A RAPID METHOD FOR ESTIMATING EXPECTED FATALITIES FROM FUTURE STRONG EARTHQUAKES

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SUMMARY

Fatalities during earthquakes are the result of a series of complex interactions between multiple variables including building types, social status, and time of day amongst many others. When considering future earthquakes, it is important to quantify the expected number of fatalities for pre-event disaster risk reduction and preparedness planning. Most current methods for estimating fatalities from future earthquakes are complex and time-consuming, and require large amounts of data on a multitude of different variables. However even the best current models can only provide a rough estimate of the expected numbers. We demonstrate an alternative, rapid method, adapted from previous work, for fatality estimates as a function of shaking intensity and population density, which is applicable for initial, order-of-magnitude-scale assessments when faced with short timeframes and/or a lack of data. The method was developed for a New Zealand CDEM Exercise and is shown to be more appropriate for New Zealand earthquakes than other available methods. We apply the method to an expected M8 Alpine fault earthquake, forecasting ~300 fatalities. The worst affected location is Greymouth with ~80 fatalities, however >60% of the total fatalities are expected to occur in rural areas.

INTRODUCTION

Since the 1950s [1] a large amount of research has been undertaken to model the expected number of fatalities to result from a given future earthquake scenario [2]. The resulting models can be broadly classified into three categories: empirical, analytical, and hybrid [2]. Empirical methods, such as [3], are generally based upon globally observed statistics of fatalities, while analytical methods, such as [4], involve a combination of seismic hazard, damage, and loss analyses on a building-by-building scale [2]. The hybrid method simplifies this by considering fatality rates by building types but does not involve the detailed engineering analyses of analytical methods [5, 6, 7].

Analytical, computer-based methods such as HAZUS [6] and RiskScape [8] are popular as they are able to simultaneously estimate factors such as infrastructure damage as well as direct and indirect financial costs. However, fatalities during earthquakes are the result of highly complex interactions among a large number of different variables not all of which are related to building damage. Factors such as time of day, age, gender, social status, disability, regional and national GDP, level of inequality and many others are important factors in controlling earthquake fatalities [9, 10, 11]. Thus there are often substantial discrepancies between estimated fatalities and observed values, regardless of model type [11]. Furthermore, while empirical approaches typically over-simplify the problem by analysing statistics for a small number of variables, hybrid and analytical methods require a vast array of different variables (such as complete building inventories, damage states, fragility curves and fatality rates for various building-types etc.) which are often unavailable or difficult to obtain [2].

When undertaking initial or rapid impact assessments, analytical or hybrid methods are inappropriate given the time, complexity, and data requirements associated with the modelling. Empirical methods however are relatively fast, simple, and have low data requirements by comparison. One of the best-known and used empirical methods is the United States Geological Survey (USGS)'s Prompt Assessment of Global Earthquakes for Response (PAGER) method [2]. PAGER has developed a series of country- or region-specific coefficients which allow for indirect consideration of factors associated with different building codes and social systems. However, PAGER requires that a country or region have sustained four fatal earthquakes since 1978 to be accurate [2]. In New Zealand only one fatal earthquake has occurred within this time and thus New Zealand is assigned coefficient values determined from earthquakes in California. Consequently PAGER proved inaccurate when applied to the 2011 Christchurch earthquake, predicting 0% probability of >100 fatalities, 19% for 10-100, 79% for 1-10, and 2% for 0 [12]; in reality, 185 people were killed in the event, >100 of which occurred in one building [13].

Following the Christchurch earthquake, in May 2013 the South Island Civil Defence and Emergency Management (CDEM) Groups undertook an exercise to test emergency response capabilites for an anticipated earthquake on the plate boundary Alpine fault (Figure 1). As part of this exercise a method to estimate the potential number of fatalities such an earthquake could cause was required. Limited modelling time and available data precluded the use of analytical and hybrid

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models such as HAZUS or QLARM, and the error associated with the PAGER prediction fro Christchurch required the development of a new method to rapidly estimate fatality numbers. This paper outlines the method established during the development of the exercise and its subsequent results. This method is presented as an alternative means to rapidly assess the number of fatalities resulting from a future earthquake when faced with short timeframes and limited data, and for which other empirical methods are inappropriate.

