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# FEATURE ENGINEERING FOR A SEISMIC LOSS PREDICTION MODEL USING MACHINE LEARNING, CHRISTCHURCH EXPERIENCE

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## Abstract

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The city of Christchurch, New Zealand experienced four major earthquakes ($M_W > 5.9$) and multiple aftershocks between 4 September 2010 and 23 December 2011. This series of earthquakes, commonly known as the Canterbury Earthquake Sequence (CES), induced over NZ$40 billion in total economic losses. Liquefaction alone led to building damage in 51,000 of the 140,000 residential buildings, with around 15,000 houses left unpractical to repair. Widespread damage to residential buildings highlighted the need for improved seismic prediction tools and to better understand factors influencing damage. Fortunately, due to New Zealand unique insurance setting, up to 80% of the losses were insured. Over the entire CES, insurers received more than 650,000 claims. This research project employs multi-disciplinary empirical data gathered during and prior to the CES to develop a seismic loss prediction model for residential buildings in Christchurch using machine learning. The intent is to develop a procedure for developing insights from post-earthquake data that is subjected to continuous updating, to enable identification of critical parameters affecting losses, and to apply such a model to establish priority building stock for risk mitigation measures. The following paper describes the complex data preparation process required for the application of machine learning techniques. The paper covers the production of a merged dataset with information from the Earthquake Commission (EQC) claim database, building characteristics from RiskScape, seismic demand interpolated from GeoNet strong motion records, liquefaction occurrence from the New Zealand Geotechnical Database (NZGD) and soil conditions from Land Resource Information Systems (LRIS).

## 1. Introduction

The Canterbury Earthquake Sequence (CES) that occurred from September 2010 to December 2011 is the costliest disaster in New Zealand's history [1]. Additionally, to the large shaking intensity felt during the main events, the CES induced widespread liquefaction which led to ground failure, subsidence and lateral spreading. High shaking combined with unsatisfactory land performance significantly affected the vulnerability of residential buildings throughout Christchurch [2]. Luckily, the Earthquake Commission (EQC) automatically insured any residential buildings against natural disaster given that private fire insurance for the home was present. This unique coverage led to an exceptional situation, with up to 80% of the losses insured. During and after the CES, a large amount of claim data were gathered. Nevertheless, quantitative studies making use of the wealth of data collected during the CES remain sparse [3].

Recent research projects demonstrated the benefits of machine learning application to civil engineering and earthquake engineering problems [4–6]. Machine learning can learn from large datasets and expose correlations between the variables which sometimes allows for a better understanding of the problem by humans [7]. Machine learning also offers the opportunity to develop models that can be retrained whenever new data becomes available.

## 2. Background

### 2.1. New Zealand's seismic setting and the Christchurch earthquake sequence (CES)

New Zealand lies on the boundary between the Australian plate and the Pacific plate. At the north-east of the north island, the Pacific plate subducts below the Australian plate, while the opposite occurs in the south-west with the Alpine Fault stretching along the west coast of the South Island. The majority of the earthquakes experienced in New Zealand originate from regions close to tectonic boundaries. Thus most of the historical earthquakes felt in Christchurch started in distant faults and the seismicity in Christchurch was deemed as moderate [8].

However, on the 4 September 2010, Christchurch was struck by an earthquake that started 45 km west of the city. The earthquake which originated from a previously unknown fault led to liquefaction, land, and building damage. There was no casualties for the $M_w$ 7.1 earthquake, later known as the Darfield earthquake. The ground motion was the first in a series of four main events [9] and more than 4,300 aftershocks above $M_w$ 3.0 [10] known as the Canterbury earthquake sequence (CES). On 22 February 2011, Christchurch experienced an $M_w$ 6.3 earthquake, centred 6.7 km south-east of Christchurch's central business district (CBD) with a hypocentral depth of 5.9 km [11]. While the Christchurch earthquake was smaller than the Darfield earthquake [12], it affected the built infrastructure more significantly and led to 182 fatalities [13]. The Christchurch earthquake was then followed by three other major aftershocks happening on 13 June 2011 ($M_w$ 6.0) and on 23 December 2011 with a magnitude of $M_w$ 5.8 and 5.9. These last earthquakes marked the end of the CES.

