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PERFORMANCE OF WINERY FACILITIES DURING THE 14 NOVEMBER 2016 KAIKŌURA EARTHQUAKE

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ABSTRACT

In-field post-earthquake performance observations of winery facilities in the Marlborough region, New Zealand, were documented following the 14 November 2016 Kaikōura earthquake and subsequent aftershocks. Observations presented and discussed herein include land damage to vineyards and the performance of winery building facilities, legged and flat-bedded storage tanks, barrel racking systems, and catwalks. A range of winery facilities were instrumented with tri-axial accelerometers to capture seismic excitations during aftershocks, with the specific aim to instrument different storage tanks having varying capacities and support systems to better understand the dynamic performance and actual forces experienced up the height of the tanks during an earthquake, with preliminary results reported herein.

INTRODUCTION

Marlborough is a region located at the north-eastern tip of the South Island of New Zealand that has experienced multiple cases of significant earthquake shaking in recent years. In particular, the M_W 6.6 Cook Strait earthquake on 21 July 2013 [1], the M_W 6.6 Lake Grassmere earthquake on 26 August 2013 [2] and the M_W 7.8 Kaikōura earthquake on 14 November 2016 [3] are the most recent examples of large earthquakes that have caused significant levels of shaking in the Marlborough region [4]. Wine production in Marlborough has experienced significant growth during the past two decades and is currently the largest wine producing region in New Zealand with 141 wineries that make up more than 75% of the country's total wine production (see Figure 1) [5]. New Zealand wine exports in 2016 were valued at $1.6 billion (NZD), with the wine industry being New Zealand's sixth largest export commodity [5]. Typical infrastructure seen at a winery includes irrigation systems, building facilities, storage tanks, piping systems, catwalks and barrel racking systems.

Wine storage facilities in the Marlborough region prior to the 2013 earthquakes and the observed damage sustained by these facilities in past earthquake are well documented [4, 6-7]. Morris et al. reported general damage reconnaissance following the 2013 Lake Grassmere earthquake, including several cases of significant damage to wine storage tanks, with limited damage to associated infrastructure [4]. Observed damage to cylindrical steel storage tanks included local buckling of tank walls, anchorage failure, and localised damage near the top of tanks where the catwalk supports were attached. As a result, a large number of storage tanks were replaced and some were retrofitted following the 2013 earthquakes. Within the region significant efforts have been made to seismically retrofit storage tanks following previous earthquakes, and as such these interventions provided the research team with an opportunity to investigate the performance of different retrofit schemes.

Numerous wineries were inspected in the Marlborough region to assess damage to winemaking facilities and identify the overall impact of earthquake shaking on the Marlborough wine industry. Observed damage to winery facilities consisted mainly of damage to storage tanks, supporting catwalk systems and in a few cases damage to cooling pipe systems. A large number of tanks had visible deformations, with some cases of tank collapse or local failure that resulted in loss of contents. Such types of damage to storage tanks were also reported during post-earthquake inspections in other regions of the world, such as the 1977 San Juan, 2010 Maule, 2012 Emilia and 2014 South Napa earthquakes [8-11]. The seismic behaviour of cylindrical steel liquid storage tanks was previously studied by Hamdan [12], who observed the failure of thin walled metallic steel tanks similar to observation during the 2016 Kaikōura earthquake. Examples of wine barrel racking system collapse were also observed. These observations are summarised and photographically presented in the subsequent sections.

New Zealand Wine reported that there was some wine loss as a result of the Kaikōura earthquake, amounting to approximately 2.0% (estimated at 5.3 million litres) of Marlborough's total production [13]. New Zealand Wine initially estimated that approximately 20% of tank capacity in Marlborough was impaired to some extent. It was estimated that there were at least 1,000 tanks that sustained minor to major damage levels and that 150 of these damaged tanks were unrepairable. The tank capacity that the industry currently estimates to be out of commission at vintage 2017 is 30-40 million litres, which is between 10-13% of the pre-Kaikōura earthquake capacity [13].

TANK DESIGN GUIDANCE IN NEW ZEALAND

Over the last several decades a series of guidelines have been developed in New Zealand for the seismic design of liquid storage tanks, as no specific design standards exist. The seismic loading standard for structures (NZS 1170.5) excludes design of liquid storage tanks [14].

In 1986 the New Zealand Society for Earthquake Engineering (NZSEE) published guidelines for the seismic design of

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storage tanks (referred to as the "Red Book") [15] with an updated version published in 2009 (referred to as the "Blue Book") [16]. The latest document, the Blue Book, adopts a similar philosophy to NZS 1170.5 and clearly outlines procedures for evaluating the design actions and analysing the seismic performance of storage tanks. Tanks in Marlborough were typically constructed between 2001 and 2013 and it is estimated that 70-80% of those tanks are designed using the Red Book and that 10-15% were designed using the Blue Book [6]. Whilst the design guidance documents cover a broad scope there is an apparent knowledge gap between the use of the guidance material and its implementation into the wine industry in New Zealand [7].

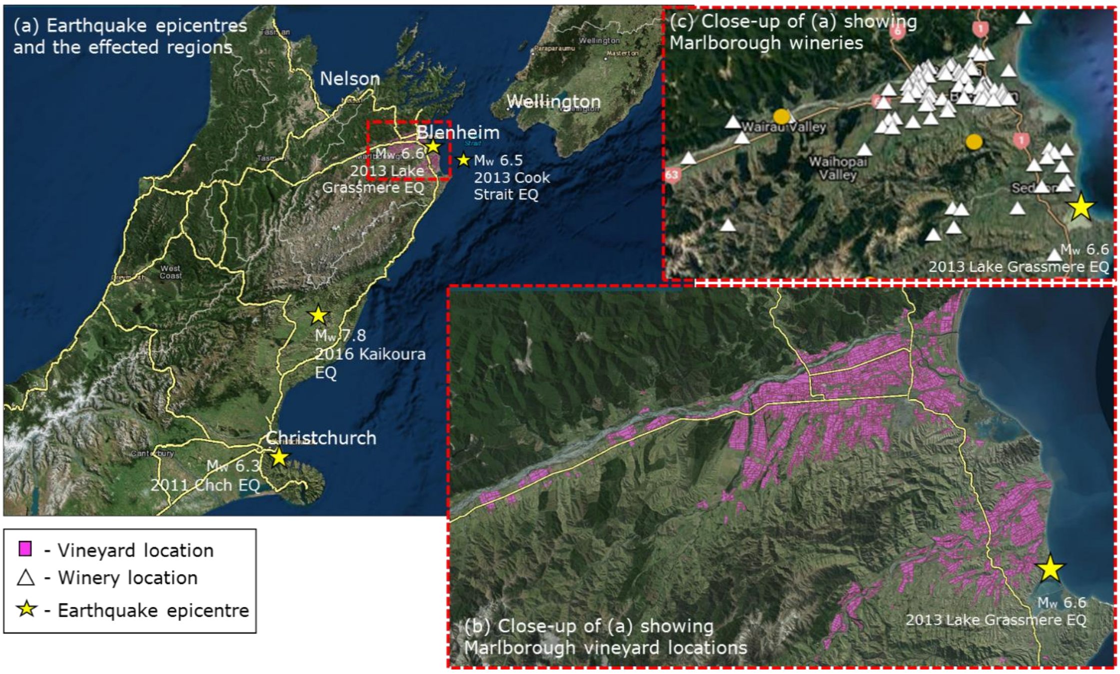


Figure 1: Affected region showing the extent of wine production and the locations of recent earthquake epicentres.

IN-FIELD OBSERVATIONS AND DISCUSSION

The subsequent sections summarise the observed damage and effects on wine making facilities following the 14 November 2016 Kaikōura earthquake and subsequent aftershocks. These observations include vineyard land damage and the performance of winery building facilities, stainless steel tanks, barrel racking systems and catwalks. Where available, the horizontal peak ground acceleration (hPGA) is included below each photograph. Horizontal PGA values were interpolated using University of Canterbury conditional PGA mean contour maps [17]. Data collected from GeoNet strong motion stations provided insights into the intensity and duration of shaking sustained within the Marlborough region (see Table 1).

Land Damage to Vineyards

Significant land damage to vineyards was sporadically observed. However, cases of lateral spreading and ground deformations near river banks were evident (see Figure 2a). For example, the Burkhart Estate will have to re-plant approximately half a hectare of grapes due to earthquake induced land damage to a relatively small area near the Opaoa River, affecting approximately 30 of the vineyard rows (see Figure 2b). Liquefaction was observed throughout the Marlborough region, but with limited affects to vineyards (see Figure 2b for example). Further details of liquefaction and general observations of land damage following the 2016 Kaikōura earthquake presented in greater detail by Stringer et al. [18].

(a) Lateral spreading and sand ejecta damage to vineyards along the Lower Opaoa river (Marlborough District Council 2016)

(b) Land at Burkhart Estate vineyard shifted north (credit Trevor Burkhart)

Figure 2: Examples of land damage to vineyards.

Table 1: Recorded PGA from GeoNet strong motion stations.