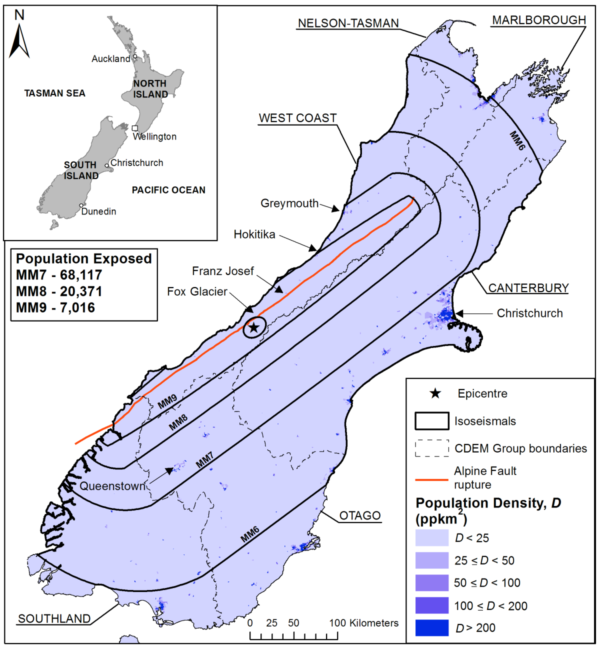

Figure 1. South Island of New Zealand showing modelled isoseismals for an M8 Alpine Fault earthquake, population density, CDEM Group boundaries, and locations mentioned in the text.

CDEM EXERCISE OVERVIEW

Following the devestating 2010-11 Canterbury earthquake sequence [14, 15], there has been a strong reaction by the public and government at all levels to address earthquake resilience throughout New Zealand [16]. Consequently, in May 2013 a South Island-wide CDEM exercise was undertaken to practise responding to a strong earthquake occurring on the Alpine fault (Figure 1). The Alpine fault is thought to be capable of producing M8 earthquakes [17, 18] and currently has an estimated 30% probability of rupture in the next 50 years [19] and thus presents one of New Zealand's largest known seismic hazards.

As part of the exercise, an estimate of the number and spatial distribution of fatalities arising from the earthquake was required, as part of a detailed disaster scenario that included descriptions of the earthquake and its subsequent geomorphic effects, as well as assessments of the impacts on lifelines [20]. In total, just four months (January to April) and limited financial resources were available for scenario development and thus a rapid and low-cost method of assessment was required. CDEM exercises require scenarios that realistically replicate the response processes and behaviours that will need to be undertaken in a real emergency [21, 22]. Thus, the method used to derive the disaster scenario and fatality estimate must provide a result that will require a similar emergency response during the exercise to that needed during the real emergency. Achieving predictions within a certain error margin of the observed fatalities (i.e. 5%, 10% etc.) is not necessarily required.

The method involved in estimating the number of fatalities therefore had to be capable of:

- Producing a credible total fatality estimate;
- Evaluating the spatial distribution of fatalities;
- Using Modified Mercalli (MM) intensity as a hazard input [see 20];
- Being completed within the allocated timeframe; and
- Requiring limited available data inputs.

As the results required a description of the spatial distribution of fatalities, the resolution of the population exposure inventory was critical. The most accurate publicly available population data in New Zealand is the meshblock data collected by Statistics New Zealand during a census. A meshblock is the smallest geographical area for which statistics are collected and accounts for 100 households. Thus herein, population data from the New Zealand 2006 Census was used at a meshblock scale to provide the finest spatial resolution possible.

REVIEW OF FATALITIES MODELS

Analytical Models

Analytical methods such as HAZUS and RiskScape are the most detailed, and thus data-intensive, types of fatalities models. They permit the development of building-specific damage and loss functions [4] and can therefore account for disasters like the 2011 Christchurch event, in which the majority of casualties occur in a small number of buildings [13]. Consequently, these methods are of a highly technical nature and thus require users to be qualified structural or seismic engineers [4]. Furthermore, models such as HAZUS require information on peak ground accelerations (PGA) rather than MM intensity [2, 4], as the structural fragility of buildings is quantified with regards to maximum PGA.

Despite offering several default databases, these models generally require the inclusion of specific, detailed local data, particularly of building inventories. Such data is not publically available within New Zealand, and with the timeframe and budget available gathering the data manually was infeasible. Further, the technical requirements to use such models requires the user to have extensive training of the model selected. For instance, the recommended training programme for HAZUS involves undertaking either a once-a-year 4-day classroom course or 12 separate online courses [23]. Such methods were therefore not feasible for this study.

