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Seismic vulnerability and inventory of at-risk elements in the wine industry: Auckland region case study

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ABSTRACT

Seismic vulnerability is a major threat to New Zealand's winery industry. Many studies have assessed the vulnerability of New Zealand wineries, especially in high seismic regions. However, few studies have been conducted to assess the earthquake susceptibility of wineries in low seismic regions, such as Auckland. This study investigated the earthquake vulnerability of wineries in the Auckland region by (i) creating an inventory of the elements at risk in the wineries and (ii) assessing the level of vulnerability of these elements. As case studies, twenty-one wineries from various parts of the Auckland region were chosen. The research findings identified key elements at risk of seismic hazard in Auckland wineries using a field survey, including buildings, storage tanks, catwalks, and barrel racks. Furthermore, the findings revealed that at-risk elements are vulnerable to moderate to high levels, emphasising the need for resilience strategies to reduce potential earthquake losses. This study concluded that low seismic risk does not imply low vulnerability, and that Auckland winery owners should reconsider their views on seismic risk mitigation. The study's findings benefit both winery owners and industry professionals by providing insights into the Auckland winery's vulnerability level and recommending approaches to improving the winery's organisational resilience.

1. Introduction

The wine industry is one of New Zealand's fastest-growing primary economic activities, worth approximately $1.95 billion and occupying 42,000 ha of productive land [27]. The wine industry in New Zealand accounts for approximately 3 % of total exports [25] and supports at least 16,500 jobs [1,8] as well as tourism benefits [4,11]. Seismic vulnerability poses a significant threat to New Zealand's wine industry, which is the country's sixth-largest export industry [7]. Earthquakes have devastated New Zealand's wine-producing regions on the upper South Island in the last decade. Previous ground motions have caused a variety of problems for wineries, including equipment failure, wine tank damage, and structural damage to buildings. These damages have contributed to longer-term issues with market access, consumer p, and tourist preferences. As a result, it is critical to strengthen the wine industries' seismic resilience [5].

Recent earthquakes in New Zealand, such as the 2010/11 Christchurch and 2013 Seddon, as well as the 2016 Kaikura earthquake (Mw, 7.8), sparked a series of research studies to investigate the vulnerability of elements in wineries (e.g., see [11,5,24,33,10]). Researchers have concentrated on high seismic-risk areas in order to improve wineries' seismic resilience. On the other hand, limited seismic evaluation programmes have been carried out in low seismic-risk areas such as Auckland. There are approximately 744 wineries in New Zealand, with 332 on the North Island and 98 in Auckland [26]. With a total of 285 ha of wine production, Auckland is one of New Zealand's most important wine regions [27]. The region is home to some of New Zealand's oldest established vineyards, and a moderate earthquake could cause significant economic losses for the region's wineries. Despite being a low seismic area, Auckland is located 300 km from the nearest high seismic activity zone (Tonga-Kermadec). On June 23, 1891, a magnitude 6 earthquake struck the Waikato River mouth, 50 km from Auckland [2]. Following the Waikato River earthquake, post-field observations revealed minor chimney damage [2]. Due to the severity of the earthquake, the damage may be minor, implying that a larger magnitude earthquake could be devastating, particularly for wineries. Therefore, it

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is critical to investigate and assess their earthquake susceptibility to ensure that the wineries in Auckland are resilient.

The country's trade-oriented agricultural economy is already highly vulnerable to climate change and extreme weather, as evidenced by the impact of floods and droughts on GDP and rural development. Climate change has received a lot of attention in recent years, including its effects and implications for wine-growing regions [3], perceptions and awareness of climate change, and its adaptation in the industry (e.g., [15,23,32]). So far, only a limited fraction of resilience research has been conducted in wineries, particularly those in low seismic-risk areas. As a result, the purpose of this study is to (i) identify and inventory the elements at risk in wineries in the Auckland region, and (ii) assess the level of vulnerability of the identified elements. This study aims to develop an extensive inventory of vulnerable components in Auckland wine region, encompassing structures such as buildings, storage tanks, catwalks, and barrel racks. The scope of this assessment extends beyond mere documentation of earthquake damage in the past. Instead, it aims to systematically evaluate vulnerability levels of each element by considering significant criteria such as year of construction, material composition, and overall condition. This novel vulnerability assessment has the potential to serve as a paradigm for future research conducted in wineries with low seismic risk. In contrast to other investigations which mostly focused on winery vulnerability in earthquake-prone regions such as Marlborough, this study offers novel perspectives on vulnerability within a low seismic risk area. The remainder of the paper is organised as follows: The following section provides a review of previous studies, such as those conducted by Dizhur et al. [11], Morris et al. [24], and Rosewitz and Kahanek [33], focusing on high seismic risk regions. Section 3 included information on winery damage caused by previous earthquakes. Simultaneously, at-risk elements were introduced based on a review of the seismic performance of the winery elements in the literature. Section 4 discussed the materials and methods of data collection and analysis, while Section 5 described the findings. Section 6 highlighted the implications of the findings, and the final section concluded the study.

2. Literature review: damage to winemakers' facilities due to past earthquakes

2.1. Global view

Earthquakes have a global impact on the wine industry. For example, the 1980 Greenville Earthquake (California, USA, M_w 5.8) [28] showed a major fracture in wine tanks in the wineries. During this earthquake, 100 wine tanks from the Wente Brothers winery in Livermore were damaged, mainly due to buckling failure mode. Two wineries were greatly affected during the 1984 Morgan Hill Earthquake (California, USA, Mw 6.2), leaving one of the wineries broken-down [19]. Five years later, the California wine industry was devastated by the 1989 Loma Prieta Earthquake (California, USA, M_w 7.1) (The Earthquake Engineering [12]. The 2010 Maule (Chile, M_w 8.8) earthquake struck Chile's largest wine-producing region [18], destroying about 125 million litres of wine and costing the industry $250 million (Gossi et al., 2011). Investigations into the Maule earthquake in Chile have shown serious damage, primarily in storage tanks and secondary damage in barrels (Gossi et al., 2011). More than 25 % of cylindrical wine tanks lost all or part of their contents during the Maule earthquake. The 2014 Napa Valley (North San Francisco, USA, M_w 6) [14] earthquake caused major damage to the wineries. Post-field observations following the Napa Valley ground movement showed different types of failures for the cylindrical steel wine tanks, including the buckling of the tank walls, failure of the anchorage and damage to the top of the tanks. Winery owners have identified barrel racks and buildings as secondary major damaged elements in wineries [18]; The Earthquake Engineering [12]. In the aftermath of the May 2012 earthquake in Italy (Emilia, Italy, M_w 6.1), extensive damage to wine tanks was also observed. Following the 2003 San Simeon (Central Coast of California, USA, M_w 6.6) earthquake [21], minor non-structural damage to buildings and barrel racks was identified [22]. Seismic events such as the San Simeon earthquake of 2003 [21], the Napa Valley earthquake of 2014 [14], the Emilia earthquake of 2012 [6] and the Maule earthquake of 2010 [18] have all caused similar damage to wineries.