### 2.2. Damage to residential buildings

Engineered reinforced concrete (RC) buildings were most affected by the 22 February 2011 earthquake. Almost one-fifth of them located in Christchurch's CBD suffered significant damaged [13]. As a result of the CES, 1,354 commercial buildings had to be demolished. Among those, 61% were located in the CBD [14]. Residential buildings were affected throughout wider Christchurch and the CES to a varying degree depending on the experienced ground motion intensity and liquefaction occurrence. Following the CES, 85% of all residential buildings subsided with around 60,000 properties suffering more than 0.2 m of subsidence. Russell and van Ballegooy (2015) presented maps with the locations of liquefaction occurrence for the 4 September 2010, 22 February 2011, 13 June 2011, and 23 December 2011 overlaid with the PGA contours for each of these events. It can be seen that moderate to severe liquefaction was widespread for the 22 February 2011 and 13 June 2011 events, while being more limited for the 23 December 2011 and 4 September 2011 event [15]. Rogers et al. (2014) showed that severe liquefaction was mostly concentrated in the north-east suburbs located along the Avon river and in Bexley [16]. Amongst the most damaged residential properties, about 5,000 were located within the residential red zone [15].

To simplify understanding and enable a comparison between the parameters and the actual residential property damage, Rogers et al. (2015) quantified building damage through a building damage ratio (BDR). The BDR is defined as the damage repair costs for the residential dwelling divided by the financial value of the residential property [2]. The BDR is a numerical value comprised between 0 and 1. A value greater than 0.5 indicates that the building damage is severe, often related to foundation damage and thus too significant to be economically repaired. BDR values comprised between 0.2 and 0.5 typically represents limited structural damage that are practically reparable. BDR values below 0.2 entail solely non-structural damage requiring minor cosmetic repairs only [15]. Rogers et al. (2015) showed a map with the BDR for residential property at the end of the CES which indicates that three-quarters of the residential buildings were only slightly affected by minimal damage (BDR < 0.3). In contrast, 17% of the residential buildings suffered significant damage (BDR > 0.5) with 10% having a BDR above 0.75 and thus unpractical economical repairs. The remaining 6% experienced moderate reparable damage (0.3 < BDR < 0.5).

Russell & van Ballegooy (2015) studied the correlation between BDR and liquefaction. They concluded that high BDR were commonly observed where the land damage from liquefaction was moderate-to-severe, or where the liquefaction related subsidence was larger than 0.3 m. Properties which suffered moderate to major foundation differential settlements also showed a high BDR. Conversely, in suburbs that experienced minor land damage, residential buildings exhibited low BDR. Rogers et al. (2015) defined four areas each representative of a different combination of liquefaction occurrence, foundation performance and BDR. The first area is in the vicinity of the Avon River. Residential properties located along the Avon River and close to the Horseshoe Lake Reserve experienced poor land performance which led to significant damage to the buildings regardless of the type of foundation. For residential properties situated in the area north-east of Christchurch, BDR values are generally lower than 0.5 as the land performed with minor-to-moderate damage. Similarly, the land performed with minor-to-moderate damage south-east of the CBD. However, residential properties showed a high BDR due to the concrete slab-on-grade floors which performed poorly. Finally, properties located north of the Avon river (but not directly close to it) performed well with most of the BDR lower than 0.3.

The seasonal variations in the groundwater levels and the influence of multiple earthquake events (main event followed by multiple aftershocks preceding another main event) are some of the complexities driving varying land performance throughout Christchurch. The influence of the earthquake shaking characteristics (the time domain characteristics, the time between events) should not be minimised. It is crucial to understand that these variations cannot be solely captured by the magnitude ($M_W$) and the peak ground acceleration (PGA) of the events [15].

