**Table A1.1(a)** Estimated westbound traffic on Main Road at Redcliffs.

| Period Ending | Mon | Tues | Wed | Thur | Fri | Sat | Sun | Averages 4Day | Averages 7Day |
|---|---|---|---|---|---|---|---|---|---|
| **01:00** | 5 | 4 | 5 | 7 | 10 | 18 | 24 | 5 | 10 |
| **02:00** | 3 | 4 | 4 | 4 | 7 | 15 | 20 | 4 | 8 |
| **03:00** | 3 | 3 | 3 | 10 | 5 | 16 | 18 | 5 | 9 |
| **04:00** | 6 | 7 | 5 | 10 | 10 | 14 | 18 | 7 | 10 |
| **05:00** | 18 | 13 | 15 | 24 | 22 | 17 | 20 | 18 | 18 |
| **06:00** | 65 | 65 | 56 | 61 | 69 | 35 | 26 | 62 | 54 |
| **07:00** | 255 | 243 | 281 | 250 | 258 | 107 | 65 | 257 | 208 |
| **08:00** | 993 | 1001 | 967 | 921 | 886 | 220 | 141 | 970 | 733 |
| **09:00** | 984 | 1028 | 969 | 1030 | 955 | 423 | 302 | 1003 | 813 |
| **10:00** | 705 | 708 | 696 | 753 | 762 | 669 | 570 | 715 | 695 |
| **11:00** | 622 | 588 | 541 | 639 | 639 | 814 | 757 | 598 | 657 |
| **12:00** | 585 | 586 | 526 | 618 | 670 | 839 | 853 | 579 | 668 |
| **13:00** | 488 | 476 | 461 | 510 | 555 | 655 | 758 | 484 | 558 |
| **14:00** | 457 | 441 | 418 | 470 | 518 | 634 | 774 | 447 | 530 |
| **15:00** | 454 | 427 | 420 | 509 | 531 | 562 | 754 | 452 | 523 |
| **16:00** | 490 | 478 | 475 | 543 | 552 | 520 | 727 | 497 | 541 |
| **17:00** | 479 | 471 | 484 | 509 | 522 | 484 | 563 | 486 | 502 |
| **18:00** | 380 | 384 | 404 | 397 | 388 | 288 | 317 | 391 | 365 |
| **19:00** | 345 | 362 | 380 | 391 | 399 | 288 | 289 | 369 | 350 |
| **20:00** | 244 | 242 | 265 | 292 | 304 | 264 | 181 | 261 | 256 |
| **21:00** | 116 | 126 | 143 | 144 | 143 | 101 | 109 | 132 | 126 |
| **22:00** | 78 | 94 | 89 | 99 | 105 | 84 | 63 | 90 | 87 |
| **23:00** | 43 | 45 | 51 | 46 | 72 | 68 | 31 | 46 | 51 |
| **00:00** | 11 | 13 | 14 | 22 | 39 | 44 | 11 | 15 | 22 |

