Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 56, No. 2, June 2023

POST-EARTHQUAKE BUILDING ASSESSMENTS: HOW LONG DO THEY TAKE?

Shreedhar Khakurel[1], Trevor Z. Yeow[2], Sandip K. Saha[3] and Rajesh P. Dhakal[4]

(Submitted *September 2021*; Reviewed *November 2021*; Accepted *March 2023*)

ABSTRACT

Major seismic events occurring around urban centres often cause widespread damage to the building stock. Engineers are then required to perform safety inspections of these buildings. This process may be time-consuming and can cause residents or businesses to be displaced for a considerable duration even if the building is safe to occupy. Furthermore, other post-earthquake recovery phases, such as repair and demolition/reconstruction works, may not even initiate until the building inspection phase is complete. As such, the disruptions caused by post-earthquake inspection need to be considered when modelling building occupancy/functionality downtime.

This study uses the data obtained from the 2011 Christchurch earthquake to develop a post-earthquake inspection duration quantification model. Firstly, the duration of the rapid assessment phase is estimated from the number of damaged buildings to be assessed, the total number of available engineers, and the median time needed for assessing each building. Secondly, the probability of a building being assigned a certain colour tag (*White*, *Yellow* or *Red*) is derived based on the extent of damage. Finally, both sets of information are combined to quantify the post-earthquake inspection duration. A case study is examined to demonstrate the application of the proposed model.

https://doi.org/10.5459/bnzsee.1568

INTRODUCTION

Socio-economic impacts arising from damage to engineered structures due to strong earthquake motions are generally classified into three main categories: (i) direct damage repair costs, (ii) death and injury, and (iii) downtime [1]. Out of these, the first two categories are obvious to understand as they represent asset loss and human loss, respectively. The third one (i.e., downtime) refers to a period during which a damaged structure fails to provide or perform its primary function. Prior to the first attempt to comprehensively quantify downtime [2], the estimates of downtime used to consider only repair time. However, the experience of recent earthquakes indicated that the time needed to repair the damage is only one component of downtime. There is often a long gap between the closure of a facility due to damage incurred and the beginning of repair [2].

Difficulties in quantifying downtime primarily arise from: (i) uncertainties associated with the availability of the required labour, materials, and capital following a major seismic event, and (ii) difficulties in relating the quantifiable damage to the need for repair and the loss of function [3]. Considering these uncertainties, Comerio [4] introduced downtime as the time necessary to plan, finance, and complete repair facilities damaged by earthquakes using the concept of rational and irrational components. The rational components include construction and/or repair time; while the irrational components consider the repair mobilisation time resulting from financing, relocation of functions, workforce availability, regulatory changes, and economic uncertainty [4]. These rational and irrational components are explicitly included in the following three critical elements of downtime modelling: (i) an estimate of construction repair time for individual facilities damaged by an earthquake, (ii) an estimate of the mobilisation time needed for various building stocks, and (iii) a representation of the economic conditions in the region at the time of the event [5]. Out of these three critical elements, mobilisation delay before commencing any repair was identified to contribute significantly to the total building downtime [6].

Although FEMA-P58 [7] specifies the median labour hours required to repair different damaged components which can be used to estimate the total repair time of a damaged building, it has certain limitations pertaining to its application in building downtime quantification. Some of the major limitations are: (i) the repair time estimates are based on potentially unrealistic labour allocation and repair sequence logic, (ii) repair time estimates only account for the time required to achieve full recovery from initiation of repair, and (iii) it does not consider delays as well as utilities disruption [8]. Redi$^{\mathrm{TM}}$ addressed these limitations to some extent by combining downtime due to delays (post-earthquake inspection, engineering review, financing, contractor mobilisation, permitting and procurement of long-lead time components), direct repairs, and utility disruption to estimate the total building downtime.

Based on the available literature, building downtime can be divided into three phases: (1) post-earthquake inspection, (2) damage analysis and decision, and (3) repair/demolition. The sequence of events in each of these phases is shown in Figure 1. The post-earthquake inspection enables the evaluation of the safety status of the exposed building stock as well as the earthquake's overall impact in the region. The decision is made either to repair or demolish a damaged building based on the post-earthquake inspection and the detailed damage assessment reports giving due consideration to the likely repair cost and terms and conditions of the insurance policy (for insured buildings). To include both scenarios, the building-specific downtime modelling framework (see Figure 1) is divided into two components: repair downtime and demolition downtime.

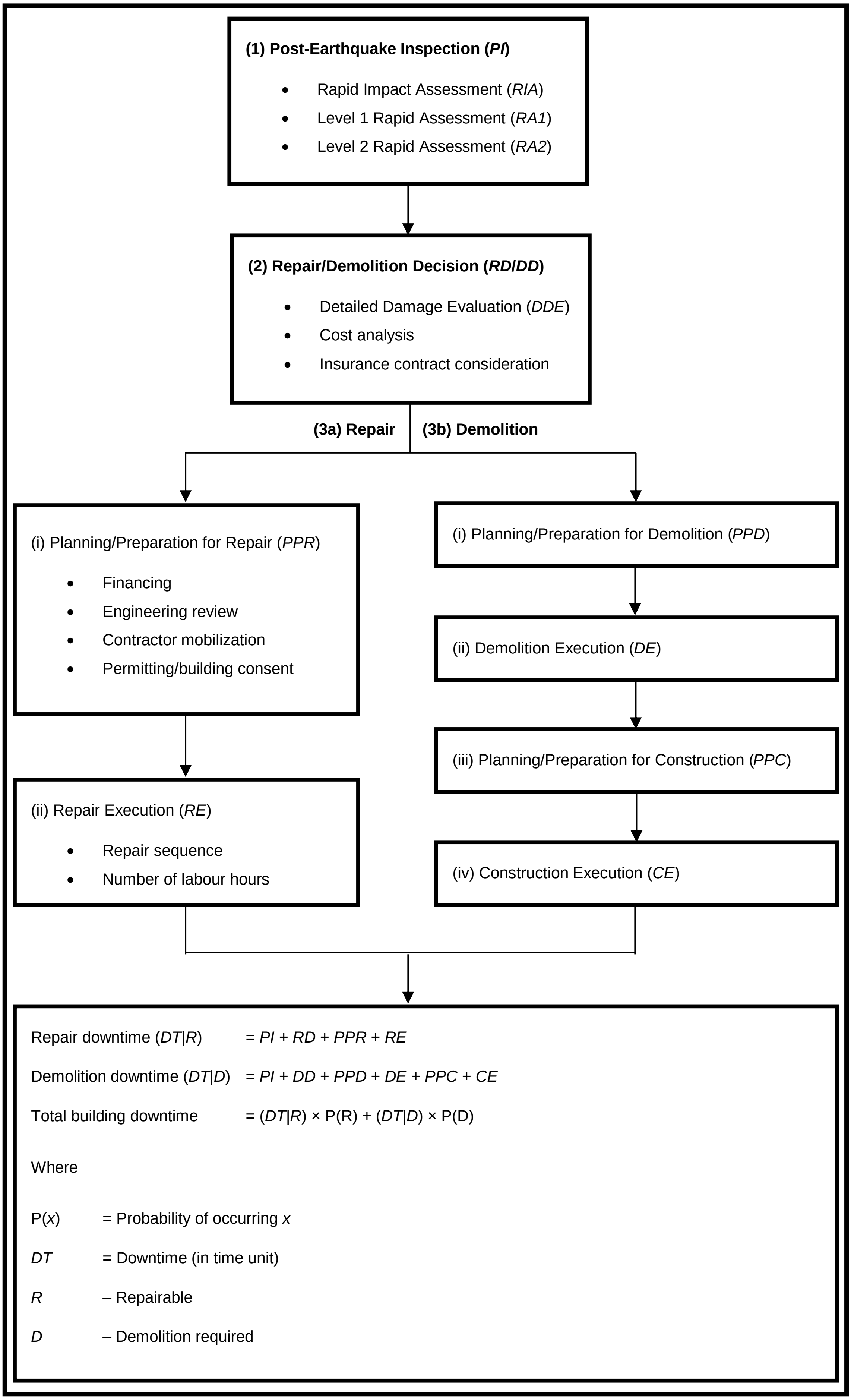
---

[1] *Assistant Professor, Institute of Engineering, Tribhuvan University, Nepal (khakurelshreedhar45@gmail.com)*