### 2.3. The CES and New Zealand insurance setting

The entire CES led to over NZ$40 billion in total economic losses [14]. Financial losses accounted for 20% of New Zealand's gross domestic product (GDP) of US$168.5 billion in 2011 [3]. However, unlike many other seismically active countries, New Zealand benefits from a unique insurance setting which has led to an insurance penetration rate of up to 80% [17,18]. A key reason for this is the automatically first NZ$100,000 (+ GST) natural disaster insurance cover for residential homes and land provided by government insurer the Earthquake Commission (EQC). This cover is available to all homeowner who has additional private home fire insurance. This enabled affordable private natural disaster insurance which is widely taken up. Since 2019, the EQC first cover was increased to NZ$150,000. At the time of the CES, EQC provided a maximum cover of NZ$100,000 (+GST) per home [19]. Owners eligible for EQC cover of a residential property which experienced home and land damage during one of the events of the CES could lodge a claim with EQC. After investigation of the claim, EQC paid the claim in full for claims less than NZD$100,000. For damage greater than NZ$100,000, EQC paid the NZ$100,000 cap per claim and transferred the remaining liability to building owner's private insurers. Nevertheless, this process was not efficient as it required significant time to investigate and transfer over cap claims to the private insurers. Thus in 2020, private insurers still receive new over cap claims from EQC. Moreover, the insurance policies guaranteed a full replacement of the house not only the sum insured. Hence, whenever a repair or rebuild was not possible, homeowner and the insurers must agree on the total value of the loss before the claims could be settled. Another difficulty throughout the CES was that each main event possibly caused further damage to residential buildings thus requiring additional assessments, such that the costs for each event could be properly apportioned between EQC and the private insurers [14].

Following the CES, 650,000 insurance claims were lodged with insurers among them about 26% with private insurers. To date, EQC paid more than NZ$10 billion with another NZ$21 billion bore by private insurers. The high insurance penetration led to a total insured cost for the CES of more than NZ$31 billion [14]. This amount surpassed by far the costs, the number of claims, and affected policyholders for any prior natural disaster in New Zealand [20]. Table 1 lists some of the major earthquakes that occurred between 2008 and 2018 and led to significant losses. It is observable that the contribution of the insurance sector in New Zealand is important, and the CES significantly surpasses the percentage of insured losses in any other earthquake events in New Zealand's history.

Table 1: Selection of worldwide seismic events from 2008 to 2018 (the Darfield earthquake has been added at the end of the list for comparison), accessed: 29 Jan 2020

| **Date** | **Area** | **Overall losses [US$bn]** [21] | **Insured losses [USbn]** [21] | **% insured** | **Overall losses [US$bn]** [22] | **Insured losses [USbn]** [22] | **% insured** |
|---|---|---|---|---|---|---|---|
| 11/03/11 | Japan | 210 | 40 | 19% | 238.90 | 37.48 | 16% |
| 12/05/08 | China | 85 | 0.3 | 0.3% | 148.09 | 0.44 | 0.3% |
| 14/04/16 | Japan | 32 | 6.5 | 20% | 28.79 | 5.21 | 18% |
| 27/02/10 | Chile | 30 | 8 | 26% | 35.20 | 9.39 | 27% |
| **22/02/11** | **New Zealand** | **24** | **16.5** | **69%** | **24.85** | **19.91** | **80%** |
| **4/09/10** | **New Zealand** | **10** | **7.4** | **74%** | **11.21** | **9.04** | **80%** |