2.2. Earthquakes in New Zealand

Marlborough region has experienced several significant earthquakes in recent years, including the Cook Strait earthquake of 21 July 2013 (New Zealand, M_w 6.6) and the Lake Grassmere earthquake of 26 August 2013 (New Zealand, M_w 6.6). The performance of wine storage tanks before the 2013 earthquakes is well documented by Morris et al. [24], Rosewitz and Kahanek [33] and Au et al. [1]. For instance, Morris et al. [24] confirmed damage to the Marlborough region following the Lake Grassmere earthquake of 2013. Their observation revealed significant damage to wine storage tanks, with limited damage to the associated infrastructure. Observed damage to cylindrical stainless tanks involved buckling of tank walls' failure of the anchorage, and damage near the top of tanks where the catwalk supports were attached. As a result, many storage tanks were either replaced or retrofitted following the earthquakes of 2013.

The Kaikoura earthquake of 2016 impacted the New Zealand wine industry, causing widespread damage. Approximately 5.3 million litres of wine were lost, and 20 % of the storage tanks were damaged; damage was also noted in vineyards, buildings, barrel racks and catwalks [11]. Storage tanks displayed significantly more damage than buildings, mostly due to buckling and fracturing of the tank wall, causing environmental damage [11]. Likewise, barrel racks collapsed due to unstable and traditional design method [11]. Catwalks were often damaged due to the movement of storage tanks [11]. Buildings in the wineries of Marlborough range from restaurants to administrative and storage [33]. These buildings were predominantly concrete and showed only minor damage, such as cracking [11]. The effects of the Kaikoura earthquake, including damage to the elements of the winery and loss of wine, have led to studies such as the study conducted by Dizhur et al. [11] on the seismic vulnerability of high-risk major wine regions. Several international studies have analysed the elements that failed during earthquakes and suggested probable causes of earthquake failure. Commonly failed elements included storage tanks, catwalk structures, barrel storage racks and buildings [18].

3. Common winemaker structures and equipment

3.1. Buildings

Buildings are the most important element in a winery because they are a kind of shelter for the other elements. Zareian et al. [38] noted that most winery buildings destroyed by earthquakes are old structures, with damage typically seen in walls, roofs, and ribbed brick vaults. Newer buildings, built to be seismically resistant, performed significantly better when exposed to earthquake lateral forces [34]. Unreinforced buildings have been identified as having the most damage during seismic events, highlighting the significance of reinforcement in the buildings [17]. Dizhur et al. [11] also observed that well-maintained buildings performed better than unmaintained buildings. Concrete buildings are common in Marlborough, and the damage caused by the earthquake in 2016 was similar to the earthquake in Canterbury in 2010/11 [11]. Limited structural damage was observed, with minor damage to panel connections and fixtures [11] after the Marlborough earthquake. Similarly, cracking to the exterior of the building and falling ceiling tiles was the limit to the damages seen as a result of the earthquake in Kaikoura [11].

3.2. Storage tanks

Compared to other winery structures, storage tanks typically experience higher levels of failure during earthquakes [11]). While steel tanks are preferred in the wine industry, they are more prone to earthquakes than concrete tanks [20]. Plinth-mounted and legged tanks are two types of tanks with different methods of failure [16,33]. The type and capacity of the tank are important factors when determining vulnerability. Sometimes the tank's design is a 'weak link' in the failure of the wine tanks [11]. Plinth-mounted tanks (see Fig. 1a) with 60,00–300,000 L capacities are installed on a concrete base [24]. Plinth tanks suffer damage to anchorage systems, walls, skirts, and connection points, while the most common damage to the plinth tanks is anchor failure. Leg-mounted tanks (see Fig. 1. b) typically have a capacity of 5,000–60,000 L and are generally supported by a frame system [24]. The performance of the leg-supported tanks showed that these tanks sustained damage to the legs, tank skirt, bracing, roof and storage systems. According to Dizhur et al. [11], the extent of damage sustained in storage tanks depends on the size and design of the tank.

3.3. Catwalks

Catwalks (Fig. 2) are access systems easily damaged by their connection to the storage tanks [24]. Determining the vulnerability and level of damage depends on whether the tank supports the catwalks (see Fig. 2a) or self-supported (see Fig. 2b) [11]. Self-supported catwalks showed almost no signs of damage, only minor denting during the past earthquakes [33]. On the other hand, Tank-supported catwalks showed large amounts of damage, especially in systems where no movement was made between the connection points of the tank and the catwalk [33]. Catwalks are directly linked to storage tanks, and damage to one of these elements usually damages the other [11]. As catwalks are expected to be designed by an engineer and have the approval to build, it is unlikely they will be used in smaller wineries.

3.4. Barrel-racks

Barrel racks store large amounts of wine and as such, they need to be well suited well-suited activity. Racks are usually unanchored and assisted by a gravity [11]. The Maule earthquake of 2010 caused significant damage to the barrel racks, as did the 2014 Napa earthquake [19]. It is important to prevent the failure of the barrel rack because it can lead to damage to barrels, loss of wine and a potential safety hazard [24]. Barrel racks, which stack four barrels instead of two, perform significantly better during earthquakes, as observed during the 2014 South Napa earthquake [17]. Occasionally, wooden rails are used to store barrels and perform the same function as the old steel rack, as described by Dizhur et al. [11], which implies that wooden and old steel rack systems have limited seismic resilience. New structural design standards for barrel racks have recently been introduced in New Zealand, resulting in a more robust rack design [11]. The performance of the old and new storage rack design was observed in the Kaikoura earthquake of 2016, where the older design system (see Fig. 3a) experienced failure. In contrast, the newer rack system, a kind of seismic reinforced design (Fig. 3b), experienced only limited movement [11].

4. Methods and materials

The purpose of this research is to create an inventory of the elements at risk and assess their risk level in Auckland wineries. The case study method is thought to be useful for understanding a research problem within a specific context or location [37]. To achieve the study's aim, a case study method was used, and Auckland, New Zealand was selected. There are 98 wineries in the Auckland region alone [26], implying that studying all of the wineries in Auckland would be nearly impossible. As a result, a sample of wineries was chosen for this study. Sampling is a practical method of collecting data and ensuring that it is representative of the population [13]. In this study, a random sampling method was used to ensure that the cases chosen were representative of the population and that the research results could be generalised. In this study, 21 wineries in Auckland were chosen at random as case studies. These wineries can be found on Waiheke Island, in West Auckland, and in Matakana. Due to the winery organisations' participation and the research's time constraints, twenty-one wineries were included in this study.

4.1. Data collection and analysis method

Field surveys, including on-site visits and observations, were used to collect data from the twenty-one randomly selected wineries. The inventory includes the industry's buildings, infrastructure, land, and business operational mechanisms. The winery Association, the wineries, and the Auckland City Council provided publicly available information to help create the inventory. A questionnaire was also used to collect data to supplement the information gathered during the on-site screening procedure. The questionnaire included demographic questions that provided information about the wineries' organisational characteristics.