**Table A1.1(b)** Estimated eastbound traffic on Main Road at Redcliffs.

| Period Ending | Mon | Tues | Wed | Thur | Fri | Sat | Sun | Averages 4Day | Averages 7Day |
|---|---|---|---|---|---|---|---|---|---|
| 01:00 | 27 | 21 | 28 | 40 | 54 | 99 | 137 | 29 | 58 |
| 02:00 | 10 | 12 | 11 | 11 | 20 | 45 | 62 | 11 | 24 |
| 03:00 | 6 | 5 | 7 | 20 | 10 | 32 | 36 | 9 | 17 |
| 04:00 | 6 | 7 | 5 | 10 | 10 | 14 | 18 | 7 | 10 |
| 05:00 | 5 | 3 | 4 | 6 | 6 | 4 | 5 | 5 | 5 |
| 06:00 | 17 | 17 | 15 | 16 | 19 | 9 | 7 | 16 | 14 |
| 07:00 | 68 | 65 | 75 | 67 | 69 | 29 | 17 | 69 | 56 |
| 08:00 | 247 | 249 | 241 | 229 | 221 | 55 | 35 | 242 | 183 |
| 09:00 | 350 | 366 | 345 | 366 | 340 | 150 | 107 | 357 | 289 |
| 10:00 | 268 | 269 | 265 | 286 | 290 | 254 | 217 | 272 | 264 |
| 11:00 | 298 | 281 | 259 | 306 | 306 | 390 | 362 | 286 | 315 |
| 12:00 | 343 | 343 | 308 | 362 | 392 | 491 | 499 | 339 | 391 |
| 13:00 | 500 | 488 | 472 | 523 | 568 | 670 | 776 | 496 | 571 |
| 14:00 | 560 | 540 | 511 | 575 | 634 | 775 | 947 | 546 | 649 |
| 15:00 | 611 | 574 | 565 | 685 | 714 | 757 | 1015 | 609 | 703 |
| 16:00 | 709 | 691 | 688 | 785 | 798 | 752 | 1052 | 718 | 782 |
| 17:00 | 789 | 776 | 798 | 840 | 860 | 798 | 928 | 801 | 827 |
| 18:00 | 930 | 939 | 988 | 972 | 949 | 703 | 775 | 957 | 894 |
| 19:00 | 562 | 589 | 618 | 638 | 649 | 469 | 470 | 602 | 571 |
| 20:00 | 317 | 314 | 345 | 380 | 396 | 343 | 236 | 339 | 333 |
| 21:00 | 227 | 247 | 280 | 282 | 279 | 198 | 214 | 259 | 247 |
| 22:00 | 205 | 246 | 234 | 260 | 274 | 220 | 164 | 236 | 229 |
| 23:00 | 155 | 163 | 182 | 164 | 257 | 243 | 111 | 166 | 182 |
| 00:00 | 56 | 65 | 70 | 107 | 193 | 217 | 52 | 75 | 109 |

There is a clear inverse correlation between traffic density and speed. Table A1.2 has been developed by the authors to provide a rough representation of the way in which vehicles speeds vary with traffic levels; it has been tailored so that, when coupled with the traffic counts here and in our Quarry Road and Deans Head reports (Massey et al., 2014a,b), the predicted average traffic speeds at different times of day are broadly consistent with our own (considerable) experience of using this road over the past 2–3 years. The average separations shown are those resulting from uniform distribution of the average number of vehicles in each category, assuming all travel exactly at the average speed.

**Table A1.2** Correlation between traffic levels and average speeds/separations.

| 1-way vehicles/hr | Speed range (kph) | | Average separation (m) | |
|---|---|---|---|---|
| | lower speed | upper speed | lower speed | upper speed |
| <400 | 40 | 50 | >95 | >120 |
| 400-600 | 38 | 48 | 95 | 120 |
| 600-800 | 36 | 45 | 60 | 75 |
| 800-900 | 32 | 40 | 40 | 50 |
| 900-1000 | 22 | 30 | 24 | 33 |
| 1000-1100 | 15 | 20 | 15 | 20 |
| >1100 | 10 | 15 | 9 | 14 |

Table A1.2 can be used in combination with the traffic levels in Table A1.1 to provide estimates of the average traffic speeds for each hour of the day and day of the week, in both directions along the road. Average traffic speeds for the purpose of estimating average times at risk from cliff collapse hazards are then estimated simply by averaging over 24 x 7 hours, to produce the following estimates at Redcliffs:

- Average speed (both directions, lower) = 34.9 km/hr
- Average speed (both directions, upper) = 44.0 km/hr

Note that the lower travel speed corresponds to higher risk estimates as it takes longer to travel through the at-risk area. A summary of assumed numbers of road users, average speeds, and numbers of journeys per day for heavy road users (used as the basis for estimating annualised individual fatality risk for heavy road users) is provided in Table A1.3.

