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IMPLEMENTING A HOLISTIC DUCTILE DESIGN APPROACH TO STAINLESS STEEL WINE STORAGE TANKS

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Abstract

The M_w6.6 Lake Grassmere earthquake on the 16th of August 2013, located near Seddon, Marlborough, New Zealand, caused significant damage to the stainless steel wine storage tanks, and associated infrastructure, at many of the wineries in Marlborough, the largest wine producing region in New Zealand. As well as costly damage to tanks, significant volumes of wine were lost and disruption to operations continue today as repairs are undertaken.

This damage highlighted many deficiencies in the tanks design and fabrication, and exposed an apparent knowledge gap between the New Zealand Society for Earthquake Engineering (NZSEE) 2009 guideline *Seismic Design of Liquid Storage Tanks* and its implementation into the wine industry. The NZSEE document for tank design appears to lack specific guidance to deal with the subtle nuances of the wine industry and the wine tank configurations which are commonly used in wine regions around the world.

This paper summarizes the common types of damage observed following the earthquake and provides indications of likely causes. It goes on to discuss improvements that can be made to current design thinking to minimize the risks of such failures. Finally, this paper outlines anchoring systems and holistic design methods recently developed by New Zealand consulting structural engineering firm Structex in the form of the Onguard seismic tank system. The Onguard system is now widely utilised in New Zealand and being installed in California. This system utilises ductile and capacity design approaches to protect the tanks and their valuable contents, using a yielding element that is easily replaceable following a large seismic event, minimising disruption to the winery.

Keywords: wine, tanks, stainless steel, liquid storage

1. Introduction

1.1 Marlborough Wine Industry

Marlborough is an internationally recognized wine growing region with an annual production on the order of 250 million litres from approximately 150 wineries, which contributes 70-80% of New Zealand's total active wine production [1]. The New Zealand wine industry as a whole contributes over $1.5 billion to the country's GDP and supports over 16,500 full-time equivalent jobs (NZIER 2009) [2].

Production facilities are distributed across the Marlborough region, though clusters of larger facilities are located near the Riverlands and Cloudy Bay business parks and many smaller facilities around Renwick.

Each production facility consists of a range of infrastructure including buildings, storage tanks, catwalks, grape presses, barrels and various plant and services, all of which have varying degrees of susceptibility to seismic events and given the significant contribution of the industry to the local and wider economy, the risk of damage to infrastructure and loss of product is something that should not be ignored. This is particularly true of the tanks which are relatively tall structures, providing storage for each years' vintage.

1.2 Wine Tank Construction

The tanks are usually arranged in parallel rows with similarly sized tanks placed adjacent to each other. Catwalks are usually installed in a double-loaded corridor fashion to permit efficient access to the top of every tank. Piping containing product, water, refrigerants and other services, run throughout the banks of tanks, and is often installed directly under the catwalks.

The tanks are constructed of Type 304 stainless steel sheet metal given its excellent hygiene and corrosion resistant properties. The support structures for the thin-walled stainless steel tanks most commonly used in Marlborough can generally be separated into two categories; smaller 5,000 to 60,000 litre leg-mounted tanks and larger 60,000 to 300,000 litre plinth-mounted tanks. This paper focuses on the plinth mounted tank types that are now more commonly used and viewed more favorably in the region. An indicative tank is shown below in Fig.1.

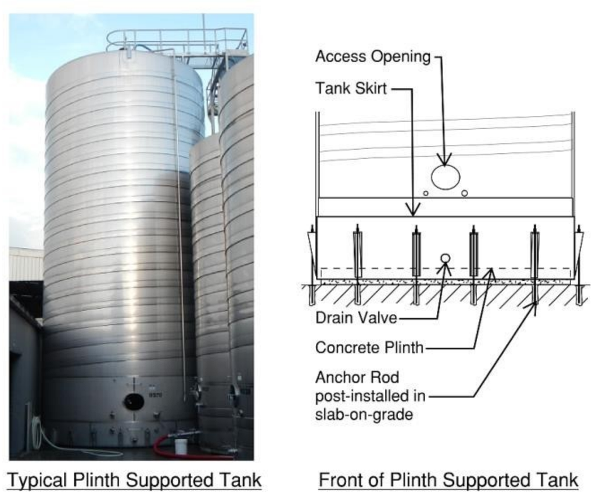


Fig.1 – Typical Plinth Supported Tank (Rosewitz & Kahanek)

These stainless steel tanks sit on a reinforced concrete plinth with a thin layer of insulation between the plinth and the tank. A "skirt" of stainless steel extends below the base of the tank and sits either on the concrete floor slab, or is suspended slightly above. The plinth is typically poured within a mould and tied to the concrete floor slab, although more recent construction techniques see the plinth poured once the tank is in place, using the skirt of the tank as permanent formwork. Where the plinth is constructed prior to the tank being lifted into place, a small (10-40mm) gap exists between the plinth and the skirt to accommodate construction tolerances.

