Geospatial Assessment of the Historic Seismic Performance of the New Zealand Bridge Stock

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ABSTRACT

This paper presents the geospatial assessment of historic seismic bridge performance of the New Zealand bridge stock from the 1968 Inangahua earthquake through to the 2016 Kaikōura earthquake. Spatial ground motion details based on recorded and observed ground motion intensities were used to estimate the peak ground accelerations (PGA) at each bridge location using kriging approaches. The quality of these estimates will vary, based on the uncertainty from the earlier events, and the influence of subsurface conditions on response. PGA, as a measure of the seismic demand at each bridge were then compared against estimate of bridge capacity defined through the New Zealand Transport Agency seismic screening process. A total of 694 bridges were estimated to have experienced an event PGA above 0.05g. They are mostly distributed around the east to the southern part of the North Island and the northern part of the South Island, which aligns with the regions with the highest seismic hazard across the country. Of the bridges that experienced an event PGA of more than 0.05g, 284 bridges with PGA information from seismic screening was available for comparison with their event PGA. Based on the 284 bridges assessed, majority of the bridges (85%) experienced an event PGA lower than the screening PGA, and 90% of bridges had none to minor structural damage. Of most interest are those bridges with none to minor damage under where the event PGA was significantly higher than the screening PGA, and those with moderate to major damage where the event PGA was much lower than the screening PGA. This finding, together with the ground motion intensity experienced by the bridges and the damage characteristics collated from post-reconnaissance reports will be used to assess the accuracy of analytical models used for the development of fragility functions and inform future assessment methods and design.

Keywords: bridge stock, seismic performance, seismic assessment, earthquake, New Zealand.

1 INTRODUCTION

New Zealand is a seismically active country, and as such the effects of earthquakes on infrastructure can be significant. Bridges are a key part of the road network, however there are currently many unknowns related to the true in-service seismic performance of the bridges across New Zealand. Having a good an understanding of bridge performance during earthquakes is essential to practicing engineers, authorities managing the bridges, and decision makers who need to make important decisions post-earthquakes to ensure the usability of the bridges and safety of the public.

This study focusses on bridge performance in historic earthquakes in New Zealand. The focus was all State Highway bridges and major earthquakes from the 1968 Inangahua earthquake through to the 2016 Kaikōura earthquake. Information that enables the assessment of the performance of bridges are available through various sources, this includes records of structural and geotechnical bridge damage in past earthquakes dispersed across post-event reconnaissance reports, commissioned reports, journal papers and other related sources. This damage evidence was collated and a damage severity assigned to each bridge.

The peak ground acceleration (PGA) experienced by the bridges in historic earthquakes, termed event PGA, was used to compare with the PGA from seismic screening, termed screening PGA. The PGA experienced by the bridges in historic earthquakes were estimated using observed recorded ground motion information from past earthquakes and interpolation methods in ArcGIS. The results of the analysis are presented herein and potential topics for further research presented.

2 OVERVIEW OF THE NEW ZEALAND BRIDGE STOCK

The highway structures on the State Highway network in New Zealand are managed by the NZ Transport Agency. The Highway Structures Information Management Systems (HSIMS) is an NZ Transport

Agency system used to support the effective management of significant highway structures on the State Highway network, including all the bridge structures along this network. There are about 2500 bridges in this database.

Figure 1 summarises the age distribution of superstructure types for State Highway bridges built after 1900. Cast in situ concrete bridges were common before the mid-1950’s and the use of precast concrete superstructures started to become popular after mid-1950’s. This is an important finding as the age distribution of the types of superstructures is useful in determining the factors affecting the performance of bridges in historic earthquakes in New Zealand.