Hybrid Models

Hybrid models such as QLARM [7] attempt to fill the gap between complex analytical models and simplified empirical models [2]. To do this, they refrain from building-specific modelling as in analytical models, and instead classify buildings into a series of different classes, primarily as a function of construction type [7]. Further, they can also classify the building damage states into a series of classes [5] as well as classifying populations into various different vulnerability classes based upon a series of social factors [7]. The resulting loss estimations are therefore a combination of these different classes describing a fatality rate which is then applied to the total population numbers exposed.

However like analytical models, hybrid models are data-intensive and require a detailed inventory of exposed buildings in order to classify them into the various classes. Further, they also require the hazard layer to be in the form of PGA in order to utilise built-in fragility curves describing damage states for different building classes in relation to shaking. Thus hybrid models were also not appropriate for this study.

Empirical Models

Empirical models such as [3] and PAGER attempt to simplify the issue by statistically analysing the number of fatalities with respect to a limited number of factors (usually shaking intensity and population density). Thus they are easy to use as they require only a basic mathematical understanding and relatively little input data. Consequently however, they are less accurate, require a variety of different assumptions, and generate results that are typically less precise (i.e. not building-specific or even building type-specific) than analytical and hyrbid models. Nevertheless, their ease, and thus speed, of use and low data requirements makes empirical models the most appropriate for this study.

The most widely used empirical model is PAGER. This is primarily used as a real-time assessment tool [24] to quickly identify how many fatalities are expected in order to allow national and international agencies to make informed decisions on the humanitarian aid likely required [2]. However, because PAGER only requires information on the extent and intensity of shaking and population figures, its method can be applied to scenario earthquakes provided they include an isoseismal model. PAGER estimates fatalities based upon a fatality rate derived from shaking intensity measured in MM intensity and country- or region-specific coefficients derived from a larger number of observations of global earthquakes.

However as discussed above, PAGER was unable to accurately estimate the number of casualties resulting from the 2011 Christchurch earthquake. This result is further compounded when the estimates of [25] are considered, which estimates >470 fatalities could have occurred in Christchurch had the initial 4 September 2010 mainshock not resulted in some areas of the central city being cordoned off. As all empirical models consider earthquake scenarios in isolation, their results must therefore be compared to this higher estimate which represents the number of fatalities that would likely have occurred had the 22 February 2011 earthquake been the mainshock rather than an aftershock. Furthermore, PAGER does not provide a spatial distribution of fatalities beyond estimating the number per isoseismal zone. Thus, PAGER was not considered appropriate for this study. Nevertheless, an alternative empirical method described by [3] and herein referred to as the Samaradjieva-Badal (SB) method after its authors, presents a more appropriate method which can be used.

SAMARDJIEVA-BADAL METHOD

The SB method is an empirical method that expands upon work by [26] and [27] linking fatalities to a function of shaking intensity and population density. An initial estmate of the total number of fatalities, $N_k(D)$, is calculated from

$$\log N_k\left(D\right) = a\left(D\right) + b\left(D\right)M \tag{1}$$

where D = population density (see Table 1);

M = earthquake magnitude; and

a, b = globally defined coefficients.

The initial estimate is then wieghted per isoseismal zone, i, to provide estimates of fatalities per isoseismal zone, N_k^i, such that

$$N_k^i = W_i N_k\left(D\right) \tag{2}$$

where W_i = weighting factor

and a final estimate of total fatalities is achieved by summing for all isoseismal zones.

Table 1. Globally derived regression coefficients for various population density classes. After [3].

Population Density, *D* (persons per km^2)	*a*	*b*
$D \leq 25$	-3.11	0.67
$25 < D \leq 50$	-3.32	0.75
$50 < D \leq 100$	-3.13	0.84
$100 < D \leq 200$	-3.22	0.92
$D > 200$	-3.15	0.97

The weighting factor is calculated assuming that the number of fatalities decreases with the square of the epicentral distance [27], such that

$$W_i = \frac{1}{R_i^2 \sum_j \left(1/R_j^2\right)} \tag{3}$$

where $R_{i,j}$ = radii of shaking intensity zone i, j; and

i, j = 7.0, 8.0, 9.0…

The global coefficients shown in Table 1 were derived from a catalogue of fatal earthquakes between 1901 and 1999 [3]. In order to account for the widespread variation in building quality globally, this method and the corresponding coefficients are only applicable in locations with average, or above average building conditions with regards to seismic performance [3]. This method is therefore both rapid and simple, and requires only information on isoseismals and local population density, which were available for this study.

