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

Post-earthquake recovery phase of winery facilities. A case study in the Marlborough area

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ABSTRACT

New Zealand wine export reached a record of NZ$1.7 billion in 2018. It constitutes an important sector of the economy of the country. Approximately 70% of New Zealand wine is produced in the Marlborough region. In recent years, this area has been subjected to a number of seismic events including the M_w 6.6 Cook strait and the M_w 6.6 Lake Grassmere earthquakes in 2013, and the M_w 7.8 Kaikōura earthquake in 2016. After the Kaikōura event, New Zealand Wine estimated that about 20% of the wine tank capacity was impaired. In 2018, repairing works on wine tanks and winery infrastructures were still underway reducing the total tank capacity and potentially impacting the wine production.

Following an overview of damage observations of winery facilities after the 2016 Kaikōura earthquake, this paper discusses the recovery phase currently underway. The performance of wine storage tanks and other winery facilities is analysed and discussed. Preliminary results from a case study show that in late 2018, the winery has recovered approximately 85% of the original functionality and interviews with winery managers highlighted that delays in the replacement of failed tanks and repair of moderately damaged tanks might be attributed to some extent to the insurance process. It is forecast a 90% recover by the 2019 harvest. Temporary and permanent mitigation strategies are critical to this recovery and some solutions are herein presented.

1 INTRODUCTION

On the 14th November 2016, a M_W 7.8 earthquake struck near Kaikōura on New Zealand's South Island east coast. The largest measured peak ground accelerations (PGA) were 1 g (horizontal) and 2.7 g (vertical) (Bradley, Razafindrakoto, & Ahsan Nazer, 2017). Damage was observed to buildings and infrastructures

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including roads, bridges and industrial facilities such as wineries (NZSEE Special Edition, 2017). One of the regions most affected was Marlborough. The region is the largest wine producer of New Zealand, accounting for over 75% of the country's total wine production (New Zealand Winegrowers Inc, 2018). The wine industry is considered one of the most successful sectors in the country's economy, exporting $1.7 billion (NZD) worth of wine in the 2017-2018 financial year, making it New Zealand's sixth largest export . In the Kaikōura 2016 event, it was estimated that 20% of Marlborough's tank capacity was damaged to some extent ("NZ wine industry plans for Vintage 2017 after Kaikoura Earthquake," 2016). Approximately 10% of the pre-earthquake capacity was unrepairable which equated to 40 million litres of the 2017 vintage and (Dizhur et al. 2017). It should also be noted that due to the time of year the earthquake occurred, many wine tanks were empty, so the level of damage was not as high as it may have otherwise been. Therefore, given the importance of the wine production industry to New Zealand's economy, ensuring that the process infrastructure, such as the storage tanks, piping systems and catwalks, is seismically resilient, is a high priority.

The paper aims to briefly overview the damage observed in the winery facilities after the 2016 Kaikōura earthquake with focus on the performance of tanks which appeared to be the most vulnerable component of the production chain. Implications of structural deficiencies on their functionality and mitigation strategies are discussed by analysing a representative case study of the Marlborough tank portfolio.

1.1 Earthquake damage from Past Earthquakes

Damage of wine industry facilities has been recorded over the last 40 years in the largest wine producing countries: New Zealand, Chile, Italy, United States, and Argentina (Brunesi, Nascimbene, Pagani, & Beilic, 2015; Dizhur et al., 2017; González, Almazán, Beltrán, Herrera, & Sandoval, 2013; Manos, 1991; Swan, Miller, & Yanev, 1985; Zareian et al., 2012). Table 1 lists five of the largest seismic events that have caused major damage to wineries from 1977 and the prevalent failure modes observed.

During the 1977 San Juan (Argentina) event, widespread tank damage was reported, mostly due to anchorage failure and tank-wall buckling (Manos, 1991). Anchorage failure was very common during the 2010 Maule (Chile). Post-earthquake assessment showed that the cause of damage was mainly due to lack of redundancy and poor seismic design (González et al., 2013).

