NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
2019 Pacific Conference on Earthquake Engineering
TURNING HAZARD AWARENESS INTO RISK MITIGATION
4 – 6 April | SkyCity, Auckland | New Zealand

A conspectus of wine storage tank damage data following the 2013 and 2016 New Zealand earthquakes

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ABSTRACT

In-field post-earthquake damage assessment of wineries located in Marlborough, New Zealand was conducted following the 2013 Seddon earthquake (M_w 6.5), the 2013 Lake Grassmere earthquake (M_w 6.6) and the 2016 Kaikōura earthquake (M_w 7.8), providing an opportunity to assemble the largest wine storage tank damage database in the world. An overview of documented damage observations is discussed herein that is based on information collected for 2058 wine storage tanks following the 2013 Seddon and Lake Grassmere earthquakes (1512 legged and 546 flat-based wine storage tanks) and 1401 wine storage tanks following the Kaikōura 2016 earthquake (599 legged and 802 flat-based wine storage tanks). In 2013, tank base shell (39%) and anchor (47%) parts of the flat-based wine tanks sustained the largest proportion of damage, while due to resilience measures implemented following the 2013 earthquakes, damage to tank base shells and to tank anchors reduced to 32% and 23% respectively. In the 2016 earthquake, damage to the barrel (54%) and cone (43%) parts of flat-based wine tanks was identified as being most significant. Indenting of the tank barrel due to impact from a catwalk during the 2013 (10.4%) and 2016 (24.4%) earthquake events was identified as the most crucial failure type that caused damage to tank barrels. Legged wine tanks sustained the largest damage to frame-leg parts, with 40% of legged tanks sustaining damage in the 2013 earthquakes and 44% of legged tanks sustaining damage in the 2016 earthquake.

Keywords: Wine tanks; Earthquake damage data; Tanks anchorage system, Tank base shell, Tank barrels.

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1 INTRODUCTION

The New Zealand wine industry contributes more than NZ$1.6 billion per year to the national economy, with the average annual growth in New Zealand wine exports over the last two decades being 17% (NZwine 2017), making it one of the fastest growing industries in New Zealand. Over two thirds of all New Zealand wine production is under the care of Marlborough wine producers (New Zealand Institute of Economic Research 2015), with Marlborough being a region located at the north-eastern tip of the South Island. During the 2013 Seddon earthquake (M_w 6.5), the 2013 Lake Grassmere earthquake (M_w 6.6) and the 2016 Kaikōura earthquake (M_w 7.8) widespread damage was observed to cylindrical steel wine tanks (see (Dizhur et al. 2017), (Morris et al. 2013), (Rosewitz and Kahanek 2014)).

Winemaking facilities typically consist of four important elements including buildings, barrel racks, wine storage tanks, and catwalks. Following previous earthquakes in New Zealand, engineering teams have inspected the affected wineries and collected detailed damage data. Based on these observations and the collected data, it was noted that wine storage tanks sustained the largest proportion of damage within the wineries (Dizhur et al. 2017). Based on the supporting condition, wine storage tanks can be divided into two types: (1) flat-based and (2) legged (see Figure 1). In the last decades, many research works have been developed with the aim to predict the dynamic behaviour of liquid storage tanks when subjected to induced earthquake shaking, focusing on vibration analysis (e.g., (Amiri and Sabbagh-Yazdi 2011), (Molin and Remy 2013), (Virella, Prato, and Godoy 2008), (Yazdanian and Ghasemi 2017)), finite element models (e.g., (Benasciutti, Moro, and Cimenti 2014), (Hosseinzadeh et al. 2013), (Moslemi and Kianoush 2012), (Spritzer and Guzey 2017)) or analytical simplified models of tank-fluid systems (e.g., (Hashemi, Saadatpour, and Kianoush 2013)) and limited research works have been developed on collecting damage database for the liquid storage tanks. A comprehensive earthquake damage database will further facilitate future predictions and aid development of mitigation solutions for wine storage tanks when subjected to future earthquake events. At the time of writing, there is a worldwide lack of a comprehensive earthquake damage data for wine storage tanks, with the primary earthquake damage data currently available being based on an inventory of 424 tanks that is composed of a mix of different water and petroleum product storage tanks that was collected between 1933 to 1995 (Cooper and Wachholz 1999). To address this lack of a specific earthquake damage database for wine storage tanks, the study reported herein introduces the largest damage database to ever be collected worldwide for wine storage tanks based on post-earthquake damage assessment data following the recent earthquakes in New Zealand.