Using population data taken from New Zealand's 2006 Census it is therefore possible to test the accuracy of this method against the 2011 Christchurch earthquake (Figure 2). This yields an estimate of 611 fatalities. Despite being about three times larger than the 185 recorded fatalities, like all empirical models this method considers each earthquake in isolation and therefore it is more appropriate to consider the result with respect to the 470 fatalities estimated by [25]. The SB result is far more credible being of similar magnitude to the estimated ~470 fatalities. Despite being larger, we note that in terms of a CDEM exercise, the response required for ~470 fatalities would not be substantially different from an event with ~600. However, the response would be significantly different for an event with ~10 fatalities, as suggest by PAGER [12]. The results are therefore sufficient to produce a scenario that would elicit a similar emergency response during an exercise as would actually have occurred had the Christchurch earthquake been the mainshock.

Nonetheless, like PAGER, this method is currently unable to provide an estimate of the spatial distribution of fatalities, which was required for the CDEM scenario. For earthquakes which affect a large geographical area like an Alpine fault earthquake, it is important to understand how fatalities are likley to be distributed spatially. Thus, this method must be adapted to provide a spatial distribution before it can be applied to an Alpine fault event.

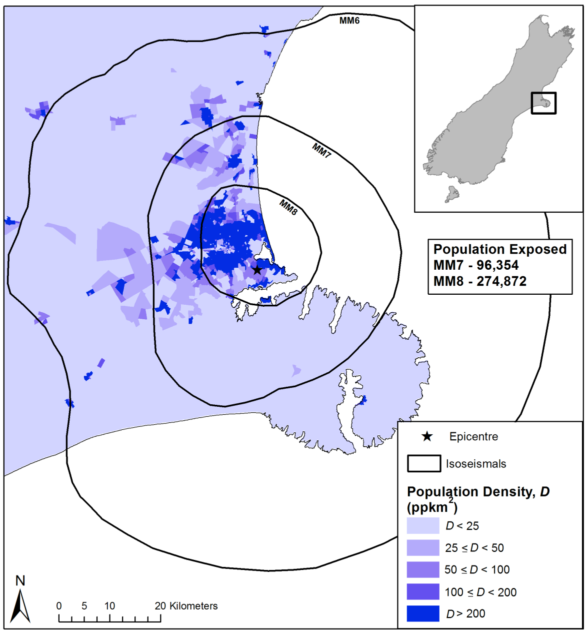

Figure 2. Isoseismals of the 22 February 2011 Christchurch earthquake and population density from the 2006 New Zealand Census classified according to the classes in Table 1.

METHOD ADAPTATIONS

Before this method can be applied to an Alpine fault earthquake (Figure 1), the method requires some minor adaptations to be fit for purpose.

Weighting Adaptation

The weighting included in the SB method assumes that as distance from the source of shaking increases, shaking intensity and therefore fatalities decrease. The SB method therefore weights the number of fatalities per shaking intensity zone by assuming that fatalities decrease with the square of the epicentral distance (see equation (5)). This assumes that the earthquake scenario is a point source which produces circular or quasi-circular isoseismals (Figure 3). However, large (>M7) earthquakes like an Alpine fault event typically involve many tens-to-hundreds of kilometres of fault rupture (Figure 1) and thus are not point source events. In this instance, the source of shaking is the fault rupture itself, resulting in elliptical or quasi-elliptical isoseismals (Figure 1 & Figure 3). Thus, equation (5), which calculates the weighting, must change accordingly. For non-point source earthquakes, the number of fatalities should therefore decrease with half the isoseismal width (Figure 3) such that:

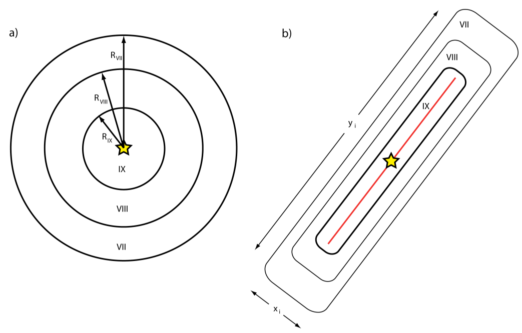

Figure 3. Comparison between different shaped isoseismal models. a) circular isoseismals in which fatalities are proportional to 1/R^2; b) quasi-elliptical isoseismals in which fatalities decrease proportional to 1/x.

$$W_i = \frac{1}{\frac{1}{2}x_i \sum_j \left(1 \Big/ \frac{1}{2}x_j\right)} \qquad (4)$$

where x = short-axis of isoseismal zone i, j; and

i, j = 7.0, 8.0, 9.0…

A comparison between the weights for an Alpine fault earthquake (Figure 1) calcualted from equations (3) and (4) is shown inTable 2.