The Kaikōura earthquake highlighted the different performance between tanks on legs (usually with a capacity of 50,000 Litres or below) and tanks on plinths (> 60000 Litres). Although the latter were subjected to a variety of damage mechanisms due to the inconsistencies in design and quality in the construction and installation phase, their performance was better than tanks on legs. In fact, tanks on legs sustained more substantial damage and their repair was more complex. This led to wineries moving away from legged tank structures in favour of plinths in order to try and mitigate future damage as per discussion with several practitioners involved in the repairing phase.

Reconnaissance of winery facilities after seismic events show that the prevalent wine tank failure modes can be categorised in four main failure modes: top cone damage, wall buckling including damage to access opening, anchorage and secondary structures failure (Figure 1 and Figure 2). Deformation of the top cone tanks is caused by wine sloshing. This causes an upward force up against the top of the tank deforming the cone. The moving fluid also changes the pressure within the tanks which can cause a pressure difference with the outside ambient pressure. The pressure difference can cause the top cone to be sucked [Figure 2(A)]. Often damage involves failure of secondary structures such as catwalks and pipes. The catwalks are lightweight structures either fixed to the tank or free standing. Fixed catwalks are connected by a sliding connection to the top of the tanks that allows for movement between the tank and catwalk. Free standing catwalks are independent structure, with a gap between them and the tank, allowing for tank displacement without hitting the catwalk. Issues arise when the earthquake produces tank displacements greater than the sliding connection gap allowance. In such cases, the catwalk can pound against the top of the tank. Damage from the catwalk can be seen in [Figure 2(B)].Wall buckling consists of inelastic deformation of the thin layer of stainless steel that constitutes the tank wall and comprises of two types: diamond buckling [(Figure 2(C)] and elephant foot [(Figure 2(D)].

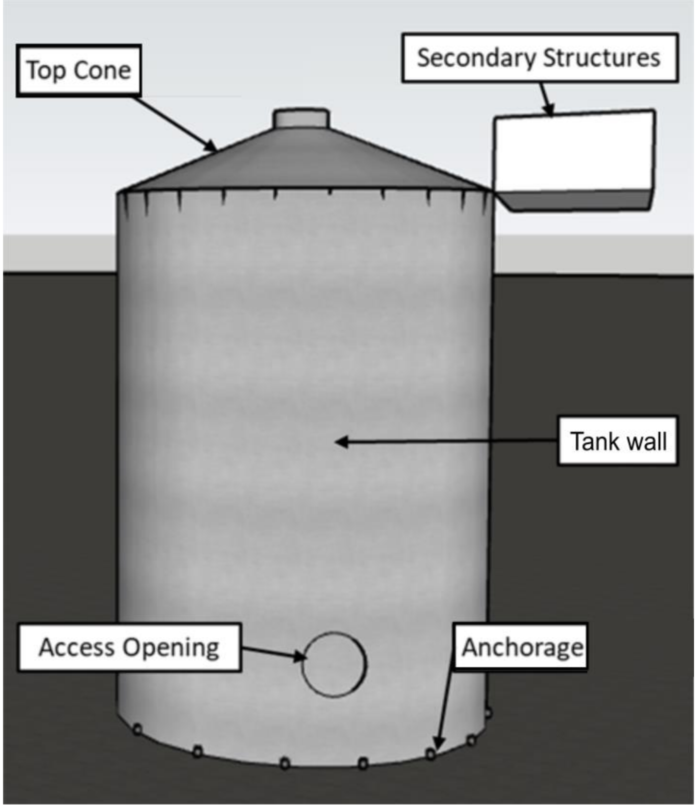

Figure 1: 3-Dimensional model of a typical wine tank.

