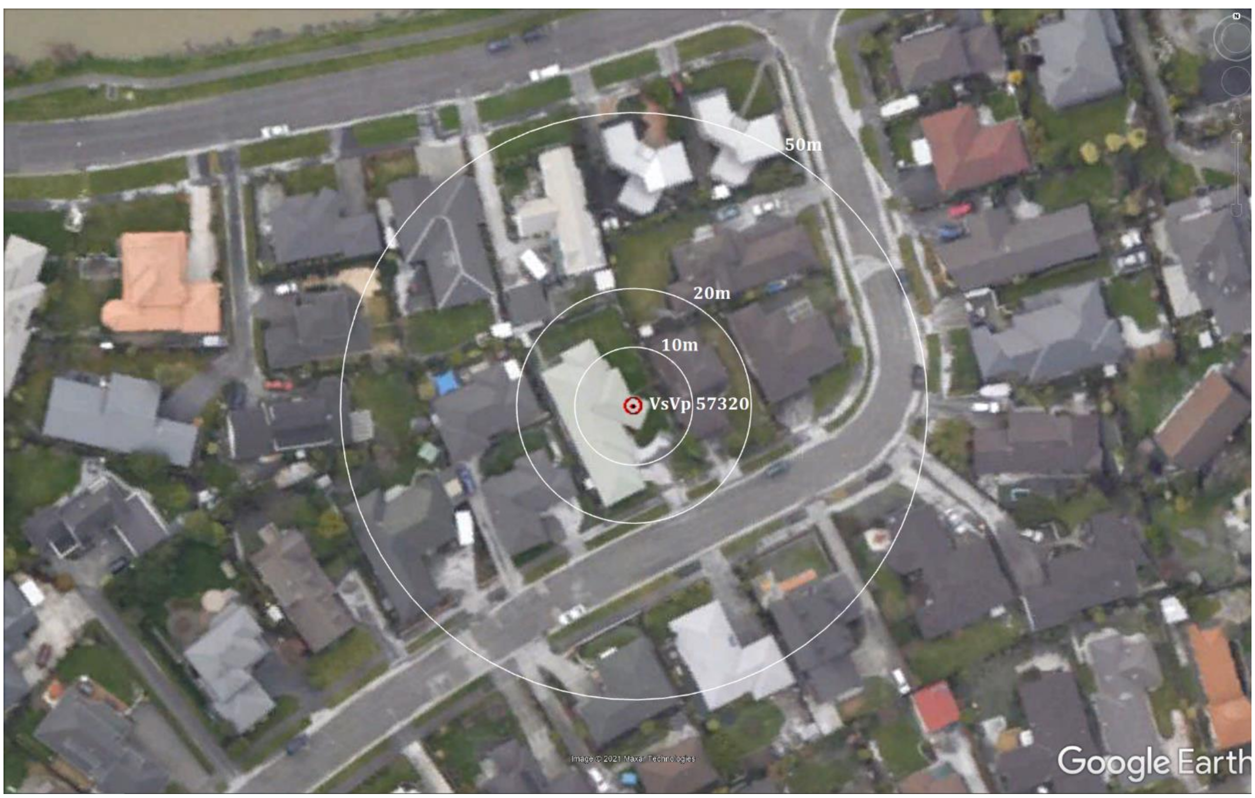

Figure 10: Aerial photograph of the site taken on Sep 4, 2010.

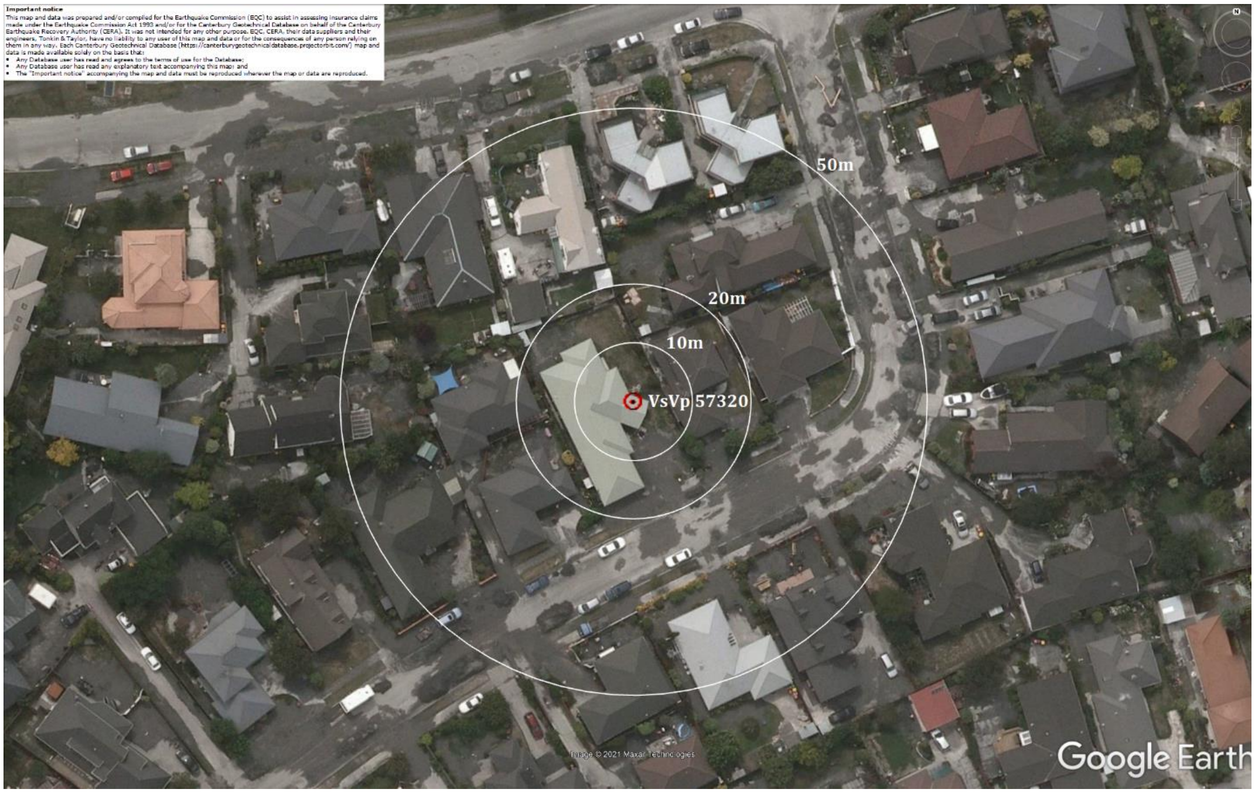

Figure 11: Aerial photograph of the site taken on Feb 24, 2011.

Figure 12: Aerial photograph of the site taken on June 14-15, 2011.

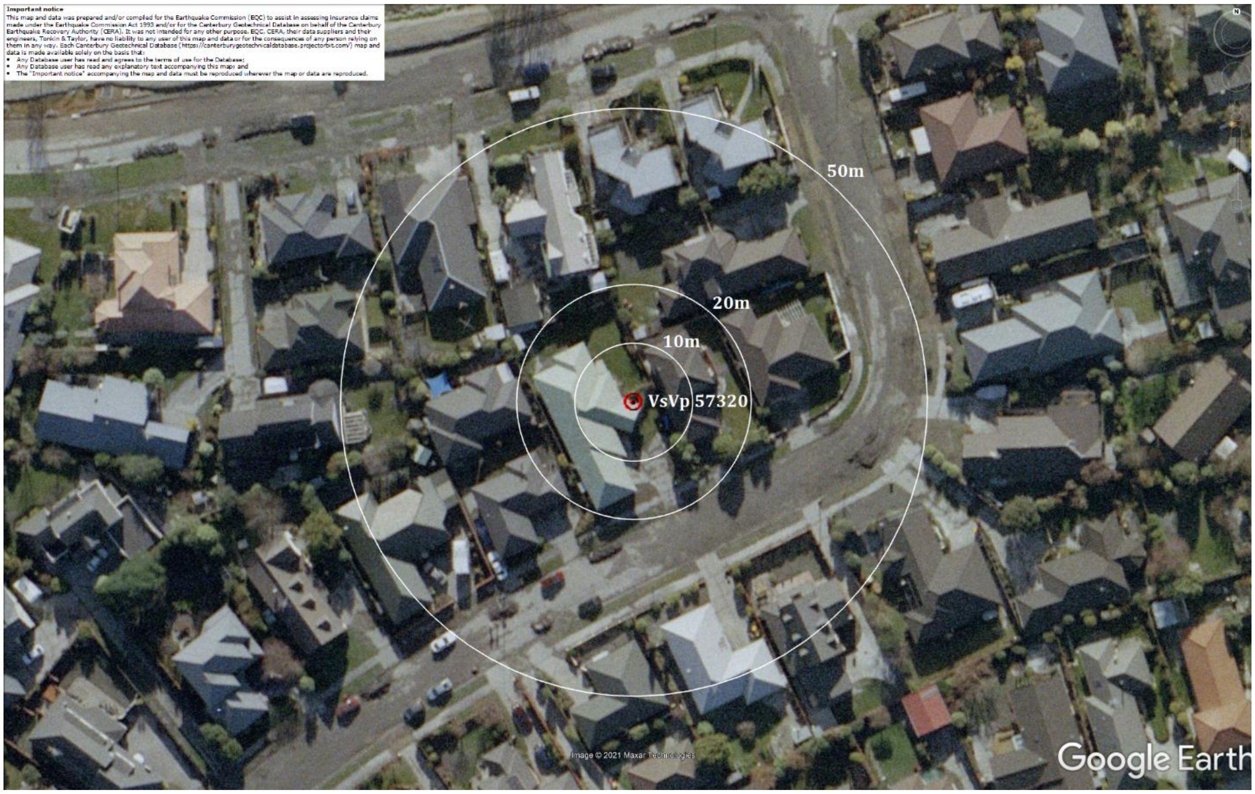

Figure 13: Aerial photograph of the site taken on June 16, 2011.