Station ID	Station site	Horizontal PGA (g)*	Vertical PGA (g)	Shaking duration (sec)**
WDFS	Ward Fire Station	1.25	1.25	25
SEDS	Seddon Fire Station	0.74	0.19	27
MGCS	Blenheim Marlborough Girls College	0.26	0.09	37
KIKS	Kaikōura	0.25	0.24	56
BWRS	Waikakaho Road	0.17	0.05	36
NELS	Nelson Hospital	0.13	0.05	55

**PGAs from the GeoNet strong motion stations were significantly larger than the values adopted and reported herein using horizontal PGA interpolated from University of Canterbury conditional PGA contour maps [17].*
*** Calculated using significant duration method, which is the time interval where 5-95% energy of earthquake signal is dissipated.*

Winery Building Facilities

Buildings housing winery facilities generally performed well, with minimal sustained damage. A large number of buildings were of tilt-up panel type construction with minor damage observed as shown in Figure 3. The observed damage appeared to be mostly associated with panel connections and fixtures, rather than extensive damage to panels themselves, which is similar to observations following the 2010/11 Canterbury earthquakes [19]. Minor cracking was also observed in some foundation pads, especially at wineries located near the East coast where accelerations were considerably higher than in the Blenheim area. Non-structural damage that was typically observed included loss of ceiling panels in office spaces (see Figure 3e). Further observations of non-structural damage sustained in the 2016 Kaikōura earthquake are reported by Furner et al. [20].

(a) Precast panels exhibiting movement that required temporary propping

(b) Concrete panels performed well, minor observed cracking at the base

(c) Cracking observed near wall base and at panel joints

(d) No damage or residual movement observed at concrete panel joints

(e) Non-structural damage of ceiling panels in office spaces

Figure 3: Performance of buildings housing winery facilities showing minimal damage (0.20g hPGA).

A large variety of tank typologies were used in the Marlborough region depending on their age of construction, tank manufacturer, and installation designer. The basic components of stainless steel tanks are the base supports, tank skirt consisting of a stainless steel ring surrounding the tank base, barrel (stainless steel tank shell), and top cone. Stainless steel tanks can be divided into two main categories based upon the type of base support: (1) Legged tanks, commonly an earlier design and used for smaller capacities from 5,000 L to 60,000 L; (2) Flat-bedded tanks, commonly on a plinth for capacities of 60,000 L and larger.

Legged Tanks

The use of legged tanks generally allows wineries to have flexibility of tank location within the facility. Legged tanks typically sustained more damage than did flat-bedded tanks. The extent of damage varied based on tank size and leg support design, and typically consisted of the following:

- Almost all legged tanks that were full sustained some level of damage. Empty legged tanks that were empty typically had no or minimal damage, as expected.
- Legged tanks that had well designed leg braces performed adequately in most cases, with no or minimal damage.

- Legged tanks with tall bases typically had braced legs. The braces were often connected to the legs 200-300 mm above ground with the unbraced portion of the leg commonly failing in bending (see Figure 4a).
- Pull-out of adhesive anchoring systems used to secure tank base plates was widely observed (see Figure 4b). It was evident that fixing of base plates reduced the horizontal translation of the tanks but dramatically increased the forces in the tank legs.
- Failure at the top of the leg in unbraced frames, (1) within the supporting beam, or (2) fracture of the weld connecting the leg and beam at the maximum moment locations. The weld connecting the leg and beam is often poorly detailed (see Figure 5b).
- Local buckling of adjustable threaded leg sections at the point of cross-section reduction (see Figure 5a) or where the thread engagement length was insufficient, resulting in an inadequate bending moment transfer mechanism (see Figure 5c-e).
- Distortion of the tank floor was a widely observed damage type to legged tanks. This damage is mainly a result of the tank wall being misaligned with the perimeter ring of the supporting structure (similar to knuckle type deformation). In cases where the tank floor support beams were infrequent, deformation of the thin tank floor was observed.
- Tearing of the tank floors was observed at the location of welded 'tags', which connect the tank to the support structure.
- Collapse of the support frame only was observed for legged tanks, where tanks with low aspect ratio (squat tanks) frequently remained vertical and there was no loss of wine contents.
- Overturning of legged tanks was also observed, resulting in severe damage to the tank, and often to surrounding tanks, catwalks and other infrastructure. Overturning of legged tanks was observed to occur in tanks with a high aspect ratio (slender tanks) not anchored to concrete slabs.
- In most cases, damage could have been predicted if the load-path was carefully followed and if well-known engineering principles were adequately applied.

Repaired and Strengthened Tanks

A number of examples were observed where repair and/or strengthening work had been undertaken following the 2013 earthquake sequence in the area. The following observations on the performance of improved legged tanks were made:

- Inadequate strengthening of tank legs (see Figure 6a).
- In cases where the legs were adequately strengthened, buckling and damage to tank skirts occurred (see Figure 6b).
- Well braced legged tanks with braces connected to the bottom-most part of the leg generally had no damage to legs or tanks (see Figure 7a,c,d).
- Tanks with stiff squat legs that were not secured to the concrete slabs generally performed well, with only minor evidence of sliding on the concrete slab (see Figure 7b) or minor damage due to pounding with adjacent tanks.

Flat-Bedded Tanks

Flat-bedded stainless steel tanks with capacities in excess of 60,000 L are typically positioned on a concrete plinth [6]. Concrete plinths are often tied to the concrete floor slab and designed with a 5% slope to assist with drainage. Plinth-mounted tanks commonly have a skirting wall and anchorage mechanism to transfer loads from the tank walls to the concrete plinth or floor slab. The skirting wall is a stainless-steel ring around the tank base that extends below the base to approximately 5-20 mm above the floor slab. Anchors are spaced at regular intervals around the circumference of the tank and are connected to the tank skirting walls by welded chairs. Many anchors are fabricated from threaded steel rods with a reduced diameter to provide a point of yielding during earthquake induced shaking. Anchors are generally epoxied or grouted into the concrete floor slab and designed as either tension only or compression/tension devices. The performance of flat-bedded tanks is divided into each major component as summarised in subsequent sections.

Anchor Rod Performance

A large variety of anchor rods connecting flat-bedded stainless steel tanks to the concrete substrate were observed during the winery inspections. It was observed that the anchor rods were mostly placed during the original tank instalment or in some cases were placed as part of seismic mitigation measures.

Anchor rod connections exhibited a variety of failure modes, some of which were also previously observed following the 2013 earthquake in the region. The common observations are as follows:

- Use of tension anchors resulting in rupture of anchor rods in tension and/or shear (see Figures 8, 9a, 11).
- Buckling or rupture of tension/compression anchor rods due to the absence of buckling restraints (see Figures 8, 9a). Anchors appeared to have yielded during tension cycle, buckled during compression cycle, and then fractured in subsequent tension cycle due to high stress concentration at the point of buckling (see Figure 10a).
- Capacity of the knuckle against distortion on the compression side is typically minimal when compared with the tension capacity of the anchors. It was observed that the tension side anchors rarely yield, although have the appearance of being stretched due to the downward movement of the tank as it deforms over the plinth. Knuckle deformation typically occurred due to inadequate compression load path, and commonly was observed at locations where the tanks skirt did not extend to the concrete nib (see Figure 10a).
- Pull-out of anchor rods due to adhesive and concrete cone failures, and inadequate design of base plate restraints (see Figures 8a, 9, 11, 16d).
- Stripping of threads at top or bottom of anchor rods due to lack of thread engagement. Common at the connection to a chair from the tank wall or a baseplate (see Figures 8b, 9c).
- Anchor bolt connections through the skirt into the concrete plinth were commonly observed to fail in shear (see Figure 13c).
- There were cases where flat-bedded tanks supported on plinths performed well, with no apparent damage (see Figures 11, 12, 13a-b).

Skirt and Tank Base Performance

There were various types of failure modes to tank skirting walls and tank bases during the 2016 Kaikōura earthquakes. Damage observations included:

- Local deformation of the thin stainless steel layer due to rocking and horizontal displacement of the tanks (as shown schematically in Figure 10b with examples in Figure 15).

- In cases of extreme tank rocking, apparent contact between the skirting wall and concrete slab was observed, with excessive compressive forces resulting in localised buckling of the skirting wall (see Figure 15).
- Local deformation at the connection between the skirting wall and anchor rods due to poor distribution of anchors.

Knuckle Deformation

Concrete plinths are constructed prior to the placement of tanks, with plinth diameters that are slightly less than the diameter of tank bases. During earthquake shaking the tank floor near the outside perimeter is prone to settlement due to the gap between the edge of the plinth and the tank wall. This deformation mechanism is referred to as 'knuckle' deformation (partially shown in Figure 15f-g). It is understood that a large portion of flat-bedded tanks installed since 2008 had concrete pumped into the void within the skirt when the tank was located in-situ on the ground. This intervention provides full support to the tank base and a shear transfer mechanism, whilst avoiding knuckle deformation.

Elephant Foot Buckling

The elephant foot failure mode is an elastic-plastic deformation mode of the tank barrel walls. Failure is typically concentrated at the base of the tank, but also frequently observed higher up the wall, where there is a reduction of tank wall thickness. At times, refrigeration channels appear to have constrained elephant foot buckling. The refrigeration channels increased the stiffness of the tank wall, and hence buckling of the tank wall portion was typically observed over the height between adjacent refrigeration channels. Commonly observed examples of elephant foot buckling are shown in Figure 15c-e.

