How big, how often and how strong?
Aftershocks and urban search and rescue operations

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ABSTRACT: The first issue in Urban Search and Rescue (USAR) is the safety of the rescuers. In the post-earthquake situation, a key consideration is the likelihood of aftershocks, how large these are likely to be and how strong the shaking will be at the site. Important features of aftershocks are that their expected frequency decreases with time, and that their maximum magnitudes are generally related to the main shock magnitude. Also, as time evolves, more information becomes available about the particular aftershock sequence, and its decay. Such specific information may be used in preference to the generic properties of aftershock sequences to guide the timing of various rescue activities. A NO-GO assessment immediately after the main shock may be reassessed as a viable operation with the passage of time, when all factors are taken into account.

As well as affecting the decision as to whether or when a site should be entered, the likelihood and expected magnitudes of aftershocks influence the strength of shoring that is required for USAR operations for parts of structures. In the New Zealand USAR manual for engineers providing guidance for those working within a rescue site, this has been developed in terms of the equivalent New Zealand Loadings Code Z-factors, which may be interpreted as the expected peak ground acceleration on rock.

This paper discusses how aftershocks affect the decision-making process, the properties of typical aftershock sequences, and how these lead to the expected largest aftershock magnitudes and Z-factors given in tables in the USAR Engineer's manual.

1 INTRODUCTION

Structural Engineers are a key part of an Urban Search and Rescue (USAR) response. They have a critical role to play in providing technical advice for rescue teams. This includes assessing the stability of all or parts of a partially or wholly collapsed structure, monitoring for any changes in the structural stability, and the development of temporary shoring arrangements.

Structural engineers who are specially trained in USAR procedures and techniques will work in support of the rescue teams on the site of a collapse(s), and will be required to make assessments of the likely magnitudes, frequencies and strength of shaking of aftershocks. These assessments are required for a number of purposes for Urban Search and Rescue following a damaging earthquake. The first issue in USAR is the safety of the rescuers. This requires an overall assessment of the possibility of total or partial collapse of the structure following the initial damaging event, or the possibility of falling hazards. A key part of the initial assessment includes addressing the question: 'Is the building safe enough to undertake the Search and Rescue operations in or is it a "NO-GO"'? The answer may change as time elapses as more information becomes available about the structure, and because information about the particular aftershock sequence and its decay may lead to a different

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assessment than an initial one based on generic properties of aftershocks. An important feature of aftershocks is that their expected frequency decreases with time, a property of aftershock sequences that may affect the timing of various rescue activities – a NO-GO assessment immediately after the main shock may be reassessed as a viable operation with the passage of time, when all factors are taken into account.

Even where the go ahead is given to perform USAR operations, doubts may remain about the stability of individual objects such as a wall, panel, chimney or staircase that may fall on to people. The quickest solution is to avoid the fall zone. Alternatively, shoring of the potentially dangerous part of the structure may be required, with the lateral forces for shoring depending on how big the aftershocks are likely to be, how often they might occur and how strong the associated shaking is likely to be at the particular location. It should be noted that the shoring is intended as a temporary measure for USAR operations, and not as a long-term measure intended to secure the overall building for the owner.

The New Zealand USAR manual for engineers (New Zealand Urban Search & Rescue 2004), providing guidance for those working within a rescue site, largely follows Californian practice in its treatment of the expected rate and magnitude-distribution of aftershocks, but uses aftershock parameters somewhat different from those in California. Use is made of a New Zealand attenuation relation to determine the strength of shaking likely for a given aftershock magnitude. The format of the New Zealand earthquake code spectra that is familiar to New Zealand structural engineers is used to specify the strength of shoring that is required for USAR operations for parts of structures at a given elapsed time since the main shock. The required strength is specified in terms of the equivalent NZS1170.5:2004 (Standards New Zealand 2004) hazard factor, Z, which may be interpreted as the expected peak ground acceleration on rock. The following sections of this paper review the properties of typical aftershock sequences, and how these lead to the expected largest aftershock magnitudes and Z-factors given in tables in the USAR Engineer's manual.