2 2013 AND 2016 EARTHQUAKES IN NEW ZEALAND

In July and August of 2013, a series of earthquake events occurred in the Cook Strait region of New Zealand. The first sequence commenced on 19 July 2013 with a M_w 5.5 earthquake centred 30 km east of Seddon. This event was followed by two more severe events, being the M_w 6.5 Seddon earthquake on 21 July centred 25 km east of Seddon at a depth of 13 km and the M_w 6.6 Lake Grasmere earthquake on 16 August 2013 centred 10 km southeast of Seddon at a depth of 8 km (Rosewitz and Kahanek 2014). For simplicity, this sequence of earthquake events is referred to as the ‘2013 earthquakes’ in the subsequent discussions. More recently, the epicentre of the 2016 M_w 7.8 Kaikōura earthquake was located 15 km from the northeast of Culverden town (a small town located in the northern Canterbury region of New Zealand's South Island) at a depth of 15 km (GeoNet 2016). The intense shaking occurred for approximately two minutes at just after midnight. The aftershocks, including four events over M_w 6.0, occurred across a complex connected series of faults in the Marlborough Fault System (Bradley, Razafindrakoto, and Nazer 2017). For simplicity, the Kaikōura earthquake event is referred to as the ‘2016 earthquake’ in the subsequent discussions.

The earthquakes in 2013 and 2016 affected the Marlborough region and led to the initiation of new research to investigate the vulnerability of elements in the wineries e.g., see (Bruneau et al. 2003), (Crowley and Elliott 2012), (Dizhur et al. 2017), (Morris et al. 2013), and (Rosewitz and Kahanek 2014). The effects of these recent earthquakes demonstrated that the New Zealand wine industry continues to be vulnerable to seismic hazards, with observations showing that wine storage tanks sustained the majority of damage. The performance of wine storage tanks in New Zealand following the 2013 earthquakes was reported by Morris et al (2013), and by Rosewitz and Kahanek (2014). Au et al. (2015) addressed the gap between the NZSEE standard for the design of storage tanks and its implementation into the wine industry. Damage data presented herein is a snapshot of damage assessment data that was collected following the 2013 Seddon earthquake (M_w 6.5), the 2013 Lake Grassmere earthquake (M_w 6.6) and the 2016 Kaikōura earthquake (M_w 7.8).

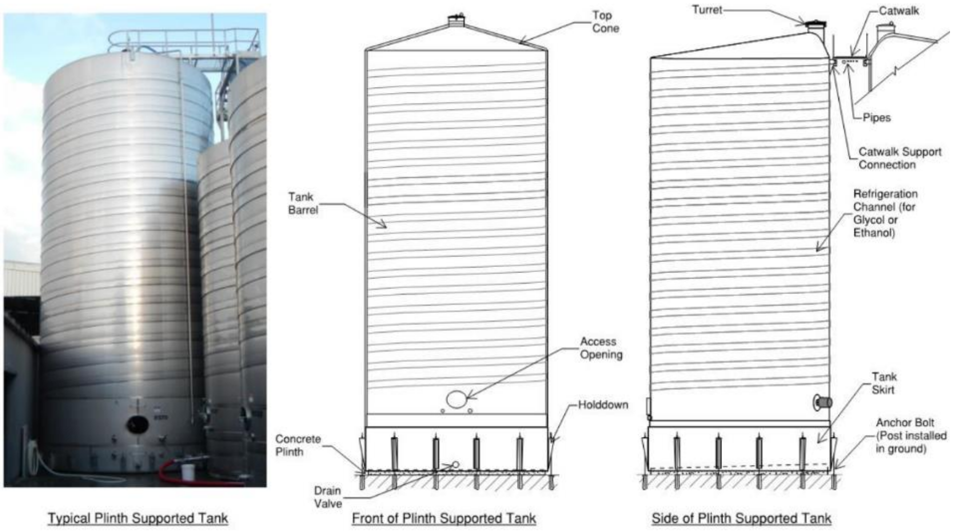
3 BACKGROUND OF NZSEE RECOMMENDATIONS FOR DESIGN OF STORAGE TANKS

A series of design guidelines were developed by the New Zealand Society of Earthquake Engineering (NZSEE) for liquid storage tanks. In 1986 NZSEE (1986) published guidelines for the seismic design of storage tanks, which were later updated in 2009 (NZSEE 2009) to allow determination of seismic design actions in accordance with NZS 1170.5 (2004). Wine storage tanks in Marlborough were typically constructed between 2001 and 2013, and it is estimated that 70-80% of those tanks were designed using the 1986 version and that 10-15% were designed using the 2009 version (Rosewitz and Kahanek 2014). Au et al. (2015) recommended that while the NZSEE (2009) guidelines provide an excellent procedure for the design of liquid storage tanks, the document must be used with caution when applied to the design of wine cylindrical tanks due to the difference in sloshing behaviour of liquid for closed top and open-top tanks. For example, K_h and K_v are period coefficients that are important for calculating impulsive modes and vertical modes, but the graphs can only be used for tanks with a height/radius ratio up to H/R= 4, whilst flat-based wine tanks typically have a higher H/R ratio. Catwalks are another element in the wineries that provides access to the cone part of the tank and are typically designed in two types: (i) self-supported; (ii) tank supported. Catwalks are either not connected or flexible enough to not have a substantial impact on the behaviour of the tank, whilst NZSEE (2009) does not make much comment on the design of the catwalks and their connections to the wine storage tanks.