Table 2. Comparison between calculated weights using the original (circular) weighting equation (3) and the adapted (elliptical) equation (4).

Intensity Zone (MM)	Weight (W_i)	
	(Quasi-) Circular	(Quasi-) Elliptical
7	0.1068	0.1775
8	0.2532	0.3437
9	0.6400	0.4786

Population Density Adaptation

To utilise population density in the SB method, the average population density per isoseismal area is calculated and the corresponding coefficients used (Table 1). This is sufficent for earthquakes such as the Christchurch event, where the variation in population density within each isoseismal is limited. However, an Alpine fault earthquake will affect a very large area with widely varying population densities (Figure 1). The vast majority of the affected area is rural, with population densities <1 pkm^{-2}, however several major townships (Greymouth, Hokitika, Queenstown) are also affected and densities here are typically >100 pkm^{-2}. Taking an average population density will favour rural regions and therefore likely under-estimate fatalities in major townships. Taking the largest density however will result in vastly over-estimated fatalities in rural areas.

Therefore, we assess population density at a meshblock level. Herein, we calculate fatalities per isoseismal zone for each of the densities in Table 1. Using the meshblock data we then calculate the observed area for each corresponding population density and scale the fatalities accordingly. Thus, N_k^i is calculated from

$$N_k^i = \sum_D W_i N_k^i(D) \times \frac{A_{io}(D)}{A_{it}} \qquad (5)$$

where A_{it} = the total area in km^2 of isoseismal zone i; and

$A_{io}(D)$ = the observed area in km^2 in isoseismal zone i of density D.

For example, if 500 fatalities are calculated to occur in zone i with A_{iT} = 100 km^2 and some value of D, the total fatalties in zone i for D when $A_{iO}(D)$ = 10 km^2 is 50. The method can now consider the variation in densities within a single isoseismal zone, accounting for large, sparsely populated rural areas as well as small, densely populated townships.

Fatalities are distributed according to the total population corresponding to the isoseismal zone and population density in question. For instance, consider two locations, A and B, with the same D in the same zone i. When A has twice the popualtion of B, A is assigned 2/3 of the total fatalities corresponding to zone i and density D, while B is assigned 1/3.

Thus for 50 fatalities, location *A* is assumed to have 33 fatalities and location *B* is assumed to have 17 fatalities. This allows the total number and geographical spread of fatalities to be estimated sufficiently for an emergency management exercise.

APPLICATION TO THE 4 SEPTEMBER 2010 DARFIELD EARTHQUAKE

Applying this adapted SB method to the 2010 M7.1 Darfield earthquake can confirm the applicability of the method. The Darfield event (Figure 4) was centered in a predominantly rural location where population densities rarely exceed 25 pkm^{-2}. Despite this, the event still produced substantial shaking and consequent damage in Christchurch city [25], however the time of the earthquake (0400hrs) resulted in zero fatalities. The adapted SB method estimates that this earthquake should have produced 140 fatalities, with 40 occurring in the rural areas near the epicentre (Figure 4) and 100 occurring in central Christchurch city. At first view this method therefore appears inappropriate. However, given that the adapted SB method does not consider the time of day the earthquake occurs, it is important to consider how the number of fatalities would differ had the event occurred at a different time.