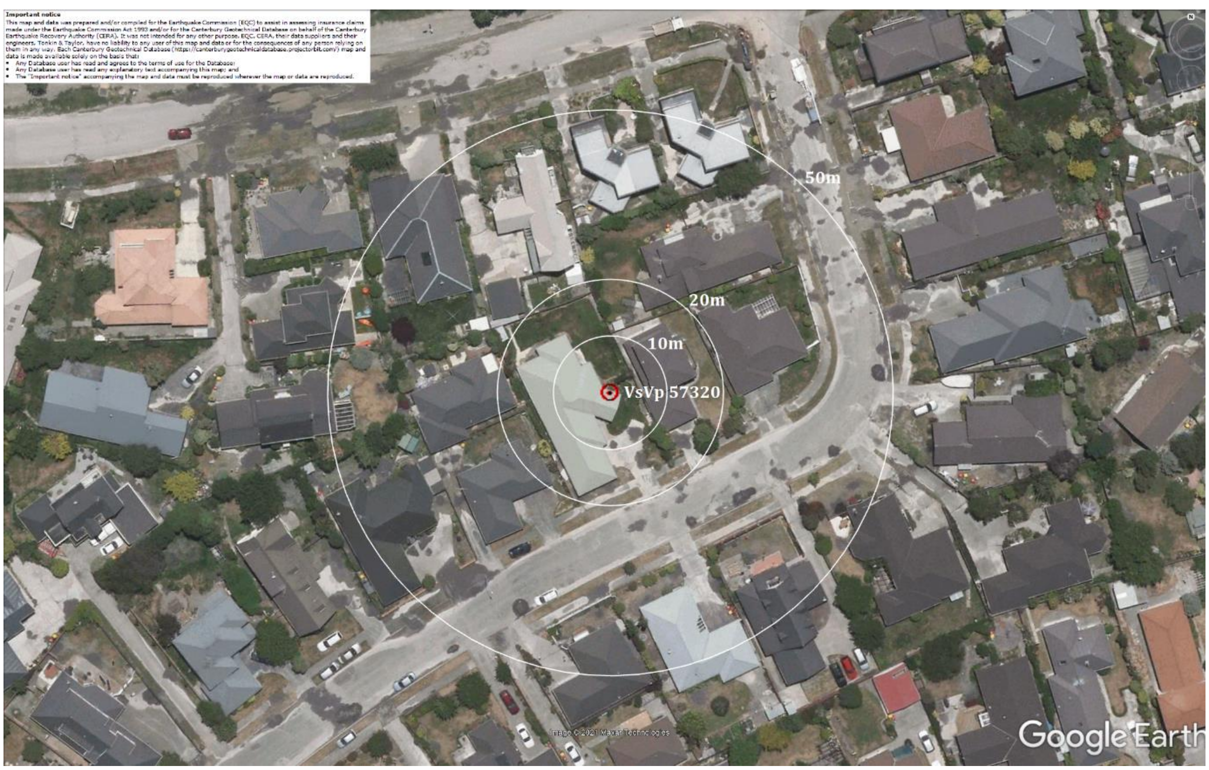

Figure 14: Aerial photograph of the site taken on Dec 24, 2011.

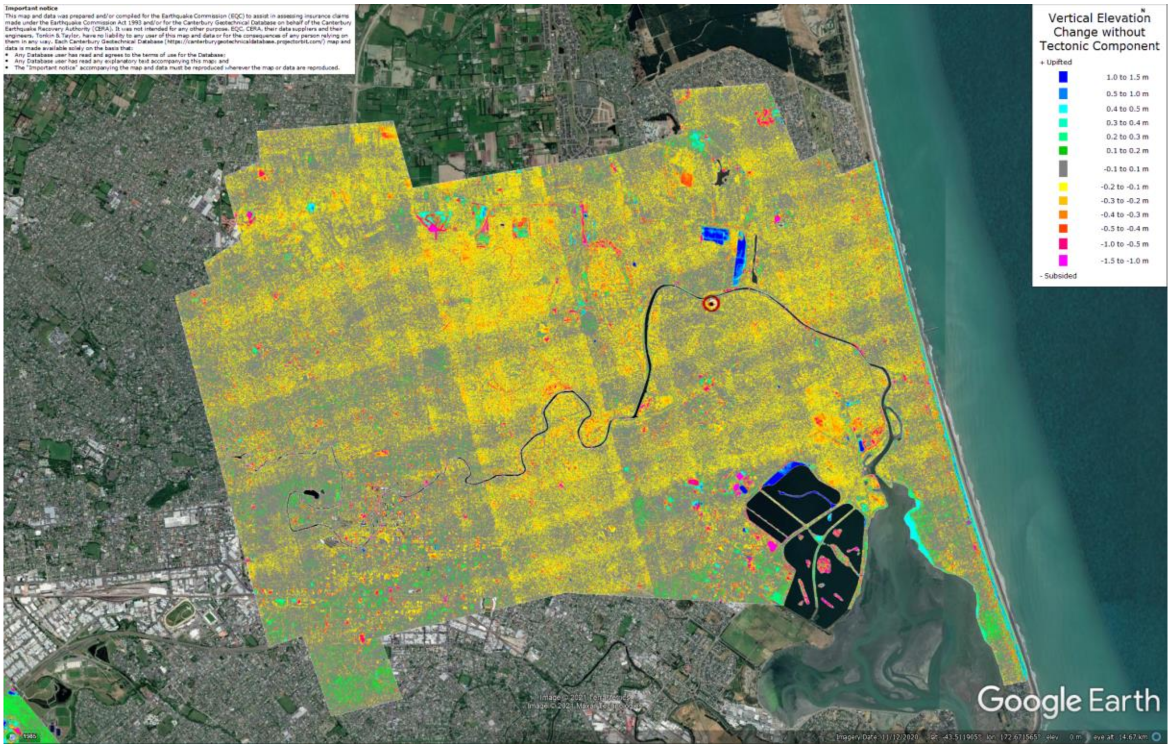

Figure 15: Vertical Ground Movements (Surface – Tectonic) for Sep 2010 Earthquake – the site is in the apparent zone of overestimated ground surface subsidence (i.e., flight error band for July 2003).

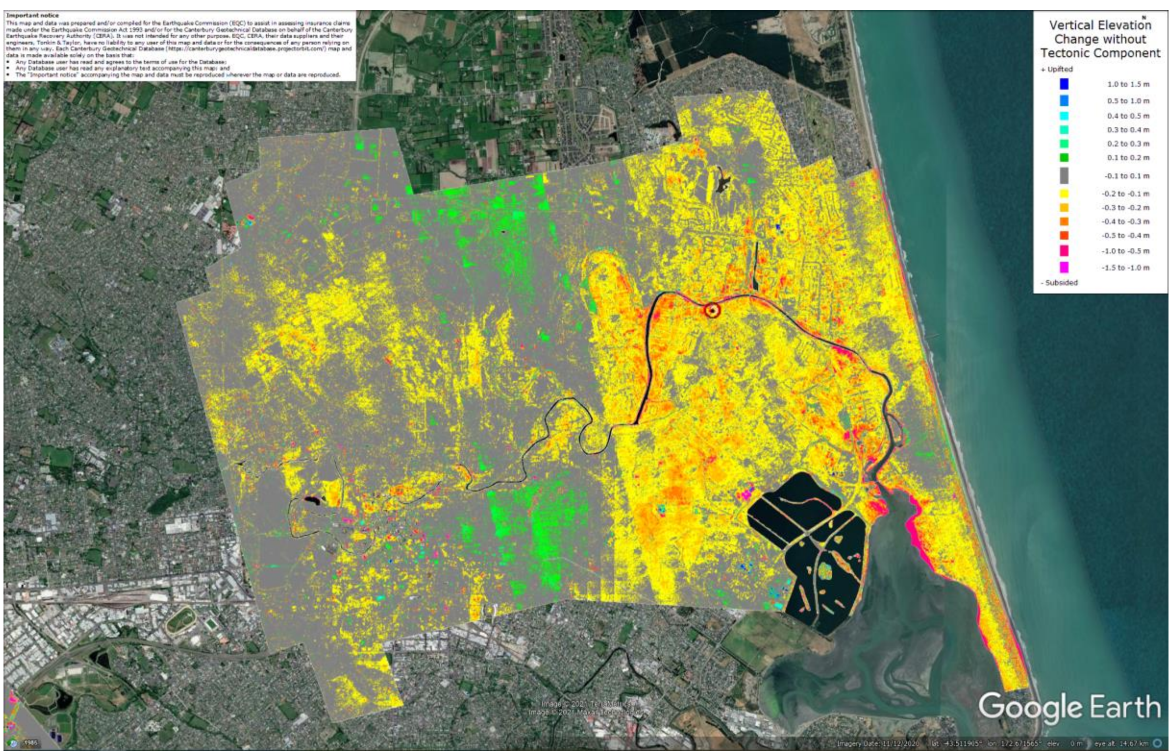

Figure 16: Vertical Ground Movements (Surface – Tectonic) for Feb 2011 Earthquake – the site is not in the apparent zone of underestimated ground surface subsidence.

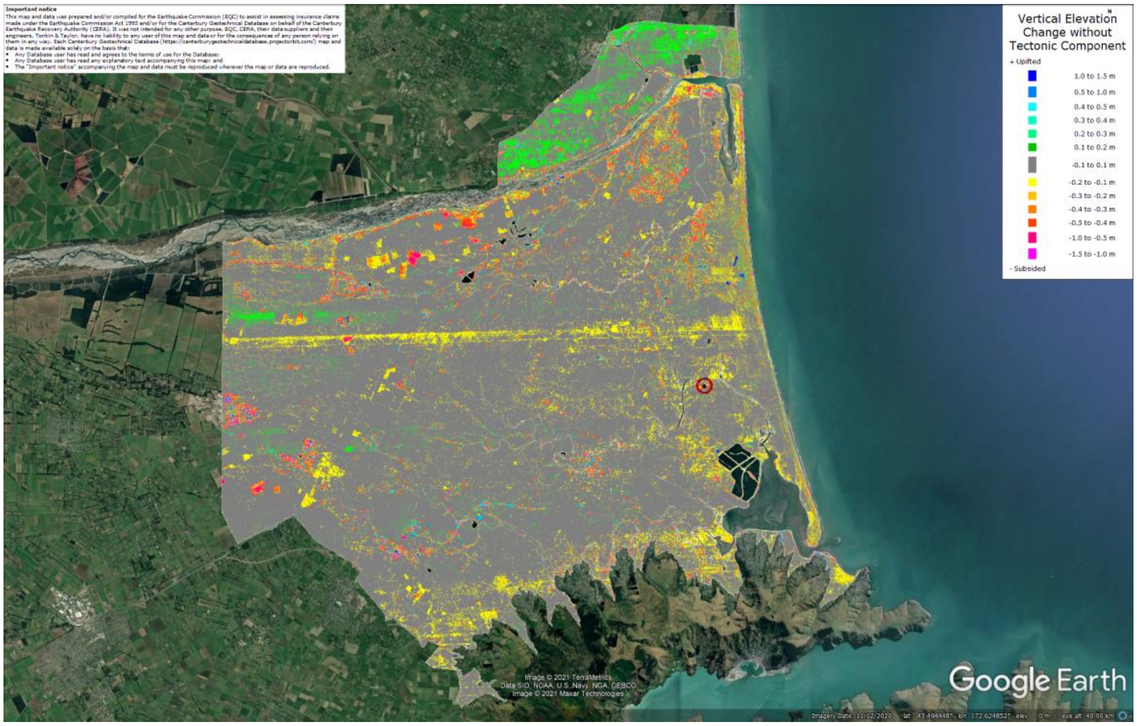

Figure 17: Vertical Ground Movements (Surface – Tectonic) for June 2011 Earthquake – the site is not in the apparent zone of overestimated or underestimated ground surface subsidence.