**Table A1.3** Summary of road user numbers and average speeds.

| Road user | Trips/day, heavy user | | Trips/year, all users | | Average speed, kph | |
|---|---|---|---|---|---|---|
| | lower | upper | vehicles | people | lower risk | higher risk |
| Cars | 1 | 2 | 5478385 | 8695720 | 44.0 | 34.9 |
| Buses | 1 | 2 | 39244 | 598660 | 44.0 | 34.9 |
| Heavy goods | 1 | 2 | 188834 | 299732 | 44.0 | 34.9 |
| Motorcycles | 1 | 2 | 292200 | 292200 | 44.0 | 34.9 |
| Cyclists | 1 | 2 | 29220 | 29220 | 25 | 15 |
| Pedestrians | 1 | 2 | 14610 | 14610 | 5 | 3 |

(cars/trucks split as per Main Rd/Ferrymead Rd junction; cycles/pedestrians estimated by authors)

### A1.2.4 Individual Risk per Journey – Hazard 1 (Impacted/Inundated by Debris)

In reviewing the model developed for assessing the impact of debris inundation, from earth/debris flows, on road users, the "rockfall" impact model has been updated in order to improve the calculation of the probability that a random boulder passing through a cell will strike a road user whose centre is also within that cell. Vulnerabilities (probabilities of death if in the path of a boulder) have also been reviewed to take into account the different circumstances.

The impact of cliff collapse, in terms of the numbers of boulders passing through a given section of road (grid cell) is assessed by analogy with the model used to assess the risk to dwelling occupants. However, for the road users, the vulnerabilities have been reduced to take into account that road users, in contrast with people in dwellings, are all outdoors and facing their direction of travel at all times.

#### A1.2.4.1 Cliff collapse modelling

A road user located within a 1 m by 1 m grid cell could be hit by a boulder, within the debris, passing through that cell or through the cells either side, as illustrated in Figure A1.4 for cell width (*W*), boulder diameter (*d*) and person diameter (*D*).

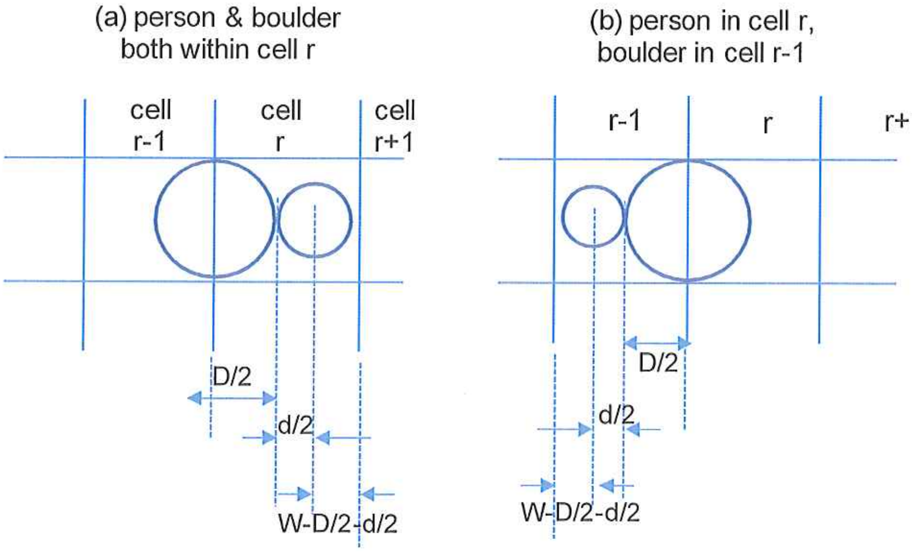


**Figure A1.4** Possible boulder/road user collision configurations.

In the first situation, if $(D+d)/2 > W$ then collision is inevitable. But in this assessment that is not the case; we have $D = 1$ m, $d = 0.5$ m and $W = 1$ m. Therefore, with the person located with their centre on the left edge of the cell as in Figure A1.4(a), there is a gap of width W – D/2 – d/2 within which the centre of the boulder can pass without striking the person. As the person shifts to the right this gap decreases, reaching zero when the person's centre is D/2 + d/2 from the right hand edge of the cell (W – D/2 – d/2 from the left edge). There is thus an average gap of width 0.5(W – D/2 – d/2) pertaining over a distance (W – D/2 – d/2) from the left hand edge of the cell, and the same again on the right. The proportion of the cell within which the boulder can pass without striking the person is thus:

2 (right and left side) x (0.5/W).(W-D/2-d/2) average gap as proportion of cell width

x (2/W).(W-D/2-d/2) proportion of cell width over which gap present.