The twenty-one wineries selected for the study were contacted and asked to participate. After they agreed, a time was set aside to visit the

(a) Tanks on concrete plinth	(b) Leg-supported tanks

Fig. 1. Two different tank types.

(a) Tank supported catwalks (b) Self-supported catwalks

Fig. 2. Catwalk types commonly used in the wineries.

(a) Older racking system (Dizhur et al., 2015) (b) New generation racking system (Dizhur et al., 2015)

Fig. 3. Two generation of racking system.

winery and conduct the field survey. This included interviewing the participant (organisational representative), taking notes and photos, and visually inspecting the winery's elements. By coding the identification of each winery and the participants, confidentiality and anonymity were maintained throughout the study. The collected data were compiled for analysis and are detailed in the following section.

4.2. Vulnerability assessment and data analysis

Table 1 summarises the vulnerability of elements at risk in wineries using parameters established in the existing literature. Each winery element's vulnerability was assessed using a 5-point Likert rating scale (5 = very low, 4 = low, 3 = moderate, 2 = high, and 1 = very high). This rating scale was piloted by seismic risk assessment experts in the industry. The vulnerability level of the wineries' buildings was determined by adding the assigned ratings and the average score.

The field survey data were analysed using descriptive statistics, which are frequently used in conjunction with quantitative approaches [35]. The descriptive method was used to present and describe the field survey results. The findings were presented graphically, with the key findings illustrated in charts such as tables and figures. The inventory was updated with the results of the analysis. The level of vulnerability was identified and reported in Section 5 based on the key elements.

4.3. Summary of winery organisations

Table 2 summarises the characteristics of the twenty-one randomly selected wineries. For the sake of confidentiality and anonymity, each winery was assigned a code number. Of the selected wineries, 71 % are privately owned, while 29 % are limited liability companies. The wineries were divided into two groups based on their organisational size: small (81 %) and large (9.5 %). Two wineries (9.5 %) politely declined to provide this information. The annual staff turnover for 43 % of the wineries was between 0 and 5 %, indicating a degree of stability and a high level of staff retention. Only 9.5 % of the wineries (04 and 07) had a high annual staff turnover rate (greater than 41 %). Annual staff turnover ranged from 6 to 20 % for 14 % of the wineries, with 33.5 % declining to disclose pertinent information. The analysis of the participants' official designations in their organisations revealed that the majority (86 %) are senior managers, with the remaining 14 % being intermediate-level managers. The senior managers have more than 10 years of expertise inside the wine sector. This implies that they possessed a comprehensive understanding of the winery's infrastructure and susceptibilities, enabling them to offer accurate assessments. This indicates that the participants can provide reliable information for this study based on their experience. The participants' average years of industry experience varied; 19 % had 1–3 years of experience, 24 % had 4–10

Table 1
Vulnerability assessment methodology.

Elements at risk	Risk Assessment Parameters	References	Subcategories	Risk rating scale (1–5) to determinate level of vulnerability. lowest vulnerability = 5 highest vulnerability = 1
building	year built	Galloway and Ingham [16], Dizhur et al. [11] and Swan et al. [34]	after 2000	5
			between 1990 and 2000	3
			between 1980 and 1989	2
			n/a	1
	building material	Galloway and Ingham [16], Dizhur et al. [11], Onescu et al. [29] and Swan et al. [34]	concrete	5
			steel, reinforced masonry wall, timber framing	3
			timber framing	1
			steel	1
	condition	Dizhur et al. [11], Onescu et al. [30], and Onescu et al. [31]	excellent	5
			good	3
			average	2
			old	1
	seismic strengthening	Onescu et al. [31], Onescu et al. [30], Onescu et al. [29], Galloway and Ingham [16], Dizhur et al. [11] and Swan et al. [34]	yes	5
			partly	3
			no or n/a	1
	bracing	Dizhur et al. [11]	no bracing	1
			diagonal, horizontal,	5
	anchorage	Dizhur et al. [11], Galloway and Ingham [16]	yes	5
			both (yes and no)	3
			no	1
storage tanks	shape	Colombo and Almazán [9], Yazdanian et al. [36]	H > D	3
			H < D	5
			H = D	3
	capacity	Dizhur et al. [11], Yazdanian et al. [36]	0–5,000L	5
			5,000—10,000L	4.5
			11,000—20,000L	4
			21,000—40,000L	3.5
			41,000—60,000L	3
			61,000—100,000L	2.5
			101,000—150,000L	2
			151,000—200,000L	1.5
			201,000—300,000L	1
catwalks	method of support	Dizhur et al. [11]	self-supported	5
			tank-supported	2
barrel-racks	type of rack	Dizhur et al. [11]	modern	5
			traditional and modern	3
			traditional	1
			wooden rails	3

years of experience, 33 % had 11–20 years, and 24 % had over 21 years of experience. The winery and its participant makeup are typical of New Zealand's small-to-medium-sized businesses.

5. Inventory and vulnerability of elements at risk

5.1. Buildings

The number of buildings used for wine production varies between wineries. Winery 17 had the most buildings (five), while approximately 57 % of the wineries had only one. Four wineries were built before 1990, eight between 1990 and 2000, five between 2000 and 2010, and four did not want this information disclosed. This finding indicates that 81 % of the buildings in the sample population were built after seismic regulations were implemented. Despite the fact that most buildings were built to meet building code requirements, 91 % lacked seismic reinforcement. Table 3 shows that all of the wineries surveyed used reinforced concrete on their floors. Internal structural elements of various types were used throughout the wineries. Some wineries used a single internal structural element, while others used a mix of structural elements. As of the time of the visit, all of the buildings were in good condition with no visible signs of damage. Only Winery 02 has an old building with visible signs of ageing (Fig. 4). Table 3 summarises the characteristics of winery buildings surveyed in the Auckland region.

The year of construction, materials, and seismic strengthening of the buildings were all included in the final inventory to investigate building seismic vulnerability. These are the most important factors for determining the vulnerability of buildings, according to Galloway and Ingham [17], Dizhur et al. [11], and Swan et al. [34]. The buildings' condition was also considered in order to investigate their vulnerability to seismic events and to substantiate Dizhur et al.'s [11] findings that well-maintained buildings perform better during earthquakes. The vulnerability level of the buildings in the wineries was determined based on the point ratings for each element. Buildings with less than a 10 were deemed highly vulnerable. Buildings with a score between 10 and 15 were classified as moderate, while those with a score higher than 15 were classified as low. As a result, it is expected that 47 % of the buildings will fail during an earthquake. Furthermore, 10 % of the buildings are unlikely to be damaged, whereas 43 % are expected to have a fair chance of failure.

5.2. Storage tanks

In wine production, legged tanks (Fig. 5) and plinth-mounted tanks are commonly used. According to the wineries surveyed, the majority (80 %) used Legged tanks (see Fig. 6). It should be noted that winery 19's storage tank type was not disclosed. However, the majority of the tanks in the research area are housed indoors (see Fig. 7). This contradicts Rosewitz and Kahanek's [33] findings that storage tanks in the Marlborough region are mostly located outside. The shape of the storage tanks varied between wineries (Fig. 8), with slender tanks being the most common (48 %). Winery 01 used only one timber storage tank, and

Table 2
Respondent's profile.