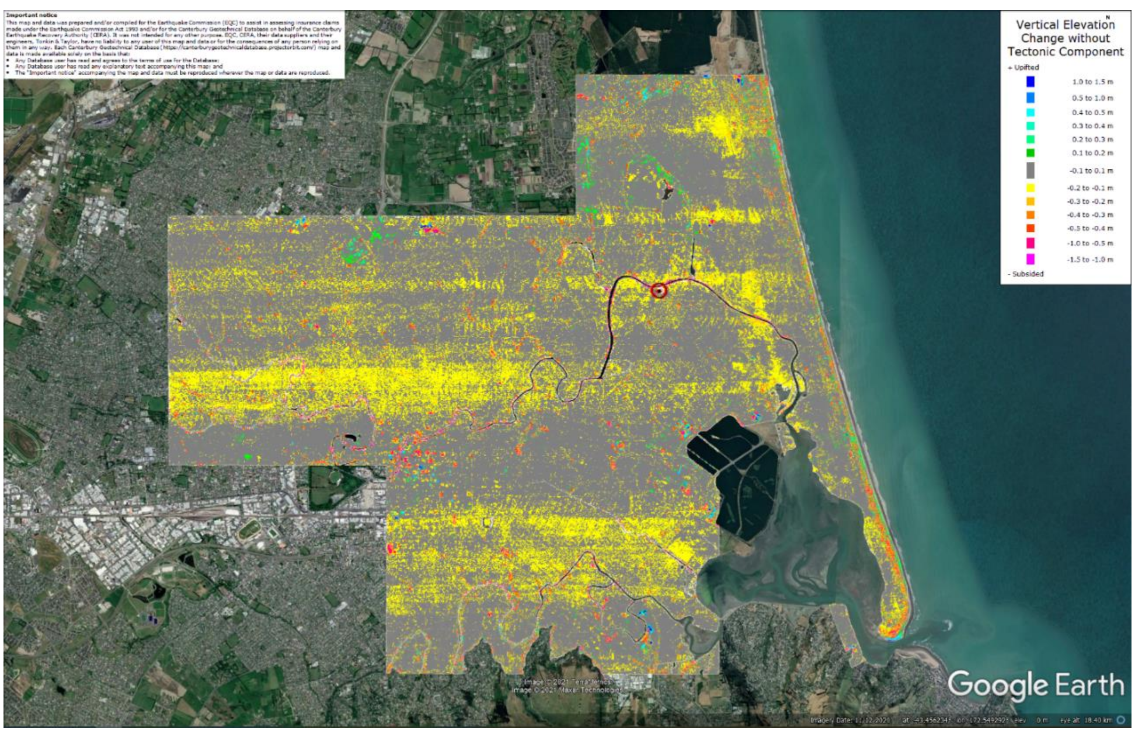

Figure 18: Vertical Ground Movements (Surface – Tectonic) for Dec 2011 Earthquake – the site is not in the apparent zone of overestimated or underestimated ground surface subsidence.

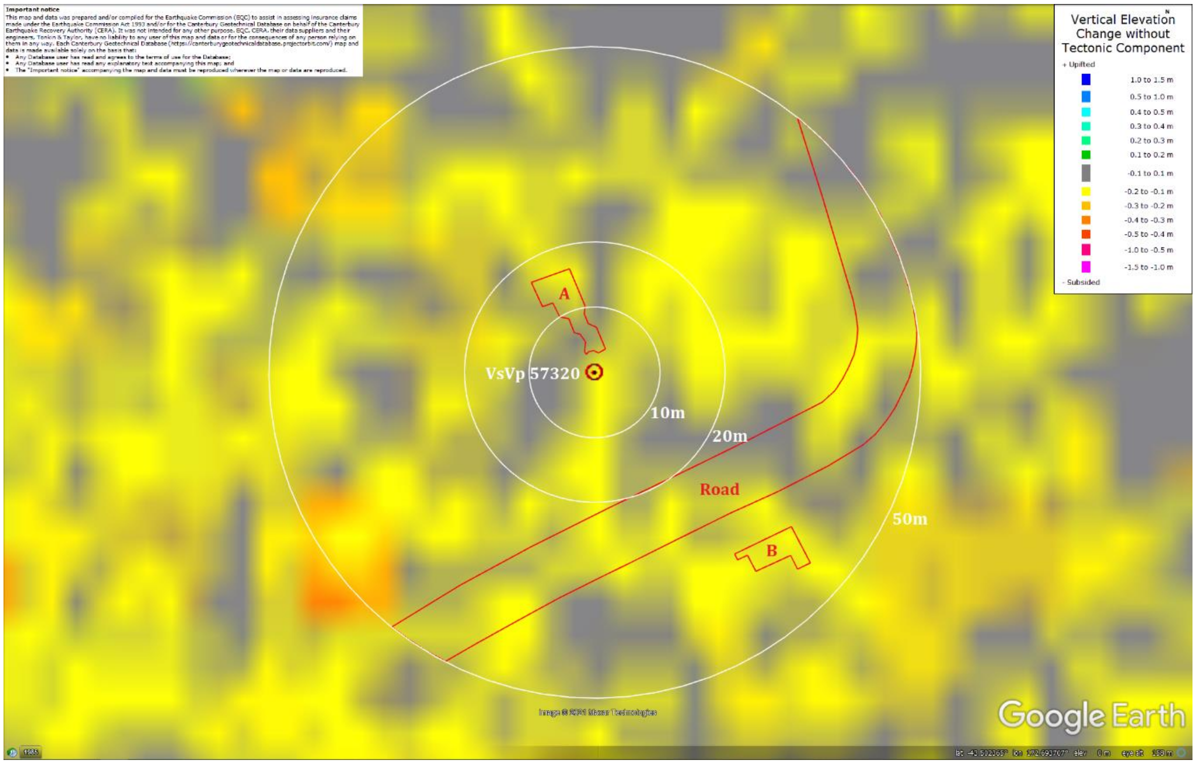

Figure 19: Ground surface subsidence without tectonic component for Sep 2010 Earthquake according to the LiDAR DEM.

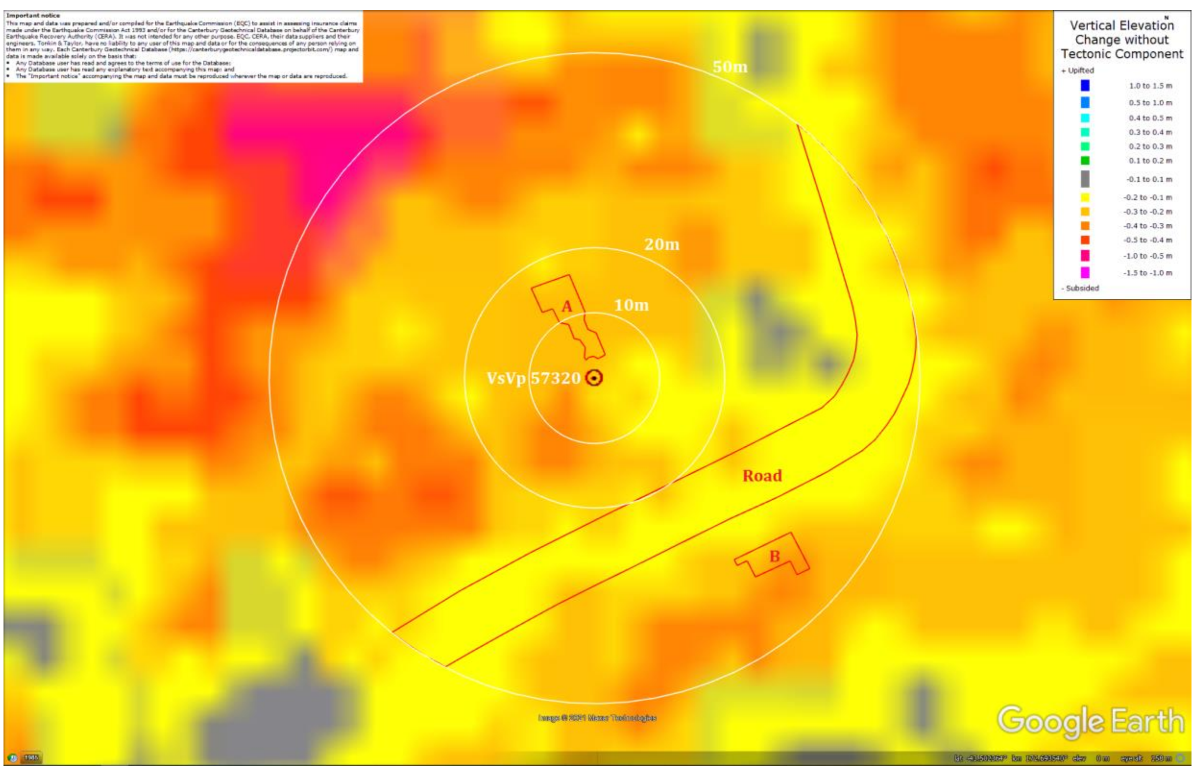

Figure 20: Ground surface subsidence without tectonic component for Feb 2011 Earthquake according to the LiDAR DEM.