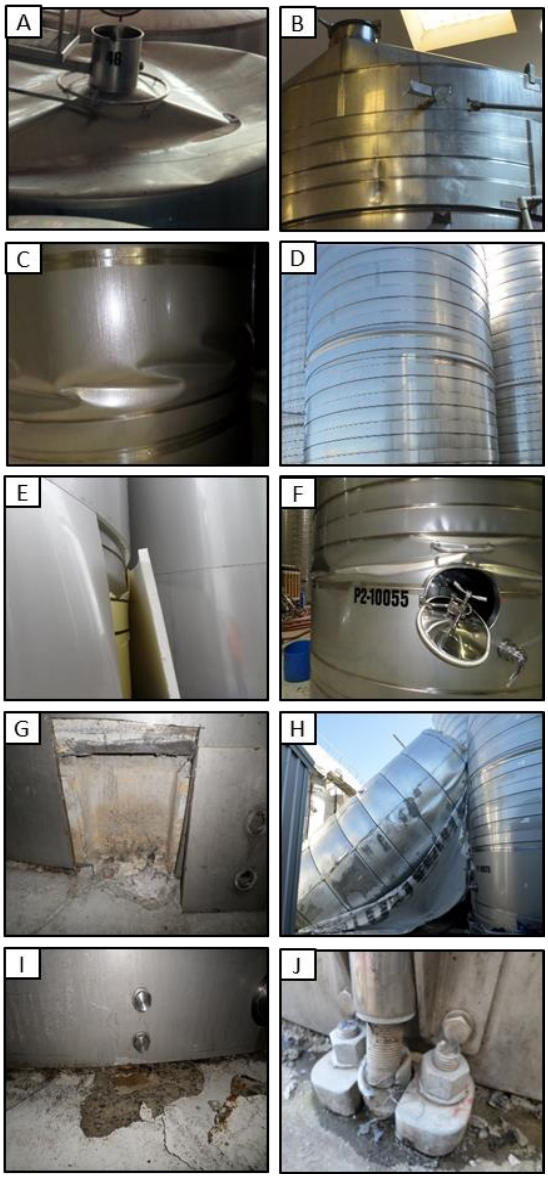

Figure 2: Main failure modes of wine tanks; (A) top cone damage; (B) secondary structure damage to tank; (C) Diamond bucking; (D) elephant foot buckling; (E) Panel failure; (F) stress concentrations causing bucking around access opening; (G) Anchor rod fracture; (H) Tank collapse; (I) concrete spalling around anchor; (J) anchor failure (thread stripping) (Photos courtesy of Structex)

Diamond buckling assumes a diamond pattern and is caused by high axial compression forces on the slender walls of the tank. On the other hand, elephant-foot buckling is an outward bulge caused by vertical compressive stresses higher than the yield limit of the steel wall. In the case of insulated tanks, buckling may cause the panels to separate from the tank as seen in Figure 2(E). Also, openings and penetrations in the tank walls cause discontinuities that can lead to stress concentrations in these areas. The stress concentrations can be much greater than that in the rest of the tank, local buckling can occur as seen in Figure 2(F). Another very common failure mechanism observed was the damage of the bolts connecting the tank to the foundations, known as anchorage failure. Three main failure modes were observed: rupture [Figure 2(G)], pull out and stripping thread [Figure 2(J)]. Rupture can be either in tension or compression from the bolt yielding in the tension cycle then in the compression cycle the bar can buckle or fracture. If the bar does not fracture in the compression cycle, in the next tension cycle, the yielding limit may be exceeded, causing fracture of the steel anchorage. Pull out failure occurs when usually the concrete foundation is thin (around 200 mm or similar) and the post-installed anchors do not develop enough development length. The failure mechanism can result in full pull-out or spalling of concrete around the top of the bolt as seen in [Figure 2(I)]. Bolt failure might also occur when the thread at the top of the bolt strips, causing the loss of the hold down ability (Hamdan, 2000).

Table 1: Prevalent failure mechanism in the past seismic events.