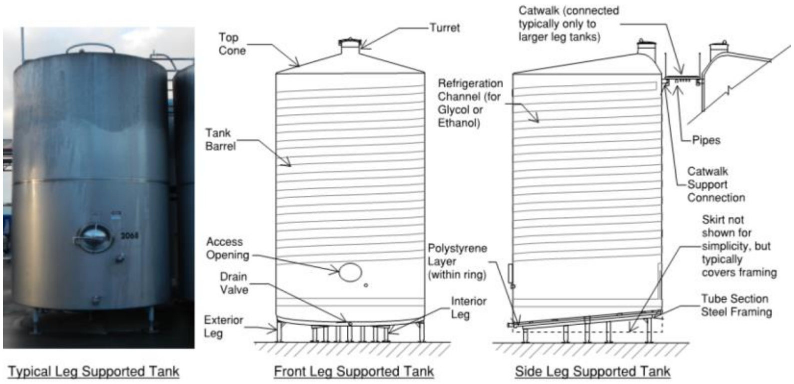
4 METHODOLOGY OF DAMAGE DATA COLLECTION AND ANALYSIS

The data presented herein is a result of interior and exterior detailed inspections of individual wine tanks in 7 major wineries following the 2013 earthquakes and in 5 major wineries following the 2016 earthquake located in Marlborough, New Zealand by competent structural engineers (see Table 1). During each of the winery site inspections, interior and exterior photographs as well as the extent and type of damage were captured for each individual tank. Inspected wineries experienced different peak ground acceleration (PGA) due to their varied geographical locations in the Marlborough region (see Table 2). Earthquake damage varied significantly from winery to winery due to variation in experienced PGA and tank inventory. To quantify the PGA that each of the wineries has experienced, Shakemap (Wald et al. 2006), an application provided by the web site of "United States Geological Survey's (USGS) Earthquake Hazards Program" and Seisfinder, a web application for obtaining of data from New Zealand earthquakes were used for the 2013 and 2016 earthquakes, respectively.

Wine tanks are composed of different parts including foundation, anchorage system, tank base shell, skirt, barrel, barrel insulation and cone. During the conducted winery site inspections, all tank parts were inspected separately, and damage data was recorded in order to present and compare the percentage of damage to each of the tank parts. In the 2013 earthquakes, damage data were categorised into three groups: (i) minor; (ii) moderate; (iii) major. In the 2016 earthquake, damage to the wine tanks were clearly defined based on the required repairs that winery stakeholders needed to follow (see Table 3).



(a) Different parts of a typical flat-based tank



(b) Different parts of a typical legged tank

Figure 1: Example of two typical tank types observed in the New Zealand wineries

Table 1: Tank database used in the present study

Earthquake names	Number of flat-based tanks	Number of legged tanks	Overall number of tanks
2013 M_w 6.5 Seddon and M_w 6.6 Lake Grassmere earthquakes	546	1512	2058
2016 M_w 7.8 Kaikōura	802	599	1401

Table 2: Tank inventory data and experienced PGA for each winery used in the present study

Earthquakes name	Winery ID	No. of tanks	Damaged tanks	PGA [g]	PGA source
2013 M_w 6.5 Seddon and M_w 6.6 Lake Grassmere earthquakes	(1)	110	45	Between 0.10g - 0.20g	Shakemap* (Wald et al. 2006)
	(2)	163	130		
	(3)	276	203		
	(4)	433	176		
	(5)	577	302		
	(6)	270	105		
	(7)	229	202	Between 0.50g - 0.60g	
2016 M_w 7.8 Kaikōura	(1)	265	141	0.32	Seisfinder**
	(2)	405	212	0.26	
	(3)	213	116	0.32	
	(4)	299	260	0.36	
	(5)	219	171	0.23	

*https://earthquake.usgs.gov/data/shakemap/

**https://quakecoresoft.canterbury.ac.nz/seisfinder/search

Table 3: Damage definition for wine storage tanks following the 2016 earthquake

Damage type	Damage definition
Minor	no repair
Moderate	localised repairs
Major	localised replacement
Severe	section replacement
Replacement	tank replacement

5 ANALYSIS OF COLLECTED DAMAGE DATA

5.1 Flat-based tanks

Typical damage examples of flat-based tanks and percentage of their damage type in the tank inventory can be seen in Figure 2. Figure 3a,b shows that although wineries sustained typically lower PGA in the 2013 earthquake, flat-based tanks sustained slightly more damage in the 2013 earthquakes (73%, 404 out of 546 tanks), compared with the 2016 earthquake (69%, 557 out of 802 tanks). Following the substantial losses during the 2013 earthquakes, wineries started to account for earthquake resilience in their short-term and long-term planning as well as undertaking repair/replacement of severely damaged tanks (Yazdanian, Dizhur, and Nicholson 2018).

Tank capacity was a parameter that had a significant influence on the extent of damage to wine flat-based tanks (see Figure 3c,d). In the 2016 earthquake, inspected wine tanks with a volume between 20-40 kL sustained the largest damage among all ranges of capacities. During the site inspection following the 2016 earthquakes, it was identified that wineries placed emphasis on strengthening of larger capacity wine tanks, leaving smaller wine tanks mostly un-anchored or with outdated anchorage systems (see Figure 4). In the 2013 earthquakes, there was a substantial decline in the percentage of damaged tanks with capacity of larger than 300 kL (59%, 13 out of 22 tanks) and tanks with capacity range of between 150 kL and 300 kL (see Figure 3c). Such large capacity tanks (above 300 kL) were typically used for water storage and sustained minor (tank base shell) or no damage due to having a low height to radius aspect ratio and continued their operation following the earthquakes (see Figure 5).