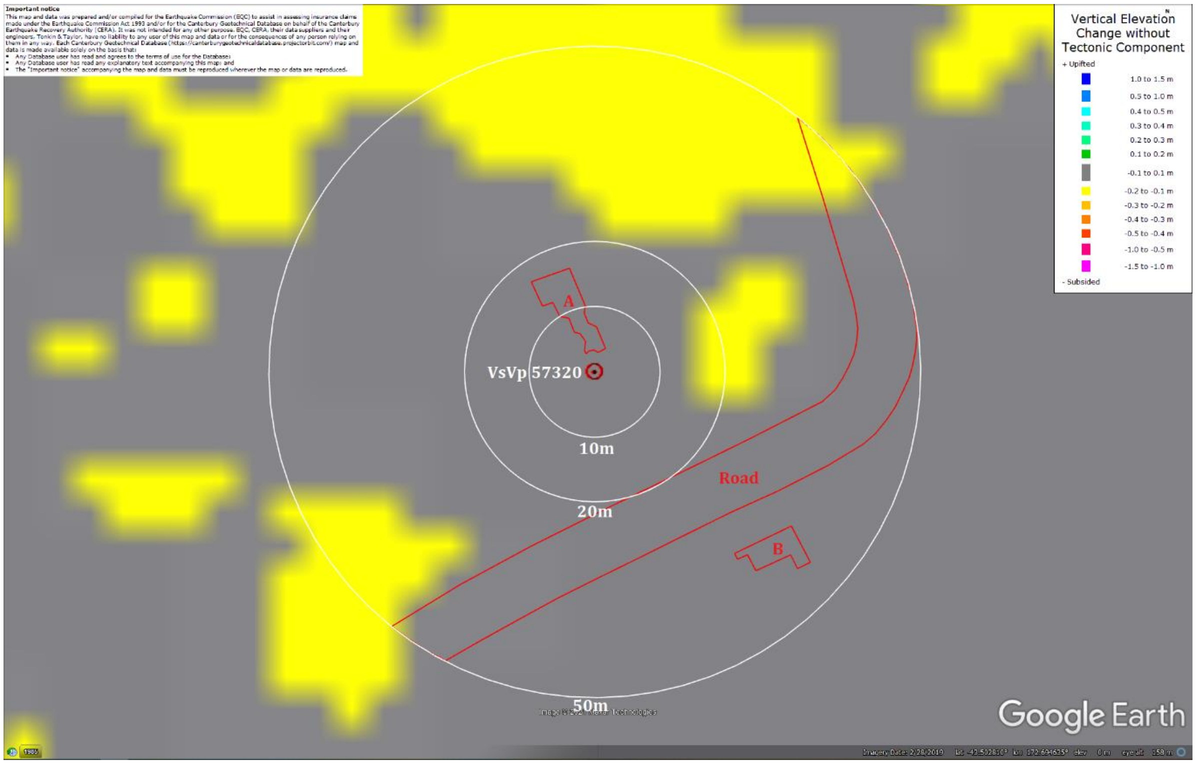

Figure 21: Ground surface subsidence without tectonic component for June 2011 Earthquake according to the LiDAR DEM.

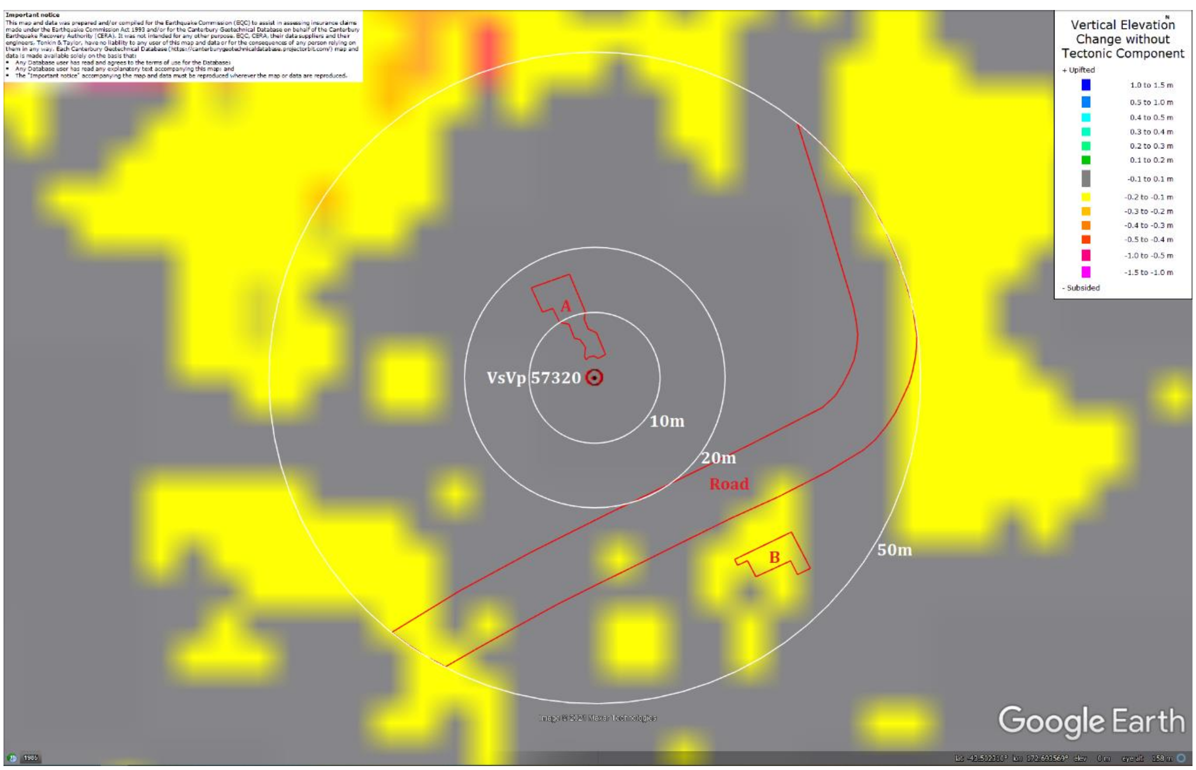

Figure 22: Ground surface subsidence without tectonic component for Dec 2011 Earthquake according to the LiDAR DEM.

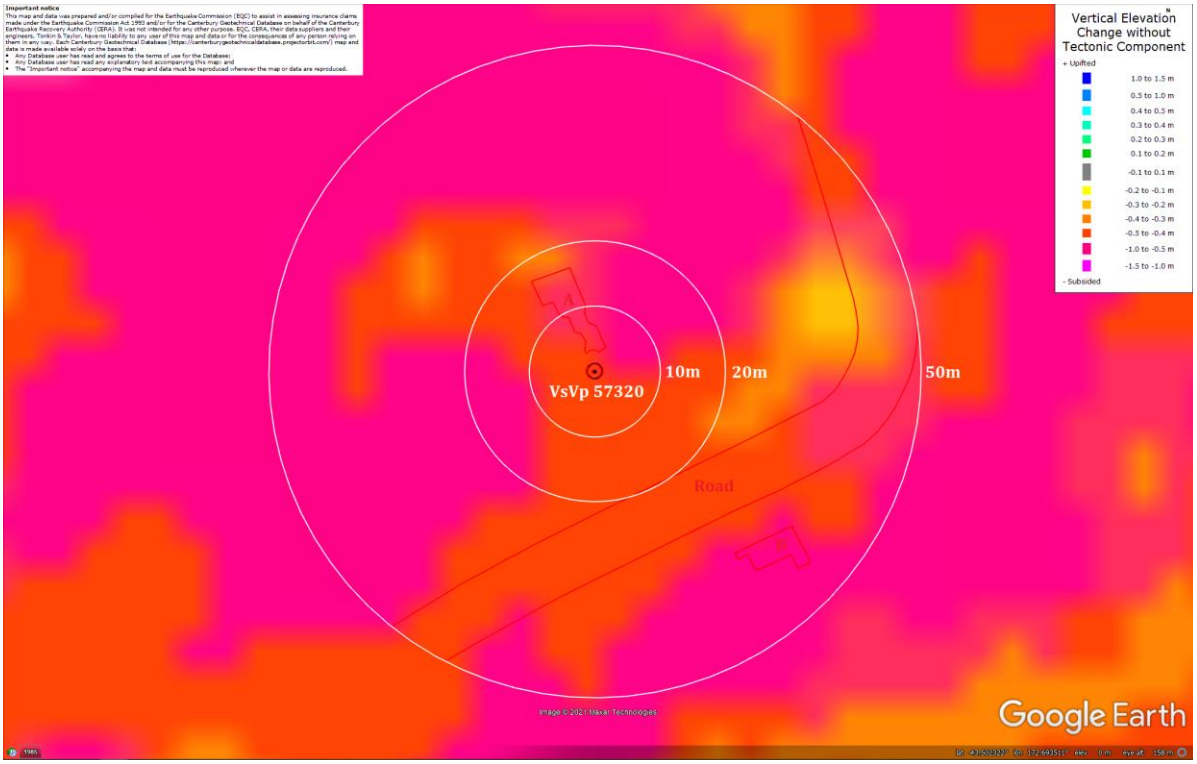

Figure 23: Ground surface subsidence without tectonic component for Canterbury Earthquake Sequence according to the LiDAR DEM.

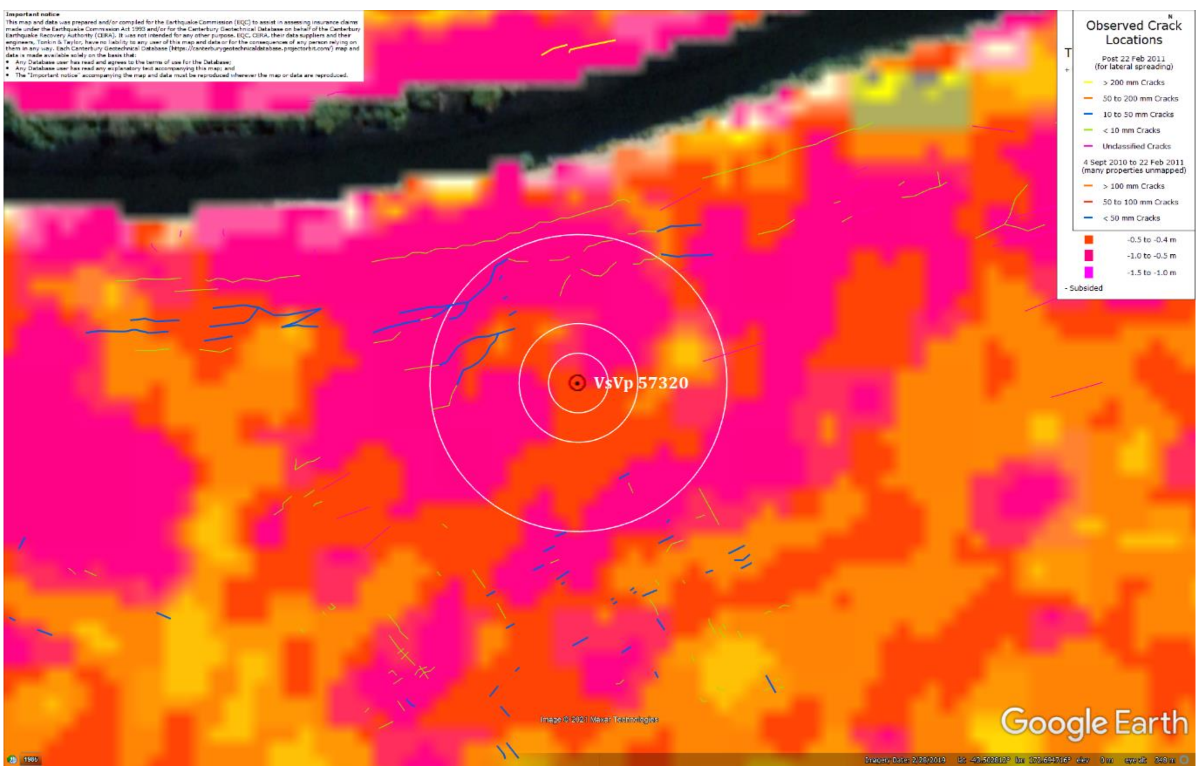

Figure 24: Lateral spreading for Canterbury Earthquake Sequence (no lateral spreading for Sep-10 EQ but Feb-11 EQ).