Earthquake	**Observed failure modes**
San Juan, 1977 (M7.4)	Anchorage failure, elephant foot buckling and complete collapse of tanks
Greenville, 1980 (M5.8)	Elephant foot and diamond buckling
Morgan Hill, 1984 (M6.2)	Anchorage failure, elephant foot and diamond buckling and secondary structure damage
Maule, 2010 (M8.8)	Anchorage failure, elephant foot and diamond buckling, top cone damage and collapse of tanks
Kaikōura, 2016 (M7.8)	Anchorage failure, elephant foot and diamond buckling, and global tanks collapse

1.2 Functionality curves

Wine facilities are complex systems and each component structural and non-structural has strong interdependencies. Assessment and mitigation strategies must be prioritized to maximise the overall resilience of the production line. A functionality curve over time is a key indicator to measure resilience. It can be used to represent the recovery time of the system after a seismic event or to calculate a resilience factor which is given by the integration of the area under the curve divided by the recovery time. (Bruneau et al., 2003). Cimellaro, Reinhorn, and Bruneau (2010) have proposed three main recovery functions depending on the system and society response: linear, exponential and trigonometric (see Figure 3). The exponential relationship, which is the most desirable, as it maximises the area under the curve, was applied to healthcare facility systems (Cimellaro et al., 2010). Functionality curves are used to assess the resilience of a system as they show the time necessary to return the system to its original (or better) level of functionality. Functionality curves can also highlight factors that contribute to a potential slow recovery and in fact the time between the event and full recovery is called the downtime. The length of the downtime can be attributed to different factors (e.g. damage assessment, slow repair works, insurance claim litigation). These curves have not been validated against wine facilities and the authors aimed to investigate if the analytical expressions can be extended or slightly modified to the purpose.

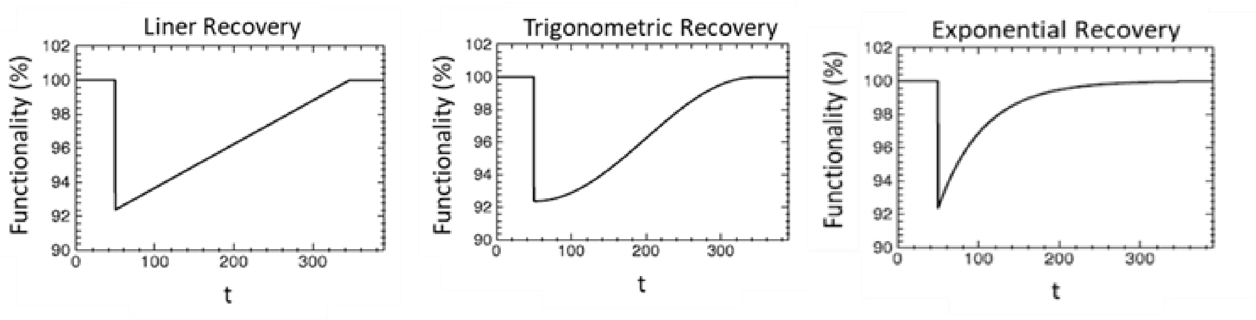

Figure 3: Three main functionality curve relationships. (Cimellaro et al. 2010).

2 CASE STUDY

As a case study, a winery in the in the Marlborough area was selected. The case study is representative of a medium-size winery in the area, the total wine capacity of the winery was approximately 15 million litres. The winery suffered damaged in the most recent Kaikōura earthquake as well as during the 2013 Cook Strait earthquake.

2.1 Damage survey

Initially, a damage survey of the winery was conducted and limited to tanks only. Data was collected from the winery engineering manager and the engineering consultant involved in the assessment/mitigation process. They were organised in four categories depending on the level of damage severity:

- Unrepairable: for tanks that collapsed
- High: for tanks with severe buckling
- Medium: for tanks with minor buckling or major bolt failure
- Low: for tanks with minor bolt failure or concrete spalling