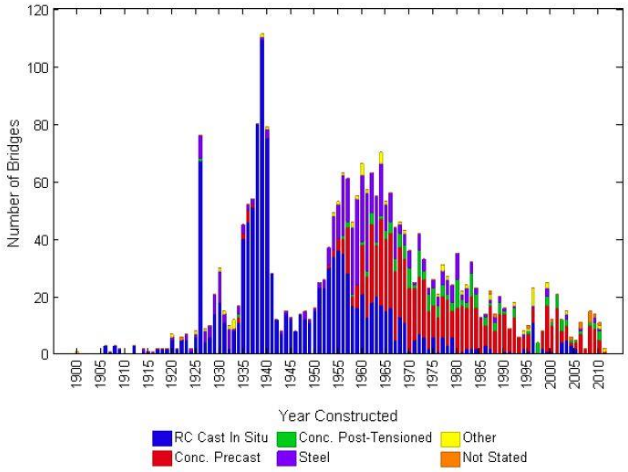

Fig. 1 Distribution of year of construction and superstructure types for State Highway bridges built after 1900 *(*Hogan, *2014)*

Figure 2 shows the distribution of state highway bridge span number for bridges constructed after 1900. It was found that the majority of the bridges are single span bridges, with three span bridges the second most prominent. This finding can be used to help further understand how bridge spans could affect the performance of bridges in historic earthquakes in New Zealand.

Figure 3 summarises the location of the NZ Transport Agency bridges in New Zealand obtained from HSIMS in November 2017 (New Zealand Transport Agency, 2017). Bridges in the database were categorized according to the respective management regions, and these are highlighted here.

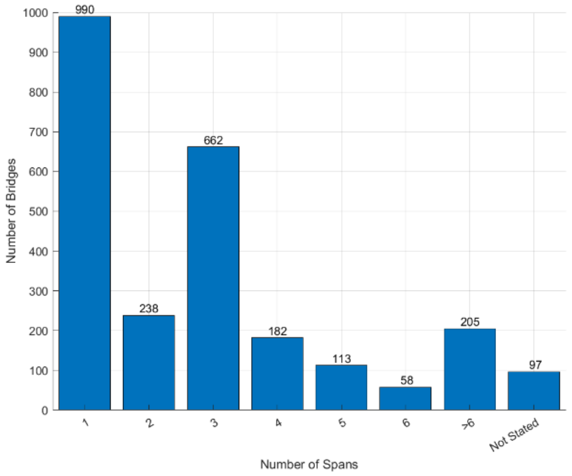

Fig. 2 Distribution of State Highway Bridge Span number for bridges constructed after 1900 (Hogan, 2014)