Diamond Buckling

Diamond buckling refers to steel membrane compression buckling of the tank shell. This deformation mechanism was commonly observed in tanks with capacities over 100,000 L (see Figures 14b, 15a-b). Diamond buckling was mainly observed near the bottom of the tank wall. It is hypothesised that refrigeration channels restrain diamond buckling higher up the tank wall because the height of the 'diamonds' typically exceeded the height between adjacent refrigeration channels. It was observed that diamond buckling typically formed where no refrigeration channels were present, which is approximately over the lower 1.0 m height of the wall. Some cases were observed following the 2016 Kaikōura earthquake where this local buckling mechanism caused tank perforation and consequently wine loss.

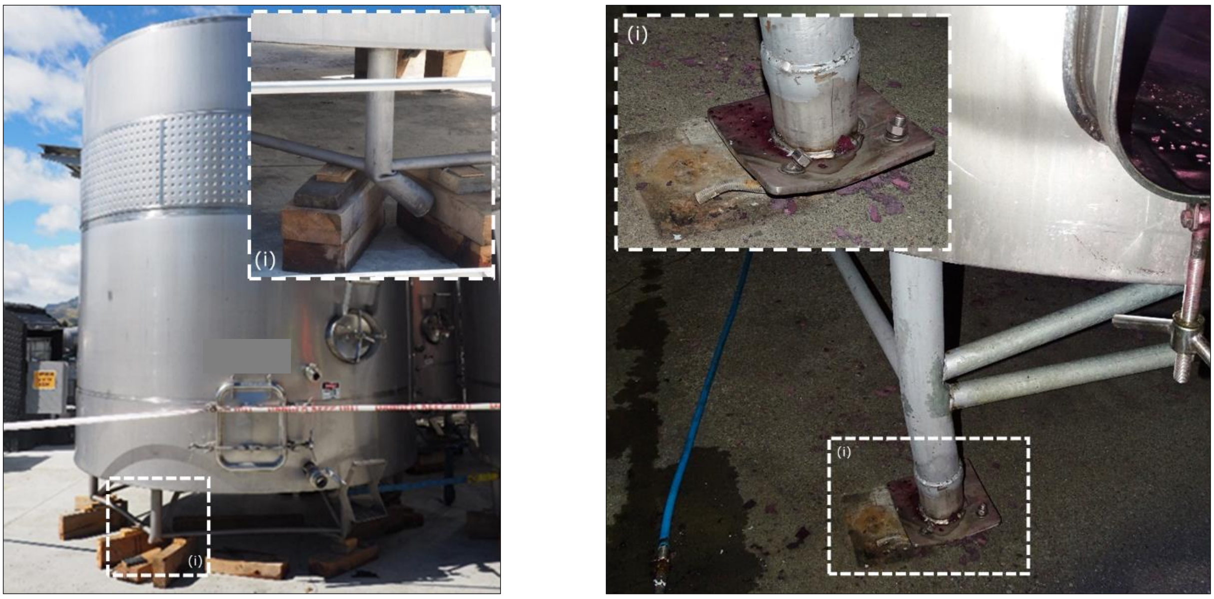
Deformation of Top Cone

In some cases deformation of the top cone of wine tanks was observed, due to the upward force applied to the top cone from the sloshing liquid. This deformation was not widely observed, and is thought to have occurred to a lesser extent than was observed in the 2013 earthquakes.

Repaired and Strengthened Tanks

Several examples were observed where repair and/or strengthening work had been undertaken following the 2013 earthquake sequence in the area. The following observations on the performance of improved flat-bedded tanks were made:

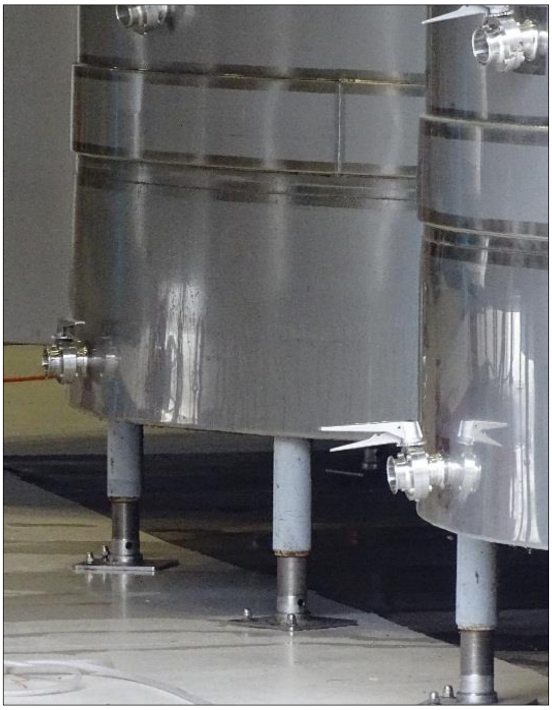
- Adding a skirt extension, or pouring a concrete nib up to the base of the skirt to provide solid bearing for the skirt and prevent knuckle deformation (see Figure 11), was observed to generally work well, although in some cases this intervention transferred failure to a different mechanism. The concrete nib was often observed to crack, particularly where it extends higher than the base of the skirt and encases anchor chairs.
- In some cases additional anchors were added. Additional anchors often resulted in the anchorage being stronger than the tank wall, leading to tank wall buckling.



(a) Bending of tank legs below brace, with tank temporarily supported on timber blocks (0.13g hPGA)

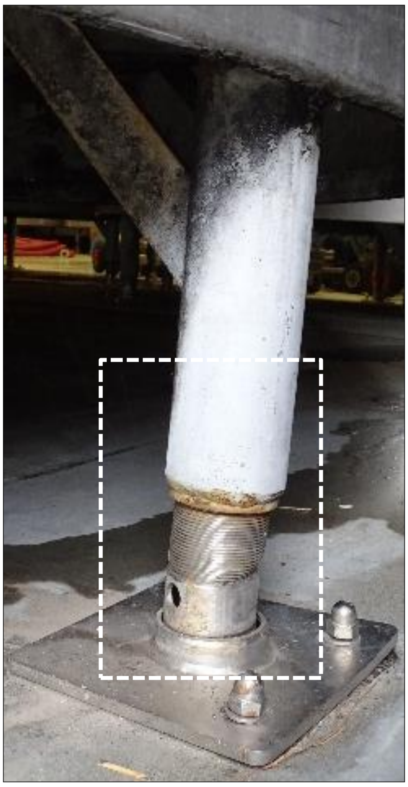
(b) Significant movement and uplift of legged base plate with bending of the leg member below bracing (0.20g hPGA)

Figure 4: Damage to legs and base plates of legged stainless steel tanks.



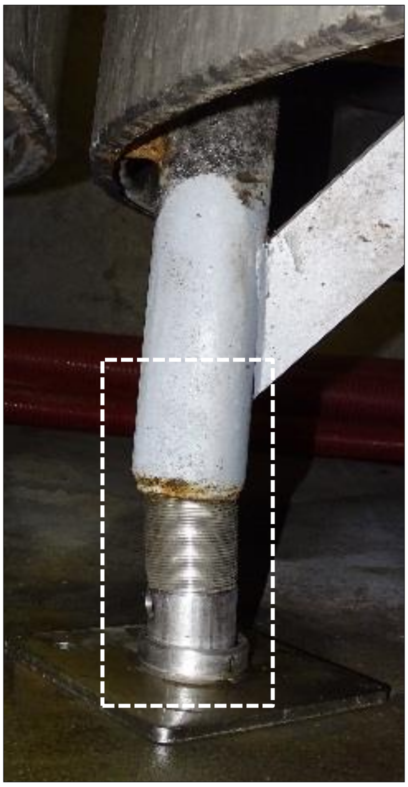
(a) *Slender adjustable legs prone to buckling at the point of cross-section reduction (0.20g hPGA)*

(b) *Collapse of tanks due to buckling of slender and understrength support legs (0.13g hPGA)*



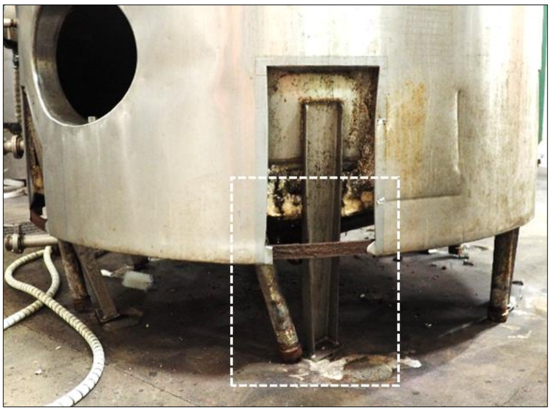
(c) *Buckling of adjustable portion of the leg support and bending of base plate (0.20g hPGA)*

(d) *Buckling of adjustable leg support portion (0.20g hPGA)*



(e) *Buckling of adjustable portion of the leg support below brace (0.20g hPGA)*

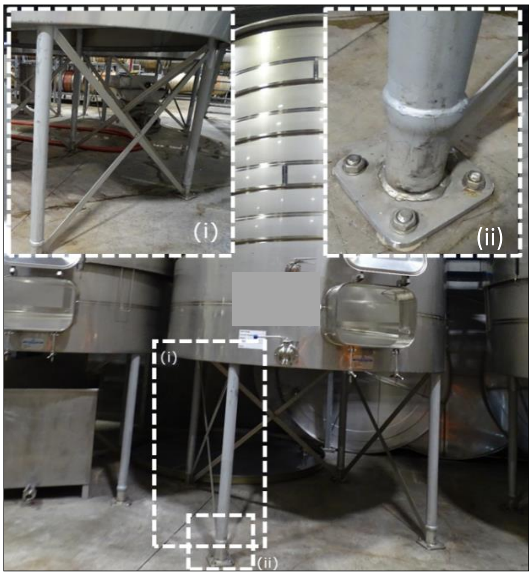
Figure 5: Damage to leg supports of legged stainless steel tanks.