In Figure 4, a simplified layout of the tanks in the three production halls (PH) of the winery is represented. The production halls do not have the same wine capacity. PH 1, PH2, and PH3 have a capacity of approximately 10%, 40%, and 50%, respectively. The different colours (red, orange, yellow, and green) identify the severity of the damage in each tank. The damage mechanisms recorded in the winery, organized per number of tanks subjected to that specific failure mode are summarised in Table 2. The most common failure mechanism was the damage of the anchorage at the bottom of the tanks. However, in most cases this was easily repairable by replacement of the bolts or reinstatement of the spalled concrete. In this case, the tanks are still fully operational. On the other hand, buckling of the tanks, including elephant foot, diamond and wall buckling, substantially limited the operability of the tanks. The repairing phase required the tanks to be completely empty and the damaged area to be removed and replaced with new material. Often, buckled tanks had to be removed from the location to be repaired off-site. This caused logistics problem; in fact, in the case of tanks located in the middle of a row, the front tanks had to be removed (even if not damaged), to have access to the damaged tanks. In some cases, damage of the anchorage then led to wall buckling, as the tanks were free to rock, creating higher compression forces in the walls.

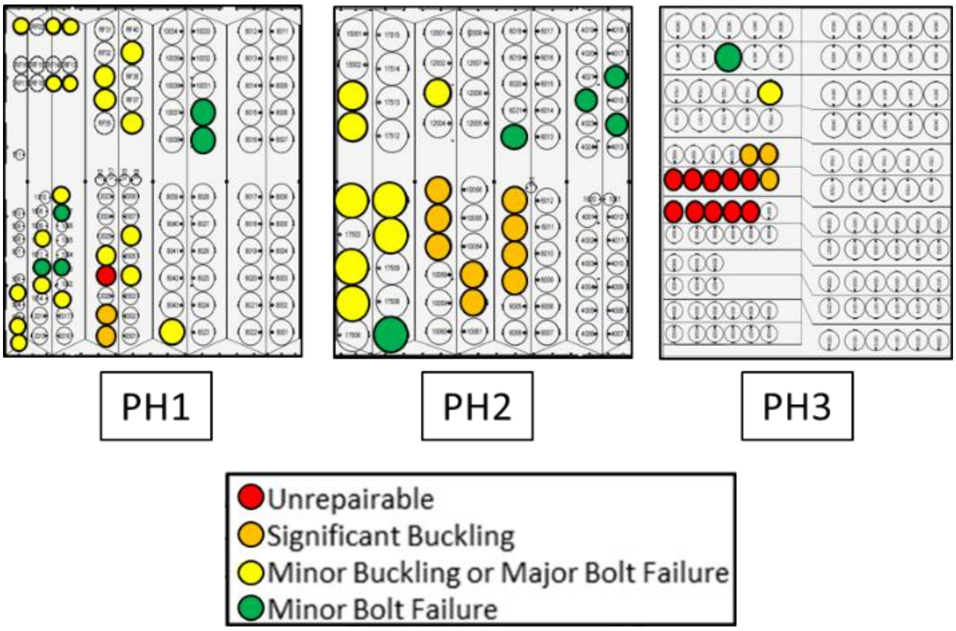

Figure 4: Winery layout and severity of damage to the tanks (Courtesy of Structex)

Table 2: Summary of tank damage by failure mode.

Failure mode	**Number of tanks**
Bolt failure	20
Elephant foot buckling	17
Diamond buckling	19
Secondary structure damage	0
Top cone damage	0
Complete collapse	12