$= (W-D/2-d/2)^2 / W^2$

The probability $P_1$,r of the person in cell r being struck by a boulder passing randomly through cell r is thus $1 - (W-D/2-d/2)^2 / W^2$. **Equation 7**

We now consider a boulder passing randomly through cell r-1 to the left of the cell containing the person situated on the extreme left edge of cell r. If the boulder centre is within (D/2 + d/2) of the right edge of cell r-1 then it will strike the person. The width of the space within cell r-1 within which the boulder must pass to strike the person in cell r decreases linearly as the person shifts to the right, reaching 0 when the person centre is D/2 + d/2 from the left edge of the cell. There is thus an average width of:

0.5 (D/2+d/2)/W as a proportion of the width of the cell, applying over a distance

(D/2+d/2)/W proportion of cell r from the left edge of the cell,

for which the boulder will strike the person. The same probability of the person in cell r being struck applies to a boulder passing randomly through cell r+1 to the right of cell r. Denoting these probabilities P1,r-1 and P1,r+1 respectively we then have:

$$P_{1,r-1} = P_{1,r+1} = 0.5\,(D/2+d/2)^2 / W^2$$ **Equation 8**

For a single boulder passing randomly through each of these three cells, the probability $P_1$ of the person being in the path of 1 or more boulders is given by:

$$P_1 = 1 - (1 - P_{1,r-1}) \times (1 - P_{1,r}) \times (1 - P_{1,r+1})$$ **Equation 9**

The probability of death for road user j per single boulder passing through each of these cells is now calculated as:

$$P_{death,1,j} = P_{1,j} \times V_{1,j,rockfall}$$ **Equation 10**

A significant complication now is that the number of boulders passing through each cell may be different. This might be possible to model if the cells formed a continuous straight line along an axis of the model grid, but in this case they do not. We therefore introduce the approximation for the purposes of calculating the probability of being killed by N boulders passing through the cell that THE SAME number of boulders passes through the cells either side. The probability of death for N boulders passing through the cell is then:

$$P_{death,N,j} = 1 - (1 - P_{death,1,j})^N$$ **Equation 11**

This is then multiplied by the proportion of a year for which the user is present in the cell (based on the average travel speeds in Table A1.3 above) and the frequency of the triggering event which gave rise to the N boulders per cell (as per Equation 6 above) to calculate the contribution of this cell and this slope collapse scenario to the road user's individual risk per journey.

The values of the parameters used in this assessment are as follows:

***No. of boulders passing through cell*** – taken directly from dwelling model output

***Years present in cell per journey*** – as shown in Table A1.4 (based on average road user speeds as in Table A1.3 above).

**Table A1.4** Road user speeds and times per journey within 2 m cell.

| Road user | Average speed, kph | | Time (yrs/jny) spent in cell | |
|---|---|---|---|---|
| | lower risk | higher risk | lower risk | higher risk |
| Car occupant | 44.0 | 34.9 | 5.18E-09 | 6.54E-09 |
| Bus Occupant | 44.0 | 34.9 | 5.18E-09 | 6.54E-09 |
| Truck occupant | 44.0 | 34.9 | 5.18E-09 | 6.54E-09 |
| Motorcyclist | 44.0 | 34.9 | 5.18E-09 | 6.54E-09 |
| Pedal Cyclist | 25 | 15 | 9.13E-09 | 1.52E-08 |
| Pedestrian | 5 | 3 | 4.56E-08 | 7.61E-08 |

***Vulnerabilities*** – Values of 0.4 (lower) and 0.7 (higher) are used for motorcyclists, and of 0.3 (lower) and 0.5 (higher) for all other road users. Note that these are probabilities of death if in the path of a single boulder; each successive boulder confers the same probability of death again. This contrasts with some of our earlier assessments in which we applied the vulnerability to the "Probability of being in the path of one or more boulders". This approach (treating vulnerability as independent of number of boulders) was based on the primary contribution to survival being the ability of the individual to get out of the way of boulders. With the lack of any obvious place of escape in the event of rockfall at the Redcliffs road section modelled we consider it more appropriate here to assume that getting out of the way is unlikely. We recognise that motor vehicles will provide some modest protection against boulders relative to the vulnerable road users (cyclists and pedestrians), but consider that for pedestrians and pedal cyclists this is offset by their greater ability to hear what is going on off the road and to take evasive action before boulders fall. Motorcyclists are considered to have the worst of both worlds (vulnerability if struck, and inability to hear environmental noises), hence their higher assumed vulnerability.