Figure 25: Vertical tectonic movements for Sep 2010 Earthquake.

Figure 26: Vertical tectonic movements for Feb 2011 Earthquake.

Figure 27: Vertical tectonic movements for June 2011 Earthquake.

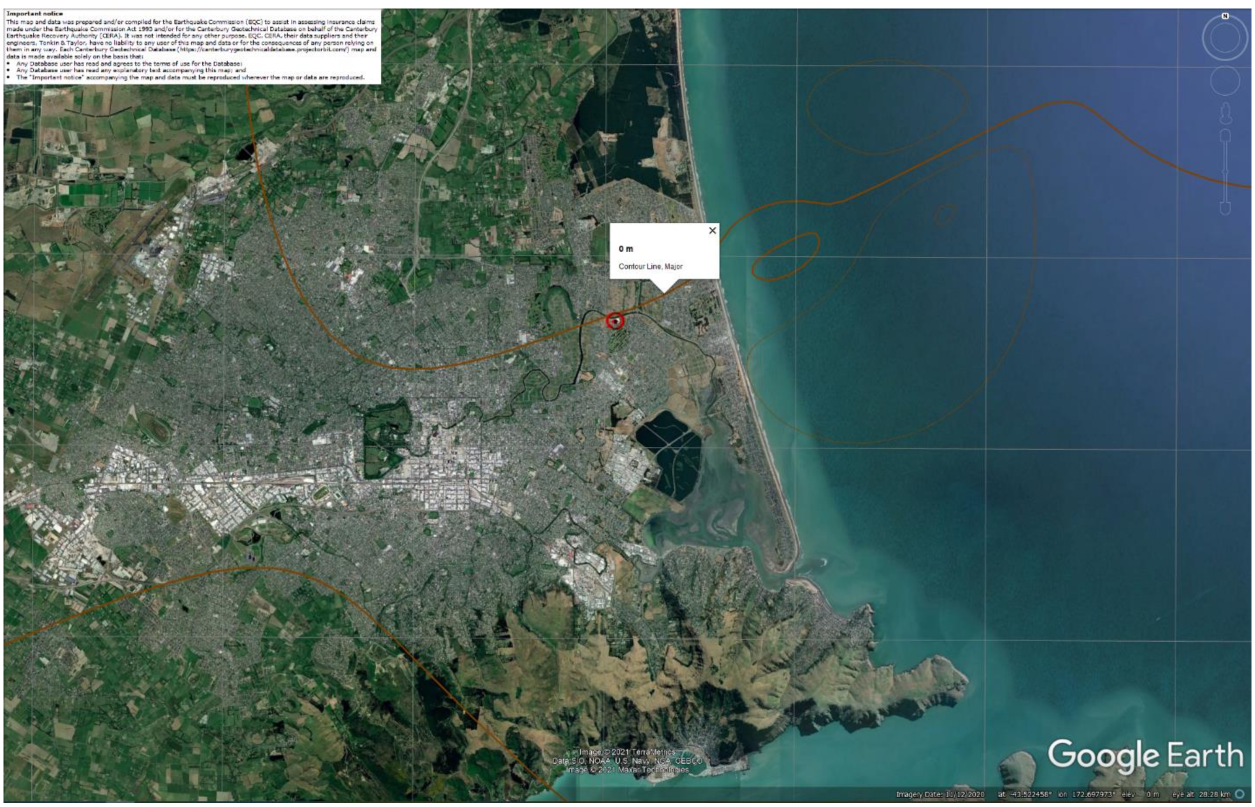

Figure 28: Vertical tectonic movements for Dec 2011 Earthquake.

Figure 29: Vertical tectonic movements for Canterbury Earthquake Sequence.

Figure 30: Ejecta outline for Sep-10 EQ.

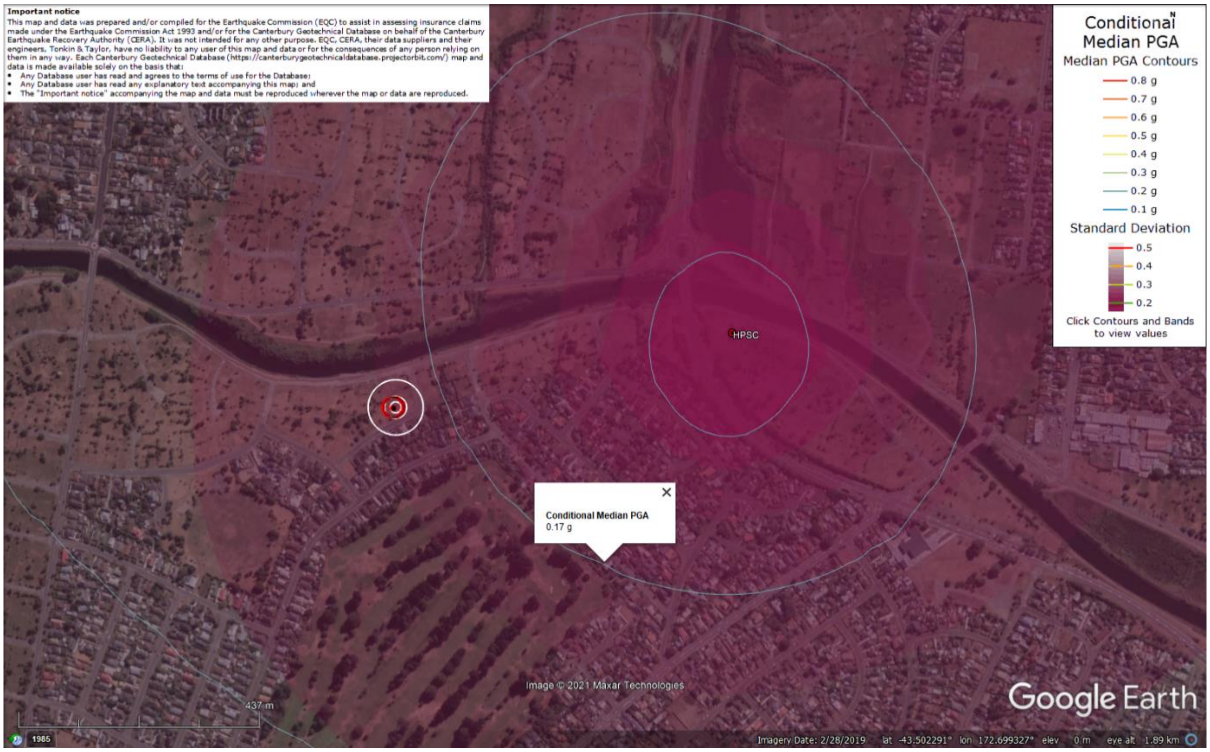

Figure 31: PGA for Sep-10 EQ (st. dev. = 0.250-0.275 ln units).

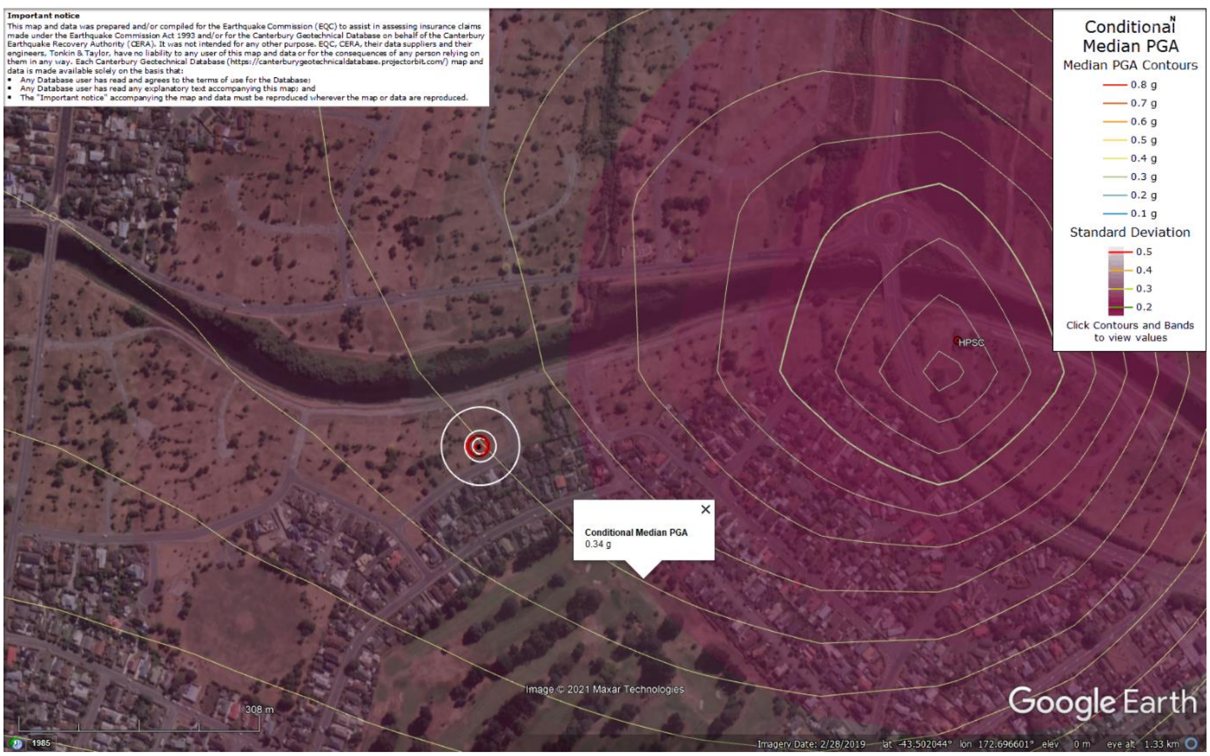

Figure 32: PGA for Feb-11 EQ (st. dev. = 0.275-0.300 ln units).