Winery ID	Gender of participant	Age	Position within organisation	Working experience within organisation (years)	Organisation classification	Number of employees		Years that organisations have been operating	Annual staff turnover (%)
						Full time	Part time		
01	Male	31–40	Senior management	1	Privately held	1	3	21+	6–10
02	Male	61+	Senior management	21+	Privately held	2	0	21+	NA
03	Male	41–50	Senior management	4–10	Privately held	8	0	1–5	11–20
04	Male	41–50	Senior management	21+	Privately held	13	3	1–5	41+
05	Female	21–30	Supervisor	1–3	Privately held	4	4	4–9	0–5
06	Male	31–40	Middle management	4–10	Limited liability company	3	4	10–49	NA
07	Male	31–40	Senior management	1–3	Limited liability company	4	3	10–49	41+
08	Male	51–60	Senior management	11–20	Privately held	2	3	10–49	NA
09	Male	51–60	Senior management	4–10	Privately held	3	5	4–9	NA
10	Male	41–50	Senior management	11–20	Limited liability company	8	5	10–49	6–10
11	Male	51–60	Senior management	11–20	Privately held	1	0	10–49	0–5
12	Male	41–50	Senior management	11–20	Limited liability company	6	0	10–49	0–5
13	Male	41–50	Senior management	11–20	Limited liability company	5	4	10–49	0–5
14	Male	31–40	Senior management	4–10	Limited liability company	7	4	10–49	NA
15	Male	21–30	Senior management	4–10	Privately held	NA	NA	10–49	0–5
16	Male	51–60	Senior management	11–20	Privately held	2	3	10–49	NA
17	Male	61+	Senior management	21+	Privately held	75	8	21+	0–5
18	Male	61+	Senior management	21+	Privately held	30	20	21+	0–5
19	Male	31–40	Staff	1–3	Privately held	10	3	21+	0–5
20	Male	61+	Senior management	21+	Privately held	6	2	21+	0–5
21	Male	51–60	Senior management	11–20	Privately held	NA	NA	21+	NA

Table 3
Building characteristics and vulnerability assessment.

Winery ID	Condition	Seismic strengthened	Building material	Floor material	Year built	Storeys	Number of buildings	Number of occupants	Building type	Vulnerability Score	Risk level
1	good	don't know	RC		1996——2014	2	1	4	commercial	14	moderate
2	old	no	Steel	concrete	1990	1	1	5	commercial	8	high
3	good	no	Steel		1999	1	1	4	commercial	10	moderate
4	good	no	TF		1997	1	1	5	commercial	8	high
5	good	n/a	steel, RCM		n/a	2	2	7	commercial	8	high
6	good	n/a	TF		19 93	1	3	5	warehouse	8	high
7	good	no	T F		19 96	2	2	4	warehouse	8	high
8	good	yes	steel, RCM		20 05	3	1	n/a	residential	16	low
9	good	n/a	steel, RC		20 08	2	3	n/a	commercial	12	moderate
10	excellent	n/a	steel, RCM, TF		2003——2009	3	4	8	commercial	14	moderate
11	aver age	no	RC M		20 06	1	1	n/a	residential	11	moderate
12	aver age	no	Steel		19 90	1	1	n/a	warehouse	9	high
13	aver age	no	Steel		19 99	1	1	n/a	warehouse	9	high
14	go od	no	steel, RCM, TF		19 82	3	1	n/a	commercial	9	high
15	good	n/a	steel, RCM		n/a	2	2	7	commercial	8	high
16	good	yes	steel, RCM		2005	3	1	n/a	residential	16	low
17	good	no	steel, RC M, TF		1910——2000	2	5	40	commercial	10	moderate
18	good	no	steel, RC M, TF		n/a	1	1	10	commercial	8	high
19	good	no	steel, RCM, TF		1950–2000	1	3	1	n/a	10	moderate
20	good	no	RC M		1990′s	1	1	6	commercial	10	moderate
21	good	partly	RCM		n/a	1	4	40	commercial	10	moderate

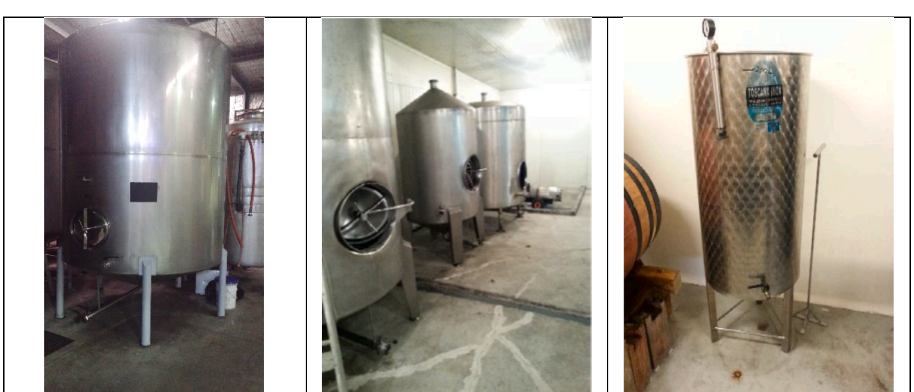
Note: TF = timber framing; RC = concrete reinforcement; RCM = reinforced masonry wall.

Fig. 4. Winery (w) 02 interior wall.

the storage tanks were mostly made of stainless steel. This is consistent with the findings of Rosewitz and Kahanek [33], who discovered that stainless steel tanks were the most commonly used in the Marlborough region. Tank capacities range from less than 5000 to more than 200,000. (Fig. 9). The pie graph (Fig. 9) shows that tanks with capacities ranging from 41,000 to 60,000 L are the most popular (21 %) in the region. Tanks with capacities of 11,000–20,000 and 21,000–40,000 L have the second highest proportion (18 %). This finding is consistent with Morris et al. [24], who found that legged tanks range in size from 5 to 60,000 L. The bracing system for the tanks was also observed. According to the findings, the most common types of bracing in wineries are non-adjustable, diagonal, and horizontal. These bracings can be used individually or in groups. In winery 03, for example, the three types of bracing were combined. Fig. 10 shows that the majority of legged tanks (83 %) lacked a bracing system. Only 17 % of the wineries used bracing in their tank designs. Tank legs of various materials, including wood, plastic, and steel, were seen in the wineries.

Fig. 11 shows that 57 % of the tanks in the wineries were inspected more than once a year. Following that, the installation period of the storage tank was determined. Fig. 12 shows how many years have passed since the storage tanks were installed. According to the data, eight wineries installed their storage tanks between 11 and 20 years ago, five wineries installed them more than 20 years ago, four wineries installed them between six and ten years ago, and three wineries installed them less than five years ago. Only one winery installed a storage tank in the last few years. According to the findings, most wineries installed their storage tanks around the time they opened for business. One of the wineries had a storage tank with a flat bottom and base plates. Base plates are used to secure storage tanks to the ground, usually on a concrete plinth. Except for one (winery 06), which had a few tanks on the base plate, none of the wineries secured the tank base plates to the ground. The flat-based tanks at Winery 06 typically had four points of attachment to the storage tanks. According to Dizhur et al. [11], the bracing method, anchorage, shape, and capacity are the most important factors to consider when determining the vulnerability of storage tanks. As a result, this information was included in the final inventory.