In-field damage assessment following the 2013 earthquakes revealed that anchor (47%) and tank base shell (39%) parts of flat-based wine tanks sustained the largest percentage of damage, while damage to the anchors and tank base shell reduced to 23% and 32%. In the 2016 earthquake, damage to the barrel (54%) and cone (43%) parts of the tanks stood as the most significant reasons that caused damage to the flat-based wine tanks (see Figure 3e,f).

Typically, two types of catwalks are used in wineries, (i) tank supported and (ii) self-supported. For tank supported catwalks, catwalk indent was one of the significant failure mode that caused substantial damage to the wine tanks in both the 2013 and 2016 earthquakes, where 10.4% and 24.4% of flat-based tanks in the 2013 earthquakes and the 2016 earthquake sustained damage in the barrel due to catwalk indent (see Figure 3g,h). However, in the 2016 earthquake, less than 1% of the tanks with catwalk-barrel related damage required localised replacement of tank barrel and the rest of damaged tanks sustained minor (no repair) and moderate (localised repairs) damage.

In the 2016 earthquake, elephant-foot buckling (11%) and diamond shaped buckling (6.1%) caused the highest percentage of severe (section replacement) damage to the barrel (Yazdanian et al. 2018), where above 90% of the buckled tanks required remedial works (see Figure 3g). Elephant-foot buckling (see Figure 2i) generally occurs in tanks that are mostly fully filled, is an elastic-plastic type of instability (NZSEE 2009), (Sobhan, Rofooei, and Attari 2017), (Spritzer and Guzey 2017), , and can be described as an outward bulge of the tank shell. Diamond shaped buckling (see Figure 2h) is a type of elastic instability (NZSEE 2009), (Sobhan, Rofooei, and Attari 2017), (Spritzer and Guzey 2017). Sobhan et al. (2017) stated that elephant-foot buckling of the steel tank wall is caused by the interaction of both circumferential tensile stress close to the yield strength and by axial compressive stress exceeding the critical stress, whilst diamond shaped buckling is caused by severe axial compressive stresses. A vast majority of the anchors with earthquake related damage (94%) in the 2016 earthquake required replacement (see Figure 3i,j).