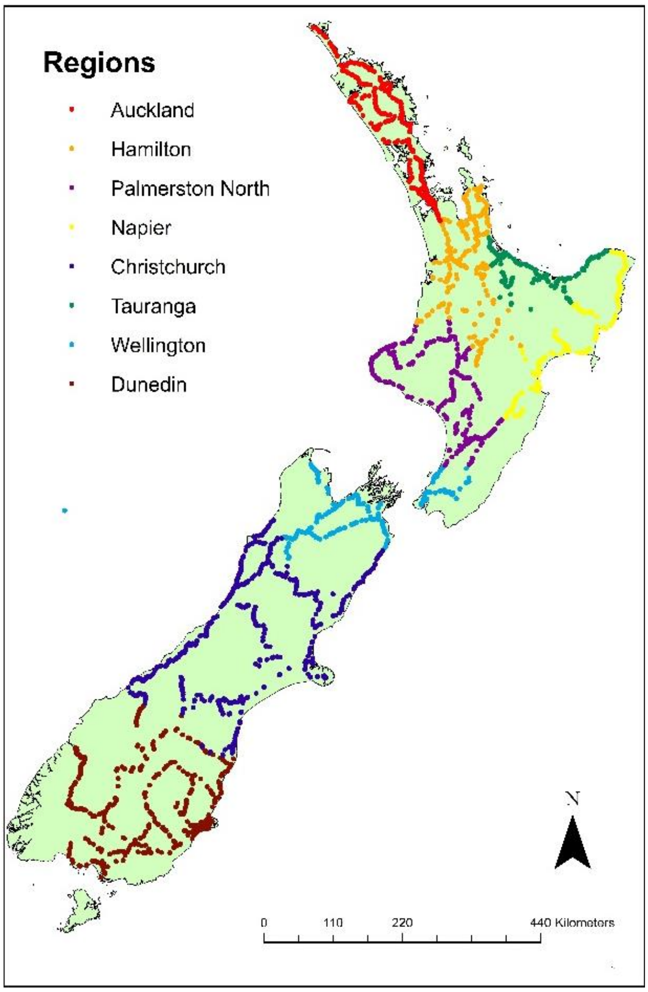

Fig. 3 Overview of the New Zealand Bridge Stock and the management regions

3 SEISMIC SCREENING

Seismic screening was performed starting in the late 1990’s to access the seismic security of State Highway bridges in New Zealand. All the bridges in the inventory were assessed using a preliminary screening procedure to define the priorities for carrying out detailed seismic assessments. In the preliminary screening, the estimated PGA for the bridges were determined. The assessment depends on experience and judgement of the assessors. This is an estimate without significant analytical work being undertaken as preliminary screening is intended to define priorities for carrying out detailed seismic assessments. (Chapman, Oakden, & Lauder, 2000).

According to the Manual for Seismic Screening of Bridges (Revision 2) SM110, the PGA for each bridge is an estimate based on the descriptive intensity of ground shaking and general expected performance of bridges. PGA at which failure is expected to have a high probability of occurring may be assessed based on the qualitative approach outlined in Table 1 (Transit New Zealand, 1998), defined as screening PGA in this study.

Table 1: Estimation of Peak Ground Acceleration Based on Manual for Seismic Screening for Bridges (Revision 2), SM110 (Transit NZ 1998).

Descriptive Intensity of Ground Shaking and Equivalent Modified Mercalli Intensity	**General Expected Performance of Bridge Structures**	**Peak Ground Acceleration (PGA)**
Extreme Earthquake MMI = X	Severe damage in say 50% of bridges. Failures expected in older bridges	0.60 to 0.80
Severe Earthquake MMI = IX	Moderate levels of damage to 70% of bridges and severe damage to 15% of bridges	0.40 to 0.60
Strong Earthquake MMI = VIII	Moderate levels of damage to 20% of bridges. Significant damage expected in bridges with poor detailing and in older bridges with little or limited ductility	0.25 to 0.40
Moderate Earthquake MMI = VII	Most bridges undamaged or sustain light damage but failures may result from very poor detailing	0.10 to 0.25

PGA values of 0.20, 0.35 and 0.50 is suggested to be adopted for MMIs of VII, VIII and IX respectively, unless observed characteristics justify the use of different values (Transit New Zealand, 1998).

4 SEISMIC DEMAND AT BRIDGE SITES IN HISTORIC EARTHQUAKES

The earthquakes assessed in this research and their characteristics are summarised in Table 2. These are include some of the most damaging earthquakes in New Zealand.

Table 2: Summary of the earthquakes assessed in this study.

Earthquake	**Date**	**Magnitude**
Inangahua Earthquake	24 May 1968	M_w 7.2
Edgecumbe Earthquake	2 March 1987	M_w 6.5
Ormond Earthquake	10 Aug 1993	M_w 6.4
Gisborne Earthquake	20 Dec 2007	M_w 6.6
Darfield Earthquake	4 Sept 2010	M_w 7.0
Christchurch Earthquake	22 Feb 2011	M_w 6.1
Cook Strait Earthquake	21 July 2013	M_w 6.5
Lake Grassmere Earthquake	16 Aug 2013	M_w 6.5
Eketahuna Earthquake	20 Jan 2014	M_w 6.1
Kaikoura Earthquake	14 Nov 2016	M_w 7.8