(a) Additional legs added following the 2013 earthquakes (see white dotted box). Torsional rotation observed with near collapse of the tank (0.14g hPGA)

(b) Strong braced legs fixed to concrete slab resulted in good performance of the legged system but lead to buckling and damage to the tank above (0.23g hPGA)

Figure 6: Poor performance of retrofitted legged tanks.



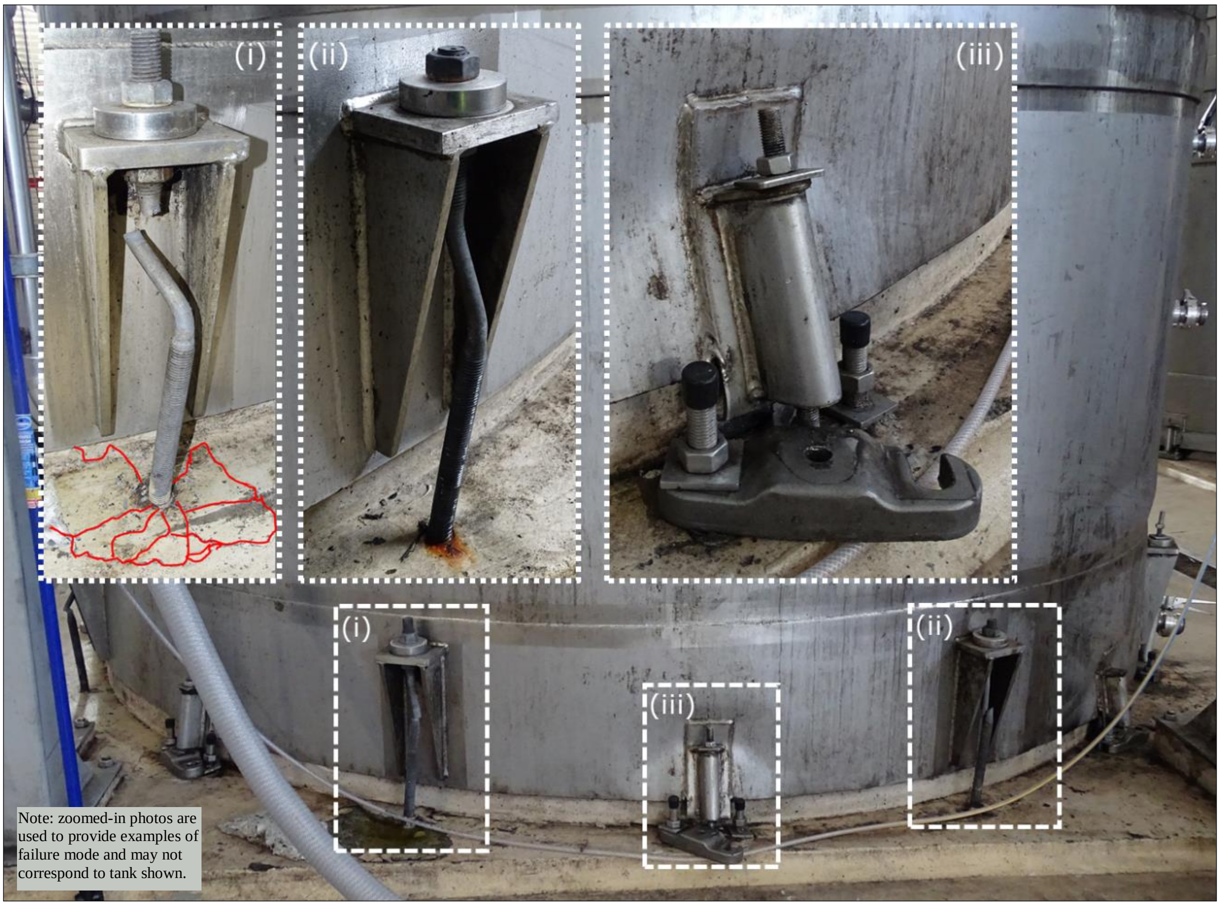
(a) No damage to legs or tanks observed (0.20g hPGA), (i) braces connected near base plate, (ii) base plate well connected to concrete

(b) Tanks with squat legs not fixed to the concrete slab – no evidence of significant movement or damage but in some cases translation of 10-20 millimetres (0.14g hPGA)

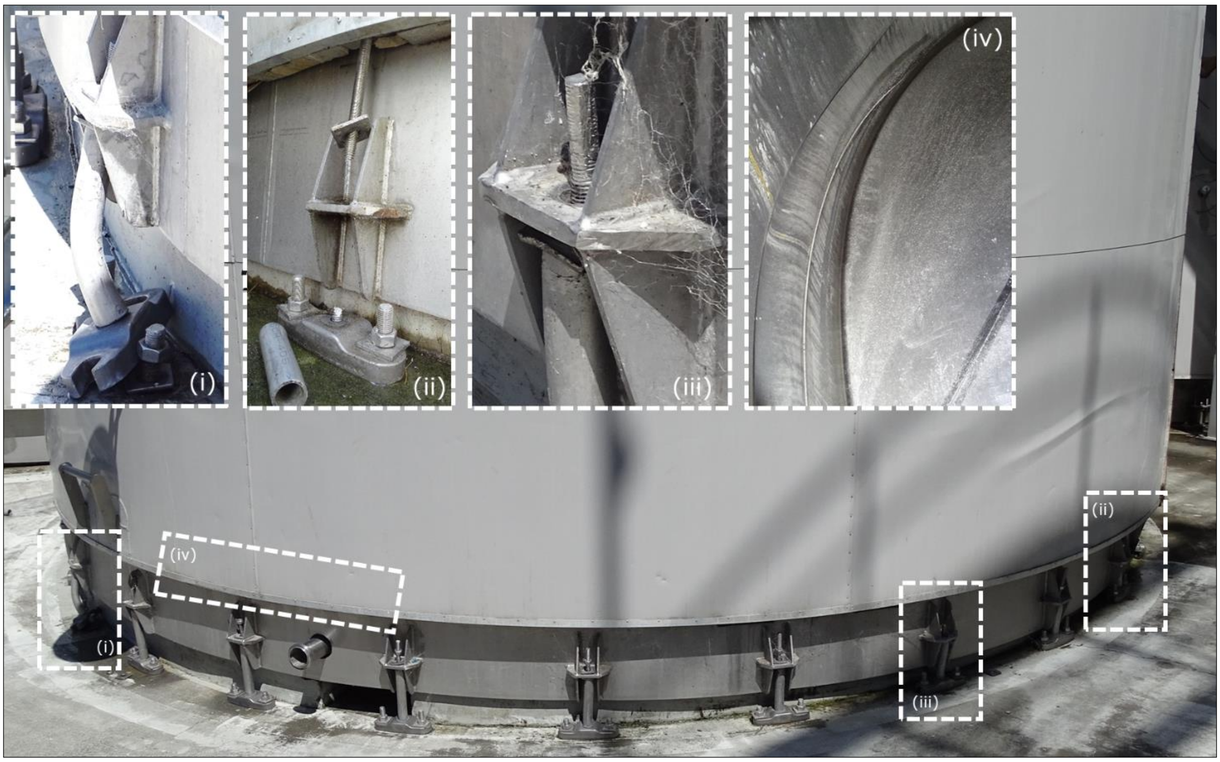
(c) Example of well braced and strong design with minimal/no damage observed (0.23g hPGA). Some of these braced tanks had lower wall fracture, with likely loss of wine, but most performed well

(d) Example of well braced tank with minimal/no damage observed (0.13g hPGA). Some braced tanks had damage to the lower part of the tank wall, with likely loss of wine, but most performed well

Figure 7: Good performance observed for well-designed legged stainless steel tanks.