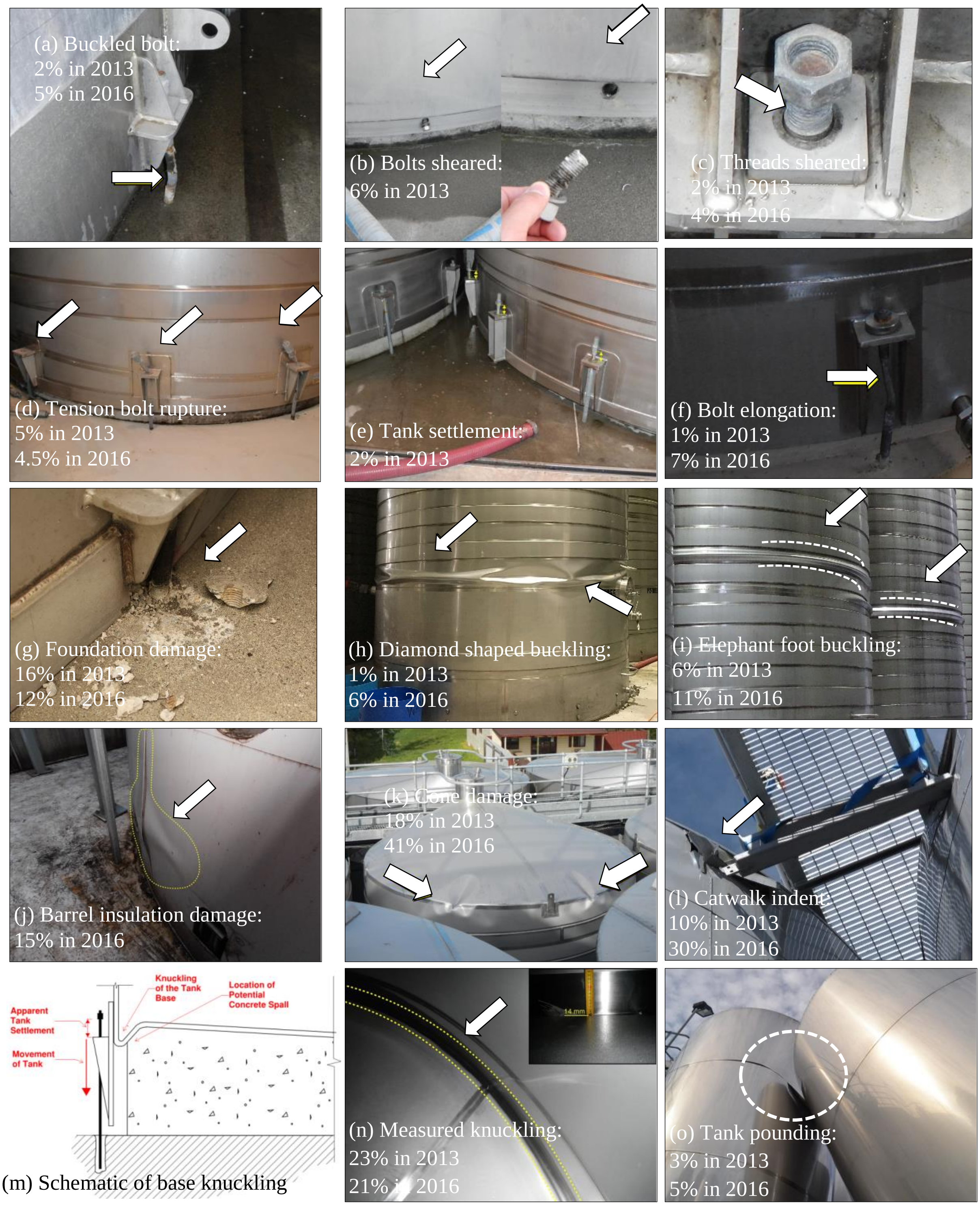
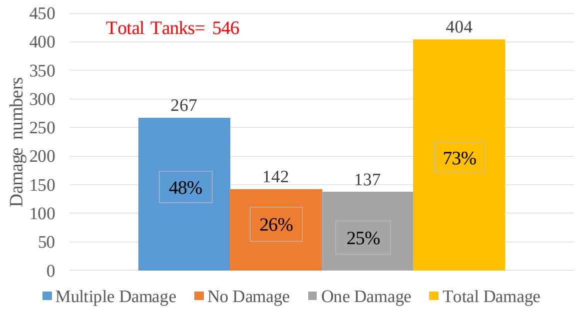
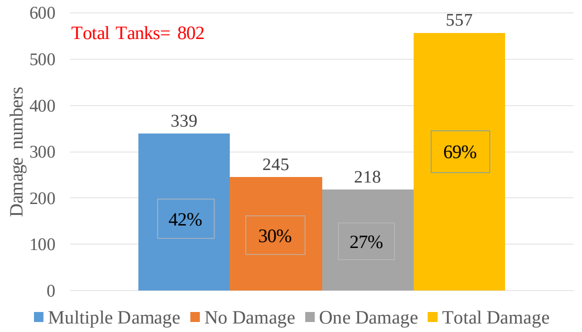


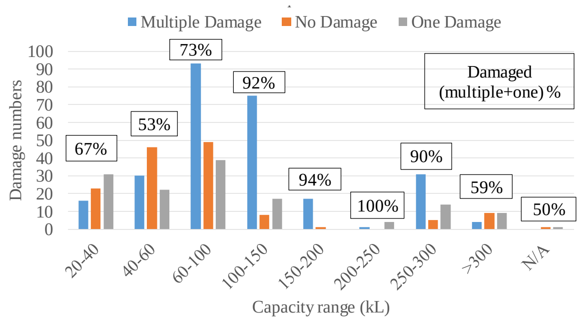
Figure 2: Typical damage to the flat-based tanks and percentage of each damage type among all tanks in the inventory



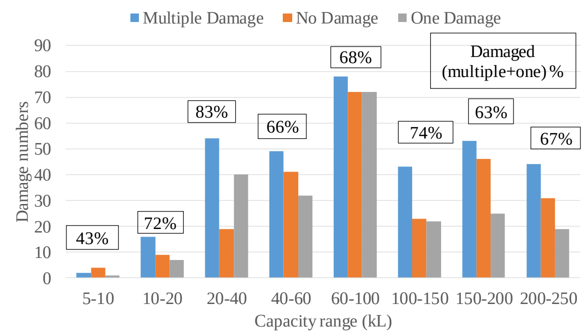
(a) Damage percentage to flat-based tanks (2013 earthquakes)



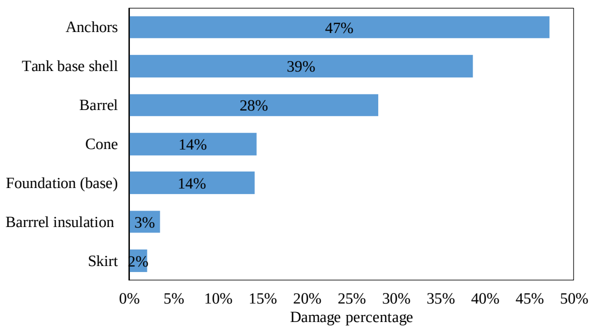
(b) Damage percentage to flat-based tanks (2016 earthquake)