[2] *Project Researcher, Earthquake Research Institute, The University of Tokyo, Japan (trevoryeow@eri.u-tokyo.ac.jp)*

[3] *Assistant Professor, Indian Institute of Technology Mandi, India (sandip_saha@iitmandi.ac.in)*

[4] *Corresponding Author, Professor, University of Canterbury, New Zealand (rajesh.dhakal@canterbury.ac.nz) (Fellow)*



Repair downtime ($DT|R$) $= PI + RD + PPR + RE$

Demolition downtime ($DT|D$) $= PI + DD + PPD + DE + PPC + CE$

Total building downtime $= (DT|R) \times \mathrm{P}(R) + (DT|D) \times \mathrm{P}(D)$

Where

$\mathrm{P}(x)$ = Probability of occurring x

DT = Downtime (in time unit)

R – Repairable

D – Demolition required

Figure 1: Building-specific downtime modelling framework.

Note that the post-earthquake inspection, damage assessment and decision phases are common for both repair and demolition downtimes. Hence, the duration of the decision phase quantified for buildings demolished in Christchurch following the February 2011 Christchurch earthquake [9] can be used to calibrate the same component of the repair downtime as well.

This study aims to quantify the post-earthquake inspection duration using the numbers of exposed/damaged buildings and engineers deployed in the post-earthquake building inspection following the 2011 Christchurch earthquake.

BACKGROUND

Post-earthquake building safety evaluation is an important component of emergency management and response/recovery after a major earthquake. The Applied Technology Council's ATC-20 report "*Procedures for Post-Earthquake Safety Evaluation of Buildings*" [10] published in 1989 is one of the earliest safety evaluation documents, which provides clear guidelines for post-earthquake building safety evaluations. Inspired by the ATC-20 document, the New Zealand Society for Earthquake Engineering (NZSEE) published, in 1998, post-earthquake building safety evaluation guidelines [11] for New Zealand. Rapid assessment procedures were first implemented in New Zealand following the 2007 Gisborne earthquake. Since then, there has been a gradual evolution in understanding, mandate and practice related to post-earthquake building inspection with each major seismic event. Department of Building and Housing supported NZSEE in developing "*Building Safety Evaluation during a State of Emergency*" guidelines [12] for territorial authorities following the Gisborne earthquake. In general, the post-earthquake evaluation process consists of three phases: (i) rapid impact assessment, (ii) rapid building assessment (Levels 1 and 2), and (iii) detailed engineering evaluation. The NZSEE guideline was more focused on the rapid assessment process as shown in Figure 2.

Immediately after a moderate-severe earthquake event, a quick survey (identified herein as rapid impact assessment) needs to be performed to understand the overall impact of the earthquake on the region. The rapid impact assessment is conducted within a couple of hours of the earthquake by quickly triaging the exposed region by ground, possibly from the air, to collect information on the post-earthquake condition of the building stock and the built environment/infrastructure in the earthquake-exposed region. This phase is important as it helps the authorities in (i) decision-making on emergency state declaration, and (ii) planning of the rapid building assessment operation [13].

The impact assessment exercise is followed by rapid building assessments, preferably within hours of the event, in which a brief evaluation of individual buildings and their immediate surroundings is conducted to determine the severity of the damage incurred and the added occupancy-risk categories for issuing the post-earthquake building safety placards (i.e., colour tags). There are two levels of rapid assessments; commonly referred as Level 1 and Level 2 rapid assessments. While only an external building inspection is carried out in Level 1 rapid assessment to assess immediate risk to public safety, both internal and external inspections are carried out in Level 2 rapid assessment. Note that Levels 1 and 2 do not necessarily follow as a linear sequence/discrete phases, and some buildings may undergo only the Level 2 assessment.

Lin et al. [14] presented the colour tagging scheme used in the post-earthquake damage assessment after the 2010-11 Canterbury earthquake sequence based on the NZSEE guidelines [12]. Table 1 lists the different safety-focused usability categories used to categorise buildings after the two levels of rapid building assessment exercises and their definitions as well as interpretations. During the Canterbury earthquake sequence, Level 1 assessment teams were comprised of one engineer, one council building control officer, and one urban search and rescue technician; whereas Level 2 assessment teams included two engineers, two council building control officers, and one urban search and rescue (USAR) technician [15]. The Authors have been informed that USAR representatives were available for the exercise following the 2010 Darfield earthquake but not for the 2011 Christchurch earthquake, when teams were often accompanied by a welfare representative. Although Level 1 and 2 post-earthquake rapid assessments are not comprehensive damage assessments in true sense, the colour tagging and the associated functionality-restriction are normally decided based on the overall damage observed during the rapid inspections. There can be odd cases where a heavily damaged building might be given a lower colour tag and vice versa as detailed damage quantification and risk analysis are not performed in rapid assessments. While rapid assessments only form a small component in a single building's post-earthquake recovery timeline, it is a vital component at a regional level. For example, there is a good chance that only limited recovery progress can be made at a regional level until the rapid assessments of majority of damaged buildings have been performed.

Table 1: Usability categories resulting from rapid building assessments [14].

Level 1 rapid assessment

GREEN (G)	YELLOW (Y)	RED (R)
Inspected: Apparently OK; No restrictions on use or entry, but may need further inspection or repairs (owner's engineer)	Restricted use: Safety concerns; parts may be off limits; entry only for short periods of time	Unsafe: Clearly unsafe – do not enter. Further assessment or evaluation required before any use

Level 2 rapid assessment

GREEN (G1)	GREEN 2 (G2)	YELLOW 1 (Y1)	YELLOW 2 (Y2)	RED 1 (R1)	RED 2 (R2)
Occupiable: no immediate further investigation required	Occupiable: repairs required	Short term entry only	No entry to parts until repaired or demolished	Significant damage: repairs or strengthening possible	Severe damage: demolition likely

Figure 2: Post-earthquake building safety evaluation [12].

Table 2: Rapid building assessment outcomes and placards [13].

Observed damage	Assessment outcome	Placard issued
Light or no damage (low risk)	W = CAN BE USED No immediate further evaluation required	CAN BE USED (WHITE)
Moderate damage (medium risk)	Y1 = USE RESTRICTED IN PART(S) No entry to parts until risk reduced by repair or demolition Y2 = USE RESTRICTED to SHORT-TERM ENTRY With or without supervision	RESTRICTED ACCESS (YELLOW)
Heavy damage (high risk)	R1 = ENTRY PROHIBITED At risk from external factors such as adjacent buildings or from ground failure R2 = ENTRY PROHIBITED Significant damage	ENTRY PROHIBITED (RED)

The post-earthquake building evaluation system has been used and tested in a number of events in New Zealand in the past decade; such as the 2010-11 Canterbury earthquake sequence, 2013 Seddon, Cook Strait earthquake and the 2016 Kaikoura earthquake. Before 2015, the Civil Defence Controller had powers under the Civil Defence and Emergency Management (CDEM) Act to implement rapid assessments during an emergency. Nevertheless, the absence of specific mandates resulted in lack of clarity on the government priorities, resourcing and criteria to transition to regular business once the emergency period was over [16]. Experiences from recent events have led to a better understanding of the process; and resulted in improvement of the mandate and practice. One such notable change is the replacing the *Green* colour tag by *White* tags following the lessons learnt from the 2010-11 Canterbury Earthquake Sequence. Although *Green* tagging was part of an internationally recognised post-earthquake colour-tagging system, it was found to mislead people about building safety. While the *Green* tag was originally intended to mean that the building did not sustain significant visible damage in the earthquake and can be occupied as it poses no greater risk than prior to the earthquake, the public often interpreted a *Green* tag as the building being earthquake-resistant and code-compliant without reading the fine lines explaining the meaning in the placard. Consequently, the current placarding system used in New Zealand includes *White*, *Yellow* and *Red* colour tags.