Fabricated brackets (anchor chairs) are welded to the tank skirt at regular centres around the perimeter and are used to fix in place anchors that are epoxied or grouted into the slab. The anchors for these tanks are often fabricated from stainless steel threaded bar and feature a length (approximately 150mm) of reduced diameter through their mid-section. The intent behind reducing the anchor diameter is to promote yielding of the anchor with an even strain distribution such that there is a desirable hierarchy of strength that ensures the protection of other components based on a capacity design approach. It should be noted, however, that these anchors cannot resist compression forces, and that therefore once they have yielded and elongated in tension they are unable to provide resistance to subsequent earthquake cycles until the tank has lifted sufficiently to accommodate the slack in the system. (The authors have observed in other international wine regions such as the USA, that it is common practice to provide no ductility in the anchorage system; tanks are often welded directly to steel plates embedded in the concrete plinth.)

The tank walls (barrels) are typically surrounded by refrigerant lines. Newer tanks are surrounded by a helix of stainless steel parallel flange channels welded continuously to the side of the barrel walls. The barrels are also often surrounded by a layer of insulation and a thinner "second skin" of stainless steel.

The typical tank base consists of rows of sheet metal laid flat and sloping toward the drain. Base sheet metal thickness is uniform and typically varies between 2 mm and 3 mm based on the tanks size. Many bases have a downward indention at the drain described as a "gullet" to allow for complete removal of the contents. The base is typically connected to the barrel wall by cold rolling its edge upward and then either butt welding or fillet welding it to the bottom strake of the barrel. This important detail, known as the "knuckle," has a constant radius that varies based on the thickness of the base sheet metal.

In order to access the tops of the tanks for inspection and winemaking processes, a series of tanks are often fitted with lightweight steel catwalks and access man-ways. The catwalks are supported either by cleats welded to the tank wall or by a separately constructed frame. Some modern facilities use floating catwalks which slide over the tanks during ground motion excitation, or in some cases the catwalks are supported on support frames completely independent of the tanks. For the first catwalk type, the connection between the catwalk structure and the supporting elements are often slotted with the intention of providing some construction tolerance. In most cases, the underside of the catwalks is connected to services such as glycol and wine distribution pipes.

2. Marlborough Earthquake

2.1 Earthquake Setting

On 16 August 2013 at 2.32pm local time, a moment magnitude M_w6.6 earthquake occurred beneath Lake Grassmere, approximately 30 kilometres south-east of Blenheim. The rural communities of Seddon and Ward, both within 10 kilometres of the earthquake rupture source, represented the worst hit regions [3].

Fig.2 illustrates the horizontal and vertical ground motions that were recorded in the Marlborough region during the 16 August 2013 Lake Grassmere earthquake. It can be seen that the strongest shaking was observed in Seddon and Ward, with the strongest portion of the shaking lasting in the order of 10-15 seconds. Notably weaker shaking was observed in Blenheim and the Wairau Valley.

Fig.3 illustrates the larger component response spectra of the observed ground motions in the Marlborough region in comparison to the NZS1170.5:2004 design response spectrum for Z=0.4 (the representative value for Seddon and Ward, while Blenheim has Z=0.33) and a Return Period Factor, R_u, of 1.0. It is the understanding of the authors that the majority of tanks in Marlborough are designed for lower levels of shaking using Importance Level of 1, corresponding to an R_u of 0.5

