A6 APPENDIX 6: RESULTS FROM THE TWO-DIMENSIONAL SITE RESPONSE ASSESSMENT FOR CROSS-SECTION 4

The results from the two-dimensional site response modelling are shown for cross-section 4. The maximum acceleration (A_{MAX}) at the slope crest derived from the modelling of each synthetic earthquake time history has been plotted in Figure A6.1. The slope crest is defined as the convex break in slope between the lower steeper slope and the upper less steep slope. Each point on the graph represents the response of this location to a given synthetic free field rock outcrop earthquake input motion (Table A6.1).

The highest modelled peak ground accelerations during the modelled earthquakes coincide with the convex break in slope (A_{MAX}) at the cliff crest.

The fundamental frequency of the slope varies from 1.8 to 2.3 Hz based on the equation in Bray and Travasarou (2007), where frequency = $1/(4 \times H/V_S)$, and H = slope height of 70 m, and V_S = average shear wave velocity for the main slope materials (basalt lava breccia) of 500–640 m/s. The dominant frequency of the input motions is between 3.6 Hz and 5.7 Hz. The "tuning ratio" defined as the ratio between the dominant frequency of the input motion and the fundamental frequency of the slope (Wartman et al., 2013), is about 2.0–3.2 for a shear wave velocity of 500 m/s, and 1.6–2.5 for a shear wave velocity of 640 m/s.

Results from the seismic response assessment suggest that the mean peak ground acceleration amplification factors (S_T) for cross-section 4 is about 2.6 (±0.1) for horizontal motions, and 3.3 (±0.3) for vertical motions – errors at one standard deviation, based on all the data in Table A5.1 (Figure A6.1).

Table A6.1 Results from the two-dimensional site response assessment for cross-section 4, using the out-of-phase synthetic free-field rock outcrop motions for the Redcliffs site by Holden et al. (2014) as inputs to the assessment. PGA is peak ground acceleration.

Earthquake (2011)	Free-field input PGA (horizontal) – A_{FF} (g)	Free-field input PGA (vertical) – A_{FF} (g)	Maximum PGA (horizontal) at convex break in slope – A_{MAX} (g)	Maximum PGA (vertical) at convex break in slope – A_{MAX} (g)
22 February	0.88	0.66	2.30	2.01
16 April	0.05	0.02	0.20	0.13
13 June	0.38	0.27	0.96	1.16
23 December	0.16	0.13	0.53	0.60

Results from the seismic response assessment suggest that the peak ground acceleration amplification factors (ST) for Redcliffs vary between 2.5 and 4.3 times for horizontal motions, with a mean of 2.2, and 3.1 and 4.4 times for vertical motions (Figure A6.2).