## 3. Data preprocessing for model development

### 3.1. Merging of EQC residential claim database with building characteristics from RiskScape

In order to develop a machine learning model for hindcasting the loss and damage during the CES, most machine learning algorithms require data to be available across all considered parameters for each instance. Analysis of EQC claim database showed that building characteristics (e.g. construction year, primary construction material, number of stories) are not normally collated, and up to 85% of the data points have missing characteristics that would be helpful for the machine learning model generation [23]. It was thus decided to supplement this by building attributes from RiskScape [24]. As there are no common identification for a property between the EQC claim and RiskScape database, the merging process had to be performed based on the geographical location. While being located closeby, there are often significant discrepancy between the EQC and RiskScape datapoint locations. This meant typical "spatial join" GIS operation was not feasible. A "Nearest Neighbor" approach also led to unsatisfactory results as the RiskScape database contained information on secondary buildings (e.g. external garages, garden shed). The final adopted approach used Land Information New Zealand (LINZ) property titles and LINZ street address datasets as an intermediary for data matching [25].



 

Despite this, some limitations remain. Figure 1 shows a map extract of Christchurch. The LINZ property titles are represented by the red outlines, the LINZ street address as red dots, and the building information provided by Riskscape are the yellow dots. It can be seen that many LINZ street addresses are within the same property title outlines; this is common case for apartments or properties to be recently subdivided. This made it difficult to assign one physical street address to one property. Moreover, as the RiskScape database catalogues information on a per buildings basis, it is essential to select the correct RiskScape point corresponding to the main dwelling to obtain the correct building characteristics. Fortunately, the RiskScape database includes two variables related to the building size (i.e. the building floor area and building footprint). Under the assumption that the main dwelling is the building with the largest floor area and footprint on a property, it is possible to filter the data to retain RiskScape information related to main dwelling only.

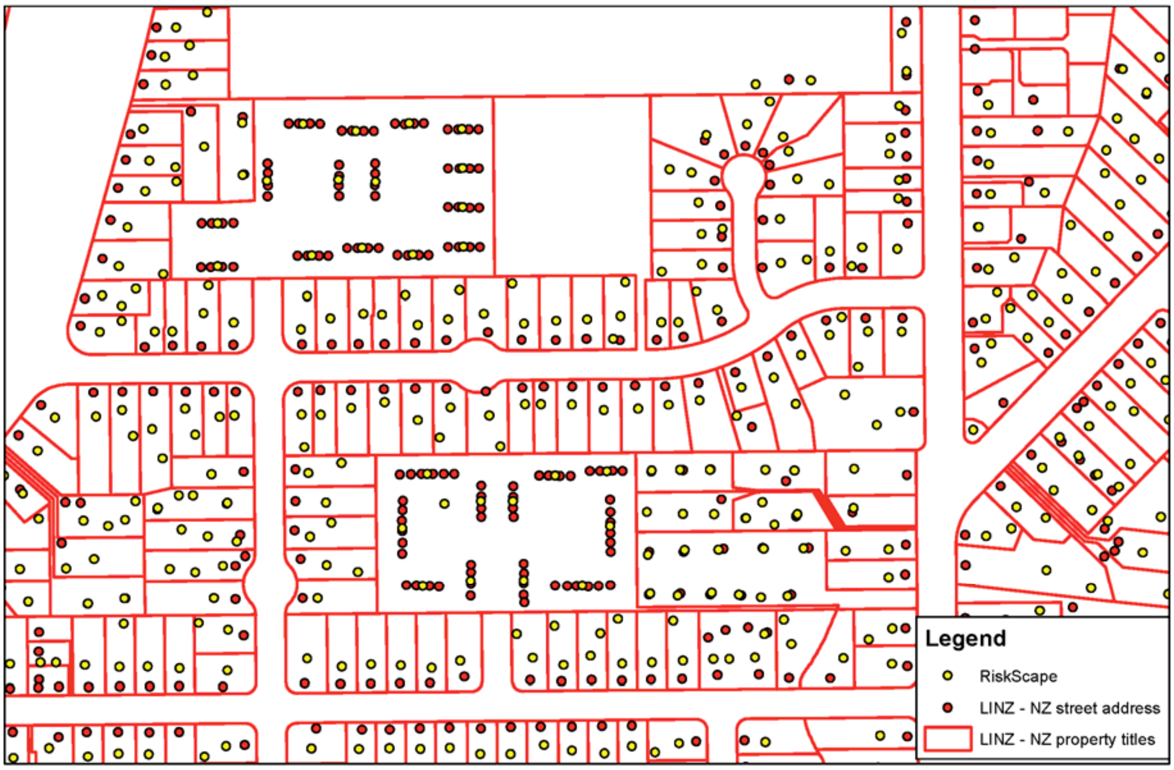


Figure 1: Map extract showing LINZ property titles (red polygons), LINZ street address (red dots), and RiskScape buildings (yellow dots)