To be fully effective in a rescue situation, structural engineers must be specifically trained in USAR procedures and techniques, and must have regular involvement with the rescue teams with which they are associated. In New Zealand, specific Level 1 and Level 2 USAR Engineer training courses have been developed. Level 1 USAR engineers typically operate on the outer perimeter of a structural collapse site alongside emergency services personnel. They are a regional resource capable of assisting local volunteer rescue teams carrying out surface search and rescue. Level 2 USAR Engineers operate within a structural collapse site and are capable of operating with USAR Task Force teams (heavy rescue). Typically these engineers are Chartered Professional Engineers (structural & geotechnical) who have completed USAR Level 1 and 2 Engineer courses. For more information on USAR in NZ, see www.usar.govt.nz . Specific information on USAR engineering is provided in Factsheet #13 on that site.

An update on NZ's rescue engineering capability is provided in the accompanying NZSEE Working Party report in these proceedings (Brunsdon 2005).

2 EXPECTED AFTERSHOCK MAGNITUDES

Important features of aftershocks are that their expected rate decreases with time, and that their maximum magnitudes are generally related to the main shock magnitude. Also, as time evolves more information may become available about the particular aftershock sequence, and its decay, perhaps allowing estimation of sequence-specific parameters rather than using generic properties of aftershock sequences.

The USGS has estimated generic properties for Californian earthquake sequences that have been used in the US to provide the public with estimates of the expected rates and magnitude-distributions of aftershock activity. The USGS routinely updates the generic parameter values with sequence-specific estimates during the course of the activity (Reasenberg and Jones, 1989, 1994). With a slight modification of parameter values, the same type of model has been used in the New Zealand USAR manual to estimates rates of aftershocks, in particular to specify the magnitude of aftershock that needs to be considered as a function of elapsed time since the main shock.

There has been preliminary work in New Zealand estimating generic properties of New Zealand earthquake aftershock sequences (Eberhart-Phillips 1998), using the same form of model as in Reasenberg and Jones (1989, 1994). The feasibility of deriving the parameters of individual New Zealand sequences as they progress to forecast the rates and magnitude-distributions of later aftershocks has been investigated (Pancha et al., in prep.), with comparison of the goodness-of-fit using sequence-specific and generic parameter values. That study showed that there are sometimes problems in obtaining stable parameter estimates over the first few days, as well as problems resulting from lack of catalogue completeness for the aftershock sequence. Nevertheless, efforts are underway in New Zealand to develop methods for estimating the short-term strong ground-motion hazard associated with earthquake clustering, building on experience gained in California (Wiemer 2000). In a review presented at last year's NZSEE Conference, Gersternberger et al. 2004 identified a number of issues and complications that still need to be resolved before the adaptation of a real-time model of short-term earthquake shaking hazard to New Zealand, among them the handling of completeness problems, dealing with aftershock properties of earthquakes at different depths, understanding the limitations of real-time data quality, and the handling of swarms.

The magnitude-frequency distribution and rate of aftershocks as a function of time are fitted well by the product of two long-standing empirical relations of seismology, the Gutenberg-Richter (1944) frequency-magnitude relation, and the modified Omori law (Utsu et al., 1995), according to which the decay in the rate of earthquakes is approximately inversely proportional to the time since the main shock. The Omori law is more than a century old in its original form. The rate $\lambda(t,m)$ of earthquakes of magnitude m or larger at time t following a main shock of magnitude M_m is given by (Reasenberg and Jones 1989)

$$\lambda(t,m) = 10^{a+b(M_m-m)}(t+c)^{-p} \tag{1}$$

Integrating the rate over time, the number of events $N(M \geq m,\ S\ to\ T)$ greater than magnitude m between times S and T days for a main shock magnitude M_m is given by

$$N(M \geq m, S \rightarrow T) = 10^{a+b(M_m-m)}\frac{(S+c)^{-p+1}-(T+c)^{-p+1}}{p-1}, p \neq 1 \tag{2}$$

For a p-value of 1, there is a more compact functional form than for other p-values, with

$$N(M \geq m, S \rightarrow T) = 10^{a+b(M_m-m)}\ln\frac{T+c}{S+c} \tag{3}$$

c is a small constant, e.g. 0.05 days, that is introduced so as to avoid a singularity at $S=0$. It has little effect on the estimated number of events after the first day or two.