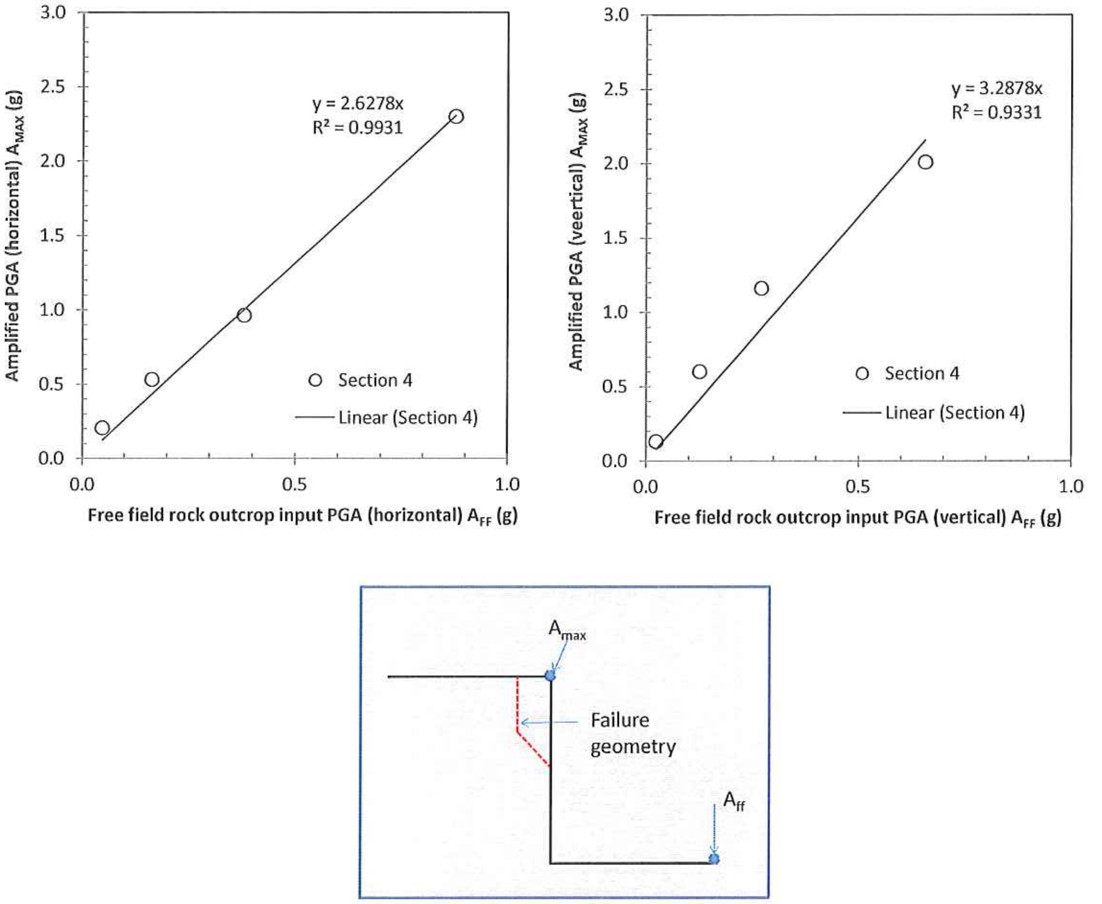

Figure A6.1 Amplification relationship between the synthetic free-field rock outcrop input motions (A_{FF}) and the modelled cliff crest maximum accelerations (A_{MAX}) for cross-section 4. A schematic diagram showing the locations of the various recorded accelerations is shown.