3.2. Preparation of EQC claim database and addition of attributes using GIS

The original version of EQC claim database is claim centric, meaning that each row entails one claim only. However, a property may have experienced damage during multiple events throughout the CES. Thus, it is necessary to transform the database to a property centric layout. The new layout facilitates the understanding of the number of events which affected each property, and enable mapping of necessary information on the seismic demand, liquefaction and soil conditions for a considered event. Figure 2 presents a map showing the GeoNet strong motion recording stations location and the extent of liquefaction occurance during the 22 February 2011 earthquake [26,27].



 

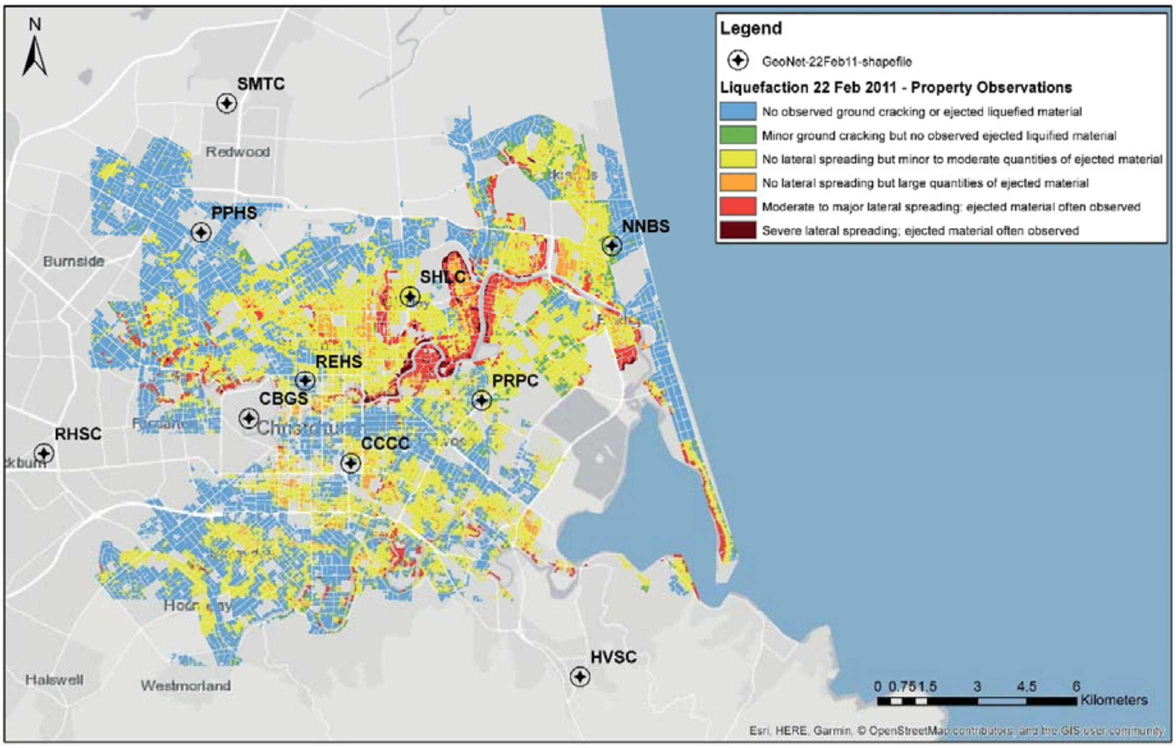


Figure 2: Map of Christchurch with the GeoNet station locations and the liquefaction occurrence for the 22 February 2011