The ground motion information for the 10 earthquakes, from the 1968 Inangahua earthquake through to the 2016 Kaikōura earthquake were obtained from the United States Geological Survey (USGS) earthquake catalogue (United States Geological Survey, 2017). The ground motion intensity, in the form of PGA contours defined from recorded and felt events was projected to the New Zealand Transverse Mercator (NZTM) coordinates in ArcGIS. The PGA at each bridge location for these events were approximated using the Empirical Bayesian Kriging interpolation, a geostatistical analyst tool in ArcGIS. Examples of the contours used for the interpolation for the Christchurch earthquake, Ormond earthquake and Cook Strait earthquake are shown in Figure 4, Figure 5 and Figure 6 respectively. The points in the figures represent the NZ Transport Agency bridges in the earthquake affected area. The PGA value at each bridge is defined as the event PGA here.

The distribution of the range of event PGA experienced by the bridges and the moment magnitude (Mw) of the respective earthquakes are summarised in Figure 7. The smallest range of event PGAs were experienced during the Gisborne earthquake while the largest range of event PGAs were experienced during the Kaikoura earthquake.

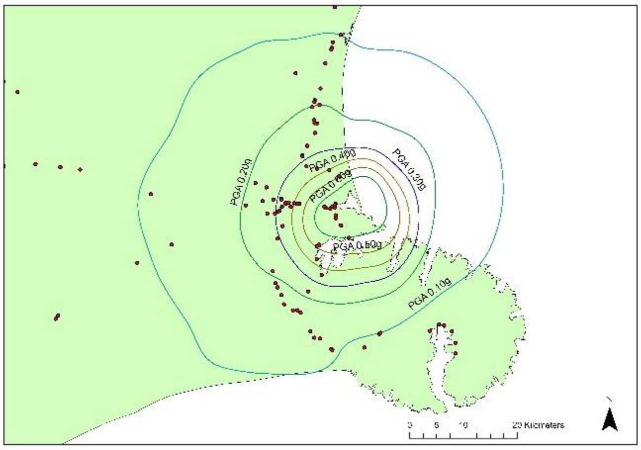

Fig. 4 PGA contours of the 2011 Christchurch earthquake and location of NZ Transport Agency bridges.

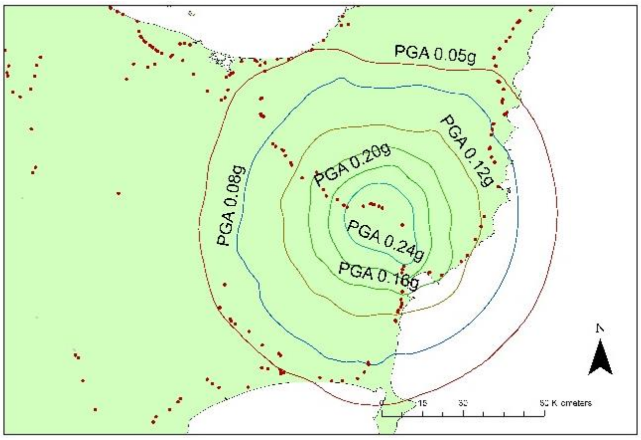

Fig. 5 PGA contours of the 1993 Ormond earthquake and location of NZ Transport Agency bridges.

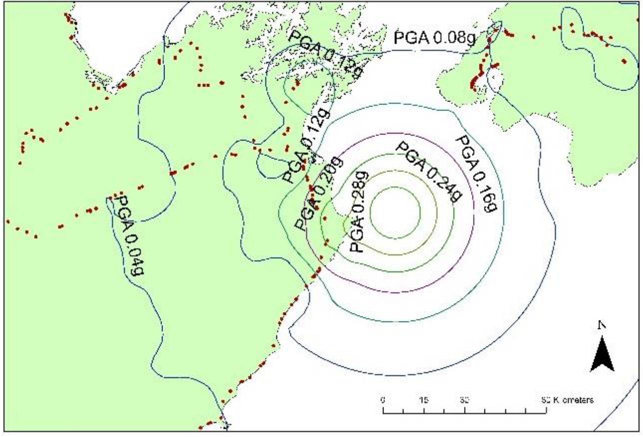

Fig. 6 PGA contours of the 2013 Cook Strait earthquake and location of NZ Transport Agency bridges.