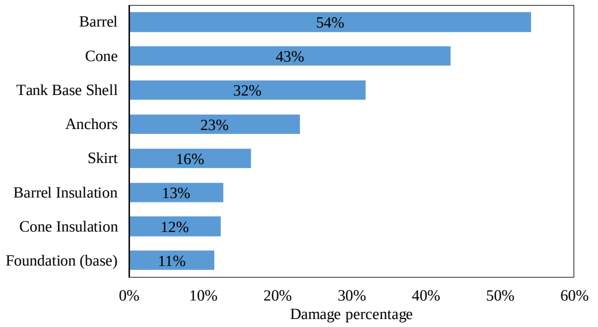
(c) Damage percentage to flat-based tanks based on capacity range (2013 earthquakes)



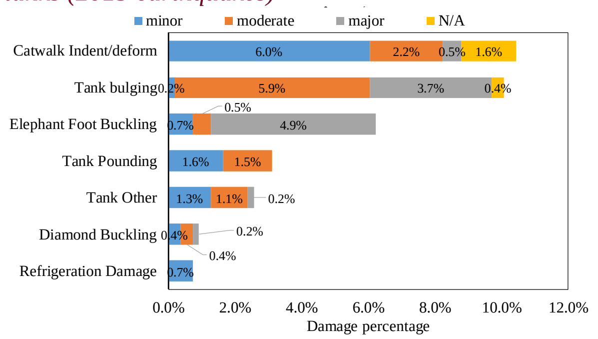
(d) Damage percentage to flat-based tanks based on capacity range (2016 earthquake)



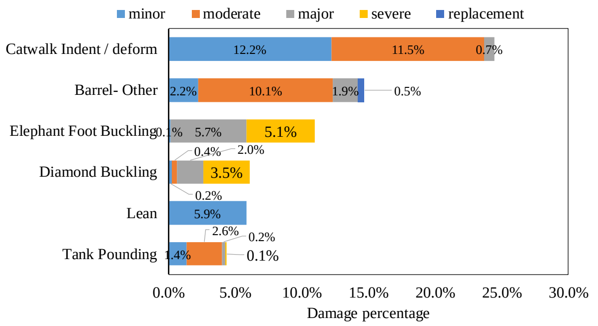
(e) Percentage of damage to different parts of flat-based tanks (2013 earthquakes)



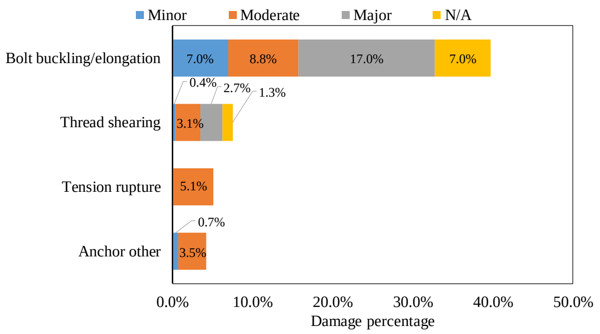
(f) Percentage of damage to different parts of flat-based tanks (2016 earthquake)



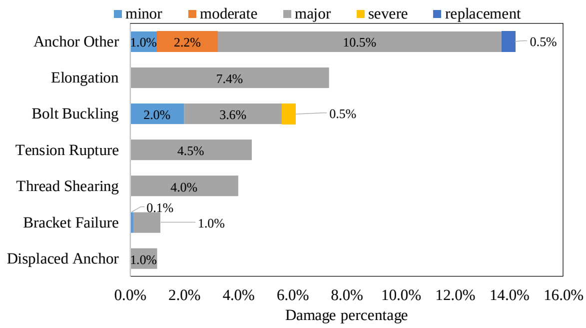
(g) Percentage of different failure modes that caused damage to barrel parts of flat-based tanks (2013 earthquakes)



(h) Percentage of different failure modes that caused damage to barrel parts of flat-based tanks (2016 earthquake)



(i) Percentage of different failure modes that caused damage to anchor parts of flat-based tanks (2013 earthquakes)



(j) Percentage of different failure modes that caused damage to anchor parts of flat-based tanks (2016 earthquake)

Figure 3: Earthquake related damage data for flat-based wine tanks

Figure 4: Damaged small capacity (25 kL) flat-based wine tanks

(a) No particular damage to the anchors around the tanks

(b) Continual operation of tanks following earthquake

(c) Minor cracks on concrete slab

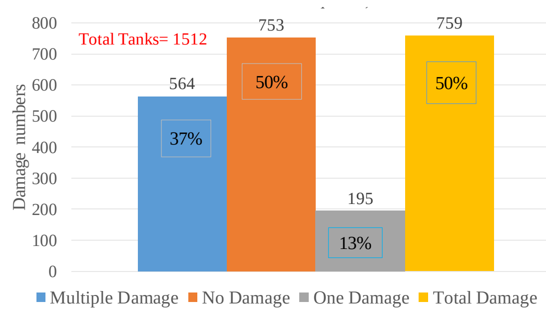
Figure 5: Water treatment tanks continued operating following the 2016 earthquake