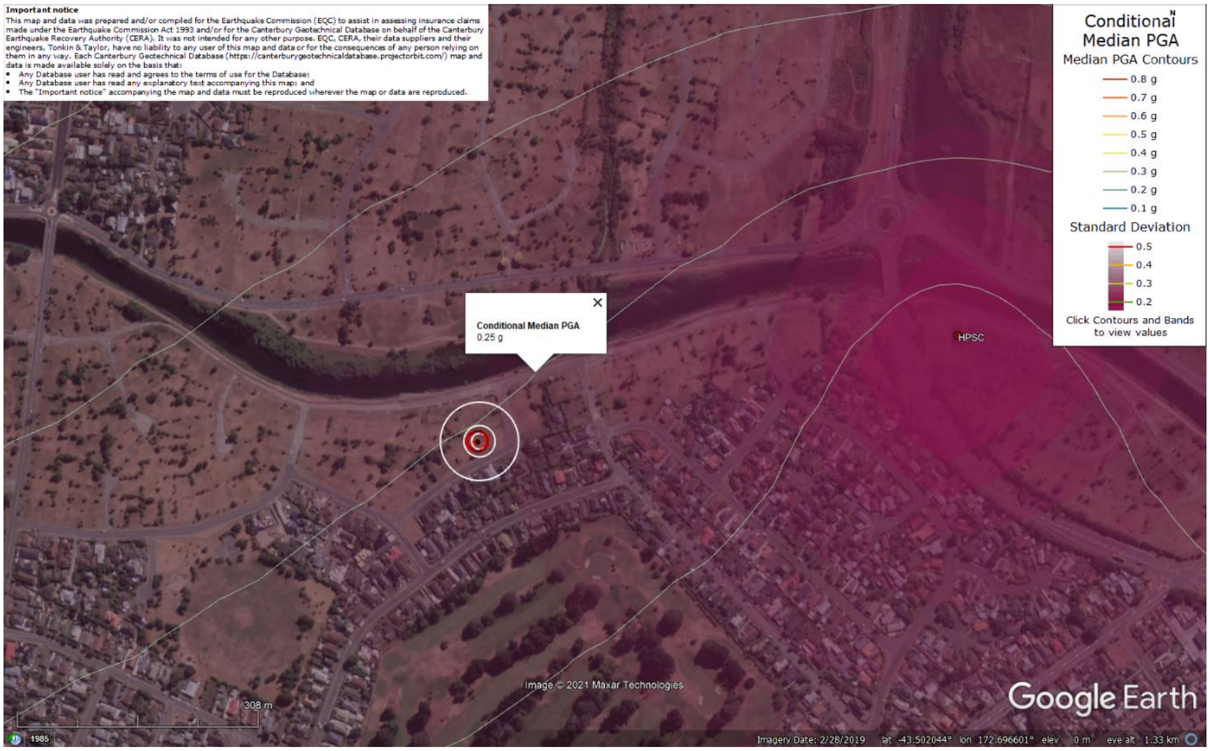

Figure 33: PGA for Jun-11 EQ (st. dev. = 0.300-0.325 ln units).

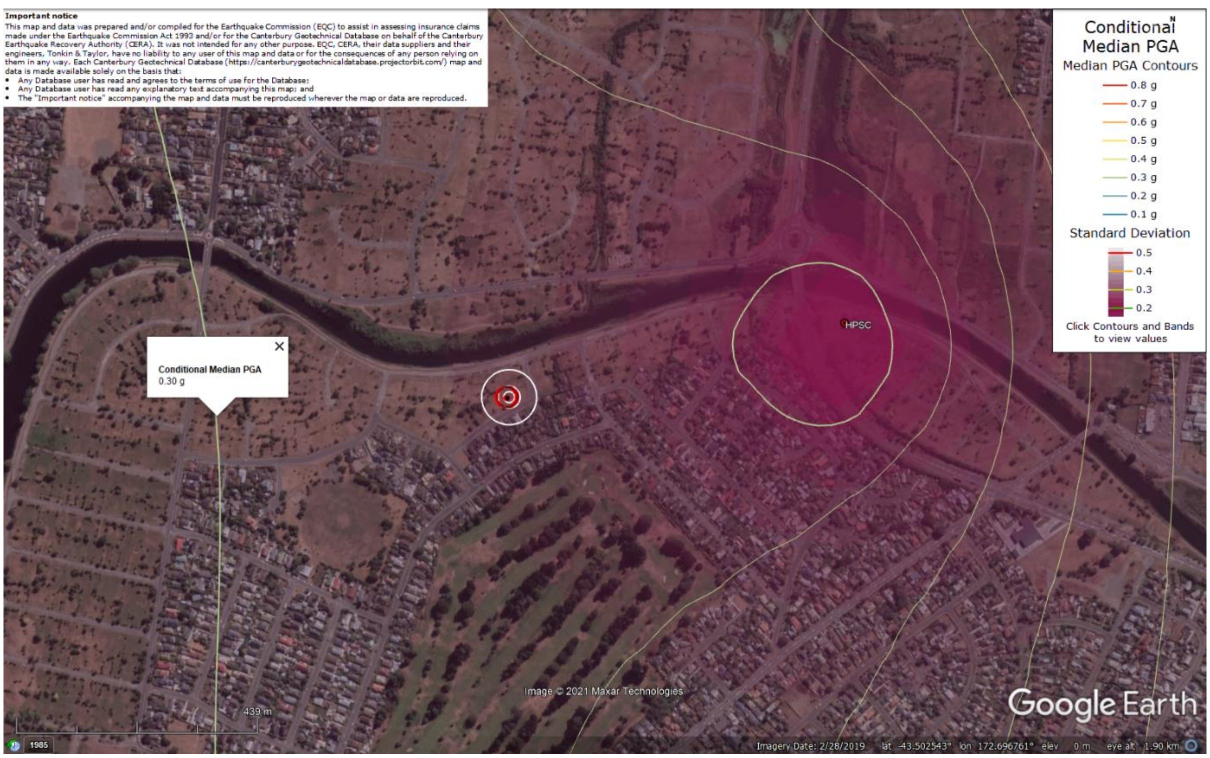

Figure 34: PGA for Dec-11 EQ (st. dev. = 0.300-0.325 ln units).

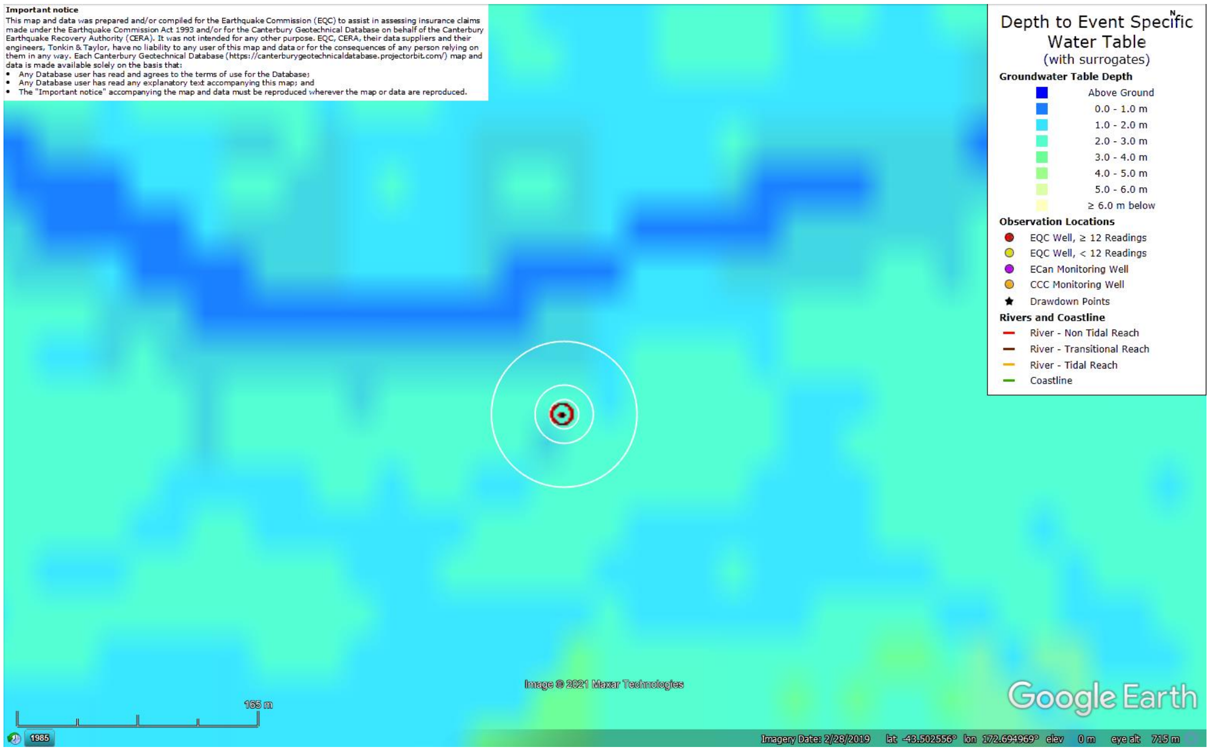

Figure 35: Depth to groundwater table for Sep-10 EQ.

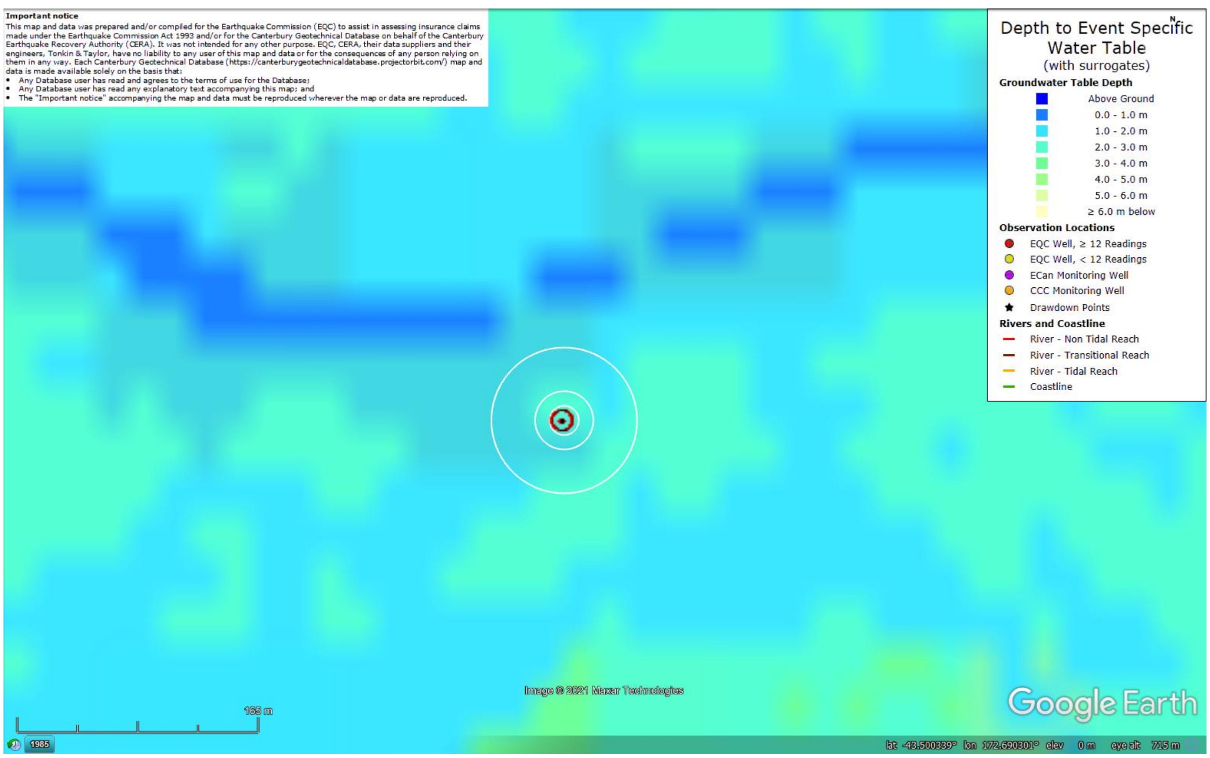

Figure 36: Depth to groundwater table for Feb-11 EQ.