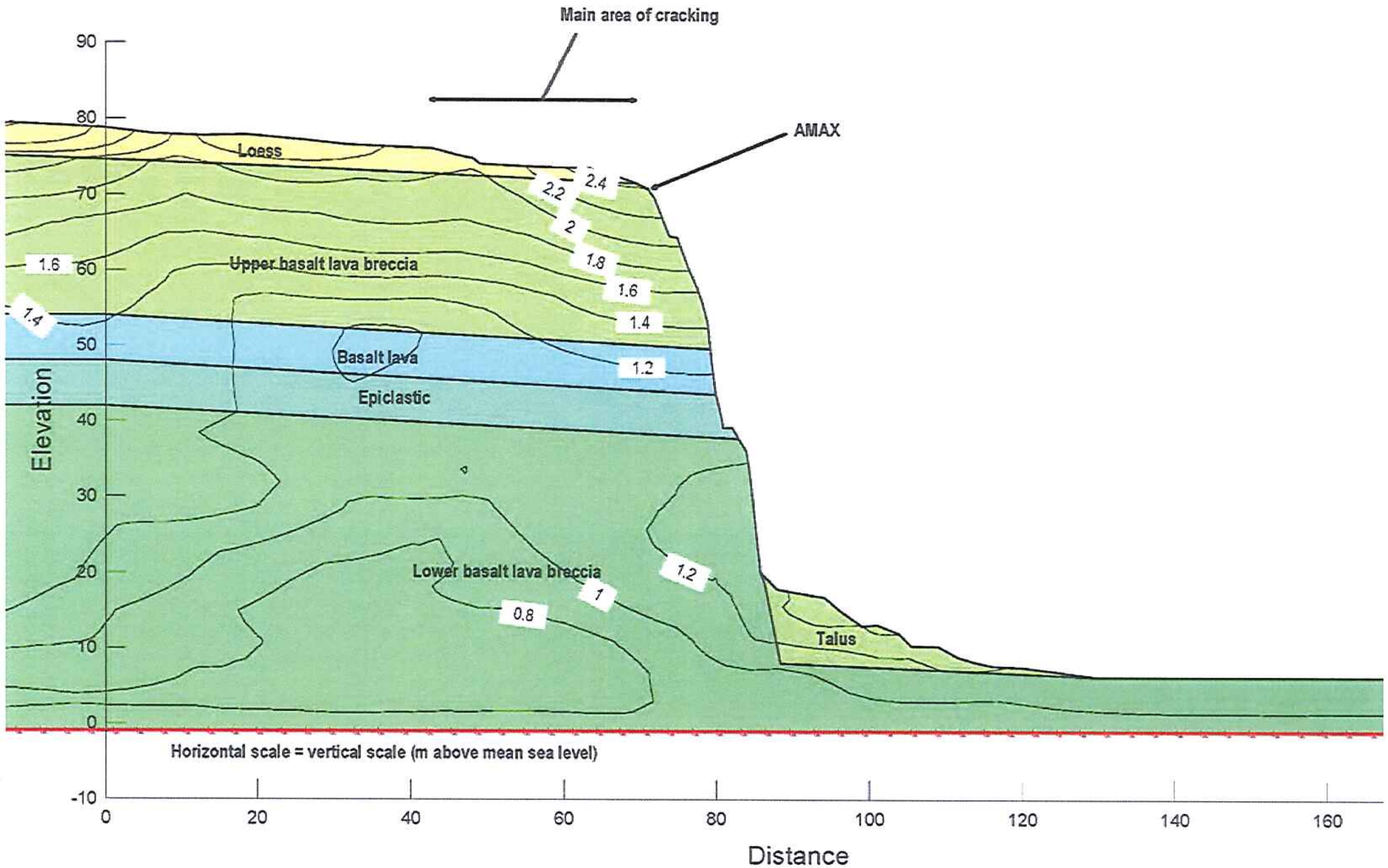

Figure A6.2 Modelled peak horizontal ground acceleration contours for the 22 February 2011 earthquake at Redcliffs, cross-section 4, adopting the 2003 airborne LiDAR slope surface geometry. Contours are peak horizontal ground accelerations (g).

The relationship between the modelled vertical and horizontal peak ground accelerations simulated at the slope crest (A_{MAX}) is shown in Figure A6.3. The gradient of a linear fit is 0.93 (±0.1) – errors at one standard deviation. However, the relationship between horizontal and vertical peak ground accelerations appears non-linear, and better represented by a curve.