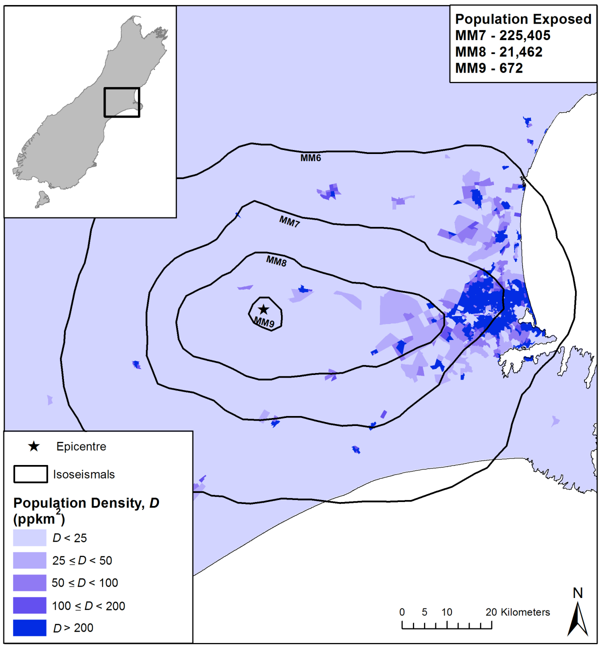

Figure 4 - Isoseismals of the 4 September 2010 Darfield earthquake and population density from the 2006 New Zealand Census classified according to the classes in Table 1.

If this earthquake had occurred during the day-time, then it is almost certain that large numbers of people would have been present in Christchurch city rather than asleep at home. The damage resulting from the Darfield earthquake (Figure 3; [25]) would almost certainly have resulted in fatalities as numerous people would have been beneath falling masonry (Figure 3). [25] estimates that buildings damaged by the Darfield event would have killed an extra 285 people in the Christchurch event. Given shaking intensities were one degree lower in the city during the Darfield event (MM7 vs MM8; Figure 2 &) the adapted SB method estimate of 100 fatalities in Christchurch city appears to be a reasonable estimate for a day-time Darfield earthquake. We therefore contend that the adapted SB method is appropriate for rapidly modelling earthquake fatalities in New Zealand, and that the results represent a potential maximum expected fatalities.

Figure 3 - Falling masonry in Christchurch city as a result of the 4 September 2010 Darfiled earthquake. Photo by Martin Hunter/Getty Images.

APPLICATION TO AN ALPINE FAULT EARTHQUAKE

Using the isoseismals shown in Figure 1 and the population from New Zealand's 2006 Census, we estimate a total of 293 fatalities would result from an Alpine fault earthquake. The worst-affected region is, unsurprisingly, West Coast region with 224 (76%) total fatalties (Figure 4). The worst-affected location is Greymouth with an estimated 77 fatalities, although Queenstown and Hokitika are both also badly affected with 10 and 12 fatalities respectively (Figure 4). Nevertheless, fatalities in rural areas dominate, accounting for 172 (60%) fatalities. Thus, we conclude that fatalities from an Alpine fault event will be widely distributed geographically, making for a complex emergency response, and could possibly be similar in number to the 1931 Napier earthquake, New Zealand's most deadly historical earthquake [28].

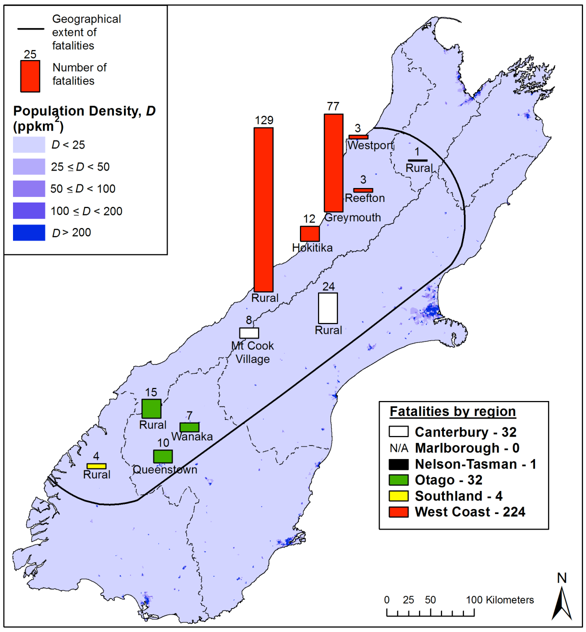

Figure 4. Estimated geographical distribution of fatalities resulting from an Alpine fault earthquake as calculated for the 2013 South Island CDEM exercise.

DISCUSSION

The results described herein for fatalities resulting from an Alpine fault earthquake are considered adequate to represent the likely scale of emergency response that will be required for this event. They were therefore appropriate for the 2013 South Island CDEM exercise for which they were estimated. Nevertheless, several points should be considered.