It appears that New Zealand aftershock sequences may be represented to a reasonable approximation by using a generic p-value of 1, as in Omori's original formulation, and by magnitude-frequency relations that have a generic b-value of 1 (i.e. a ten-fold increase in number as the magnitude decreases by 1). Analysis of 17 earthquake sequences between 1987 and 1995 gave a median p-value of 1.02 and b-value of 1.03 (Eberhart-Phillips 1998), compared to the generic Californian values of p=1.08 and b=0.91 (Reasenberg and Jones 1994). Values for individual sequences may vary considerably from the generic values, with p-values ranging between 0.20 and 1.61 and b-values between 0.78 and 1.27 in the 17 New Zealand sequences.

There are potential difficulties with differences in quoted magnitudes depending on the type of magnitude. The order of preferred type of magnitude is moment magnitude M_W, followed by surface wave magnitude M_S and local magnitude M_L. A conservative approach would be to take the largest of these (generally expected to be M_w).

Guidance for USAR Task Force Engineers in the United States (Module 1C Structural Engineering Systems, Parts 1 & 2 from http://www.fema.gov/usr/sctc.shtm) is to expect a largest aftershock with a magnitude about one less than the main shock magnitude M_m, although a number of moderate earthquakes of magnitude 6+ have had aftershocks with magnitudes similar to the mainshock magnitude. There is about a 50 per cent chance of an aftershock of magnitude M_m-1 in the first three days after the main event (Reasenberg & Jones 1994). Also used is the rule of thumb that the number of aftershocks increases by a factor of ten for every unit decrease in magnitude, starting from the largest aftershock of about one magnitude unit less than the main shock. This corresponds to a Gutenberg-Richter *b*-value of 1. A largest aftershock magnitude of about one unit less than the main shock is an empirical result, with a difference of 1.2 corresponding to Båth's law (Richter 1958), although observed differences vary from 0 to 3 or more (Utsu 2002). This observation can also be demonstrated theoretically.

With the rate of aftershocks decreasing with time, the magnitude that has a particular rate of exceedance in a day also decreases with time. Using the generic Californian parameter values b=0.91, p=1.08 and c=0.05 days in equation 2, the rate of exceeding magnitude M_m on the first day, from S=0 to T=1, (i.e. a normalised value of 1.0 in Table 1) is about the same as that of exceeding magnitude M_m-1 in the third day, i.e. in the interval S=2 to T=3, and of exceeding M_m-1.5 on day 6 or 7. The probabilities of exceeding M_m-1 within three days of the main shock and M_m-1.5 after day 3 up to the end of day 7 are both about 50±10 per cent, using the Californian generic *a*-value of -1.67 as well as the other generic parameter values.

Table 1: Expected daily numbers of events greater than magnitude M normalised by expected first day number for main shock magnitude M_m

	Normalised number of events $N(M \geq m, \text{day } S \rightarrow S+1)/N(M \geq M_m, \text{day } 0 \rightarrow 1)$				
	California p=1.08, b=0.91, c=0.05 days *		**New Zealand p=1.0,b=1.0, c=0.03 days ****		
S (days)	**$m=M_m$-1**	**$m=M_m$-1.5**	**$m=M_m$-1**	**$m=M_m$-1.5**	**$m=M_m$-2**
1	1.54		1.92		
2	0.87		1.13		
3		1.73	0.81		
4		1.32		1.97	
5		1.06		1.61	
6		0.89		1.34	
7				1.16	
8				1.05	
9				0.94	
10				0.88	
13					2.09
27					1.03
28					0.99