Figure 3 gives an overview of the datasets that were added on top of the EQC residential claim database. The RiskScape database [24] delivers key buildings characteristics such as the material of the structural elements, wall and roof cladding, year of construction, total floor area and deprivation index. The seismic demand expressed via the PGA is interpolated from measurements recorded at the GeoNet stations [28]. The Christchurch City Soil Map from Land Resource Information Systems (LRIS) [29] delivers technical information on the type of soil present in the different areas of Christchurch [30]. Finally, the Canterbury maps on liquefaction susceptibility [27] and the maps on liquefaction and lateral spreading observation from the New Zealand Geotechnical Database (NZGD) website [26] provided information on liquefaction occurance and the extent of ejected material and lateral spreading observed after the 4 September 2010, 22 February 2011 and 13 June 2011 earthquakes.

### 3.3. Feature engineering

#### 3.3.1. Creation of a target feature: building loss ratio

Similarly to the BDR proposed by Rogers et al. (2015), it has been decided to create a building loss ratio (BLR) by normalising the losses by the dwelling value. The target feature is independent of the initial value of the residential property and the extent of damage can be adequately compared.



 

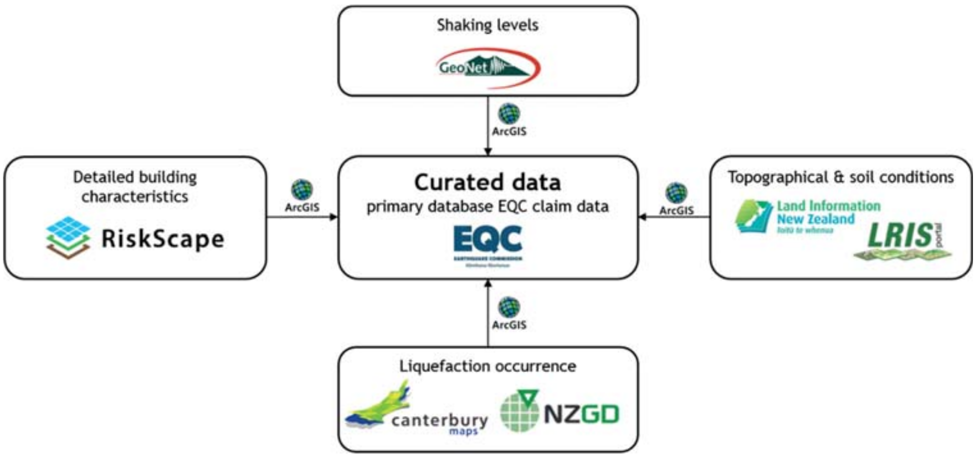


Figure 3: Curated EQC database with additional information

3.3.2.Handling missing values

Before fitting a machine learning model to a dataset it is necessary to "clean" the data and to remove any instance with missing value as many of the machine learning algorithms are unable to make predictions with missing features [7].

3.4. Merged dataset

Figure 4 summarises the information that was added to each property on top of the EQC residential claim database. It shows variables added on an extract of the EQC claim dataset from the 22 February 2011 earthquake event. The presented dataset contains 29 variables related to the building location, losses, building characteristics, seismic demand, land condition, and soil. Detailed information on the added features can be found in Table 2.