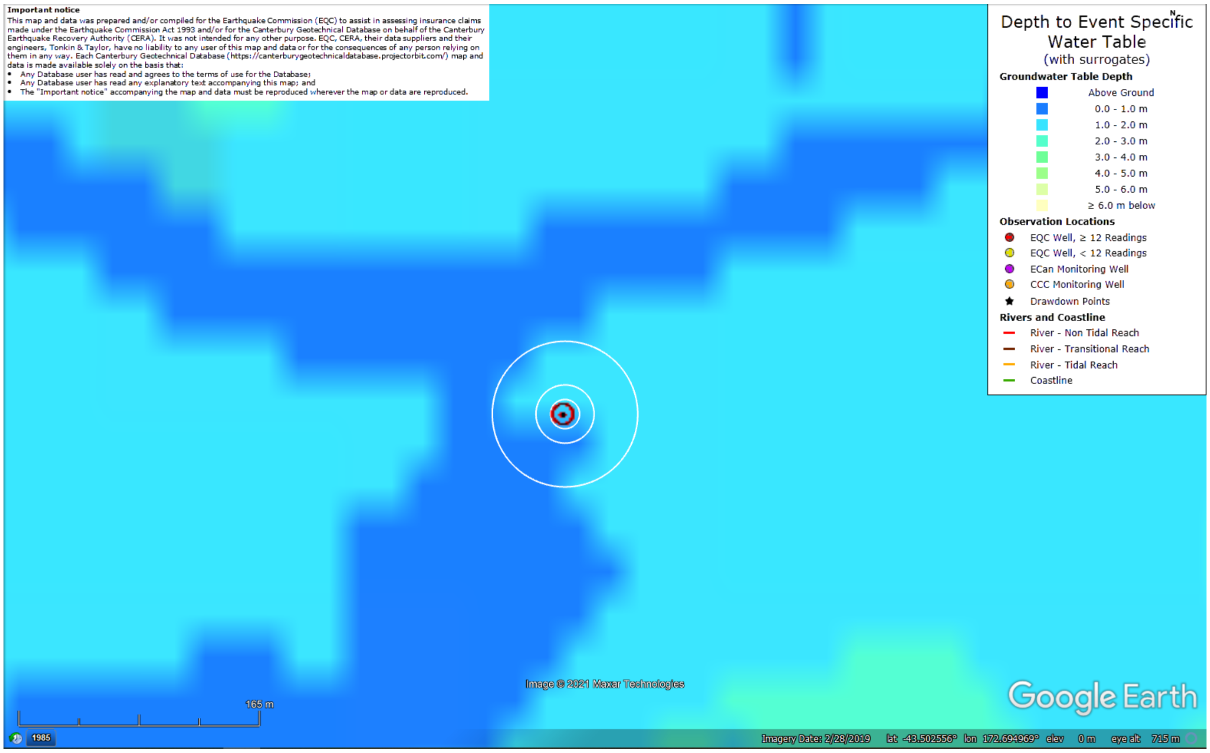

Figure 37: Depth to groundwater table for Jun-11 EQ.

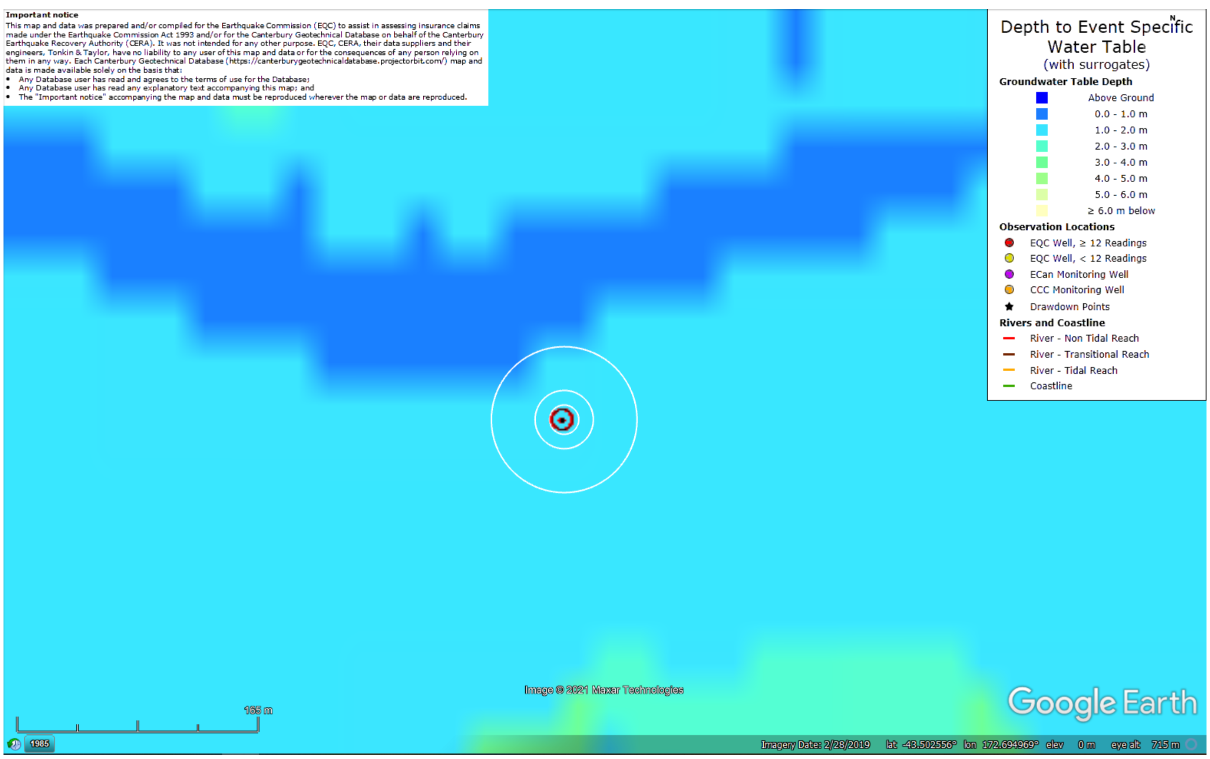

Figure 38: Depth to groundwater table for Dec-11 EQ.

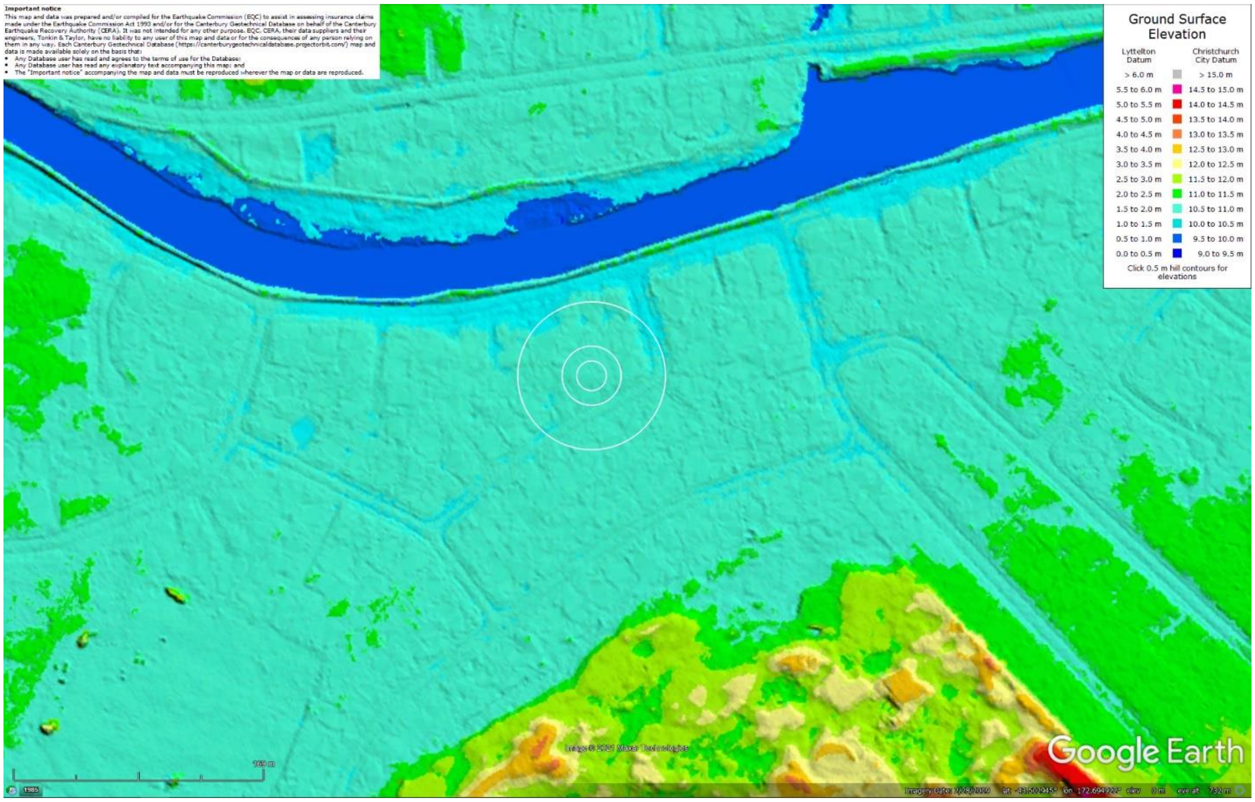

Figure 39: Ground surface elevation according to the Sep-11 LiDAR survey.