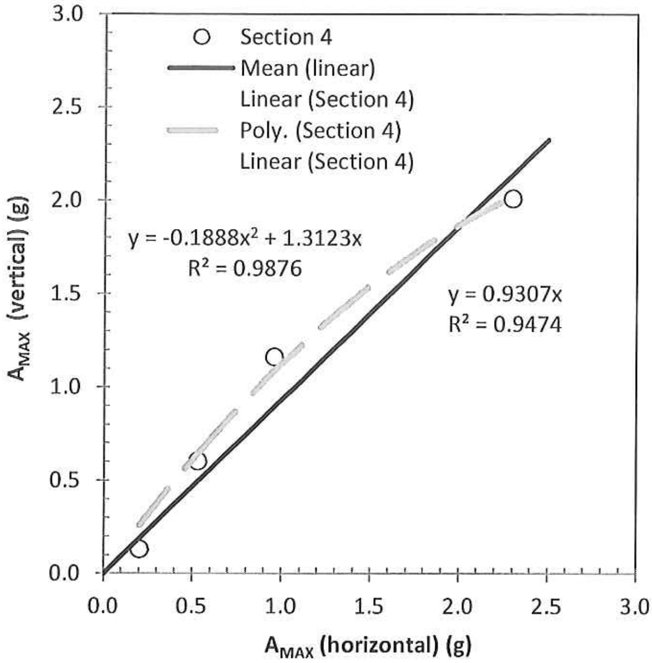

Figure A6.3 Relationship between the modelled horizontal and vertical maximum accelerations modelled at the convex break in slope (A_{MAX}) for cross-section 4, using the synthetic free-field rock outcrop motions for the Redcliffs site by Holden et al. (2014) as inputs to the assessment.

Results from this assessment have shown that the relationship between the peak ground acceleration of the free-field input motion and the corresponding modelled peak acceleration at the slope crest (A_{MAX}), although approximately linear for all horizontal motions assessed, is non-linear at lower peak input ground accelerations. Vertical motions are non-linear over the range of motions assessed. For the range of modelled peak horizontal accelerations, the horizontal amplification factor (S_T) is typically in the order of about 2.6 times the input free-field peak horizontal acceleration.

The results from this assessment show that the amplification of peak ground accelerations at the cliff crest are higher for the 16 April and 23 December 2011 earthquakes (between 3.2 and 4.3 times the peak acceleration of the free field input motions, Table A6.1) when compared to the 22 February and 13 June 2011 earthquakes (between 2.6 and 2.5 times the peak acceleration of the free field input motions, Table A6.1). These results are similar to those reported by others, e.g., Bray and Rathje (1998) and Kramer (1996), indicating that the choice of amplification factor used, should vary with the magnitude of the peak acceleration of the input motion.

Eurocode 8, Part 5, Annex A, gives some simplified amplification factors for the seismic action used in the verification of the stability of slopes. Such factors, denoted S_T, are to a first approximation considered independent of the fundamental period of vibration and, hence, multiply as a constant scaling factor.

Eurocode 8, Part 5, Annex A recommends:

1. Isolated cliffs and slopes. A value $S_T \geq 1.2$ should be used for sites near the top edge;
2. Ridges with crest width significantly less than the base width. A value $S_T \geq 1.4$ should be used near the top of the slopes for average slope angles greater than 30° and a value $S_T > 1.2$ should be used for smaller slope angles;
3. Presence of a loose surface layer. In the presence of a loose surface layer, the smallest S_T value given in a) and b) should be increased by at least 20%;
4. Spatial variation of amplification factor. The value of S_T may be assumed to decrease as a linear function of the height above the base of the cliff or ridge, and to be unity at the base; and
5. These amplification factors should in preference be applied when the slopes belong to two-dimensional topographic irregularities, such as long ridges and cliffs of height greater than about 30 m.

Ashford and Sitar (2002) recommend an S_T of 1.5 be applied to the maximum free-field acceleration behind the crest based on their assessment of slopes in homogenous materials, typically >60° to near vertical and of heights (toe to crest) of typically >30 m. This factor is based on the assessment of slopes that failed during the 1989 Loma Prieta M_W 6.9 earthquake.

Results from the seismic response assessment suggest that the horizontal peak ground acceleration amplification factor (S_T) for Redcliffs range from 2.5 to 4.3 (mean of 2.6) (cross-section 4) times greater than the free field input motions, and that the relationship is non-linear. These are larger than those values reported by Ashford and Sitar (2002), and in part reflect the different materials forming the slopes at Redcliffs (rock rather than soil). These higher factors may also be a function of the site to earthquake source distances. In the case of Redcliffs, the site is within 10 km of the epicentres of the 22 February, 16 April, 13 June and 23 December 2011 earthquakes, making them all "near-field" earthquakes.