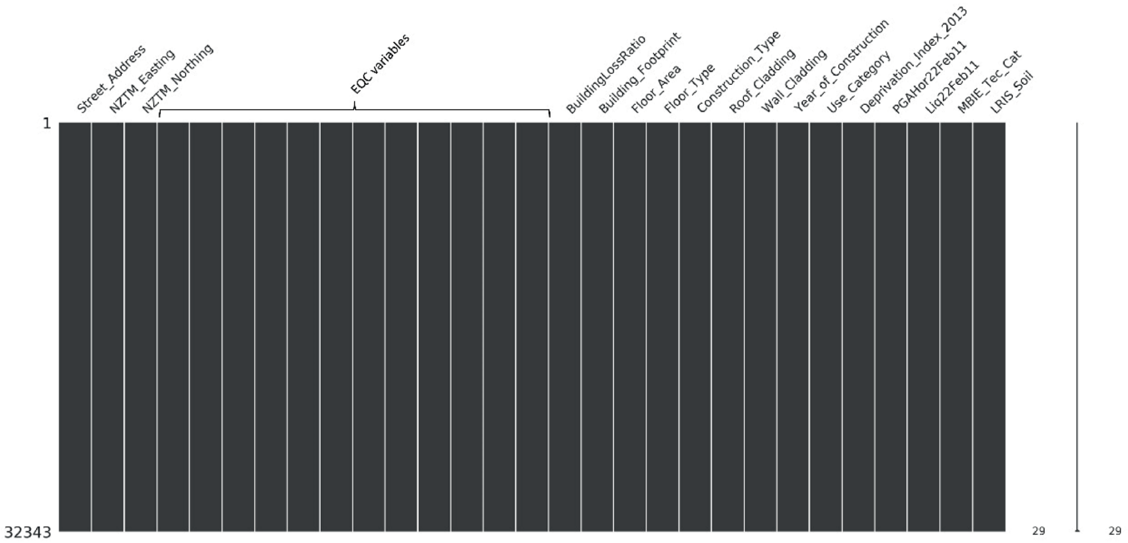


Figure 4: Graphical overview of a processed dataset for the Christchurch earthquake. Each column represent a variable and each row a property

Table 2: Feature added on top of the EQC residential claim database

| FEATURE NAME | FEATURE DESCRIPTION | SOURCE |
|---|---|---|
| **Street_Address** | Building street address | LINZ Data Service – NZ Street Address [31] |
| **NZTM_Easting** | Building coordinates (longitude) | RiskScape [24] |
| **NZTM_Northing** | Building coordinates (latitude) | RiskScape [24] |
| **BuildingLossRatio** | Building losses normalised by the modelled dwelling value | Calculated based on EQC variables |
| **Building_Footprint** | Footprint area of the building | RiskScape [24] |
| **Floor_Area** | Total floor area of the building | RiskScape [24] |
| **Floor_Type** | Timber or concrete slab | RiskScape [24] |
| **Construction_Type** | Structural system (e.g. RC shear wall, light timber) | RiskScape [24] |
| **Roof_Cladding** | Material of roof cladding (e.g. clay/concrete tile, metal tile) | RiskScape [24] |
| **Wall_Cladding** | Material of wall cladding (e.g. weatherboard, brick) | RiskScape [24] |
| **Year_of_Construction** | Building year (from 1800 onwards) | RiskScape [24] |
| **Use_Category** | Primary use of the building (e.g. residential dwelling) | RiskScape [24] |
| **Deprivation_Index_2013** | The deprivation index combines census data relating to income, home ownership, employment, qualifications, family structure, housing, access to transport and communications [32]. | RiskScape [24] |
| **PGAHor22Feb11** | PGA interpolated from GeoNet strong motion records of 22 February 2011 event | GeoNet [28] |
| **Liq22Feb11** | Liquefaction occurrence for the 22 February 2011 | NZGD [26] |
| **MBIE_Tec_Cat** | Residential technical categories [33] | NZGD [26] |
| **LRIS_Soil** | Soil type from the soil map for Christchurch City [30] | LRIS [29] |

## 4. Conclusion

This paper described the necessary data preparation for developing a machine learning model for the hindcasting of seismic loss from residential buildings in Christchurch. A method to merge the RiskScape building information with the EQC claims database was developed. The final technique involved utilises the LINZ property titles and street address as an intermediary. The GIS-based approached also enabled detailed information related to seismic demand, liquefaction occurrence, subsoil condition and other social-economical factors to be included in the machine learning model.



 

## 5. Acknowledgements

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