Epicentres of the earthquakes assessed in this paper are summarised in Figure 8, and the location of the bridges in regions with a PGA of 0.05g or higher are highlighted in black. Bridges affected by the earthquakes and experiencing PGA of 0.05g or higher are mostly distributed around the east to the southern part of the North Island and the northern part of the South Island. This aligns with the regions with the highest seismic hazard across the country. A total of 694 bridges were estimated to have experienced an event PGA above 0.05g. Of these, 284 bridges had PGA information from seismic screening that could be used for further assessment.

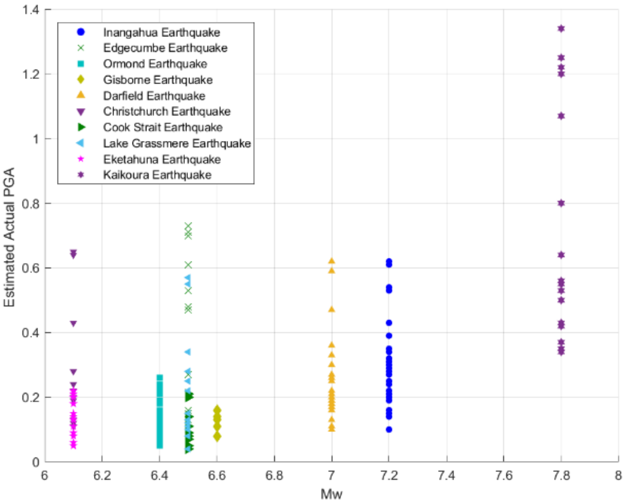

Fig. 7 Distribution of the event PGA experienced by the bridges for each of the respective earthquake events.

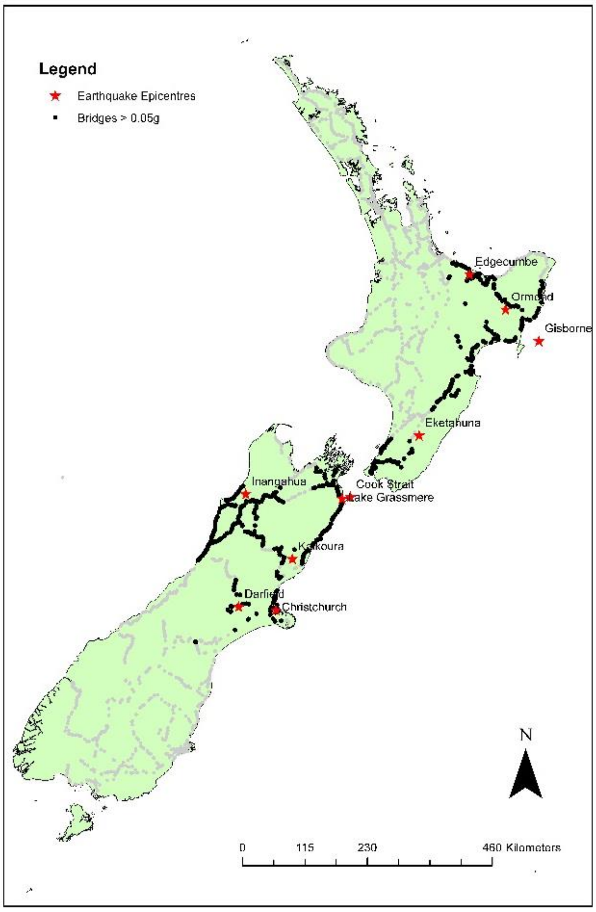

Fig 8: Epicentres of Earthquakes and location of bridges with event PGA greater than 0.05g.