Firstly, it is of note that northern West Coast region, the worst-affected area in our model, has sustained similar shaking intensities historically, during the 1929 M7.3 Murchison earthquake and the 1968 M7.1 Inangahua earthquake [29, 30]. Despite this, the number of fatalities in each event was substantially smaller than suggested herein for similar shaking intensities. Given that building codes in New Zealand have substantially improved since these earthquakes, and that following the Christchurch earthquake, known earthquake-prone buildings are undergoing mandatory strengthening, the total fatalities suggested herein may be over-estimated. While the population in this region has not changed dramatically since the Murchison and Inangahua earthquakes, the number of tourists visting the region has increased substantially [31]. Thus, during a future Alpine fault earthquake more people are likely to be exposed to strong shaking than were exposed in either the 1929 and 1968 earthquakes. Furthermore, an Alpine fault earthquake is approximately an order of magnitude larger than either of these events, and thus the duration of strong shaking is likely to be considerably larger, possibly up to 2 minutes in this region [32]. Thus there is a greater potential for fatalities to occur during an Alpine fault earthquake and the totals estimated herein are considered representative.

Secondly, we note that the number of rural fatalities estimated for the Darfield earthquake (40) appears to be too large, even for a day-time event. In large urban areas in New Zealand many buildings are comprised of unreinforced masonry (URM) which are typically responsible for a large number of fatalities, as seen in the 1931 Napier and 2011 Christchurch events [25]. In rural areas the dominant building type is timber framed, and while damage to and within these buildings typically result in substantial injuries, rarely does it cause large numbers of fatalities. This suggests that for rural regions in New Zealand (i.e. population densities <25 pkm^{-2}) different coefficients may be required (see Table 1). With limited observations however, it is difficult to appropriately derive these coefficients. Thus, we suggest that the results herein for urban areas such as Greymouth and Queenstown. are appropriate, while the values for low density rural areas are likely too large, although not substantially.

The results herein have been estimated using the 2006 New Zealand Census, which only accounts for typical resident populations and therefore does not consider tourist numbers. The West Coast region, which is estimated to be the worst-affected, is an increasingly popular tourist destination [31, 33]. This is particularly notably in central Westland, West Coast region, where the townships of Fox Glacier and Franz Josef, which have URPs of ~200 can have up to 2,000 tourists each in the high tourist season. This number fluctuates between the summer (high season) and winter (low season) months, and thus should this event occur in the summer, there is clearly the potential for substantially more fatalities than estimated herein. Despite winter being the low tourist season, it should be noted that alpine areas, especially around Queenstown and Wanaka, support large snow sport industries. Thus, even in winter there is the potential for the numbers herein to substantially underestimate actual fatalites.

The estimated fatalities for an M8 Alpine fault earthquake presented here correlate well with the similarly sized 1931 M7.8 Napier earthquake, New Zealand's most deadly earthquake with 256 fatalities [28]. During this event approximately 30,000 people were exposed to shaking intensities of MM7 or larger. In an Alpine fault event, we estimate that at least 90,000 people will be exposed to similar levels of shaking (not including tourists). However, the Napier event affected a far smaller area with much higher population densities compared to an Alpine fault event. Thus, our estimate of 293 fatalities is considered a reasonable estimate.

CONCLUSIONS

Many different methods with varying degress of complexity currently exist for estimating casualties from future strong earthquakes. Nevertheless, because all methods simplify a highly complex process involving a large array of different parameters, very few methods have proven to be highly accurate. We utilise and adapt a published empirical method for which only information on expected shaking intensity and population density is required. We show that this method is able to appropriately model fatalities resulting from the 2011 Christchurch earthquake, achieving far better results than the USGS PAGER model. This adapted method offers a rapid approach to the assessment of fatalities when faced with short timeframes and/or a lack of data, demonstrated by its application during a recent Alpine fault CDEM exercise.

Our adaptations to the SB method allow it to be used for estimating casualties from non-point source earthquakes, such as an Alpine fault event, and to estimate the potential spatial distribution of fatalities. We demonstrate that these adaptations are able to adequately model the 2010 Darfield earthquake, assuming it had occurred during the day-time. Applied to an expected future Alpine fault earthquake, we estimate a total of ~300 fatalities with 76% of these occurring in the West Coast region. Greymouth is anticipated to be the worst-affected location with ~80 fatalities, while Queenstown and Hokitika are estimated to have ~10 fatalities each. Nevertheless, the majority (60%) of fatalities will occur in rural areas resulting in the need for a highly geographically-distributed emergency response. The results do not consider tourist numbers and we emphasise that, depending on the time of year the earthquake occurs, these estimates could thus be substantially higher.

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