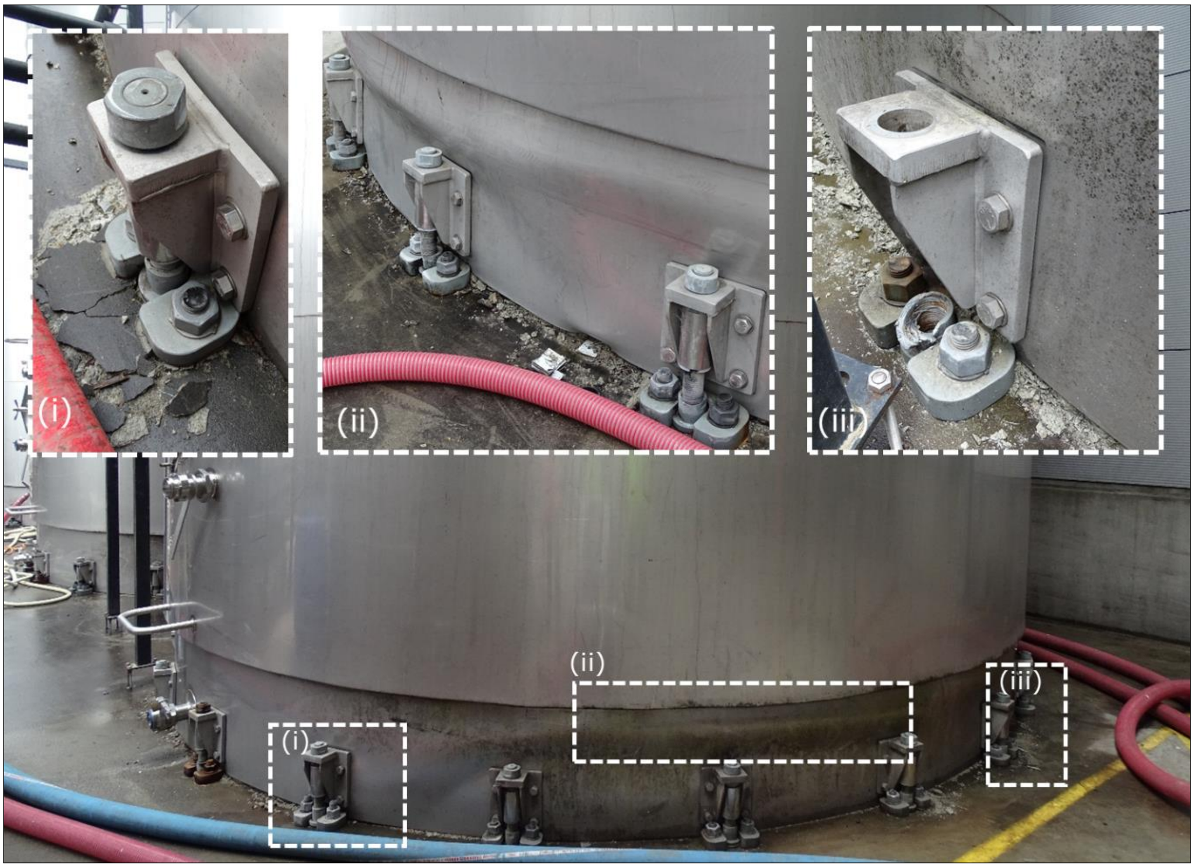


(a) Use of mixed anchor systems resulting in pull-out of anchors from concrete and yielding, rupture and compression failures of anchor rods, resulting in major damage to the base of the tank (0.13g hPGA)

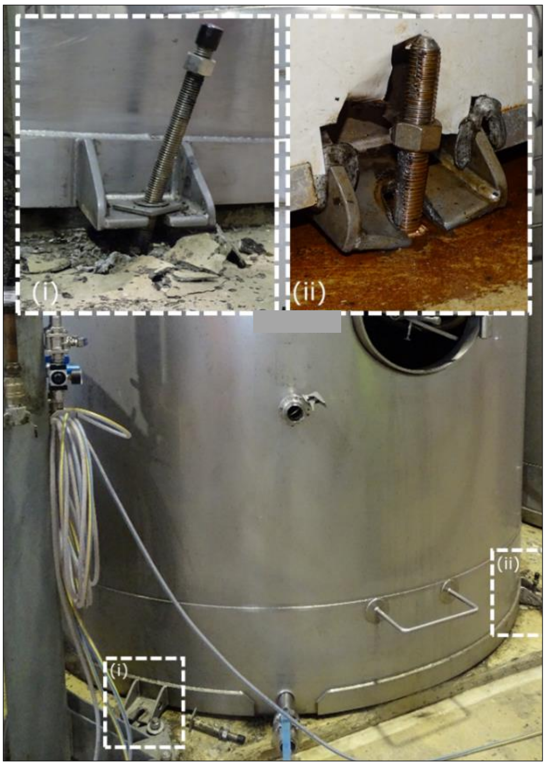


(b) 150 kL tank showing damage to anchoring connections and tank base; (i) buckling of the anchor rod and dislodgement from anchoring bolts; (ii) rupture of anchor rod; (iii) stripped thread and fully coming off the holding nut; (iv) evidence of tank base distortion in 'knuckle-squash' type deformation (0.13g hPGA)

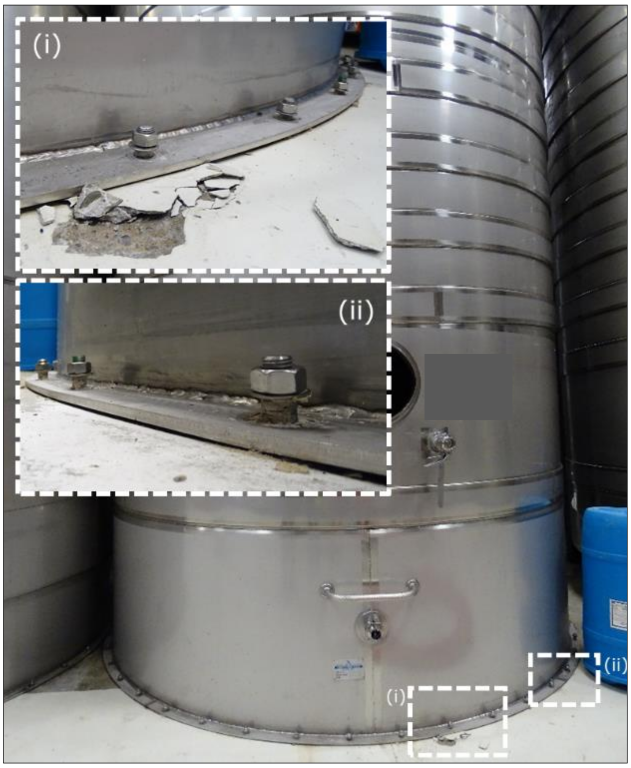
Figure 8: Damage observations to anchorage systems of flat-bedded stainless steel tanks.



(a) 240 kL tank showing various forms of damage to anchors and base skirt (0.23g hPGA)

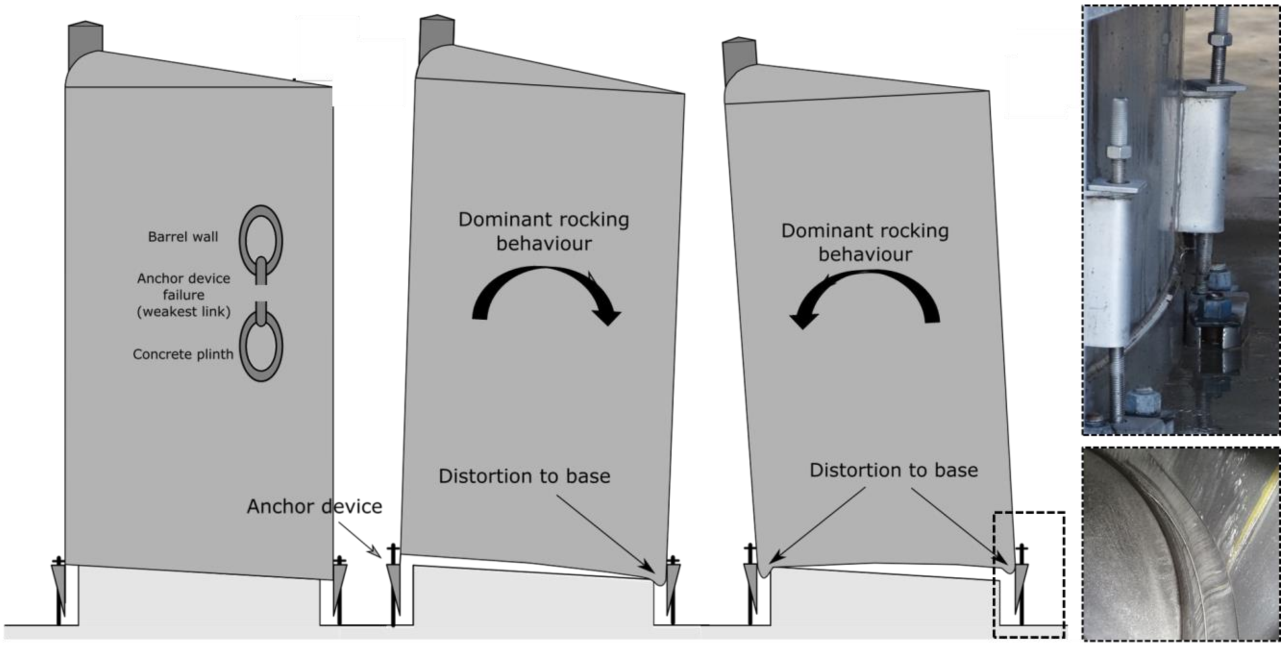


(b) Failure at threaded rod/adhesive interface indicating poor workmanship of adhesive installation (0.13g hPGA)