2.2 Recovery timeline

The information collected during the interview with the winery manager was used to develop the winery repair time and establish the cause of any delay. The repair timeline was derived in terms of percentage of time taken for inspections, insurance claim, temporary and permanent repairs. An empirical functionality curve was developed (see Figure 5). It was assumed that before the seismic event, the winery was at full production capacity. However, during that period, repairs from the 2013 Seddon earthquake were still being carried out. From there, the Percentage of Full Capacity (PFC) lost after the 2016 Kaikōura earthquake was calculated. The information displayed in Table 3 was used to develop the empirical functionality curve plotted in Figure 5. Each point was added to the graph when repairs were completed and consequently the PFC increased. Further repairs are forecast up to the 2019 harvest season. The graph demonstrates that three production halls (PH1, PH2 and PH3) did not suffer the same amount of damage. Also, it must be noted that the difference in capacity of the production halls is taken in account. PH3 suffer the least damage, compared to PH1 and PH2. This may be attributed to the fact that PH3 was recently built (approximately 5 years ago). On the other hand, as it houses the largest tanks, there has been a minimal increase in functionality. Conversely, PH1 lost the highest PFC, but as the tanks are smaller and more economical to repair or replace, PH1 will have the total capacity available by the 2019 harvest season. Although, this production hall only counts for 10% of the total winery capacity. Finally, PH2 is the worst combination of the other two halls, being old and having larger tanks, hence the large loss of PFC and also the slowest recovery time.

The empirical functionality curve shows that there was a rapid recovery in the first four months after the earthquake. However, there has been very little improvement in capacity since. This is because the bulk of the repairs done were short term repairs designed to recover capacity for the 2017 harvest with more permanent repairs to be designed after the harvest period. At this stage, the winery is aiming to be at 90% PFC by the 2019 harvest. This means that after two years the winery has been able to recover 34% of its capacity of the initial 47% wine capacity loss.

Table 3: Timeline of repairs for the whole winery until the 2019 harvest.

Date	**Percent of full capacity (PCF), %**	**Reason**
November 2016	53	Kaikōura
January 2017	78	Short term repairs on 5k, 100k, 120k, 150k, and 175k Litres tanks
March 2017	82	Repair of 38k Litres and replacement of 20k and 80k Litres tanks
April 2017	83	Repair of 13k Litres
November 2018	88	Repair of 100k Litres tanks
December 2018	90	Repair of the remaining 38k Litres tanks
March 2019	90	Harvest

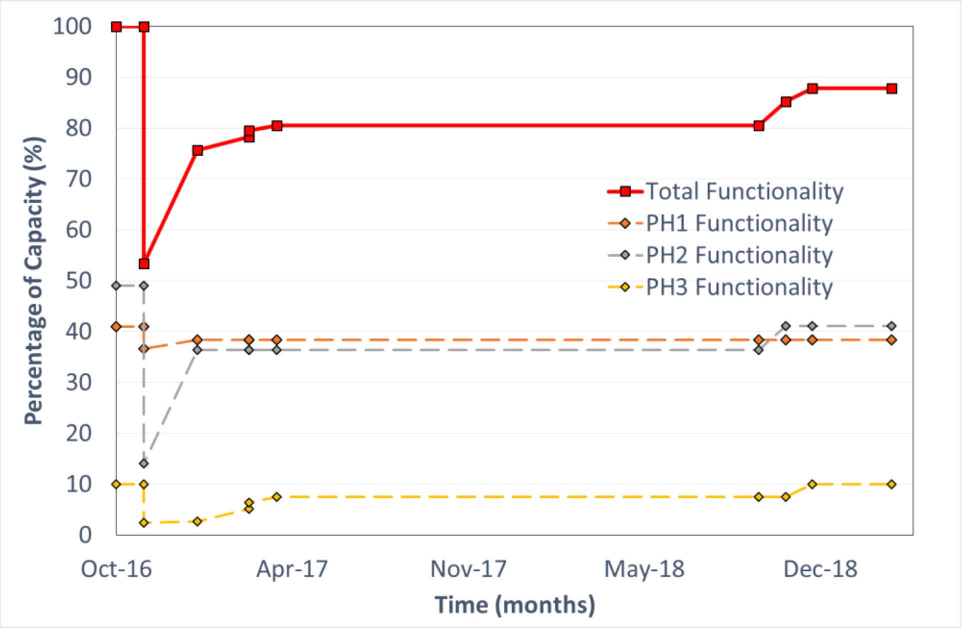

Figure 5: Empirical functionality curve developed for the case study

Given the nature of the repairs, the exponential model proposed by Cimellaro et al. (2010) seemed to be the best fit to the empirical curves. Results showed that the analytical expression underestimates by almost 20% the recovery transition to 90% capacity (Figure **6**). This model does not take in account the delay caused by the insurance litigations. The recovery function is best represented by a series of exponential functions for each repair phase: an initial exponential relationship that corresponds to the initial temporary works carried out to respond to an immediate/short-term emergency; a plateau, which is the negotiation period with the insurance; and a final exponential relationship corresponding to the permanent works.