5.2 Legged tanks

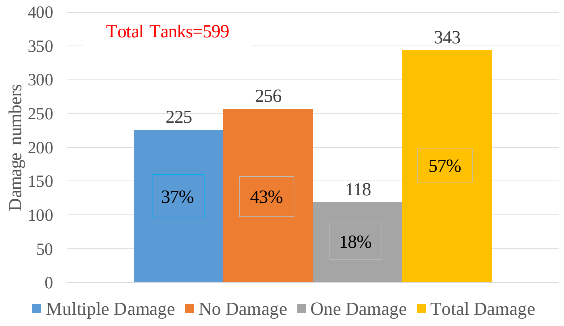
Examples of typical damage for legged wine tanks and percentage of each damage type for all legged tanks in the inventory can be seen in Figure 6. In the 2013 earthquakes, 50% (756 tanks) of the 1512-legged tanks in the inventory sustained damage (see Figure 7a). Out of 599-legged wine tanks that were inspected following the 2016 earthquake, 57% (341 out of 599 tanks) sustained damage (see Figure 7b). The effect of tank capacity was more severe for the legged wine tanks compared with the flat-based wine tanks, where in the 2013 and 2016 earthquakes, percentage of damaged legged wine tanks increased with increasing tank capacity (see Figure 7c,d).

Damage to the frame/legs of legged wine tanks had the highest percentage among the tank elements in the 2013 (40%) and 2016 (44%) earthquakes (see Figure 7g,h). The second most damaged parts of the legged wine tanks were the tank base shell, with 39% in 2013 and 43% in the 2016 earthquake, where almost 68% of the tanks with base shell related damage required section replacement (see Figure 7j). Rippled base, knuckle deformation (see Figure 6m,n), and settlement (see Figure 6 f) in the 2013 earthquake (see Figure 7i) was summarised to base deformation in 2016 (see Figure 7j).

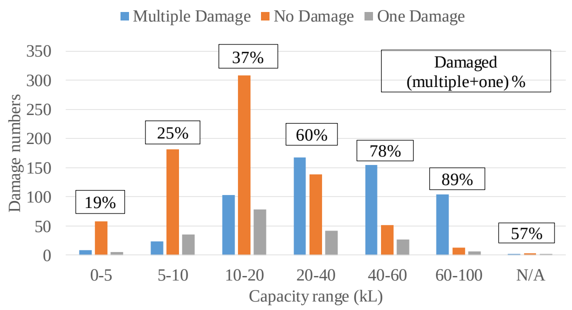
Figure 6: Typical damage to the legged tanks and percentage of each damage type among all tanks in the inventory



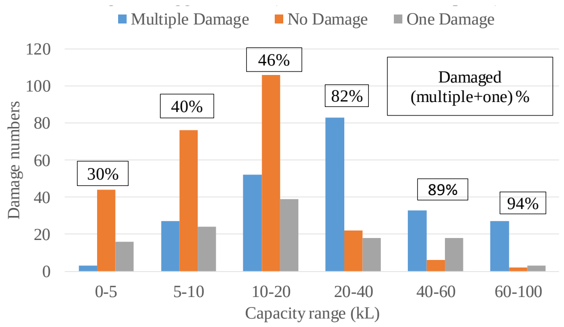
(a) Damage percentage to legged tanks (2013 earthquakes)



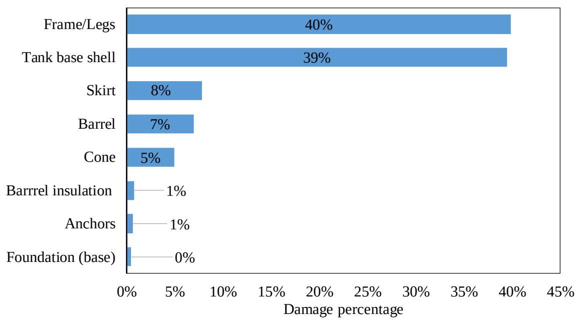
(b) Damage percentage to legged tanks (2016 earthquake)



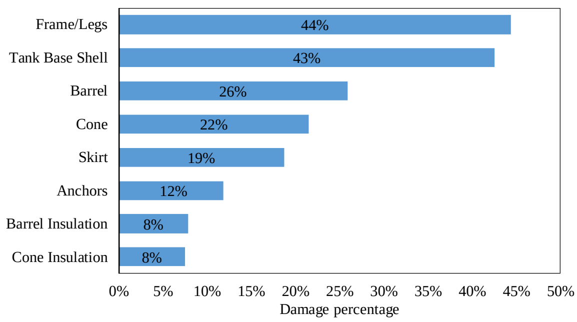
(c) Damage percentage to legged tanks based on capacity range (2013 earthquakes)



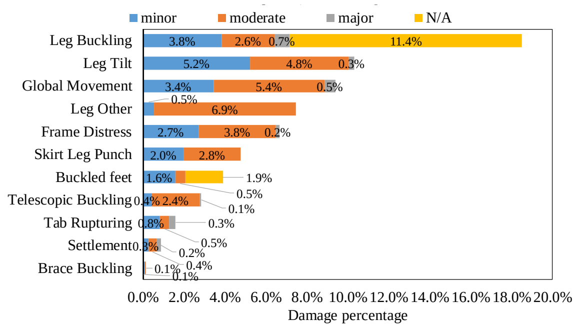
(d) Damage percentage to legged tanks based on capacity range (2016 earthquake)