### A1.2.5 Road user risk per journey and risk parameters derived from it

The parameters shown in the above tables are uncertain. As in our previous work on road user risk from rockfall, inputs and outputs are presented as ranges from “reasonable lower” to “reasonable upper” values. No statistical significance is attached to these ranges; the results are regarded as providing a sensible range, given the associated uncertainties, within which to assume the actual risk might lie. Perhaps the single largest uncertainty is in the volume of material which flows from the debris sources; as for the dwelling risk assessments this has been explicitly considered by carrying out all assessments three times, for upper, central and lower estimates of debris source volumes.

The risk equation is evaluated for each cell in the grid for each cliff-collapse scenario considered, as described in Section A1.2.4. The grid used was simplified relative to that used in modelling dwelling risk by excluding cells that did not form part of the roadway in order to streamline the calculation process; in all other respects the rockfall modelling used to estimate individual road-user risk was identical to that used to estimate individual dwelling occupant risk.

As in the dwelling occupant assessment, the set of scenarios modelled covers:

- Seven seismic trigger scenarios ranging from 0.1–0.3 g up to 2–3 g peak ground acceleration, with an increasing probability as shaking increases that cliff collapse will be triggered;
- Four non-seismically triggered cliff collapse scenarios (corresponding to different severities of weather-induced rockfall); and
- Source areas 1, 2 and 3, with probabilities of triggering in each seismic scenario taken exactly as for the dwelling assessment (note – only source area 3 generates debris sufficient to reach the road).

The risk per journey in a given cell is then calculated by summing over all source areas.

The overall risks per journey were calculated by summing over all cells making up the NEAR (landward) side of Main Road and the FAR (seaward) side of Main Road, allowing the risks on either side of the road to be compared with each other and with the existing motor vehicle crash risk (based on average statistics for New Zealand urban roads, from Ministry of Transport publications on road crashes and casualties and on number of journeys and distance travelled by different road user groups; NZ MoT, 2012).

The individual risk per journey is then used to calculate individual risk per year for heavy users of the road, the average expected fatalities per year, and the average time expected between fatal accidents as shown in Table A1.5.

Current New Zealand road traffic accident statistics were used to provide comparison information on the risk road users would face in their ordinary travel along this section of Main Road for a journey of the same length (81 m) as that covered in the risk assessment model.

**Table A1.5** Calculation of risk parameters of interest from single cell risk per journey.

### Aggregation of Risk Parameters for Cells

**(a) Risk per journey**

| | | |
|---|---|---|
| Risk $R_{ij}$ for road user j within cell i = | $R1_{ij} + R2_{ij}$ | |
| Risk $R_j$ per journey to road user j = | sum of $R_{ij}$ for all relevant i (all cells on uphill side or downhill side of road, as appropriate) | |

**(b) Other key risk parameters**

| | | |
|---|---|---|
| Annual Individual Fatality Risk for user j | $= Rj \times M_{j,ind}$ | $M_{j,ind}$ = Journeys/year by individual heavy road user of type j |
| Average expected fatalities per year, user j | $= Rj \times M_{j,tot}$ | $M_{j,tot}$ = Journeys/year by ALL road users of type j |
| Probability of 1 or more fatal accidents/year (road user type j) | $= Pj = 1 - (1-R_j)^{Mj,tot}$ | |
| Probability of 1 or more fatal accidents/year (among ALL road users) | $= 1 - (1-P_{car}) \times (1-P_{motorcycle}) \times (1-P_{cycle}) \times (1-P_{pedestrian})$ | |