The national CDEM plan assigns responsibilities to the Ministry of Business, Innovation and Employment (MBIE) to (i) plan for the national co-ordination of building management in an emergency, (ii) co-ordinate training and mobilisation of building assessors, (iii) maintain the rapid building assessment processes, and (iv) maintain sufficient capability of assessors nationally. More comprehensive process guidance for territorial authorities on building management in an emergency has been published in 2018 [13]. Table 2 describes the rapid building assessment outcomes and placards provided in the MBIE document. As seen in Table 2, five usability categories (*White*, *Yellow* 1, *Yellow* 2, *Red* 1, and *Red* 2) are specified for the three categories of damage observed (*light*, *moderate* and *heavy*). These categories are based on the damage factor (DF), which is the ratio of repair cost to the replacement cost. This is often referred as the loss ratio as well, and varies from 0 (no damage) to 100 (full replacement).

Mitrani-Reiser et al. [17] proposed a procedure for a virtual inspection to assess the safety of buildings based on the ATC-20 inspection guidelines. The virtual inspection procedure uses an event tree model (see Figure 3) to evaluate a building's safety risk based on its exterior and interior structural damages. The probabilities of the building being *Red*, *Yellow* or *Green* (or *White* as is currently used in NZ) tagged, given an intensity measure, are determined from the likely extent of exterior and interior structural damages obtained from the structural and damage analyses.

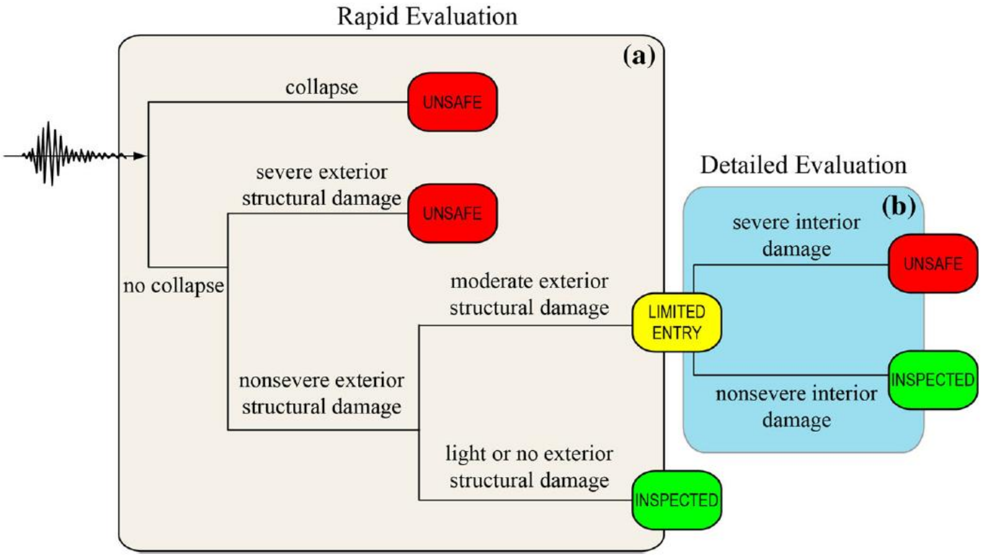


Figure 3: Event tree model for building safety evaluation [17].

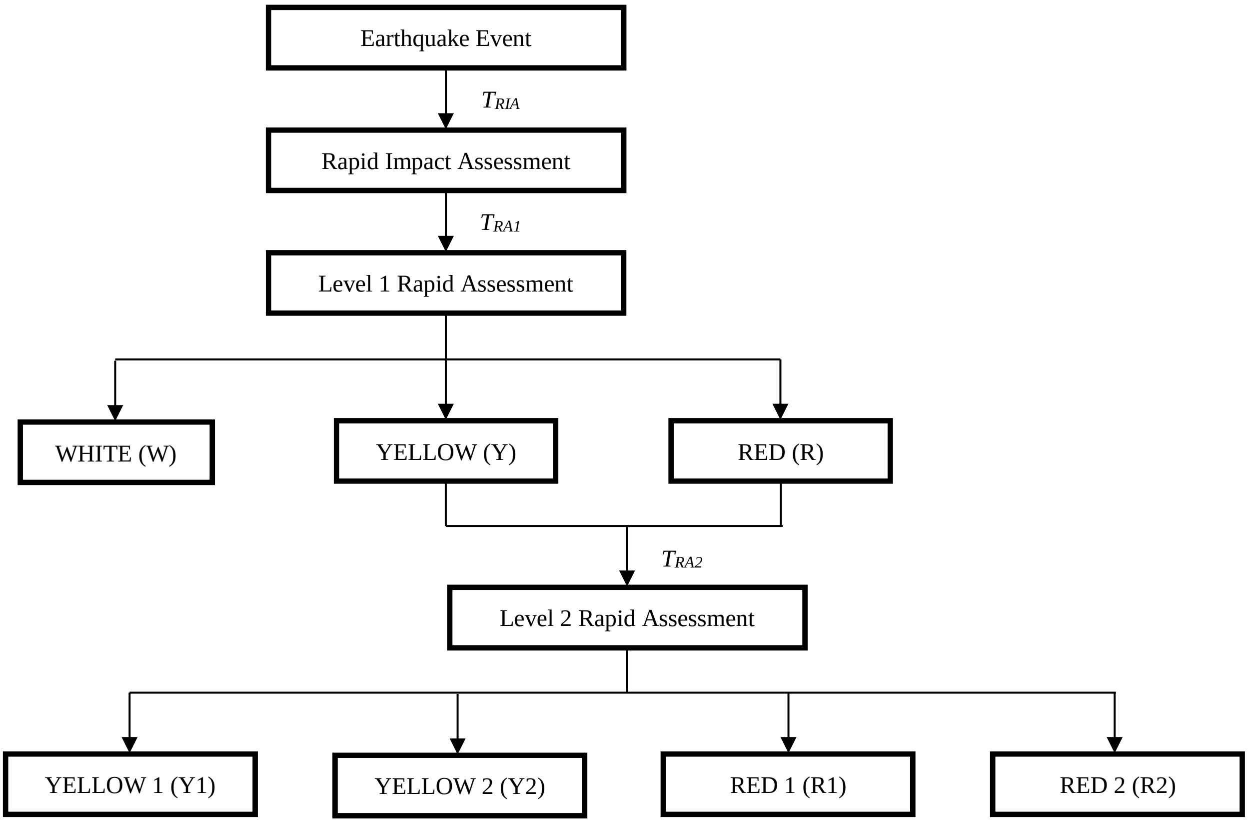


Figure 4: Post-earthquake inspection duration quantification model.