5 COMPARISON OF ESTIMATED ACTUAL PGA AND SEISMIC SCREENING PGA

Figure 9 shows the distribution of event PGA experienced by the 284 bridges assessed. 89 bridges experienced an event PGA between 0.05g to 0.10g, accounting for 36% of the total number of bridges assessed. 77% of bridges experienced an event PGA below 0.30g.

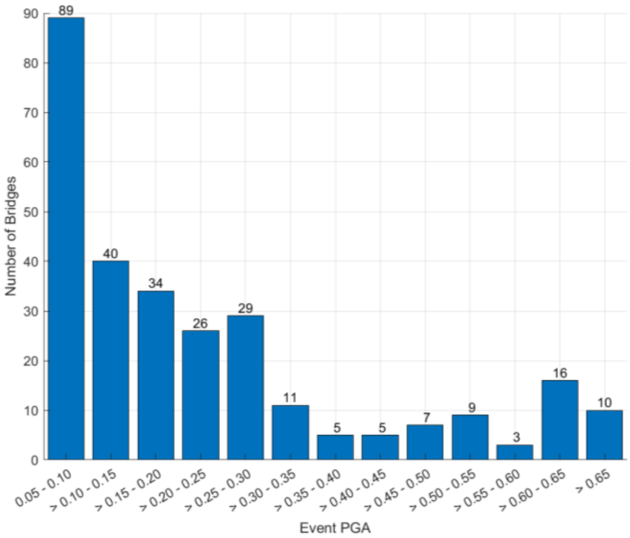

Fig. 9 Distribution of event PGA of bridges in historic earthquakes.

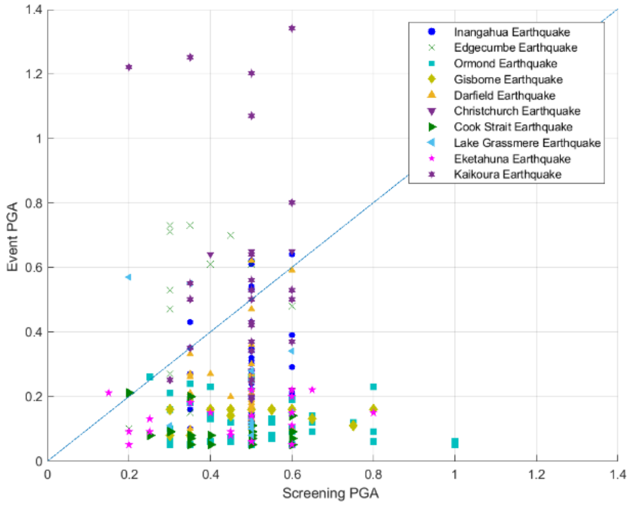

Fig. 10 Distribution of the event PGA versus the screening PGA experienced by the bridges.

The distribution of the event PGA versus the screening PGA experienced by the 284 bridges assessed is summarized in Figure 10. A total of 43 bridges (15%) experienced an event PGA greater than the screening PGA, while a total of 241 bridges (85%) have experienced anevent PGA less than the screening PGA. To further understand the bridge performance, the level of damage for each bridge needs to be assessed.

6 CLASSIFICATION OF DAMAGE

Bridge performance in historic earthquakes collected from various sources have varied level of detail according to the age of the earthquake. Information from more recent earthquakes are more detailed while information from older earthquakes are less clear. The damage and the characteristics of the bridge were summarised in a database including the construction year, construction form, bridge length, distance from earthquake epicentre and estimated ground motion characteristics.

Damage descriptions were mostly qualitative. Most of the bridges were found to have damage descriptions such as spalling, cracking, shearing, plastic hinging, flexural cracking, rotation, tilting, settlement, lateral spreading, surface sliding, soil gapping and other. All these relate to either structural or geotechnical damage, with both type of damages also evident at some bridges.