*From Reasenberg and Jones (1994)

**From Eberhart-Phillips (1998)

A generic *b*-value of 1 for New Zealand earthquake sequences rather than the Californian value of

0.91 leads to greater exceedance rates for magnitudes less than the main shock magnitude. This combined with the smaller *p*-value of 1, rather than 1.08, produces a longer duration over which the exceedance rate of a given aftershock magnitude is above a particular target level. Based on the concept of daily exceedance rates similar to the theoretical first-day rate for the main shock magnitude, the 0-3 day interval seems reasonable for New Zealand for an event of magnitude M_m-1, but the higher relative rate of magnitude M_m-1.5 than in California leads to a recommendation of a period up to 10 days over which this magnitude should be considered (Table 2). The New Zealand USAR Manual also gives a period of 10-14 days for considering M_m-2, but the equal exceedance rate principle suggests that this should be extended up to about 28 days (Table 1). However, because the initial rapid falloff in aftershock rates flattens out as time increases, the USAR manual also recommends that beyond 2 weeks magnitudes up to the largest magnitude that has occurred in the past week should be considered. With this recommendation, it is not critical whether M_m-2 is considered up to 14 days or 28 days, because the requirement to consider magnitudes up to the largest magnitude in the past week is likely to require consideration of events up to at least M_m-2 over the 14-day to 28-day interval. In all cases, magnitudes up to at least 5.0 should be considered.

Table 2: Time periods recommended in New Zealand USAR manual for considering various aftershock magnitudes for main shock magnitude M_m

Aftershock Magnitude	Recommended time period for consideration
M_m-1.0	Up to 3 days after the main shock
M_m-1.5	3 to 10 days after the main shock
M_m-2.0	10 to 14 days after the main shock*

* Equal daily exceedance rate principle suggests extension to 28 days

These time periods tie in reasonably well with those for which aftershock projections are required for planning different USAR operations at the site of a collapsed structure. Activities in the first few days (e.g. 0-3 days) are likely to include rescue of live victims, where greater risks to rescue personnel could be tolerated, changing to possible body recovery in the days following (days 3-10 or longer), where exposing rescuers to higher risks would not be justified. The numbers of personnel and types and amount of equipment will differ between these two activities. Therefore estimation of the likely rates and magnitudes of the aftershocks in these periods of different activities is desirable. The actual time involved in these two activities will vary between earthquakes and depends on the extent of damage and numbers of trapped people. A further consideration is that specialist rescue teams with the capability of extracting victims from collapses will arrive from 1 to 4 days after the main event.

3 EXPECTED MOTIONS ASSOCIATED WITH AFTERSHOCKS

The expected motions in aftershocks depend on the magnitude and distance from the rupture plane. The previous section has discussed the aftershock magnitudes to be considered within various elapsed times after the main shock, but it is also necessary to determine appropriate distances to estimate the expected motions at the sites of interest. For a crustal main shock of sufficient magnitude to be relevant for USAR purposes, the distance can be measured in terms of the shortest horizontal distance from the site to the aftershock zone, which should be readily identifiable from information available from GeoNet (www.geonet.org.nz) soon after the earthquake. It remains to associate a lateral force with this magnitude and distance pair.

A convenient format for specifying the expected aftershock motions is that of the elastic site hazard spectrum $C(T)$ of the recently published New Zealand Standard NZS1170.5 (Standards New Zealand 2004). The spectrum $C(T)$ is defined in terms of a spectral shape factor $C_h(T)$, a hazard factor Z , a return-period factor R, and a near-fault factor $N(T,D)$. The near-fault factor $N(T,D)$, which accounts for systematic rupture-directivity and polarisation effects in large-magnitude earthquakes, differs from 1.0 only for longer-period structures (T>1.5s) close to New Zealand's most active major faults, and so can be taken as 1.0 for aftershocks. Few aftershocks will be greater than magnitude 7, one of the criteria used in determining faults for which this factor applies.