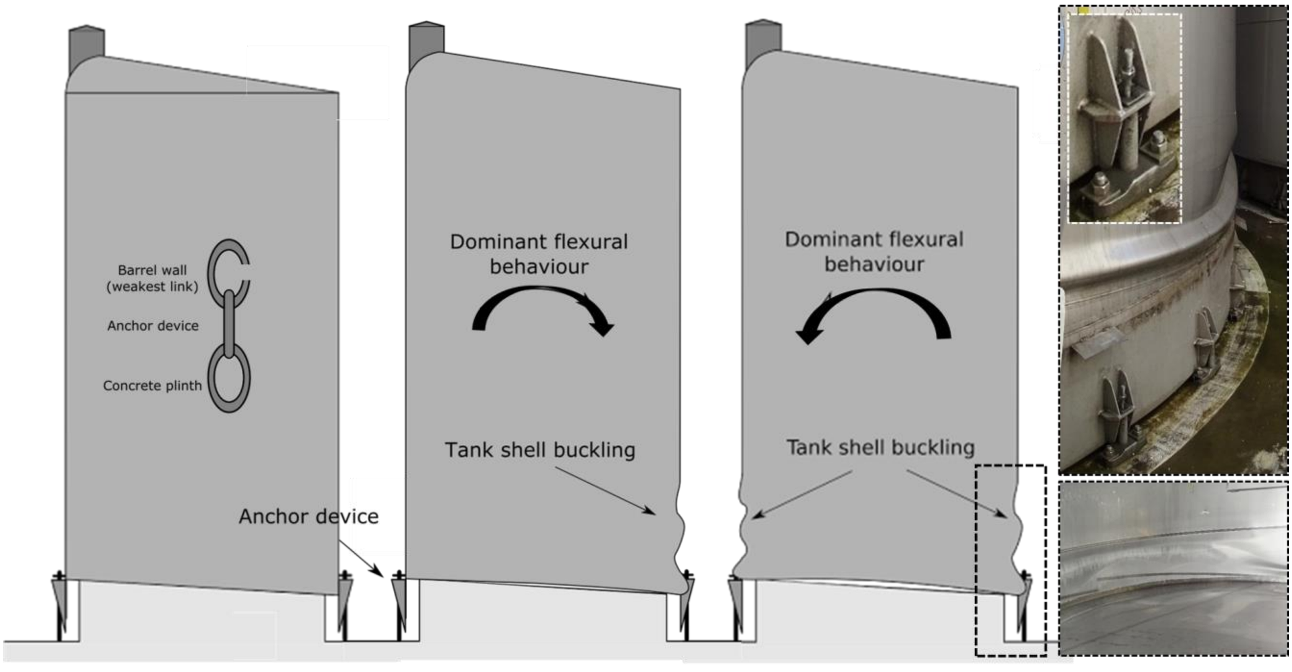


(c) Stripped thread and bolt pull-out from concrete floor (45 kL tanks) (0.20g hPGA)

Figure 9: Damage observations to anchorage systems in flat-bedded stainless steel tanks.



(a) Schematics and photographic examples of flat-bedded tanks with anchor devices



(b) Schematics and photographic examples of flat-bedded tanks with tank shell buckling

Figure 10: Schematics and photographic examples of flat-bedded tank modes of failure.

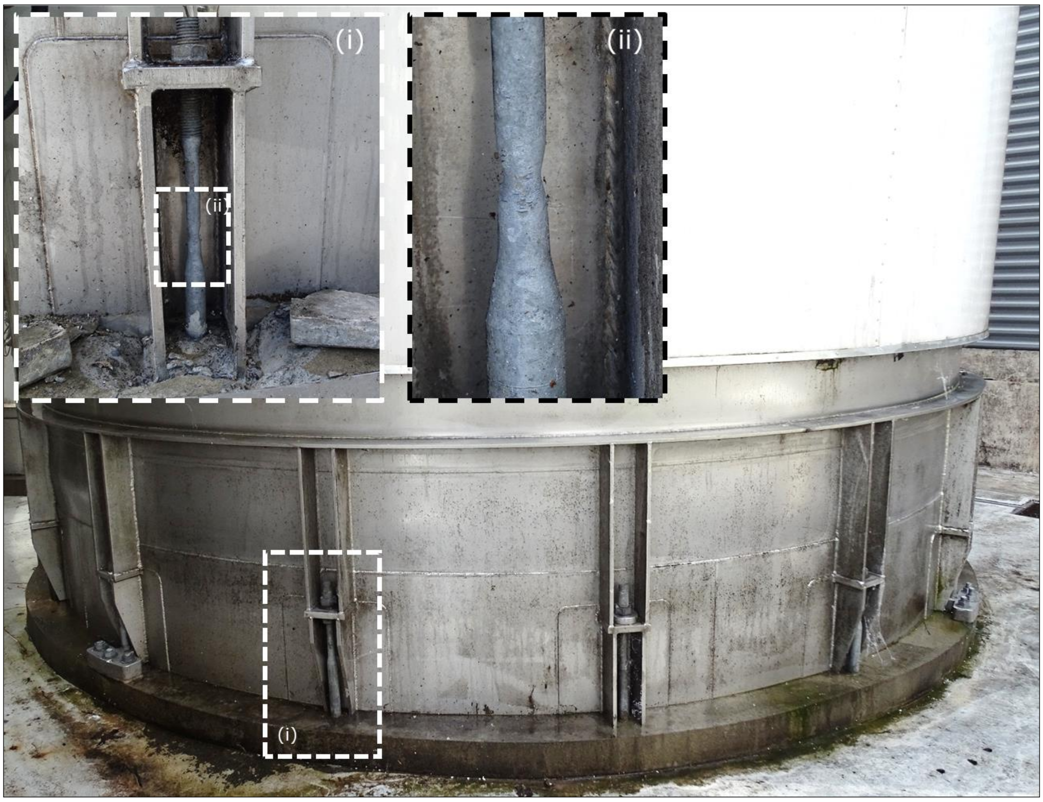


Figure 11: Tank skirting strengthened using extra welded stiffeners and addition of a concrete nib following the 2013 earthquakes; (i) close-up of the anchor connections showing crushing and spalling of concrete at base; (ii) close-up view of cup-and-cone yielding of the fuse rod (0.13g hPGA).

(a) 225 kL tanks secured using frequently spaced steel rod anchors exhibited apparent good performance (0.13g hPGA)

(b) 60 kL tanks with good anchor performance (0.23g hPGA)

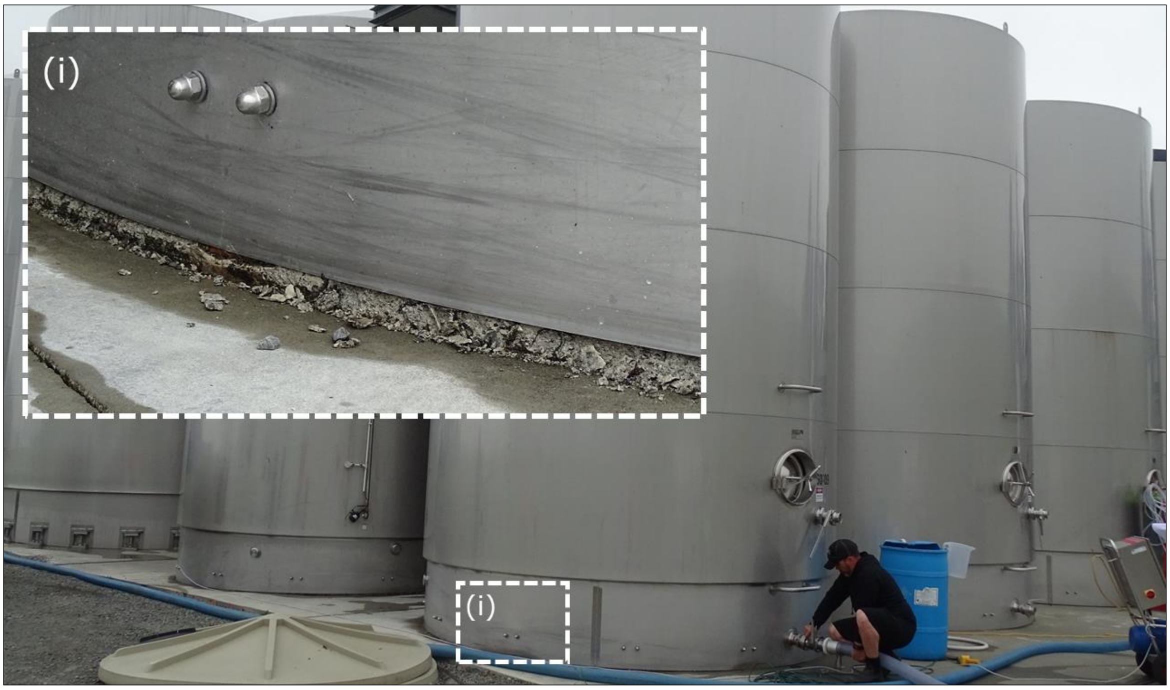
Figure 12: Good performance observed for anchor systems in flat-bedded tanks.