The damage severity was classified into three major categories, none - minor, minor – moderate and moderate - major depending on the severity of the damage. If there are obvious damage which affects the overall structural integrity or stability of the bridge and require the bridge to be closed to traffic but operational shortly after some repairs, through to being closed for a longer period of time, the damage was considered as moderate - major. If the damages have minor effects on the structural integrity of the bridge and the bridge is operational almost immediately, the damage is considered as minor - moderate. If there is no damage or very little damage and the bridge is safe to be used after the earthquake event after some minor repairs without the need for closure to traffic, or given an absence of reported performance, a general none - minor damage severity was assigned.

The distribution of PGA shown in Figure 10 was further classified according to the type of damage and their severities. Figure 11 shows the distribution of bridges with structural damage based on PGA ratio. , where PGA ratio refers to the ratio of the event PGA to the screening PGA. PGA ratio is divided into five categories, less than 0.50, between 0.50 to 0.75, between 0.75 to 1.25, between 1.25 to 1.50, and above 1.50. Bridges with PGA ratio of less than 0.75 indicates that they experienced relatively lower event PGA as compared to screening PGA while bridges with PGA ratio above 1.25 indicates that bridges experienced relatively higher event PGA as compared to screening PGA. Bridges with PGA ratio of 0.75 and 1.25 indicates that the event PGA and the screening PGA are comparable.

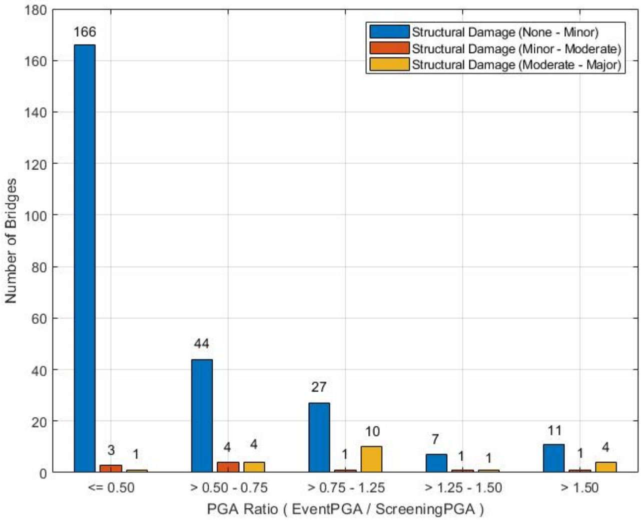

Fig. 11 Distribution of bridge structural damage based on PGA ratio.

Based on the findings, 90% of the bridges assessed have none to minor structural damage, only 10% of the bridges have minor to moderate and / or moderate to major damage. Most of the bridges which suffered none to minor damage experienced a PGA ratio of less than 0.50. There are some bridges experiencing PGA ratio of less than 0.50 but suffering minor to moderate damage and moderate to major damage. There are also some bridges experiencing PGA ratio of more than 1.50 but still suffer none to minor damage. These are of interest and further analysis is needed to identify the factors affecting this performance.

7 CONCLUSIONS

From the geospatial analysis conducted, a total of 694 bridges were estimated to have experienced an event PGA above 0.05g. They are mostly distributed around the east to the southern part of the North Island and the northern part of the South Island, which aligns with the regions with the highest seismic hazard across the country. Of the bridges that experienced an event PGA of more than 0.05g, 284 bridges with PGA information from seismic screening was available for comparison with their event PGA. Based on the 284 bridges assessed, 90% of the bridges assessed have none to minor structural damage. Although the data shows that most of the bridges are performing well, some bridges are significant outliers, with none to minor damage under high PGA ratios, and some with moderate to major damage under low PGA ratio.

Further analysis of the bridge performance is underway, particularly in relation to bridges that performed well under high ground motions, and those that were damaged in low excitation levels. This will include assessment of characteristics such as age and geometry, and how this may have contributed to the severity of the damage. These findings, together with the ground motion intensity experienced by the bridges and the damage characteristics collated from post-reconnaissance reports will help assess the accuracy of the analytical models used for the development of fragility functions for the bridges and inform future assessment methods and design.

8 ACKNOWLEDGEMENTS

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