The bracing method, anchorage, shape, and capacity were used to assess the vulnerability of legged storage tanks. Minor damages to the walls, base, and legs of storage tanks were observed and documented. Buckling of the tank legs is a common damage for legged tanks. The severity of the damage would be determined by whether the legs are anchored or unanchored to the ground. According to recent research, unanchored legged tanks displace during seismic movements, whereas anchored tanks buckle to the point of failure and overturn due to insufficient bracing. The vulnerability of legged tanks in wineries is increased by a lack of bracing. Anchorage, shape, and size were also used to evaluate plinth-mounted tanks (see Table 4). As per Dizhur et al. [11], a lack of anchorage increases vulnerability in plinth-mounted tanks. According to Colombo and Almazán [9], larger capacity tanks are more vulnerable. The anchorage system used for storage tanks may have an impact on the tanks' seismic performance. Unanchored tanks, according to Galloway and Ingham [17], can move freely, improving the resilience of these wineries. As shown by Dizhur et al. [11], vulnerability is frequently determined by tank shape, anchorage system, and capacity. Yazdanian et al. [36] demonstrated that broad (wide) tanks are more seismically resilient than slender tanks against overturning and base sliding failure modes. According to the vulnerability assessments, it is estimated that 71 % of the storage tanks would tolerate various types of



(a) W03 (b) W02 (c) W04

Fig. 5. Slender and small legged tanks used in wineries (W).

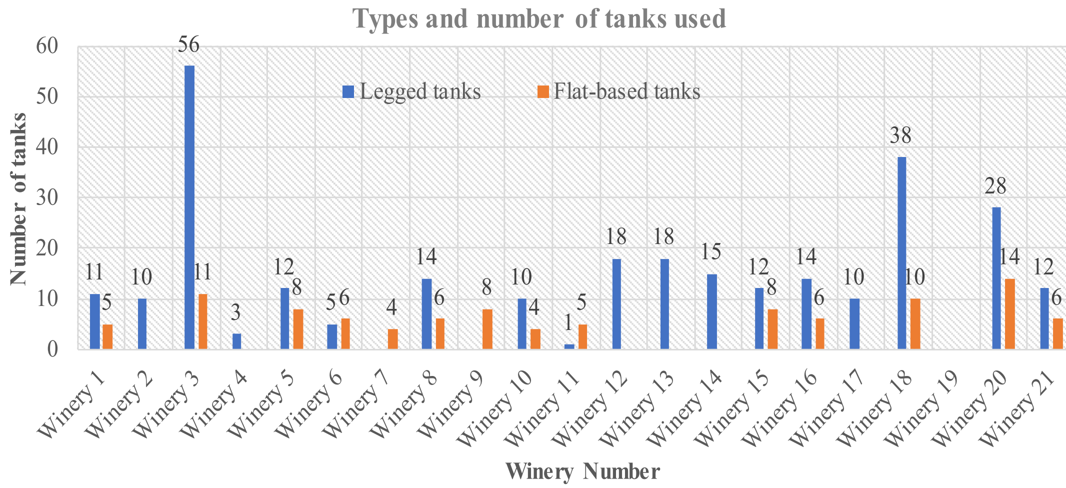


Fig. 6. Type of storage tank used in wineries.

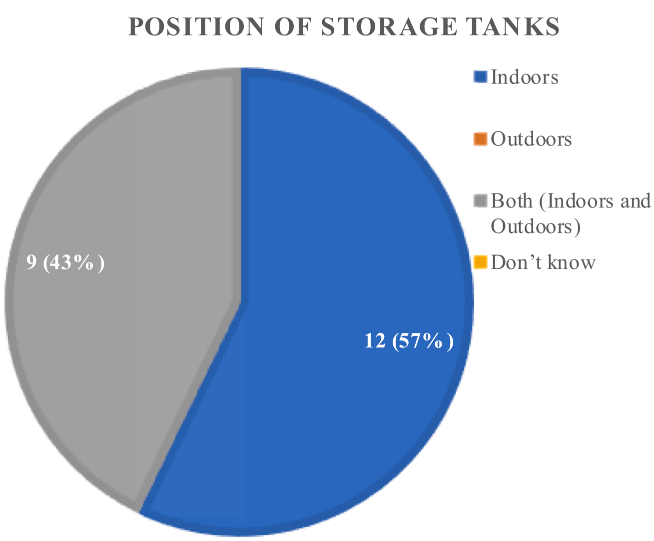


Fig. 7. Position of storage tanks.

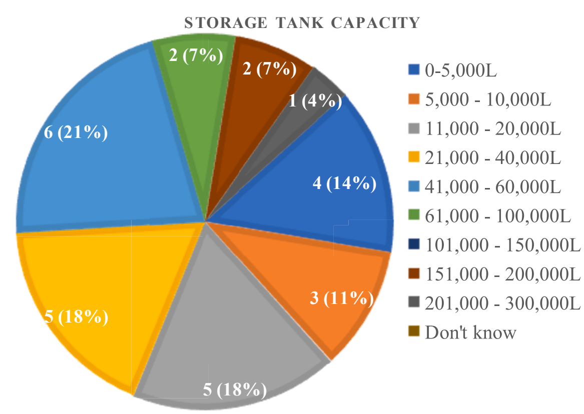


Fig. 9. Storage tank capacity.

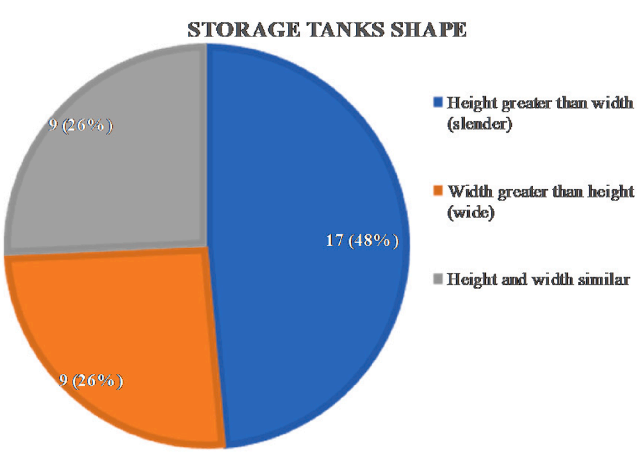


Fig. 8. Storage tank shape.