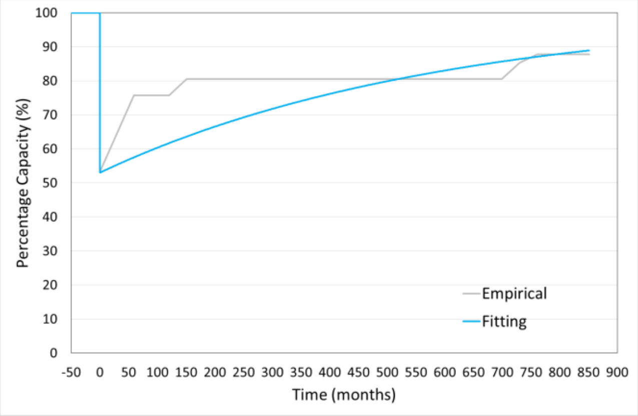

Figure 6: Analytical fitting of the empirical recovery function

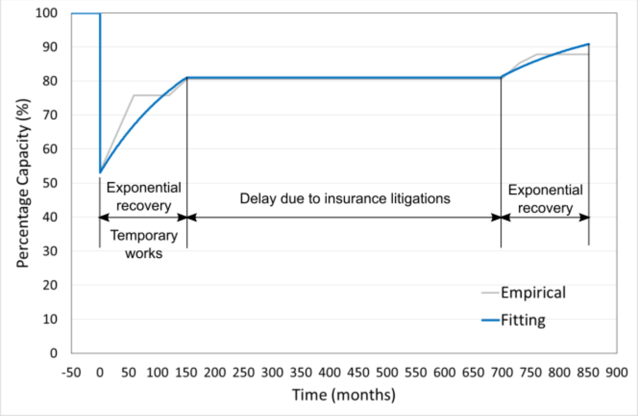

Figure 7: Analytical fitting of the empirical recovery function

There are many factors behind the progress of the recovery. The recovering time attributed to each of them is shown in Figure **8** as a percentage of the total time since the earthquake. A large percentage, 59%, of the delay was caused by the insurance claim litigation (this mostly corresponds to the flat section in Figure 5). Tank assessment and design of repairs was the second contributor to the recovery time (28%). On the other hand, temporary works only took 18% of the total recovery time. Delays during repairing were also caused by the accessibility to tanks in the middle of groupings. It was not practical to get equipment in between the tanks in order to be repaired. This means that the majority of the damaged tanks in the middle of groupings of undamaged tanks have yet to be repaired.

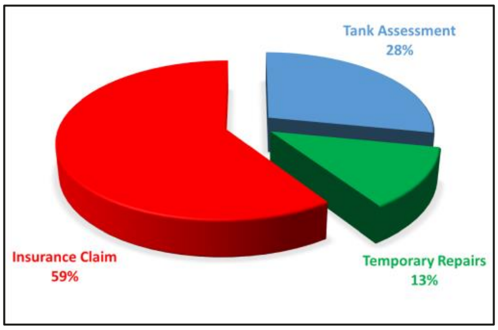

Figure 8: The amount of time each recovery factor took as a percentage of the total time.

3 MITIGATION OPTIONS

Mitigation strategies can aim to reduce the risk of damage and therefore increase the reparability.

The majority of wine tanks in New Zealand have been designed to Importance Level 1, based on NZSEE (2009). One approach to mitigating risk is to design tanks to Importance Level 2, which will increase the design load, and hence, increase the level of seismic acceleration at which damage will initiate.