POST-EARTHQUAKE BUILDING INSPECTION DURATION MODELLING

Quantification of the time taken by building safety evaluations can be a useful tool for planning post-earthquake response and recovery after major earthquakes. Figure 4 shows the post-earthquake inspection duration quantification model proposed in this study. Here, T_i refers to the time required to conduct the i^{th} assessment phase (e.g., T_{RA2} is the time required to perform Level 2 rapid assessment). This model is developed from the perspective of regional authorities so that they can estimate the total time needed for completing the post-earthquake assessment of the exposed building stock. Immediately after the occurrence of an earthquake event, the overall impact survey (identified herein as rapid impact assessment) is carried out, which is then followed by rapid building assessments. After the Level 1 rapid assessment, buildings with no visible damage are posted with a *White* tag (occupiable), whereas those with clear visible damage are posted with either *Yellow* (restricted use) or *Red* (no entry) tags depending on the severity of the damage and the resulting safety status of the building. Only *Yellow* and *Red*-tagged buildings are recommended for Level 2 rapid assessment as the emergency control authorities do not investigate white tagged buildings further. It is also likely that the authorities may decide to conduct Level 2 assessment (including external as well as internal inspections) on critical buildings without a prior Level 1 assessment [18]. However, this model assumes that all buildings subjected to Level 2 assessment have undergone Level 1 assessment, which is likely to overestimate the overall building assessment phase duration. This assumption is justified because the overestimation will likely be marginal as the proportion of the building stock going directly to Level 2 assessment is normally very small.

Current post-earthquake inspection guidelines result in five usability categories (*White*, *Yellow* 1, *Yellow* 2, *Red* 1 or *Red* 2) after rapid building assessments, as shown in Table 2 [13]. In this model, the *W* category is considered as *White* tagged buildings from the Level 1 rapid assessment, and hence, the usability categories after Level 2 rapid assessment are reduced to four. Note that there can be rare cases where buildings tagged *Yellow* in Level 1 assessment can be downgraded to *White* after getting a better idea of the triviality of minor external damage during the closer internal inspection in Level 2 assessment. Such cases are overlooked in the model, but given the rarity of this occurrence it is unlikely to make noticeable difference to the expected length of the building assessment phase duration. Moreover, as someone has to perform a Level 2 assessment in such cases before the downgrade which consumes time and resources, the downtime is not nil for such cases. Considering travel time, usage of resources, etc, the downtime in such cases is already comparable with normal level 2 assessments; further justifying that overlooking such rare cases are unlikely to make significant difference.

Probability of Colour Tag

Since the colour tagging is based on the observed damage and the likely extent of repair needed, the probability of a building being assigned different colour tags depends on the probability of the building being damaged to different visible extent; ranging between no damage to collapse. The extent of damage a building undergoes in an earthquake mainly depends on the relative measures of capacity and demand; i.e., the design strength (and ductility) of a building and the severity of the ground motion at the building site. For a single building, it may be possible to estimate the extent of likely damage if the above two measures are known, but it is very difficult to rationally predict the extent of damage to the building stock and distribution of the colour tags used in an earthquake-affected area, because: (i) not all buildings in the area will (need to) be assessed; (ii) the exposed area will have buildings built in different era and a mix of old/un-engineered buildings and buildings designed to different levels of seismic demand as per the codes prevailing in the different era; and (iii) the variation of ground motions within a small area due to local site effects requires close array of tremor measurements which is normally not available. Hence, it is inevitable that some gross assumptions will have to be made in quantifying the distribution of different colour-tags in an earthquake-affected region.

In this study, seismic intensity and size of the building stock are considered as the key contributing parameters to the number of damaged buildings after an earthquake event. The number of buildings requiring Level 1 rapid assessment after an earthquake event (N_{BRA1}) can be calculated from Equation 1.

$$N_{B_{RA_1}} = BS \times P[A|im] \tag{1}$$

where, *BS* is the size of building stock in a region struck with an earthquake and *P*[*A*|*im*] is the proportion of buildings requiring assessment in the building stock for a given intensity measure. Note that the later term can also be interpreted as the probability of an average building requiring rapid assessment for a given intensity measure (assuming uniform distribution of buildings).

The size of building stock can be determined from the regional census data, but the second term (probability of buildings needing assessment) requires a vulnerability curve as shown in Figure 5. For a given intensity, determining the probability of a building requiring assessment is a challenging job as no fragility model can ever replicate the practical decision made in the field. The decisions made by those leading the response (e.g., cordoning) can have a significant impact on the post-earthquake activities [19]. Rapid assessments may not be carried out uniformly throughout the region as it is likely to be done only in more extensively damaged areas.

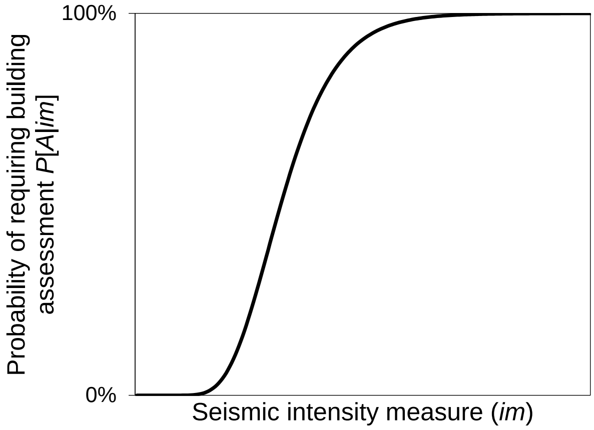


Figure 5: Vulnerability curve depicting the probability of building requiring assessment.

Since the outcomes of the rapid building assessment are *White*, *Yellow* 1, *Yellow* 2, *Red* 1, and *Red* 2 tags, the summation of the probabilities of a building receiving all five colour tags for a given intensity is equal to the probability of the building requiring assessment for that intensity. This relationship is mathematically shown in Equation 2.

$$P[A|im] = P[TAG_W|im] + P[TAG_{Y1}|im] + P[TAG_{Y2}|im] + P[TAG_{R1}|im] + P[TAG_{R2}|im] \tag{2}$$

where $P(TAG_W|im)$, $P(TAG_{Y1}|im)$, $P(TAG_{Y2}|im)$, $P(TAG_{R1}|im)$, and $P(TAG_{R2}|im)$ are the probabilities of the building receiving *White*, *Yellow* 1, *Yellow* 2, *Red* 1, and *Red* 2 colour tags, respectively, for a given level of intensity measure. Equation 2 is shown graphically using the colour tag fragility functions in Figure 6.

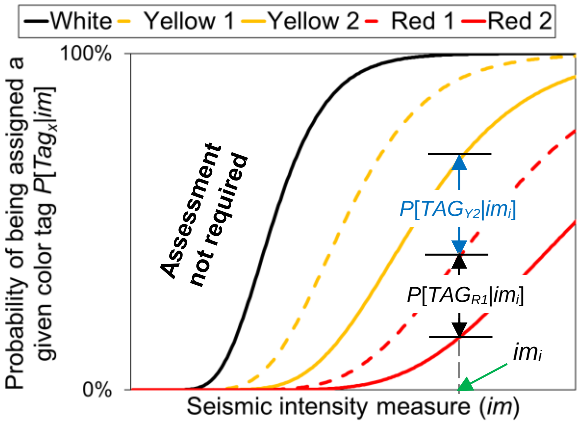


Figure 6: Colour tag fragility functions.