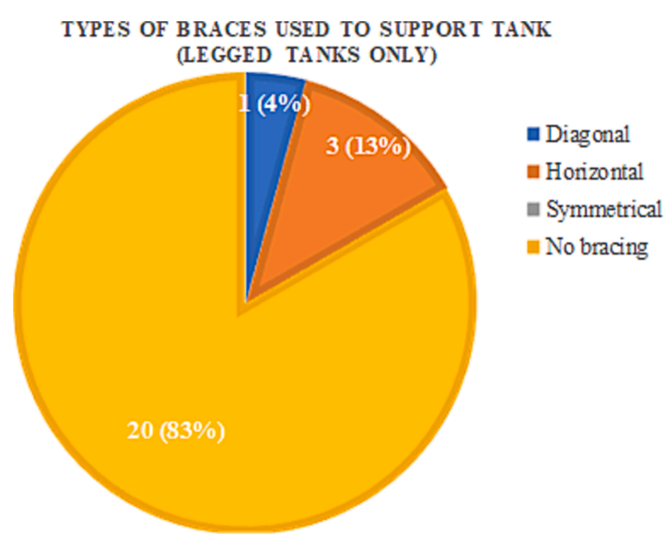


Fig. 10. Type of braces used for the legged tanks.

failures due to their high earthquake risk level. It is worth noting that the remaining wine tanks (29 %) may experience minor failure, demonstrating that wine tanks are the most vulnerable element in wineries. This is consistent with the findings of Dizhur et al. [11] as well as Colombo and Almazán [9].

5.3. Catwalks

Table 5 summarises the characteristics and level of vulnerability of

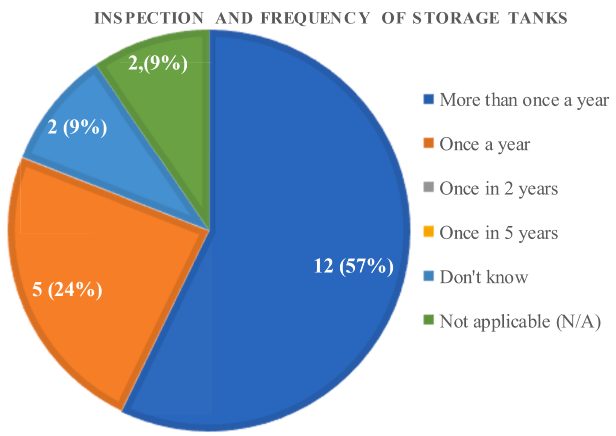


Fig. 11. Inspection and frequency of tanks.

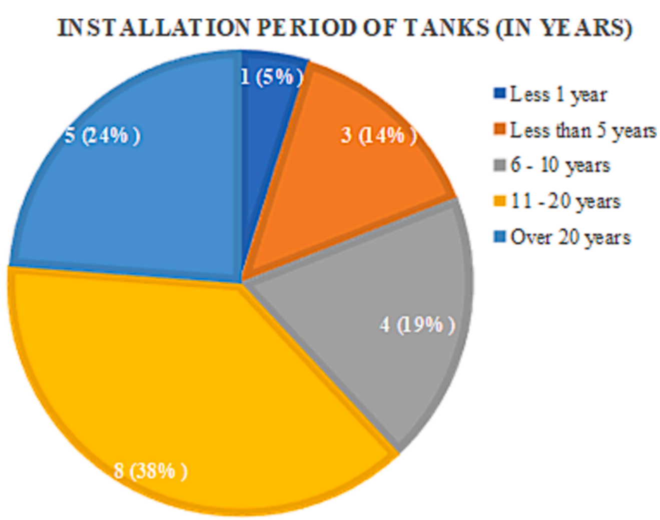


Fig. 12. Installation period of tanks.

the catwalks. Catwalks are used by more than half of the wineries surveyed (52 %). In terms of catwalk support methods, the results show that 50 % of the catwalks were self-supported and 50 % were tank-supported. Catwalks are commonly made of wood and galvanised steel, as shown in Figs. 13 and 14. Some wineries did not use a catwalk system. Instead, they used ladders to reach the tanks' top (Fig. 15). This method is more dangerous, increasing the likelihood of falls and tank damage, as evidenced by the owner's recent damage during drainage. Table 5 shows that only two of the 11 wineries with catwalks had long catwalks (11–15 m in length). Other wineries' catwalks were less than 11 m long, ranging from one to ten metres. Seven wineries had catwalks ranging in width from 0.6 m to 1 m, while two had catwalks ranging in width from 1.1 to 1.5 m. The inspection frequency results show that 45 % of the 11 wineries inspect the catwalk once a year. According to Galloway and Ingham [17], the most important factor determining the vulnerability of the catwalk is metsupport methods. As a result, data obtained for the support method were recorded as part of the final inventory.

The extent of damage is determined by the method of support, according to Dizhur et al. [11]. As a result, the metsupport method was used to assess the vulnerability of the catwalks. Self-supported catwalks are more seismically resilient than tank-supported catwalks. Damage to catwalks was typically caused by tank-supported systems, including damage to the plates welded to the sides of the tank's wall. Concerning the vulnerability assessment for the catwalks, it is challenging to determine the precise level of vulnerability because 48 % of the wineries did not disclose the information. However, based on the analyses of the remaining 52 %, it is expected that at least half of the catwalks in the wineries would not fail during an earthquake.

5.4. Barrel racks

Steel racks (traditional and modern) and wooden rails were used in wineries for barrel storage. Interestingly, traditional rack rails were used by the majority of wineries, accounting for 64 % of all racks in the studied region. At 32 %, the use of modern racks was the second highest. This is consistent with the findings of Dizhur et al. [11], who discovered that traditional steel racks were in use in Marlborough wineries. Barrels were typically stored in a single or double layer (see Fig. 16), with the exception of winery 03, where three barrel racks were stacked vertically (see Fig. 17). It should be noted that the barrel racks were not anchored to the ground, confirming the findings of Dizhur et al [11]. Five wineries stated that they have a once-a-year inspection for their barrel racks, while 14 wineries stated that they have more than once-a-year inspections. Notably, during the site visit, winery 21 did not use any barrel racks. Furthermore, one of the wineries did not want to reveal the frequency of inspections. Because the type of barrel rack is important in determining vulnerability, this information was recorded in the final inventory to estimate the vulnerability.

The last winery element identified was the barrel stacking systems. Table 6 summarises the barrel rack characteristics. The barrels were mostly stacked on their sides, with only a few standalone barrels stacked upright. Traditional storage racks and wooden barrel wedges were the most commonly used systems for barrels stacked on sides. None of these barrel systems were securely fastened to the ground. Traditional storage racks ranged in size from one to two metres and were made of welded steel and could hold up to two barrels per rack. The wooden wedges used were not as large as a door wedge. As they were portable, wooden barrel wedges were widely used in most wineries.

Furthermore, this system was thought to be practical for storing barrels in underground cellars. According to the research findings, the height of these racks used in wineries could stack up to five barrels, not exceeding the maximum stacking height of six. This system poses a risk to wineries because it collapsed during the 2016 Kaikoura earthquake due to insufficient structural performance to seismic movements [11]. Depending on the maximum number of barrels lining up next to each other, the toppling effect caused by the collapse of traditional racks can be considered a high risk. During an earthquake, placing barrel racks closely next to each other in a long row can cause a domino effect, posing a risk to neighbouring barrels, life safety, and other winery elements. According to Dizhur et al. [11], the type of rack used determines vulnerability. The old steel barrel rack is less stable than the new design and has a history of toppling during earthquakes [11,16], indicating high vulnerability. The barrel racks were unanchored, and gravity loaded, which was consistent with the findings of Dizhur et al. [11].