External tank farms allow for tanks in the centre of a row to be craned out and replaced, which is not generally possible for tanks inside a building. Additionally, catwalks and services that are supported independently of tanks allow for easier removal of tanks. While mitigation strategies should aim to prevent severe damage to tanks that would require them to be replaced, this is an outcome that should be considered.

Finally, a capacity design approach will limit damage to a specified component (usually a yielding pin between the tank and concrete slab) which can be replaced following a seismic event. Tank walls are designed for the overstrength of the anchorage, which prevents buckling of the walls. Anchors designed for cyclic loading (yielding in tension and compression) were demonstrated to perform well in the earthquake, while tension-only anchors still allowed damage to tank walls as they introduced a ‘slackness’ on subsequent cycles following the initial yield. A similar capacity design approach could be applied to tanks supported on base frames.

One such example that demonstrated good performance in the 2016 Kaikōura earthquake was a locally designed seismic anchorage system (Figure 9 and Figure 10). This is an anchor welded to the base of the tank and connected to the concrete slab foundation. The anchor contains a yielding mechanism, restrained against compression buckling, so is able to yield in tension and compression. All other components, including tank walls, skirt, connections and concrete adhesive anchorage are designed for the overstrength force of the anchors, so do not sustain damage as the anchor yields (Sarti, Palermo, & Pampanin, 2016). Following an earthquake, the yielding mechanism is easily replaced. Advantages of this system is that it limits damage to one defined replaceable component, so cost of repairs is very low compared with repairing damaged tank walls. The yielding mechanism is a stock component of a particular size, so can be directly replaced without the need for a drawn out assessment and repair design, and the replacement is quick and simple. The yielding mechanism replacement is carried out on site without the need for removing tanks, so can be done for tanks located anywhere in the winery. The disadvantage of this system is the higher cost compared to a simple tension-only anchor.

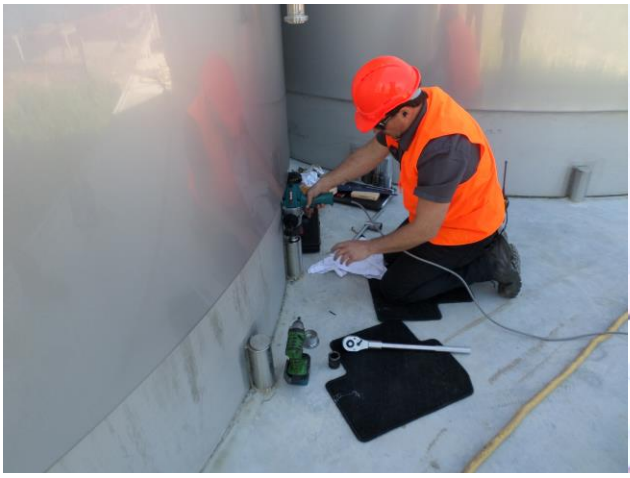

Figure 9: Removing the yielding pin mechanism of the seismic anchorage system

Figure 10: Measuring the diameter to check yielding of the seismic anchorage system

4 CONCLUSIONS

Wine facilities are complex systems and given the nature of the repairs, the existing functionality curves present in literature cannot be adopted. However, the authors demonstrated that, through some minor modifications, special ad hoc analytical expressions can fit well the empirical curve.The advantage of these systems is that temporary repair can be achieved quite effectively and speeds up the recovery phase during the first four months after the event; this allowed the main wine producers to cope with the 2017 vintage season. The specific case study here analysed lost approximately 47% of total tank capacity but recovered up to 90% after two year after the earthquake occurred.

Novel and smart permanent mitigation strategies such as tension-compression yielding device can drastically increase the overall resilience of the tanks. However, it appeared that an increase of Importance Level and a more comprehensive standard will be as highly beneficial to reduce claim litigation and therefore reduce the overall recovery time.

5 ACKNOWLEDGMENTS

The writers would like to thank the winery for agreeing to partake in the case study.

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