(a) 120 kL tank with no evidence of damage due to good anchor performance (0.20g hPGA)

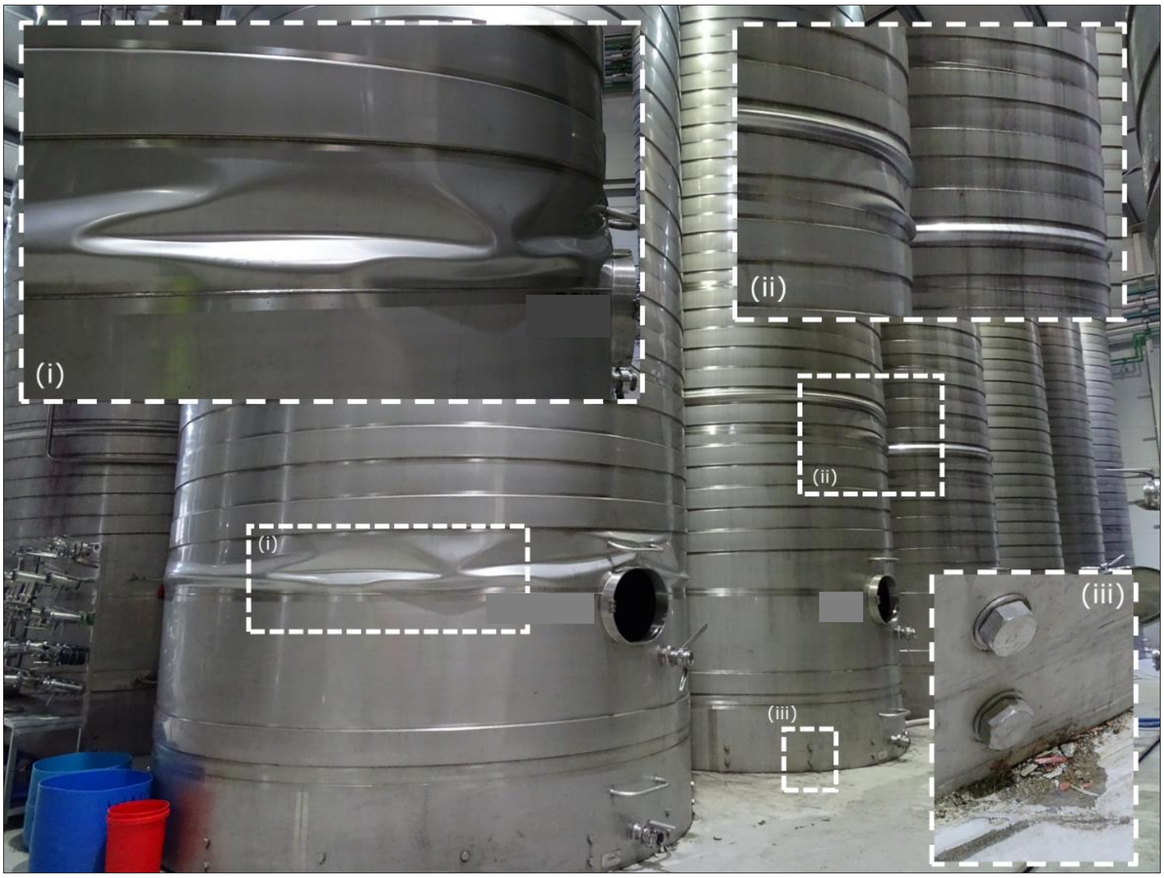
(b) 240 kL capacity tanks with no damage (0.23g hPGA)

(c) Flat-bedded tanks showing buckling near tank base and shear failure of anchor connections (0.14g hPGA)

Figure 13: Examples of observed performance of anchor systems in flat-bedded tanks.



(a) 60 kL tanks with minor evidence of concrete spalling (0.20g hPGA). Note that upon cutting away the skirting for closer inspection, some of the base connections were observed by others to be fractured



(b) Minor damage to base connections and observed diamond buckling of the tanks at varying heights (0.23g hPGA). Note that some of the base connections were observed by others to be fractured

Figure 14: Observed examples of concrete spalling damage near tank skirt and diamond buckling damage in flat-bedded stainless steel tanks.

(a) Diamond buckling at the base of the barrel (note the use of double anchors to strengthen following 2013 earthquakes)

(b) Buckling of the tank shell. This type of damage is also known as "diamond" buckling

(c) Elephant foot damage example 1

(d) Elephant foot damage example 2

(e) Elephant foot damage example 3

(f) Local buckling of the skirt where damage is concentrated at the steel base bracket locations

(g) Local buckling of the skirt where damage is concentrated above the locations of the steel base brackets

Figure 15: Damage to lower portion of flat-bedded stainless steel tanks (0.14g hPGA).

(a) *Complete collapse of slender tanks ('domino effect')*

(b) *Complete collapse of different sized tanks*

(c) *Extreme buckling of tanks and pull out of catwalk support frames (0.23g hPGA)*

(d) *Detail of the base and plinth of a collapsed tank*

Figure 16: Full collapse of tanks.

Collapse

In some wineries complete tank collapse was observed, which was likely a result of excessive rocking and displacement of the tanks. In some cases the collapse of one tank led to a 'domino effect' of the neighbouring tanks. This effect was more likely to happen in cases where full tanks were located adjacent to empty ones (see Figure 16). In some cases full collapse was restrained due to the support provided by the neighbour tanks.

Damage to Tank Insulation Systems

Limited examples of damage to the 'non-structural' insulation layer elements of the tank were observed (see Figure 17).

Racking Systems

Two generations of racking systems were commonly used to store wine barrels. The older racking system consists of a welded steel rack that typically holds two wine barrels (see Figure 18a). These racks are loaded in vertical stacks up to six barrels high, where each rack is gravity supported by the barrels below. The vulnerability of these wine barrel stacks has previously been investigated in detail [21]. The new generation racking system consists of a 4-legged welded rectangular hollow section (RHS) steel frame (see Figure 18b). The individual frames are designed to stack vertically by interlocking the RHS frame legs into one another to create a rigid structure. These racking systems performed well, with some cases of minor sliding on the concrete slab (see Figure 18d). Toppling of upper barrel racks was observed, and in some cases complete collapse of barrel stacking systems (see Figure 18c). It is noted that in observed collapse cases, no wine loss occurred. This damage to barrel racking systems was similar to that observed during the Lake Grassmere earthquake [4].

Catwalks

Catwalks are lightweight structures designed to support light foot traffic in order to provide access to the top level of tanks. Unlike tanks, catwalks must be designed by an engineer and require a building consent. Some catwalks are designed as self-supporting systems where load paths do not rely on adjacent tanks, whereas other catwalks are partially or completely supported by adjacent tanks. Tank-supported catwalks are generally designed as multi-portal frames where the stiff direction (portal frame direction) is usually where the walkway was poorly connected to the tanks. Observed damage to tank-supported catwalks included brittle shear failures of bolts and localised damage at the top-part of tanks due to pounding (see Figures 19, 20).

(a) *Local buckling of the external insulation layer due to buckling of the tank walls*

(b) *Local buckling of external insulation and loss of layers (0.23g hPGA)*

Figure 17: Cases of observed damage to tank insulation.

(a) *Older racking system consisting of welded steel racks*

(b) *New generation racking system showing no damage*

(c) *Collapse of new racking system for wooden barrels (0.14g hPGA)*

(d) *New racking system with no damage but minor sliding at base (0.20g hPGA)*

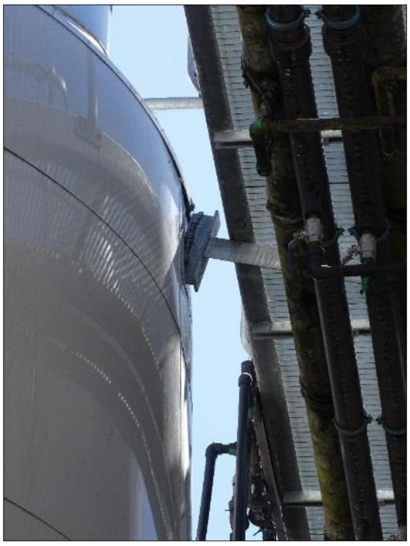
Figure 18: Barrel racking systems.

(a) *Damage to catwalk connection due to tank movement*

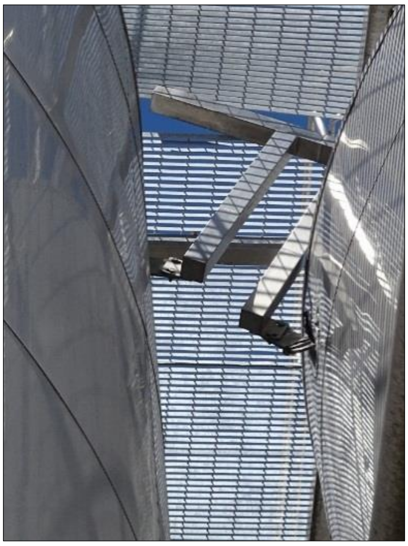
(b) *No damage observed in 60 kL tanks where catwalks were well secured at base*

Figure 19: Performance of tank suspended catwalks.

(a) Tank damage from catwalk punching



(b) Significant bending of catwalk connections



(c) Detachment of catwalk connections

(d) Tank top cone damage due to catwalk

Figure 20: Performance of tank suspended catwalks.

INSTRUMENTATION OF TANKS

Following the Kaikōura earthquake a range of winery facilities in the Marlborough region were instrumented with tri-axial accelerometers to capture seismic excitations during aftershocks. The aim was to instrument a range of storage tanks of varying capacities and supporting systems to better understand the dynamic performance and actual forces experienced up the height of storage tanks during an earthquake.