5.5. Economic loss analysis

Damage or interruption to company operations caused by risks such as natural disasters can have a significant economic impact, which can be quantified using economic loss analysis. It gives numerical estimates of monetary losses due to lost productivity, increased prices, and other indirect causes. Typical methods include econometric studies measuring links between risks and economic factors, computable general equilibrium models exposing market and price changes, and input–output modelling to capture supply chain propagations (Rose and Liao, 2005). Losses in productivity, sales, jobs, taxes, and GDP growth at the company, industry, and regional levels are only some of the output measures calculated by economic loss analysis. It's an essential part of any thorough evaluation of risk. The data provides the foundation for making decisions based on facts, improving the effectiveness of risk mitigation techniques and financial safeguards for vulnerable organisations and

Table 4
Storage tank vulnerability assessment.

Winery ID	Bracing	Anchorage	Shape	Capacity	Vulnerability score	Risk level
01	no	no	H > D, H < D	Less than 2000L	10	moderate
02	no	no	H > D	21,000–40,000L	6.5	high
03	un-adjustable, diagonal, horizontal	no	H > D, H < D, H = D	5,000–10,000L	13.5	moderate
04	no	no	H > D	Less than 2000L	8	high
05	no	no	H > D, H < D	41,000–60,000L	8	high
06	no	yes and no	H < D, H = D	11,000–20,000	12	moderate
07	no	no	H = D	5,000–10,000L	9.5	high
08	no	no	H > D, H < D, H = D	61,000–100,000	7.5	high
09	no	no	H < D	21,000–40,000L	10.5	moderate
10	no	no	H = D	41,000–60,000L	8	high
11	no	no	H > D, H = D	11,000–20,000	8	high
12	no	no	H > D	41,000–60,000L	6	high
13	no	no	H > D	41,000–60,000L	6	high
14	diagonal	no	H > D	41,000–60,000L	10	moderate
15	no	no	H > D, H < D	41,000–60,000L	8	high
16	no	no	H > D, H < D, H = D	61,000–100,000	7.5	high
17	no	no	H > D	11,000–20,000	7	high
18	no	no	H > D	11,000–20,000	7	high
19	un-adjustable, diagonal, horizontal	no	H > D	21,000–40,000L	10.5	moderate
20	no	no	H > D	5,000–10,000	7.5	high
21	adjustable, diagonal, horizontal	no	H > D	5,000–10,000 151,000–200,000 201,000–300,000	9.3	high

Table 5
Catwalk characteristics and vulnerability assessment.

Winery ID	Length (m)	Width (m)	Height (m)	Support	Material	Inspection frequency	Vulnerability score	Risk level
01	11–15	0.6–1	1.1–1.5	self-supported	timber, galvanised steel	n/a	5	low
02	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
03	11–15	0.6–1	4	self-supported	stainless-steel	more than once a year	5	low
04	6–10	0.6–1	0.6–1	self-supported	timber	once a year	5	low
05	1–5	1.1–1.5	3	self-supported	lightweight steel	n/a	5	low
06	1–5	0.6–1	2.1–2.5	tank-supported	lightweight steel	more than once a year	1	high
07	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
08	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
09	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
10	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
11	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
13	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
15	1–5	1.1–1.5	3	self-supported	lightweight steel	n/a	5	low
16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
17	1–5	0.6–1	2.1–2.5	tank-supported	stainless-steel	once a year	1	high
18	1–5	0.6–1	1.6–2	tank-supported	timber	once a year	1	high
19	1–5	0.6–1	3	self-supported	stainless-steel, timber	n/a	5	low
20	less than 1	less than 0.5	2.1–2.5	tank-supported	mild steel	once a year	1	high
21	1–5, 6–10	0.6–1	2.1–2.5	tank-supported	stainless-steel	once a year	1	high

communities.

This study assessed 21 wineries located in the Auckland area of New Zealand. According to the seismic vulnerability assessment, it was determined that around 71 % of storage tanks were deemed to possess a high risk of failure. The mean storage tank capacity within the specified region ranges from 41,000 to 60,000 L. Based on an estimated average loss of 50,000 L per tank, it may be inferred that the collective quantity of wine lost due to damaged tanks may amount to around 745,500 L (i. e., 71 % of 21 wineries × 50,000 L average loss per tank).

Based on the average retail price of $15 per litre for New Zealand wine, it may be estimated that the potential income loss resulting from damaged tanks amounts to around $11.2 million.

Approximately 47 % of the buildings were categorised as having a high level of vulnerability. Assuming an average rebuilding cost of $300,000 for small to medium-sized wineries, the total cost of reconstructing all 21 wineries would be around $3 million. This value represents 47 % of the total number of wineries, calculated as 47 % of 21 wineries multiplied by the average rebuilding cost of $300,000.

A significant proportion of wineries, specifically 64 %, were found to employ outdated steel barrel racks that exhibit a susceptibility to

(a) W01 (b) W04

Fig. 13. Catwalks used in wineries.

Fig. 14. Legs and top of catwalk used in W04.

structural failure. The anticipated cost for replacing a 10-rack unit is around $5,000. Based on the data provided, it can be inferred that approximately 64 % of wineries would incur a potential total replacement cost of $67,200 (i.e., 64 % of 21 wineries × $5,000 per rack replacement). The potential financial ramifications stemming from the destruction of catwalks, wine barrels, production equipment, and other related assets were not explicitly measured in this analysis. However, it is plausible that these losses may reach a substantial sum, potentially totalling millions of dollars. The cumulative quantifiable losses have the potential to exceed $50 million, encompassing direct expenses incurred due to damage, revenue losses, and the need for reconstruction. There may be further indirect consequences stemming from company disruption, expenses related to relocation, workforce downsizing, and a decline in tourism and visitation.

6. Implications of research findings

This study created an inventory of the elements in the Auckland winery region that are vulnerable to earthquakes. The inventory shown in Tables 3, 4, and 5 was created by (i) identifying the key elements at risk in Auckland wineries and (ii) assessing the degree of vulnerability of these elements. The inventory and vulnerability assessments' implications could help increase understanding of wineries and their elements in the Auckland region.

Fig. 15. Ladders used to access top of storage tanks.

The study's findings offer wineries the opportunity to seismically prepare their operations. Although the inventory of at-risk elements will not immediately reduce the damages that could occur in a seismic event, it may encourage re-evaluation and, if necessary, further improvements to the elements. This study's vulnerability assessment demonstrates the wineries' awareness and knowledge of seismic events. The level of risk assigned to each winery reflects their organization's view of seismic events as a crisis. A lower risk winery, for example, is more informed, knowledgeable, and has more structurally sound winery elements than an at-risk winery.