Mitrani-Reiser [17] estimated the mobilisation time based on the global damage state of a building which is defined by three colour tags (*Green*, *Yellow*, and *Red*) related to the building damage level (from *low* to *severe*). In doing so, a virtual inspector tool was used to evaluate the probability of a building being tagged *Green*, *Yellow*, and *Red*. Using the same approach, for an existing undamaged building, the likely extent of damage in the earthquake (quantified by probable value of the damage factor) can be computed from the results of structural and damage analyses. Equations 3a-3e determine the probabilities of a building being *White*, *Yellow* 1, *Yellow* 2, *Red* 1, and *Red* 2 tagged, based on the damage factor for different damage states as defined in Table 3.

$$P[TAG_W|im, A] = \frac{P[TAG_W|im]}{P[A|im]} = P[DF(0-1)|im] \tag{3a}$$

$$P[TAG_{Y1}|im, A] = \frac{P[TAG_{Y1}|im]}{P[A|im]} = P[DF(2-10)|im] \tag{3b}$$

$$P[TAG_{Y2}|im, A] = \frac{P[TAG_{Y2}|im]}{P[A|im]} = P[DF(11-30)|im] \tag{3c}$$

$$P[TAG_{R1}|im, A] = \frac{P[TAG_{R1}|im]}{P[A|im]} = P[DF(31-60)|im] \tag{3d}$$

$$P[TAG_{R2}|im, A] = \frac{P[TAG_{R2}|im]}{P[A|im]} = P[DF(61-100)|im] \tag{3e}$$

where, $P(TAG_W|im, A)$, $P(TAG_{Y1}|im, A)$, $P(TAG_{Y2}|im, A)$, $P(TAG_{R1}|im, A)$, and $P(TAG_{R2}|im, A)$ are the probabilities of the assessed building receiving *White*, *Yellow* 1, *Yellow* 2, *Red* 1, and *Red* 2 colour tags, respectively, for a given level of the intensity measure. Similarly, $P[DF(0\text{-}1)|im]$, $P[DF(2\text{-}10)|im]$, $P[DF(11\text{-}30)|im]$, $P[DF(31\text{-}60)|im]$, and $P[DF(61\text{-}100)|im]$ are the probabilities of the building incurring damage states *slight*, *light*, *moderate*, *heavy*, and *major*, respectively.

The interrelationship between the damage states, damage factor and usability categories is shown in Table 3. Damage state classifications used in this study are based on the percentage of the damage factor range provided by Lin et al. [14]. Note that despite the simplistic distinction between the usability categories indicated in Table 1, in reality these categories are not always necessarily distinguished based on the overall damage. For buildings that suffered severe damage in some parts and minor/no damage in others, different levels of restrictions (hence, different usability categories) could be imposed to different parts of the same building.

Table 3: Relationship between damage states and usability categories obtained from rapid building assessment.

Damage states	**Damage factor range (%)**	**Damage states**	**Damage factor range (%)**	**Usability category**
(ATC-13 [20])		**(MBIE [21] based on Lin et al. [14])**		
None	0	*Slight*	None	*White*
Slight	0 – 1			
Light	1 – 10	*Light*	0-10	*Yellow* 1
Moderate	10 – 30	*Moderate*	11-30	*Yellow* 2
Heavy	30 – 60	*Heavy*	31-60	*Red* 1
Major	60 – 100	*Major*	61-100	*Red* 2
Destroyed	100			

ATC-13 [20] recommended seven damage states based on ranges of damage factor. Lin et al. [14] condensed these seven damage states into five. In doing so, *none* and *slight* damage states were merged as *slight*; and *major* and *destroyed* damage states were merged as *major*. As is obvious in Table 3, the damage factor ranges specified by MBIE [21] are similar to those used by Lin et al. [14]. The only difference between the two is that DF = 0-1 was categorized as *light* damage state in the former document and *slight* damage state in the later. Hence the five damage states (*slight*, *light*, *moderate*, *heavy*, and *major*) are considered in this study to represent the five usability categories (*White*, *Yellow* 1, *Yellow* 2, *Red* 1, and *Red* 2) assigned after rapid building assessments.

Using the terms derived in Equation 3, the number of buildings requiring Level 2 rapid assessment (N_{BRA2}) can be calculated as shown in Equation 4.

$$N_{B_{RA_2}} = \{P[TAG_{Y1}|im, A] + P[TAG_{Y2}|im, A] + P[TAG_{R1}|im, A] + P[TAG_{R2}|im, A]\} \times N_{B_{RA_1}} \quad (4a)$$

which can also be written as:

$$N_{B_{RA_2}} = \{P[TAG_{Y1}|im] + P[TAG_{Y2}|im] + P[TAG_{R1}|im] + P[TAG_{R2}|im]\} \times BS \quad (4b)$$

Phase Duration

In this study, phase duration is defined as the total time required to conduct an individual assessment phase of the post-earthquake inspection sequence. Based on the MCDEM document "*Rapid Impact Assessment-Information for the CDEM Sector*" [22], the total duration to conduct the rapid impact assessment phase (T_{RIA}) can be considered as one day. Phase duration for rapid building assessment levels can be estimated using Equation 5.

$$T_i = \alpha_i \times \frac{N_{Bi}}{N_{Ei}} \quad (5a)$$

$$\alpha_i = \frac{T_{Bi} \times N_{ei}}{E_E} \quad (5b)$$

where, T_i is the time required to perform the i^{th} assessment phase; and N_{Bi} and N_{Ei} are respectively the total number of buildings to be inspected and the total number of engineers available for building inspections in the i^{th} assessment phase. Moreover, α_i in the equation is the phase duration coefficient defined as the gross equivalent time required for a single engineer to complete the i^{th} assessment phase of a single building, which can be computed using the phase-specific values of: (i) the median time required to inspect a single building (T_{Bi}), (ii) the total number of engineers involved to inspect a single building (N_{ei}), and (iii) the estimated efficiency of each engineer (E_E). As described earlier, the number of engineers involved in assessing a building (N_{ei}) is taken as 1 and 2 for the rapid building assessment Levels 1 and 2, respectively.

To estimate the duration required to complete the building inspection phase at a regional level, the time required to inspect a single building is essential. Different times have been proposed in literature for inspecting buildings in the two assessment phases. Table 4 shows the ranges (in brackets) of building inspection times reported in literature, from which the average values are calculated for each entry, and the median estimate of all averages is used in this study. As can be seen in the last row in Table 4, the median values of building inspection time for the rapid building assessment Levels 1 and 2 are computed to be 20 minutes and 2.25 hours, respectively.

Table 4: Building inspection time for different assessment phases.

***RA1* (minutes)**	***RA2* (hours)**	**References**
30	~2 (few)	Mitrani-Reiser [6]
30	2 (1-3)	Saito and Thakur [23]
20 (10-30)	1.5 (1-2)	Anagnostopoulos and Moretti [24]
20 (10-30)	3 (1-5)	Vidal et al. [25]
15 (10-20)	2.5 (1-4)	NZSEE [26]
17.5 (15-20)	3 (2-4)	MBIE [13]
20	2.25	Median value

Despite knowing the total number of engineers practicing in the affected region and in the whole country, the number of engineers available for building inspection after a seismic event is difficult to predict and is bound to induce significant uncertainty in the estimated phase duration. The proportion of total engineers available after a seismic event is heavily influenced by appropriate requests being made by the affected jurisdiction and the ability of the engineering association to efficiently mobilise sufficient and appropriate resources. The representative distribution of the total number of engineers available for building inspections during the post-earthquake inspection is shown in Figure 7. Herein, the first day allocated for rapid impact assessment can provide a lead-up time to mobilise the available and interested engineers for the rapid assessment phases beginning the next day. Normally, an engineer works five days a week (i.e., the working hours of an engineer is 40 hours per week, considering eight working hours in a day). Though post-earthquake building inspections are carried out throughout the week, an engineer is not expected to be working every day. This partial unavailability of an engineer to work in full capacity during the assessment phases is addressed in the proposed model by assigning a factor to represent the efficiency of an engineer.