It is recommended that appropriate seismic loadings for temporary retrofit or shoring for USAR purposes can be obtained by replacing the *ZR* product in the NZS1170.5 expression for *C(T)* by a value, as listed in Table 3, that is governed by the expected magnitude of the largest aftershock given the time since the main shock, and the distance of the site from the aftershock zone. Taking *R* as 1.0, *Z* is defined as 0.5 times the magnitude-weighted spectral acceleration *SA(0.5s)* at period *T=0.5s* for shallow soil site conditions, and is numerically equal to the code value of peak ground acceleration on rock. Magnitude-weighting, by the factor $(M_W/7.5)^{1.285}$ (Idriss 1985), is applied to convert spectral accelerations for a given magnitude earthquake into their equivalent values in a magnitude 7.5 earthquake. Magnitude-weighting is applied in recognition that a given maximum strength of shaking is associated with greater damage potential in larger magnitude earthquakes, because of the greater duration of strong shaking as magnitude increases. For a given magnitude, distance from the source, and probability of exceedance level (e.g. 50-percentile for median accelerations), *SA(0.5s)* and hence *Z* can be calculated from an attenuation model.

Table 3: *ZR*-factor for USAR purposes

Expected largest aftershock magnitude (rounded to nearest half unit)	**Distance from aftershock zone (km)**				
	0-5 km (3 km) *	**5-15 km (10 km)**	**15-30 km (20 km)**	**30-50 km (40 km)**	**50-75 km (60 km)**
7.0	0.4	0.3	0.2	0.15	0.10
6.5	0.3	0.2	0.15	0.10	-
6.0	0.2	0.15	0.1	-	-
5.5	0.15	0.1	-	-	-
5.0	0.1	-	-	-	-

*The distances in brackets are those used for the calculations, with the resulting *ZR* values rounded slightly

A feel for the level of motions corresponding to the *ZR*-values of Table 3 is that when the code spectral shapes are used the *ZR*-product corresponds to the peak ground acceleration value on rock.

The values of Table 3 are obtained by placing step-functions through the median *Z*-values for strike-slip earthquakes of magnitudes 5.0, 5.5. 6.0, 6.5 and 7.0 calculated directly from the New Zealand attenuation model (McVerry et al. 2000) that was used in calculating the NZS1170.5 *Z*-factors. The step-function representations of Table 3 are shown as the bolder lines in Figure 1, compared to the directly calculated *ZR*-values, the continuous functions of distance shown as the lighter curves. The recommended *ZR*-values are slightly rounded versions of the values calculated at distances of 3 km, 10 km, 20 km, 40 km and 60 km.