7. Conclusions

This research developed an inventory of at-risk elements in the Auckland wine region and assessed the vulnerability levels of those identified elements. Twenty-one wineries, ranging in size from small to moderately large, were chosen as case studies to provide industry professionals with insight into the level of vulnerability in low seismic risk regions. The vulnerability of elements at risk was also evaluated and identified using a quantitative approach. The vulnerability of storage tanks was mostly attributed to their specific characteristics, such as their type, capacity, and insufficient anchoring and bracing. According to the findings, a significant proportion (71 %) of the tanks were deemed to be susceptible to failure in the event of an earthquake. In general, the vulnerability of buildings was moderate, as indicated by 47 % of them being classified as high risk. The primary determinants of building susceptibility were the year of construction, the materials used, and the absence of seismic retrofitting measures. The catwalks exhibited a high degree of resilience, with a conservative assessment suggesting that at least 50 % of them were classified as low risk. The resilience of self-supported catwalks exceeded that of tank-supported catwalks. The vulnerability of barrel racks was found to be moderate, as shown by the fact that 64 % of the racks employed were constructed using outdated conventional steel materials that are susceptible to collapsing under seismic activity. The research inventory presents a model that has the

(a) W 01	(b) W 02

Fig. 16. Layout of barrel racks.

Fig. 17. Racking system used in the winery 03.

potential for further development and application in the comparative analysis of vulnerabilities across various winery regions.

The findings were consistent with the reviewed literature, demonstrating that the key elements at risk in Auckland wineries, such as buildings, storage tanks, catwalks, and barrel racks, are the same as those found in other New Zealand and international wineries. Due to their smaller capacity, legged tanks were the most common; despite their size, almost all wineries had catwalks. In contrast to larger Marlborough wineries, the wineries studied mostly used wooden rails rather than steel racks. The materials used in winery construction varied, indicating that each would perform differently during a seismic event. The research is significant because wineries in the Auckland region have a small number of moderately vulnerable assets. Based on the findings, vulnerability is determined by the design and implementation of the elements themselves, rather than the level of seismic risk or the size of the winery. The main implication is that the susceptibility to seismic events is predominantly influenced by the design and construction of structural components, rather than only being determined by the amount of seismic danger in a given place. Even in regions with relatively low seismic risk, such as Auckland, the absence of adequate seismic design measures can lead to significant vulnerability. Therefore, seismic upgrading should prioritise the reinforcement of storage tanks and aged barrel racks.

7.1. Limitations and opportunities for future research

The study offers valuable insights into the seismic risk of Auckland wine region; nonetheless, it is important to acknowledge several limitations in terms of its scope and methodology. The generalizability of the findings to other wineries in New Zealand may be limited due to changes in geographic exposure to seismic hazards and differences in structural features. Climate change has been identified as a significant factor contributing to the increased occurrence of extreme weather events, such as floods, storms, and bushfires, which in turn provide substantial

Table 6
Barrel-rack characteristics and vulnerability assessment.

Winery ID	Number of wooden barrel-racks	Number of traditional barrel-racks	Number of modern barrel-racks	Type of barrel-racks	Barrel-rack inspection frequency	Number of barrel storage rooms	Vulnerability score	Risk level
01	4	–	–	wooden	more than once a year	1	3	moderate
02	2	–	–	wooden	more than once a year	1	3	moderate
03	–	153	–	traditional	more than once a year	2	1	high
04	2	–	–	wooden	once a year	2	3	moderate
05	2	18	–	wooden and traditional	more than once a year	2	3	moderate
06	4	–	–	wooden	more than once a year	1	3	moderate
07	2	12	–	wooden and traditional	more than once a year	2	3	moderate
08	2	4	–	wooden and traditional	more than once a year	2	3	moderate
09	4	–	–	wooden	more than once a year	1	3	moderate
10	2	–	–	wooden	more than once a year	1	3	moderate
11	–	8	–	traditional	once a year	1	1	high
12	–	100	–	traditional	once a year	2	1	high
13	–	100	–	traditional	once a year	1	1	high
14	2	7	–	traditional	more than once a year	–	1	high
15	2	18	–	traditional	more than once a year	2	1	high
16	2	4	–	traditional	more than once a year	2	1	high
17	–	–	50	modern	more than once a year	1	5	low
18	–	2	7	traditional and modern	n/a	1	3	moderate
19	–	100	–	traditional	more than once a year	2	1	high
20	–	–	200	modern	once a year	1	5	moderate
21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

risks to wineries. To have a comprehensive understanding of the resilience difficulties confronting the wine business, it is imperative to do a multi-hazard vulnerability assessment that encompasses seismic, weather, and other associated threats. The primary focus of this study was limited to the assessment of both structural and non-structural components specifically within wineries. A potential avenue for future research might be broadening the scope of analysis to evaluate the susceptibility of other assets, such as vineyards, wine stocks, transportation networks, and utilities. This approach would offer a more comprehensive perspective on seismic risk. Conducting comprehensive structural engineering studies of the identified risks can effectively facilitate the prioritisation of retrofitting requirements and the development of customised solutions specifically designed for wineries. More so, the lack of access to building structural drawings and site-specific geotechnical data posed limitations on the extent of vulnerability modelling, necessitating reliance only on visual inspections and qualitative interviews. To get a more rigorous quantitative calculation of losses, it would be necessary to conduct a full examination of structural engineering and incorporate accurate hazard input factors.

The established inventory format offers a valuable foundation for facilitating comparative seismic risk studies across various winemaking facilities globally. This study provides valuable opportunities for future research studies to expand upon current findings about the vulnerability of wineries to seismic events. Potential opportunities for further research might involve the augmentation of the sample size and geographic coverage to facilitate the development of a comprehensive assessment of seismic preparedness throughout the various wine areas in New Zealand. The results of this study might be used as a starting point for the development of a comprehensive international database that consolidates information on vulnerabilities in wineries. This database would facilitate the exchange of knowledge and enable comparative benchmarking. In addition, the findings of this study underscore the importance of enhanced seismic awareness and preparedness among winemakers, especially in areas with relatively low seismic activity. Subsequent investigations may employ same methodologies for vulnerability assessment in other wine areas, therefore facilitating comparative analyses. Further research is necessary to explore the social dimensions of resilience, specifically pertaining to the educational background, preparedness measures, and recovery capabilities of those involved in winemaking.

Ethical approval

This study involved data collection from human participants and was carried out in compliance with internationally recognised ethical guidelines. Prior to the start of the study, the Massey University Ethics Committee granted ethical approval. Privacy and confidentiality of all participants, and any associated risks were minimised as possible. Data were collected and stored in conformity with all applicable laws and regulations and was used for research purposes.

Informed consent

All participants provided informed consent before being included in the study. They were given a detailed explanation of the purpose, procedures, risks, benefits, and other important information about the study that might influence their decision to participate. Consent was obtained in writing and signed by participants after their questions or doubts were answered and clarified.

Author contribution

Author 1 [OO]: Study design, data analysis, data collection, data interpretation, writing, and preparation.

Author 2 [TE]: Conception, study design, methodology, data collection, data analysis, and revision.

Author 3 [TO]: Drafting, data analysis, data interpretation, and revision.

Author 4 [AS]: Data analysis, data interpretations, and revision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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