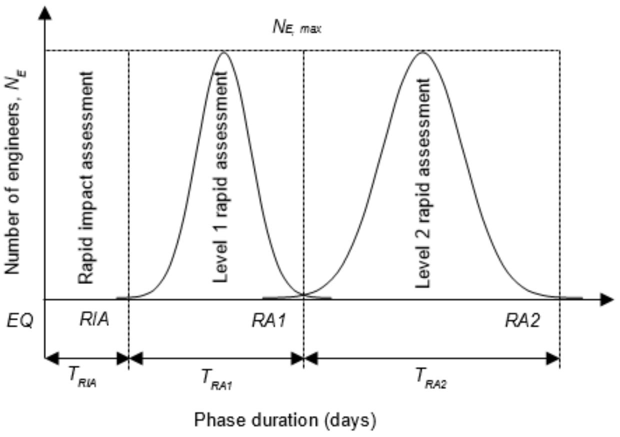


Figure 7: Distribution of the total number of engineers available for building inspections.

In this study, the efficiency of an engineer is calibrated using the actual engineer mobilisation and building assessment data following the 2011 Christchurch earthquake. For this purpose, the daily building inspection data reported by ATC [27] (see Table 5) and the total number of engineers (equal to 352) available for building inspections for the same event reported by Brunsdon et al. [28] are used herein.

Table 5: First ten days building inspections data from February 2011 earthquake [27].

Day	**1**	**2**	**3**	**4**	**5**
Buildings	2,302	4,015	4,260	3,263	4,726
Day	**6**	**7**	**8**	**9**	**10**
Buildings	7,998	11,709	17,945	14,305	2,359

The corresponding Author's discussion with the ex-Chief Engineer of the Department of Building and Housing, who coordinated the post-earthquake rapid damage assessment exercise, revealed that the 352 engineers reported in Brunsdon et al. [28] include only the engineers provided through IPENZ (Institute of Professional Engineers in NZ; now Engineering NZ). It did not include team members from the territorial authorities and BOINZ (Building Officials Institute of NZ) who undertook inspection of residential houses. The residential inspections did not systematically have engineers assigned to each inspection team, but a small group of engineers was made available for the inspection teams (primarily made up of building official from various territorial authorities from around New Zealand) to refer to as/when needed.

The ex-Chief Engineer also informed that the inspection of non-residential buildings in the CBD commenced from Day 1, whereas the residential inspections commenced from Day 6, and the total building numbers reported from Day 6 onwards in Table 5 include both the residential and non-residential buildings. Although the daily building inspection data was available only for 10 days, the rapid assessment exercise continued for 21 days, in which more than 130,000 buildings were assessed [27]. As the number of engineers involved in residential inspections could not be ascertained, to avoid the inconsistency between the number of engineers involved and number of buildings assessed, only the buildings assessed in the first 5 days (when the predominant majority of the inspected buildings were non-residential) are taken into consideration herein. Note that a small number of non-residential buildings were inspected after the fifth day. Hence, counting all 352 engineers but only the number of buildings within the first five days may slightly underestimate the average efficiency of the engineers. Nevertheless, this will be counterbalanced by exclusion of inevitable few residential houses which were inspected within the first five days involving some of the 352 engineers, and exclusion of inspection team members coming from territorial authorities and BOINZ who were not included in the 352 engineers' register but participated in inspecting some of the non-residential buildings within the first five days.

Calculation of E_E:

The efficiency of each engineer was estimated in the following steps:

- Building inspection time (T_B) = 20 minutes = 20/(60×8) days = 0.042 days
- Number of engineers involved per building inspection (N_e) = 1
- Total number of building inspections performed (N_B) = 18,566
- Time duration to inspect N_B (T) = 5 days
- Total number of engineers involved in building inspections (N_E) = 352

Therefore, from Equation 5 we get,

$$E_E = \frac{T_B \times N_e \times N_B}{T \times N_E} = \frac{0.042 \times 1 \times 18566}{5 \times 352} = 0.44 \qquad (6)$$

Thus, the efficiency of an engineer is calibrated to be 0.44. This is equivalent to an engineer working, on average, approximately three days a week for the building assessment teams, or in other words, being cumulatively available for building inspections for about 44% of the total duration. From the corresponding Author's recollection based on interaction with dozens of engineers involved in the building assessment exercise following the 2011 Christchurch earthquake, this appears to reasonably represent the extent of an average engineer's involvement (at least for that event). Using this value for the engineer efficiency factor, the phase duration coefficients (α_i) for Level 1 and 2 rapid assessments can be calculated using Equation 5b, which are found to be 0.095 and 1.28 days, respectively (considering 8 working hours per day).

Phase Length

In this study, phase length is defined as the total time duration required for the usability category of a building to be decided;

i.e., duration for the building to be assigned a final colour tag. If a building was posted as *White* after Level 1 rapid assessment, no further assessment would be required, whereas a building assigned a *Yellow* or *Red* tag in Level 1 assessment would require Level 2 rapid assessment. The sequence of phases to be followed for different colour tags is obvious from the flowchart shown in Figure 4. Based on this, the phase durations for buildings with different colour tags can be estimated using Equations 7a-7b. Note that a particular building can be assigned with a colour tag anytime within the duration of the tagging phase. For example, a building can receive a *White* tag, either at the start or end or at any time within the Level 1 rapid assessment phase. Hence, while computing the phase length for the *White* category, only half of the Level 1 rapid assessment duration is considered. This implies that half of the *White* category buildings can receive the tag midway through the Level 1 rapid assessment. A similar approach is considered for other usability categories during their phase length computation.

$$T_W = T_{RIA} + 0.5 \times T_{RA1} \tag{7a}$$

$$T_{Y1} = T_{Y2} = T_{R1} = T_{R2} = T_{RIA} + T_{RA1} + 0.5 \times T_{RA2} \tag{7b}$$

In Equation 7, T_W, T_{Y1}, T_{Y2}, T_{R1}, and T_{R2} are the phase lengths computed for the colour tags *White*, *Yellow* 1, *Yellow* 2, *Red* 1, and *Red* 2, respectively. Note that the time gap between each assessment phase is not considered in this study and the Level 2 rapid assessment is assumed to start only after the completion of the Level 1 rapid assessment. In reality, to minimise the business interruption losses due to building closure, Level 2 assessment of most commercial buildings will normally occur soon after their Level 1 assessment (time wise, this can be well before the Level 1 assessment of other less-urgent buildings). On the other hand, owners of most less-critical buildings would not mind waiting until the earthquake-induced demand-surge of engineers settled, which will lead to significant time gap between the Level 1 and Level 2 assessments of their buildings. Given that the exact spread of the start of Level 2 assessments in relation to the completion of Level 1 assessments in the region cannot be predicted in advance and the early and late starts will compensate for each other to some extent, the overall phase length is estimated here assuming Level 1 and Level 2 assessments occur in perfect sequence.