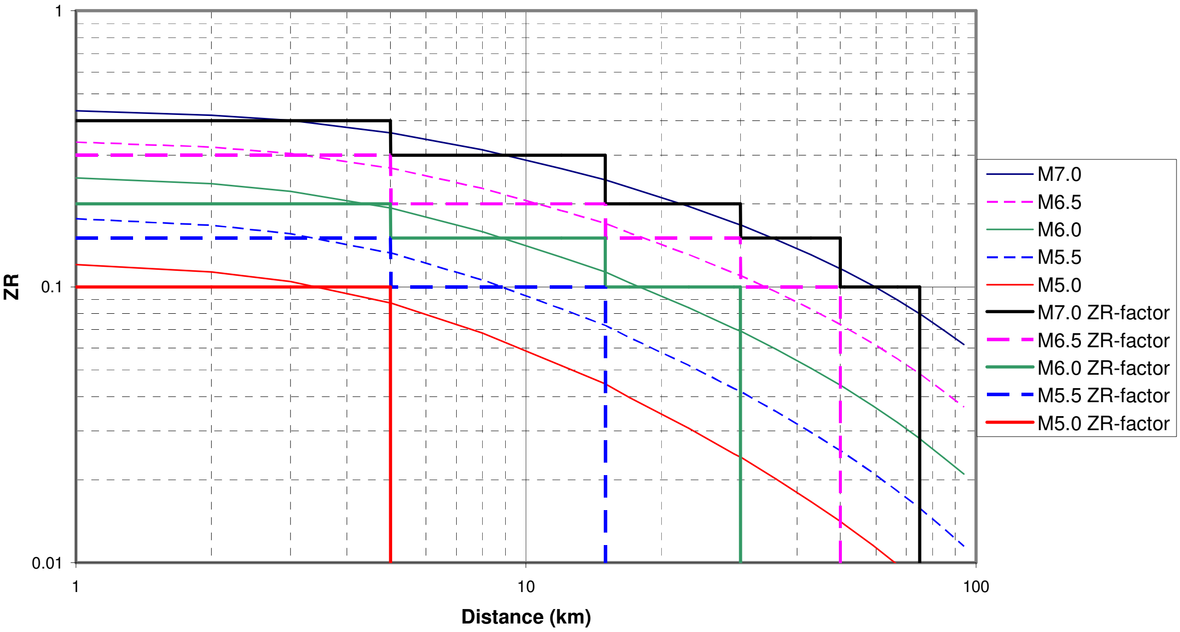

Figure 1: The recommended *ZR* values of Table 3 (bold step-function curves) compared to those calculated from 0.5 times the magnitude-weighted *SA(0.5s)* values on shallow soil for strike-slip earthquakes of magnitudes 5.0, 5.5, 6.0, 6.5 and 7.0. *ZR* values less than 0.1 may be taken as zero.

The spectral shape factor $C_h(T)$, as a function of the fundamental translational period T of the structure, is specified in Table 3.1 of NZS1170.5 for various site subsoil classes. For USAR purposes, it is expected that most structures or parts of structures that need to be evaluated will be of short period. For short-period structures, a factor of 3.0 is approximately right to convert the numbers of Table 3 from *ZR*-factors to the $C_h(T)ZR$ value for the short-period plateau of the code spectrum. This corresponds closely to the values of the code peaks for soil site classes C, D and E, although for Class C it is the spectral value rather than the equivalent static coefficient. A factor of 3 over-estimates the rock values, but a single factor avoids having to take site classes into account for preliminary shoring.

4 SUMMARY

This paper provides the background to the aftershock magnitudes that are recommended for consideration in post-earthquake Urban Search and Rescue operations in New Zealand, and the associated lateral force coefficients for short-term shoring. The recommended magnitudes are based on a simple aftershock magnitude-frequency and rate model, with generic properties determined from preliminary studies of New Zealand earthquake sequences. The recommended magnitudes are a function of main shock magnitude, and reduce with time in recognition of observations that the rates of earthquakes in aftershock sequences generally diminish with time elapsed since the main shock. The force coefficients are specified in terms of a table of *ZR* products to replace the standard values for earthquake-resistant design as specified in the recently released NZS1170.5:2004 standard, which should quickly become familiar to New Zealand engineers as the basis for deriving earthquake loadings for New Zealand structures. The recommended *ZR* products for USAR are specified as a function of the aftershock magnitude required to be considered and the distance of the structure from the aftershock zone. Information on the location of the aftershock zone is expected to be readily available to Civil Defence Emergency Management agencies and from the GeoNet Service. Preliminary studies have been carried out at GNS into the feasibility of obtaining sequence-specific aftershock parameters while a sequence is in progress, and work is continuing on development near real-time estimates of earthquake hazard with time-varying models that make use of current earthquake information.

Many of the rescue engineering decisions required to be made across multiple collapse or partial collapse sites following a major earthquake are of necessity knowledge-based judgements made within a rapid time frame, with a minimum of calculations. The material presented in this paper provides an important technical basis for such judgements, which represent some of the most difficult decisions that a structural engineer can be asked to make.

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