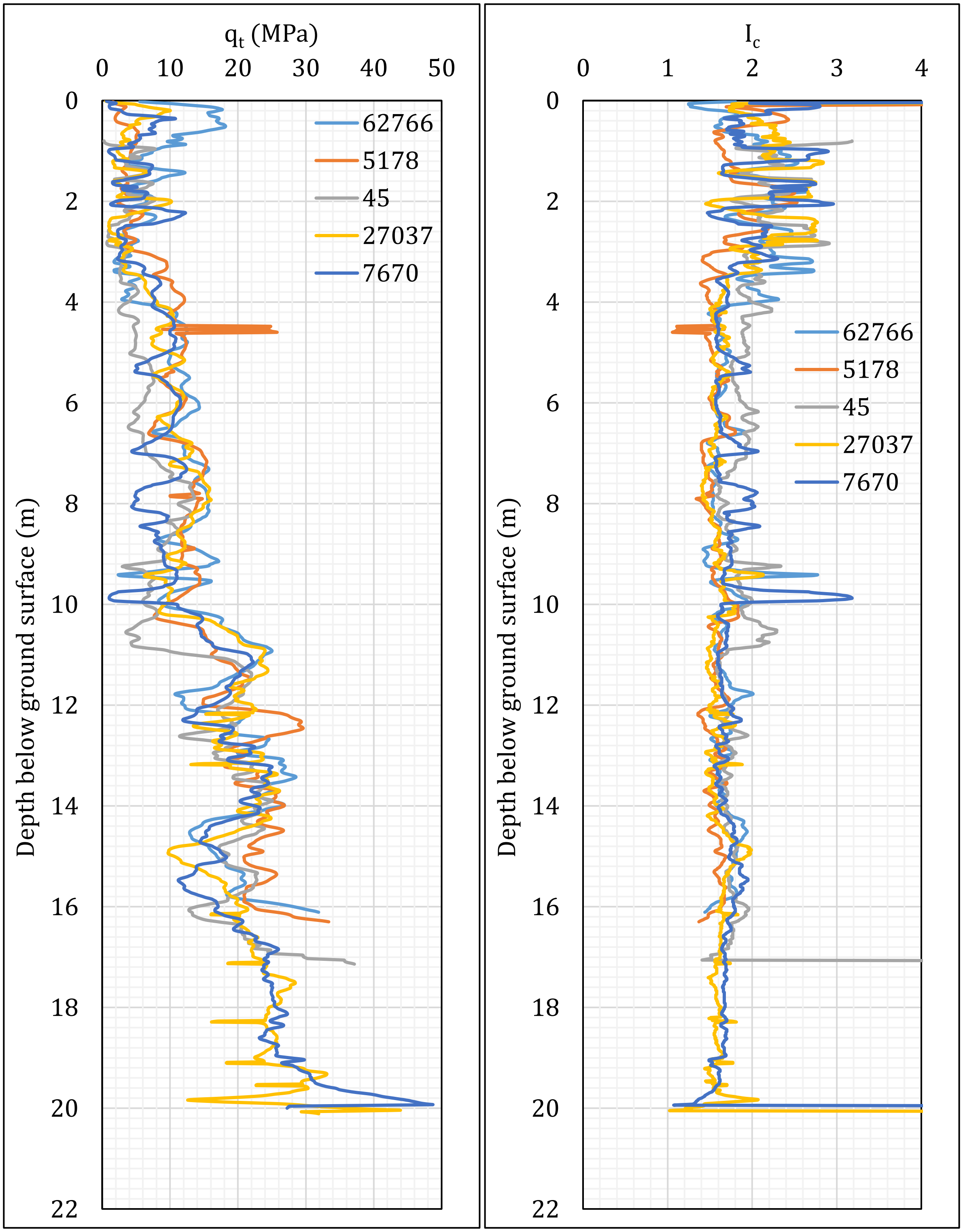

Figure 40: q_t and I_c profiles.

Note 5: The selection of CPTs for the area considered for settlement assessment (Figure 1) is based on the proximity of the CPTs to the considered areas. In accordance with that, the following table shows CPTs that were used for the volumetric settlement analysis in *Cliq v.3.0.3.2*, a CPT soil liquefaction software developed by GeoLogismiki. (The average volumetric settlements were reported in Table 8.)

Table 12: CPT profiles used in volumetric settlement analysis for areas selected for settlement assessment.

CPT ID No.	Patch A	Patch B	Road
62766 (60913)	✓		
5178		✓	
27037			✓
45			✓
7670			✓

Notes: CPT 27307 was used to estimate the volumetric settlement for a depth range from 16m to 20m for CPTs 62766 and 5178 and a depth range from 17m to 20 m for CPT 45; There are no pore water pressure measurements for CPT 45.

Table 13: CPT-based results.

		CPT ID				
EQ Event	Parameter	62766	5178	45	27037	7670
Sep-10	S_{V1D} (mm)	2	7	20	9	15
	LSN	0	1	3	1	2
	LPI	0	0	0	0	0
	LPI_{ish}	0	0	0	0	0
	$D_{FS<1}$ (m)	undet.	undet.	undet.	undet.	undet.
Feb-11	S_{V1D} (mm)	ND	ND	ND	ND	ND
	LSN	ND	ND	ND	ND	ND
	LPI	ND	ND	ND	ND	ND
	LPI_{ish}	ND	ND	ND	ND	ND
	$D_{FS<1}$ (m)	ND	ND	ND	ND	ND
Jun-11	S_{V1D} (mm)	ND	ND	ND	ND	ND
	LSN	ND	ND	ND	ND	ND
	LPI	ND	ND	ND	ND	ND
	LPI_{ish}	ND	ND	ND	ND	ND
	$D_{FS<1}$ (m)	ND	ND	ND	ND	ND
Dec-11	S_{V1D} (mm)	ND	ND	ND	ND	ND
	LSN	ND	ND	ND	ND	ND
	LPI	ND	ND	ND	ND	ND
	LPI_{ish}	ND	ND	ND	ND	ND
	$D_{FS<1}$ (m)	ND	ND	ND	ND	ND

Notes: $D_{FS<1}$ = Depth to the first liquefiable layer (FS_L<1) that is at least 200-mm thick, as determined by the Boulanger and Idriss (2016) liquefaction-triggering procedure (P_L=50%, C_{FC}=0.13, and $I_{c,cutoff}$ =2.6), and exported from *Cliq v.3.0.3.2*; undet. = the specified soil layer was not detected.

Note 6: Based on the borehole log (BH 15467, Figure 1), the groundwater table is at a depth of 1.5 m below the ground surface. The soil profile consists of (1) topsoil to a depth of 0.5 m, (2) silty fine to coarse gravel, GW, of the Springston formation (Yaldhurst member, alluvial) to a depth of 1.5 m, (3) silt, ML, of the Springston formation (Yaldhurst member, alluvial) to a depth of 1.95 m, (4) silty fine to medium sand, SM, of the Christchurch formation (marine/estuarine) to a depth of 3.5 m, and (5) fine to medium sand, SP, of the Christchurch formation (marine/estuarine) to a depth of 20 m.

Note 7: The ejecta-induced free-field settlement provided in Table 11 is an areal average settlement due to ejecta, which is based on the total settlement assessment area, A_T (provided in Table 9 and repeated in Table 14). However, the considered area was not always covered completely with ejecta; thus, it is important to provide the localized ejecta-induced settlement, too. The localized settlement due to ejecta is estimated using photographic evidence only as

$$S_{E,P\_localized} = \frac{V_E}{A_E}$$

where V_E is the total volume of ejecta within A_T and A_E is the total coverage area of ejecta within A_T. Please note that the areal ejecta-induced settlement provided in Table 14 as S_{E,P_areal} is the same as $S_{E,P}$ in Table 11, which was estimated as

$$S_{E,P\_areal} = S_{E,P} = \frac{V_E}{A_T}$$

where V_E is the total volume of ejecta within A_T and A_T is the total settlement assessment area.

Table 14a: Areal and localized ejecta-induced settlement estimates for Patch B (50-m buffer) based on photographic evidence.

Earthquake Event	A_T (m^2)	A_E (m^2)	V_E (m^3)	S_{E,P_areal} (mm)	$S_{E,P\_localized}$ (mm)
Sep-10	39.1	27.0	0.7-1.3	25±10	35±10
Feb-11	39.1	ND	ND	ND	ND
Jun-11	39.1	ND	ND	ND	ND
Dec-11	39.1	ND	ND	ND	ND

Notes: S_{E,P_areal} = $S_{E,P}$ reported in Table 11 = areal ejecta-induced settlement; $S_{E,P\_localized}$ = localized ejecta-induced settlement; A_T = total settlement assessment area; V_E = total volume of ejecta within A_T; A_E = total area of ejecta within A_T; The estimates of both areal and localized ejecta-induced settlement are rounded to the nearest 5; Final plus/minus values are also rounded to the nearest 5.

Table 14b: Areal and localized ejecta-induced settlement estimates for Road (50-m buffer) based on photographic evidence.

Earthquake Event	A_T (m^2)	A_E (m^2)	V_E (m^3)	S_{E,P_areal} (mm)	$S_{E,P\_localized}$ (mm)
Sep-10	1009	258	2.8-4.9	5±5	15±5
Feb-11	1019	ND	ND	ND	ND
Jun-11	1019	ND	ND	ND	ND
Dec-11	1019	ND	ND	ND	ND

Notes: S_{E,P_areal} = $S_{E,P}$ reported in Table 11 = areal ejecta-induced settlement; $S_{E,P\_localized}$ = localized ejecta-induced settlement; A_T = total settlement assessment area; V_E = total volume of ejecta within A_T; A_E = total area of ejecta within A_T; The estimates of both areal and localized ejecta-induced settlement are rounded to the nearest 5; Final plus/minus values are also rounded to the nearest 5.

Summary 2:

- **The best estimate of the localized ejecta-induced free-field ground settlement at the 1/19 Chardale St site for the SEP 2010 earthquake is 35±10 mm. The localized ejecta-induced settlement for the FEB 2011, JUN 2011, and DEC 2011 earthquake was not evaluated due to lateral spreading.**
- **The best estimate of the localized ejecta-induced settlement of the road at the 1/19 Chardale St site for the SEP 2010 earthquake is 15±5 mm. The localized ejecta-induced settlement for the FEB 2011, JUN 2011, and DEC 2011 earthquake was not evaluated due to lateral spreading.**