Post-Earthquake Inspection Duration

So far, equations have been developed to estimate the probability of a building being assigned a certain colour tag (based on the observed damage) and the duration of the rapid building assessment stages (based on the number of assessed buildings, the total number of available engineers, and the median building inspection time). Now, these two estimates can be combined as shown in Equation 8, which quantifies the expected post-earthquake inspection duration at the building level (D_B).

$$\begin{aligned} D_B = \{&P[TAG_W|im,A] \times T_W + P[TAG_{Y1}|im,A] \times T_{Y1} + \\ &P[TAG_{Y2}|im,A] \times T_{Y2} + P[TAG_{R1}|im,A] \times T_{R1} + \\ &P[TAG_{R2}|im,A] \times T_{R2}\} \times P[A|im] \end{aligned} \tag{8a}$$

which can also be written as:

$$\begin{aligned} D_B = &P[TAG_W|im] \times T_W + P[TAG_{Y1}|im] \times T_{Y1} + \\ &P[TAG_{Y2}|im] \times T_{Y2} + P[TAG_{R1}|im] \times T_{R1} + \\ &P[TAG_{R2}|im] \times T_{R2} \end{aligned} \tag{8b}$$

Further, post-earthquake inspection duration at a regional level (D_R) can be calculated from the proposed model by simply adding all three phase durations, as shown in Equation 9.

$$D_R = T_{RIA} + T_{RA1} + T_{RA2} \tag{9}$$

CASE STUDY

The 2011 Christchurch earthquake database is used herein as a case study to examine the applicability and reliability of the proposed post-earthquake inspection duration quantification model. Although the earthquake affected a large portion of Canterbury region, it is difficult to precisely estimate the size of the building stock exposed to major shaking. Following the intensity map of the earthquake, it can be argued that the moderate-major shakings were constrained mainly to three councils (Christchurch, Selwyn and Waimakariri). Hence, the greater Christchurch (covering the majority of the affected area) is used as the exposed region for this case study. As per Page and Fung [29], greater Christchurch had 171,704 buildings in 2006, which is adopted herein to represent the building stock exposed by the 2011 earthquake.

Note that this building stock includes mostly residential houses, whose inspection process can differ from that for non-residential buildings. For example, after 2011 Christchurch earthquake, the inspection of residential buildings did not systematically involve the second level assessment phase (i.e. RA2). Hence, although to show the application of the proposed procedure the residential and non-residential buildings are treated similarly in this case study, in reality they should be considered separately. If the exact numbers of residential and non-residential buildings are known, the framework proposed herein can still be used to estimate the corresponding durations by distinguishing between the different inspection sequence (e.g., excluding RA2 for residential inspections).

As per ATC report [27], 130,000 buildings were registered for rapid assessments after the earthquake, which amounts to 76% of the exposed 171,704 building stock. As the breakdown of colour tags for these 130,000 buildings in greater Christchurch could not be tracked, colour tagging statistics from a smaller building stock inside the jurisdiction of Christchurch City Council is used here. Christchurch City Council (CCC) record shows that 53,418 buildings inside the council were subjected to rapid building assessment following the February 2011 event, out of which 36,798 buildings (i.e.; 69% of the assessed buildings) were tagged *White*, 12,464 buildings (23%) were tagged *Yellow 1*, 2,404 buildings (5%) were tagged *Yellow 2*; 1,156 buildings (2%) were tagged *Red 1* and the remaining 596 buildings (1%) were tagged *Red 2* (see Table 6).

Table 6: Buildings tagged different colours in Christchurch after the February 2011 earthquake.

Tag	W	Y1	Y2	R1	R2
Number of buildings in CCC	36,798	12,464	2,404	1,156	596
Fraction of assessed buildings	0.69	0.23	0.05	0.02	0.01
No. of buildings in greater Christchurch	89,553	30,333	5,850	2,813	1,450

Next, the fractions of buildings in different colour tags are applied to the 130,000 buildings subjected to rapid assessments. As shown in Table 6 (last row), almost 90,000 of these buildings (i.e. 69% of the total assessed building stock) would have been tagged *White* after Level 1 assessment and only the remaining 31% buildings (slightly more than 40,000) would have required Level 2 assessment. These estimates, together with the number of engineers and the previously calibrated phase duration coefficients, were used to estimate the time taken to complete different phases of building inspection after the 2011 Christchurch earthquake (see Table 7).

Table 7: Post-earthquake inspection duration quantification parameters calculated for the case study.

Parameters	***RIA***	***RA1***	***RA2***
N_B	171,704	130,000	40,447
N_E	N/A	352	352
α	N/A	0.095	1.28
T (days)	1	35	147

Phase durations for the individual assessment phases reported in Table 7 are computed using the proposed model (Equation 5). As can be seen in Table 7, the phase durations for the rapid impact assessment, Level 1 rapid assessment, and Level 2 rapid assessment were found to be 1 day, 35 days, and 147 days, respectively. Note that despite the significant reduction in the number of inspected buildings (from 130,000 in RA1 to 40,447 in RA2), as the assessment levels advanced further from Level 1 rapid assessment to Level 2 rapid assessment, the time taken for the Level 2 rapid assessment phase was found to be about four times greater than that for Level 1 rapid assessment. This is because the median building inspection time for Level 2 rapid assessment is 7 times greater than that of the Level 1 rapid assessment.

Next, the proposed model was used to calculate the phase lengths for different usability categories (i.e., colour tags) using Equation 7. As shown in Table 8, the average phase length for *White* tagged buildings is estimated to be 18.5 days (rounded off to 19 days), whereas for all other colour tags the phase length was estimated as 109.5 (rounded off to 110) days.

Table 8: Phase lengths of different colour tags for the case study.

Tag	**W**	**Y1**	**Y2**	**R1**	**R2**
Phase length (days)	18.5➔19	109.5➔110			

These phase lengths were fed into Equation 8 to calculate the likely post-earthquake inspection duration at the building level. Note that Equation 8 also needs the probabilities of a building receiving different colour tags; i.e. $P[TAG_i|im,A]$, which are taken as the fractions of the assessed buildings receiving different colour tags shown in Table 6 (second row). Similarly, for this case study the probability of a building being assessed $P[A|im]$ is calculated as the ratio of the number of assessed buildings (130,000) to the number of exposed buildings (171,704). Thus, the calculated value of the post-earthquake inspection duration likely at a building level for this case study is 35.4 (round up to 36) days.

As shown in Equation 9, post-earthquake inspection duration at a regional level is the algebraic sum of phase durations involved in the post-earthquake inspection. Hence the post-earthquake inspection duration for this case study at the regional-level is 183 days. Note that any gaps or overlaps between the completion of former assessment phases (RIA and RA1) and the start of later assessment phases (RA1 and RA2) were not included in this estimation.

DISCUSSION

The proposed model will not be able to precisely predict the seismic downtime, but rather quantify a small component of downtime (i.e., delay due to inspection). It provides a handy tool for predicting the likely building inspection phase duration following an earthquake. Using the proposed model, regional and emergency management authorities can quickly estimate the time required to complete building inspections if/when an earthquake of a certain intensity strikes the region. To do so, they will need to acquire data on the total number of available engineers in that region from the national association of professional engineers, or other similar organisations. Also, for a given building stock (census data), the fraction of buildings likely to be damaged (i.e. requiring assessment) in a given shaking intensity will need to be obtained from vulnerability curves of the building stock in the region. If such vulnerability curves are not already available for any seismically active region, it is recommended that earthquake engineering researchers in the country give this a priority.

Taking the number of available engineers and the number of affected buildings as inputs for the proposed model, regional authorities can predict the number of days required to conduct different building assessment phases following an earthquake. This will give an idea for them to decide (i) the duration of the emergency period, and (ii) whether or not the available engineers are enough to complete the inspection within the emergency period. If the locally available engineers are likely to need a longer time, then engineers from other unaffected regions can be mobilised to complete the inspection within the planned emergency period.

CONCLUSION

Following the post-earthquake building safety evaluation guidelines, a model has been developed in this study to quantify the post-earthquake building assessment duration.

Durations of the rapid assessment phases are calculated as the product of a phase duration coefficient and the ratio of the number of buildings requiring post-earthquake inspection to the total number of engineers available for building inspection. The phase duration coefficient depends on the median inspection time for a building, the number of engineers involved in each assessment team, and an efficiency factor to cater for partial availability of the engineers. The probability of a building being assigned a colour tag is derived based on the likely extent of damage (obtained from building fragility functions) and the phase lengths for different colour tags are computed by adding the individual assessment phase durations. Finally, building level post-earthquake inspection duration is calculated using the phase lengths and probabilities of different colour tags. At the regional level, post-earthquake building assessment phase duration is calculated as the algebraic sum of durations of all phases in the post-earthquake building assessment exercise.