The tri-axial accelerometer devices used in this study were standalone devices with high sensitivity (±1.25g), 15-bit resolution and a real time clock to allow accurate time stamping of recorded data. All devices were set to a sampling frequency of 128 Hz and equipped with sufficient on-board power supply and storage to allow the continuous collection of acceleration data for the duration of approximately 6 weeks.

Accelerometer devices were securely mounted near the base and top of six different sized storage tanks; with tank capacities (in kL) of 40, 100, 120, 150, 175 and 240. Additional accelerometers were mounted onto catwalk platforms and at the roof height of winery buildings to record the performance of other structural components commonly found throughout a winery. Data was continuously collected from 28 November 2016 to 7 January 2017.

In total, there were approximately 480 separate aftershocks of a magnitude greater than M_W 3.0 in the Marlborough region during the monitoring period. Earthquakes located within 50 km of Seddon during the monitoring period are plotted in Figure 21. The accelerometers recorded at least 40 aftershock events that resulted in medium to significant levels of observed shaking to various winery structures. The largest recorded excitation was during a M_W5.49 earthquake on 4 December 2016, which was located less than 10 km from many instrumented storage tanks. During this M_W5.49 event, the recorded accelerations revealed significant amplifications in acceleration response up the height of many storage tanks. For example, the peak recorded accelerations at the base and top of an instrumented tank (175 kL capacity) were 0.032g and 0.514g respectively in the horizontal direction and 0.128g and 0.323g respectively in the vertical direction, as illustrated in Figure 22. An in-depth analysis of the recorded data is currently being conducted to investigate the true dynamic response of tanks of varying capacities and different anchorage systems. These results will be published in the near future and will include correlations between instrumented data and observed damage.

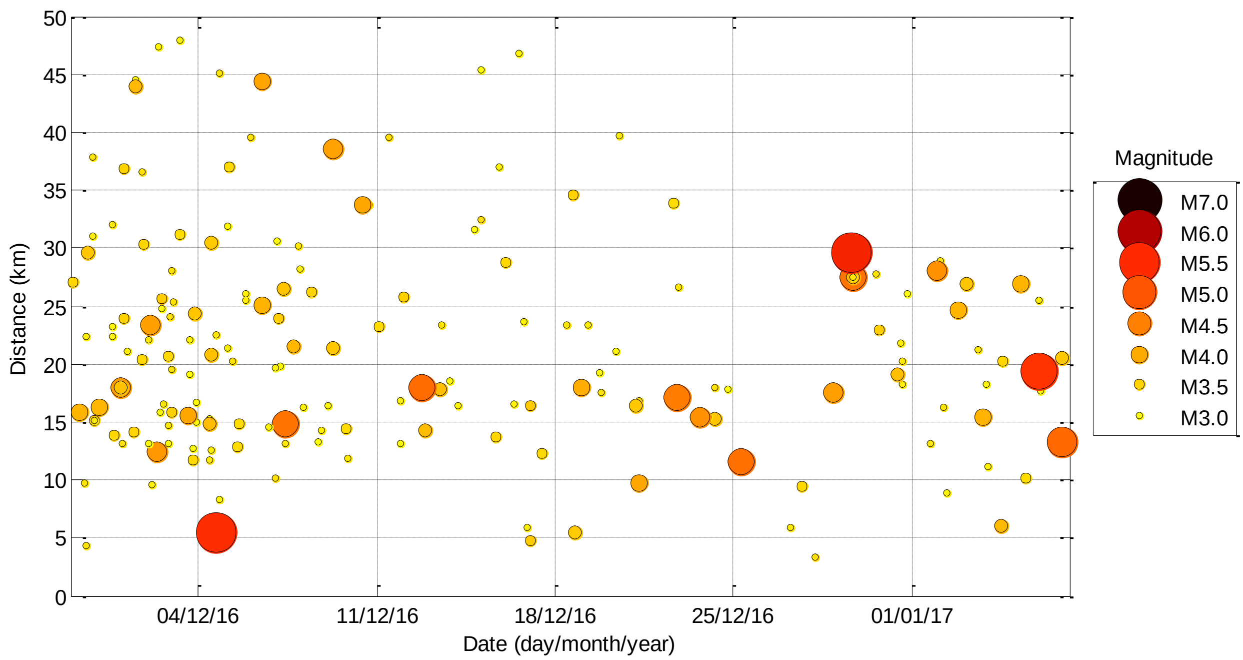


Figure 21: Magnitude of aftershocks within 50 km of Seddon, Marlborough, during the monitoring of winery facilities (from 28/11/16 to 07/01/17).

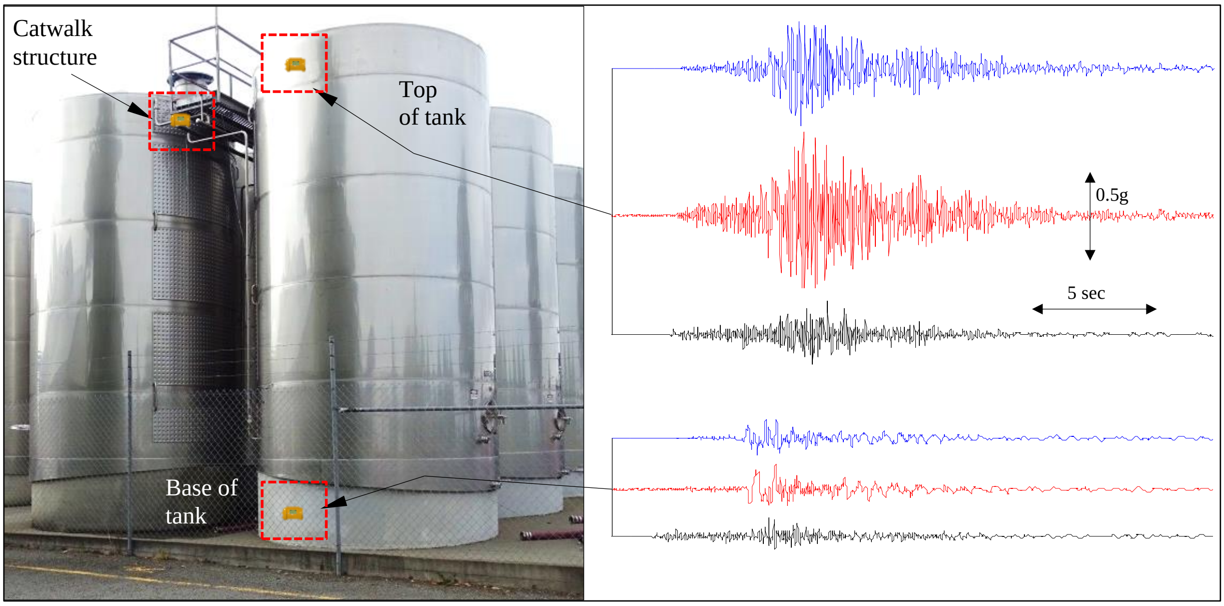


Figure 22: Illustration of accelerometer devices mounted at the base and top of a storage tank, and on the supporting catwalk structure. Recorded accelerations during the M_W5.49 earthquake on 4 December 2016 at the top and base of a 175 kL storage tank in the horizontal directions (blue and red) and vertical direction (black) are plotted.

SUMMARY AND CONCLUSIONS

Damage to winery facilities in the Marlborough region following the 14 November 2016 Kaikōura earthquake is reported herein. Conclusions based upon these observations are as follows:

- New Zealand Wine reported that the volume of wine loss amounted to approximately 2.0% (estimated at 5.3 million litres) of Marlborough's total production.
- New Zealand Wine initially estimated that 80% of tank capacity in Marlborough was undamaged, and that approximately 20% had been impaired to some extent.
- It was estimated that there are at least 1,000 tanks that sustained damage and that at least 150 of these damaged tanks are unrepairable.
- Observed performance of tanks varied depending on tank typology (legged tanks and flat-bedded tanks), tank capacity and whether the tank was empty or full.
- Damage to legged tanks was generally concentrated at the base frame support with partial tank collapse observed in some cases.
- The extent of damage to flat-bedded tanks (larger in terms of storage capacity) was more widely observed compared to legged tanks. Damage was observed to various tank elements such as buckling of the stainless steel shell, creasing of the top cone, localised buckling of the tank skirt and damage to anchorage rods and bolts.
- Wine loss was observed in extreme cases, such as when tank wall perforation and tank collapse occurred.
- Damage to other infrastructure such as catwalks and thermal tank insulation was observed.

- The 2016 Kaikōura and 2013 Cook Strait earthquakes had different characteristics (duration, intensity) but in general tanks performed similarly with a limited number of cases where different tank performance was observed.
- Tanks on plinths had a large variety of failure modes, mainly due to apparent inconsistencies in design, and inconsistent quality of installation and construction.
- Some repairs and retrofits conducted following the 2013 Cook Strait earthquake did not improve tank performance because other failure mechanisms were triggered or damage was relocated elsewhere within the tank.

Further effort is required to better understand appropriate techniques for design and securing of liquid storage tanks, and these techniques need to be communicated to the professional engineering community.

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