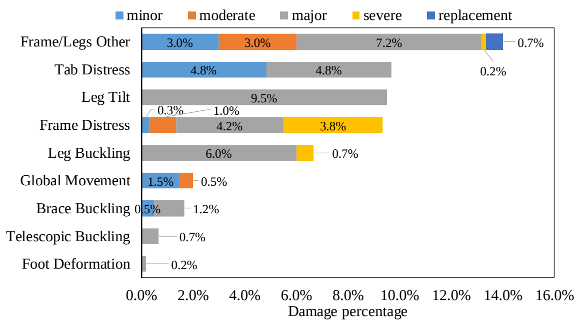
(e) Percentage of damage to different parts of legged tanks (2013 earthquakes)



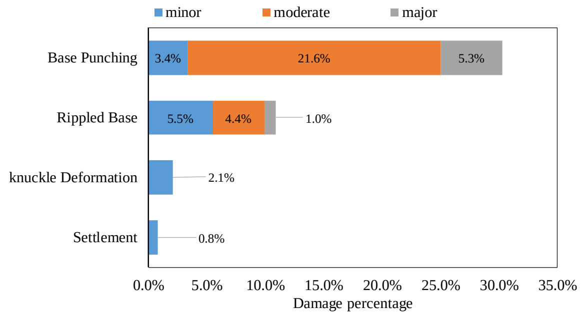
(f) Percentage of damage to different parts of legged tanks (2016 earthquake)



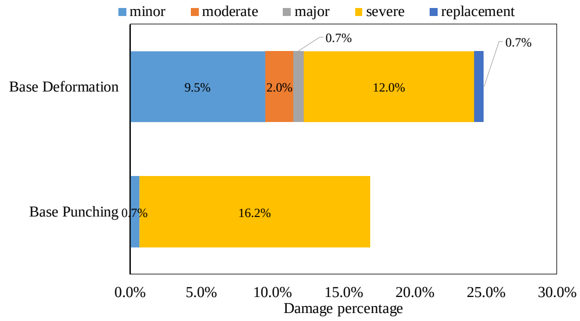
(g) Percentage of different failure modes that caused damage to frame/legs of legged tanks (2013 earthquakes)



(h) Percentage of different failure modes that caused damage to frame/legs of legged tanks (2016 earthquake)



(i) Percentage of different failure modes that caused damage to tank base shell of legged tanks (2013 earthquakes)



(j) Percentage of different failure modes that caused damage to tank base shell of legged tanks (2016 earthquake)

Figure 7: Earthquake related damage data for legged wine tanks

6 SUMMARY AND CONCLUSIONS

An overview of the world's largest damage database for wine storage tanks is presented herein using post-earthquake damage data collected following the 2013 Seddon earthquake (M_w 6.5), the 2013 Lake Grassmere earthquake (M_w 6.6) and the 2016 Kaikōura earthquake (M_w 7.8). The data collectively documented herein included post-earthquake performance of 2058 wine storage tanks from the 2013 earthquakes (1512 legged and 546 flat-based wine storage tanks) and 1401 wine storage tanks from the 2016 earthquake (599 legged and 802 flat-based wine storage tanks).

Based upon high-level discussions and limited results reported herein, the following conclusions can be drawn:

- Small capacity tanks still observed to be mostly simply anchored, where tanks with a capacity between 20-40 kL sustained the largest damage mong all ranges of capacities in the 2016 earthquake.
- Broad water treatment flat-based tanks performed well compared with flat-based wine tanks, where 13 tanks (59%) sustained mostly minor damage of the tank base shell.
- In the 2013 earthquakes, tank base shell (39%) and anchor (47%) parts of flat-based wine tanks were the most damaged elements, while in the 2016 earthquake, damage to the barrel (54%) and cone (43%) parts of the tanks sustained largest percentage of damage.
- Catwalk indent was the most frequently observed cause of damage to the barrel parts of the tanks in 2013 and 2016 earthquakes, where 10.4% and 24.4% of flat-based tanks sustained damage in their barrels due to indenting of catwalk towards the tank barrel. In many cases, catwalks also led to damage to the cone part of the tanks. It should be noted that in the 2016 earthquake, only 58% of the tanks in the inventory owned tank-supported catwalks.
- For the 2013 and 2016 earthquakes, the increased level of earthquake related damage due to increasing tank storage capacity had a more pronounced trend for the legged wine tanks, compared with flat-based wine tanks.
- Frame and leg parts of the legged wine tanks sustained the largest damage population in the 2013 (40%) and 2016 (44%) earthquakes.

An overview of the available data was presented, but because the study is ongoing further conclusions are anticipated.

ACKNOWLEDGMENT

The authors express their appreciation to the New Zealand Ministry for Primary Industries for the financial support (project number 5000132) provided to the authors to conduct this research project. The authors thank Michael Cairns, Senior Project Manager in Auckland Council for his advice on analysis of damage data.

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