The 2011 February Christchurch earthquake was taken as a case study to demonstrate the application of the proposed post-earthquake building assessment duration quantification model. The phase length and the probabilities of a building being assigned different colour tags were computed from the model using the Christchurch City Council building assessment database. For this case study, the proposed model predicted the post-earthquake assessment durations at the building and regional levels to be 36 days and 183 days, respectively.

This model is believed to be useful: (i) for regional authorities to decide the length of the emergency period, and the sufficiency of available engineers to conduct a post-earthquake building inspection within the desired emergency period, and (ii) for researchers to quantify the delay due to inspection for a downtime modelling framework.

ACKNOWLEDGEMENTS

The Authors would like to thank Christchurch City Council for kindly supplying the building assessment database (for the February 2011 Christchurch earthquake) used in this study. Sincere thanks are also extended to David Brunsdon and Mike Stannard for providing useful feedback based on their experience in leading the Canterbury earthquake response, which helped refine the manuscript. The first Author is grateful to the University of Canterbury and QuakeCoRE for providing financial support to conduct his PhD, which included the research presented in this manuscript.

REFERENCES

1 Deierlein G, Krawinkler H and Cornell C (2003). "A framework for performance-based earthquake engineering". *Pacific Conference on Earthquake Engineering*, Christchurch, NZ.

2 Comerio MC (2005). "Downtime modeling for risk management". *Ninth International Conference on Structural Safety and Reliability* (*ICOSSAR'05*), 19-23 June, Rome, Italy.

3 Krawinkler H and Miranda E (2004). "*Performance based earthquake engineering*". Chapter 9 of *Earthquake Engineering: from Engineering Seismology to Performance-Based Engineering*. Boca Raton: CRC Press.

4 Comerio MC (2006). "Estimating downtime in loss modelling". *Earthquake Spectra*, **22**(2): 349-365. https://doi.org/10.1193/1.2191017

5 Comerio MC and Blecher HE (2010). "Estimating downtime from data on residential buildings after the Northridge and Loma Prieta earthquakes". *Earthquake Spectra*, **26**(4): 951-965. https://doi.org/10.1193/1.3477993

6 Mitrani-Reiser J (2007). "*An Ounce of Prevention: Probabilistic Loss Estimation for Performance-Based Earthquake Engineering*". PhD Dissertation, California Institute of Technology, USA. https://doi.org/10.7907/JXPV-1Q19

7 Hamburger R, Rojahn C, Heintz J and Mahoney M (2012). "FEMA P58: Next generation building seismic performance assessment methodology". *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

8 Almufti I and Willford M (2013). "*ReDi^{TM} Rating System: Resilience-based Earthquake Design Initiative for the Next Generation of Buildings*". ARUP Co.

9 Tombleson ZW, Dawson CJ, Yeow TZ, Khakurel S and Dhakal RP (2018). "Quantifying downtime due to building demolitions in Christchurch". *New Zealand Society for Earthquake Engineering Annual Conference*, 13-15 April, Auckland, NZ.

10 ATC (1989). "*Procedures for Post-Earthquake Safety Evaluation of Buildings*". ATC-20 Report. Applied Technology Council. Redwood City, California, USA.

11 NZSEE (1998). "*Post-Earthquake Building Safety Evaluation Procedures*: *Preparedness Checklist and Response Plan for Territorial Authorities*". New Zealand Society for Earthquake Engineering, Wellington, NZ.

12 NZSEE (2009). "*Building Safety Evaluation during a State of Emergency: Guidelines for Territorial Authorities*". 2nd Ed., New Zealand Society for Earthquake Engineering, Wellington, NZ.

13 MBIE (2018). "*Managing Buildings in an Emergency – Guidance for Decision-Makers and Territorial Authorities*". Ministry of Business, Innovation and Employment, Wellington, NZ.

14 Lin SL, Uma SR, Nayyerloo M, Buxton R and King A (2014). "Engineering characterisation of building performance with detailed engineering evaluation (DEE) data from the Canterbury earthquake sequence". *ASEC 2014 Conference*, 20 July, Auckland, NZ.

15 Brunsdon D (2012). "*The Evaluation and Management of Buildings following Earthquakes*". Overview Presentation to the Canterbury Earthquakes Royal Commission. 3 September, Christchurch, NZ.

16 Brunsdon DR, Stannard MC and Elwood KJ (2019). "Building management in emergencies: An update on New Zealand arrangements". *Pacific Conference on Earthquake Engineering*, 4-6 April, Auckland, NZ, 10pp.

17 Mitrani-Reiser J, Wu S and Beck J (2016). "Virtual Inspector and its application to immediate pre-event and post-event earthquake loss and safety assessment of buildings". *Natural Hazards*, **81**:1861-1878. https://doi.org/10.1007/s11069-016-2159-6

18 Galloway B, Hare J, Brunsdon D, Wood P, Lizundia B and Stannard M (2014). "Lessons from the post-earthquake evaluation of damaged buildings in Christchurch". *Earthquake Spectra*, 30(1): 451-474. https://doi.org/10.1193/022813EQS057M

19 Shrestha S, Orchiston C, Elwood K, Johnston D and Becker J (2021). "To cordon or not to cordon: The inherent complexities of post-earthquake cordoning learned from Christchurch and Wellington experiences". *Bulletin of the New Zealand Society for Earthquake Engineering*, **54**(1): 40-48. https://doi.org/10.5459/bnzsee.54.1.40-48

20 ATC (1985). "*Earthquake Damage Evaluation Data for California*". ATC-13 Report. Applied Technology Council. Redwood City, California, USA.

21 MBIE (2014). "*Rapid Post-Disaster Building Usability Assessment - Earthquakes*". Ministry of Business, Innovation and Employment, Wellington, NZ.

22 MCDEM (2013). "*Rapid Impact Assessment*". Ministry of Civil Defence and Emergency Management, Wellington, NZ.

23 Saito T and Thakur SK (2007). "Post-earthquake quick risk inspection system for buildings". *Journal of Experimental Psychology: General*, **136**(1): 23-42.

24 Anagnostopoulos S and Moretti M (2008). "Post-earthquake emergency assessment of building damage, safety and usability-Part 2: Organisation". *Soil Dynamics and Earthquake Engineering*, **28**(2008): 233-244. https://doi.org/10.1016/j.soildyn.2006.05.008

25 Vidal F, Feriche M and Ontiveros A (2009). "Basic techniques for quick and rapid post-earthquake assessments of building safety". *8th International Workshop on Seismic Microzoning and Risk Reduction*, 15-18 March, Almeria, Spain.

26 NZSEE (2011). "*Building Safety Evaluation following the Canterbury Earthquakes*". New Zealand Society for Earthquake Engineering, Wellington, NZ.

27 ATC (2012). "*Building Safety Evaluation after the February 22, 2011 Christchurch, New Zealand Earthquake: Observations by the ATC Reconnaissance Team*". Applied Technology Council, California, USA.

28 Brunsdon D, Hare J, Stannard M, Berryman K, Beattie G and Traylen N (2013). "The impact of the Canterbury earthquake sequence on the earthquake engineering profession in New Zealand". *Bulletin of the New Zealand Society for Earthquake Engineering*, **46**(1): 56-67. https://doi.org/10.5459/bnzsee.46.1.56-67

29 Page I and Fung J (2008). "*Housing Typologies – Current Stock Prevalence*". Report Number EN6570/8 for Beacon Pathway Limited, November, 42pp.