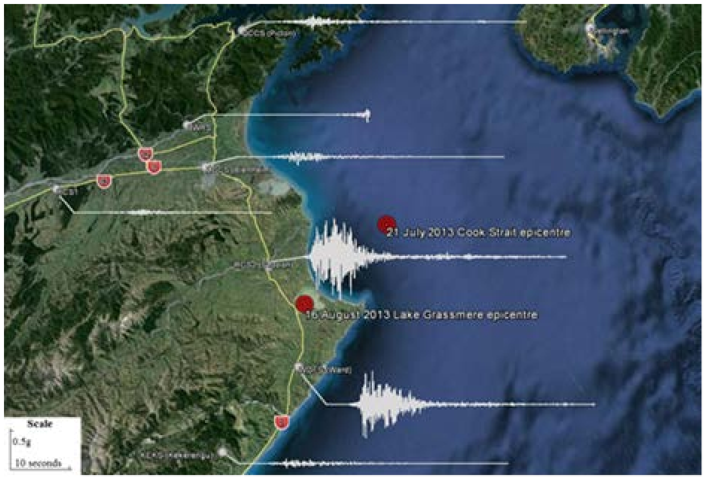


Fig.2 - Acceleration time histories observed in the Marlborough from the 16 August 2013 Lake Grassmere earthquake. (Source: Morris et al. 2013)

It can be seen that shaking in Seddon (i.e. RCS2) and Ward (i.e. WDFS) significantly exceeded the site class C design spectrum for vibration periods less than 0.3 seconds. For periods greater than T=0.3s the spectral amplitudes in Ward rapidly reduce (due to very shallow soil overlying rock), while the spectrum in Seddon exceeds the design spectrum for periods beyond T=1.0s. As previously noted, the ground motion amplitudes in Blenheim and the Wairau Valley can be seen to be significantly smaller than those in Seddon and Ward, and well below design levels.

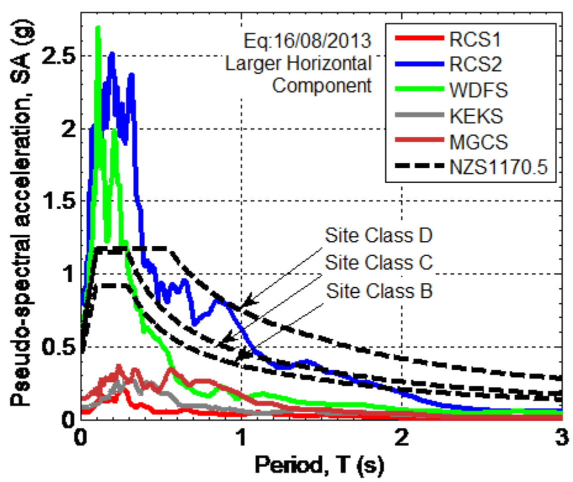


Fig.3 - Larger horizontal response spectra recorded at strong motion stations in Marlborough during: (a) the 16 August 2013 Lake Grassmere earthquake. (Source: Morris et al. 2013)

There are two pre-dominant modes of tank response contributing to seismic demands that are transferred through the tank walls, connections and support structures (base mounts or steel legs). For tanks with a high aspect ratio the impulsive mode is dominant as a larger portion of constrained fluid contributes to the inertial mass. For tanks with small aspect ratios the convective mode (sloshing of tank contents) is dominant, which is more sensitive to long-period ground motion. The majority of wine tanks are completely filled and sealed at the top meaning the response is dominated by the impulsive mode and thus the periods are relatively low.

2.2 Earthquake Damage

No casualties were reported and only a few cases of moderate non-critical injuries were sustained. While ground shaking in the Marlborough region was severe, the population density is relatively low and the distribution of structural forms is quite different to larger urban areas such as Christchurch and Wellington. A large proportion of the region's non-residential structures are used for the purposes of agriculture and viticulture and consequently numerous water storage dams and wine storage tanks suffered various levels of damage. In the near-source region, damage to residential housing, roads and bridge structures was found to be moderate. Details of the damage are detailed further in Morris et al. 2013 and Rosewitz & Kahanek [4].

2.2.1 Tank Damage

Various damage states to plinth-mounted tanks in the 16 August earthquake included:

- Anchor failure in the form of anchor fracture, anchor yielding, pullout through the epoxy, or concrete cone failure as shown in Fig.4 (a)-(e).
- Lateral movement on the plinth, leading to bending of anchors.
- Settlement of tank around the plinth (illustrated in Fig.5) due to deformation of the tank floor across the gap between tank skirt and plinth. In rare instances tank deformation was sufficient to rupture the tank floor at the knuckle, resulting in loss of product. In cases where hold-down anchors had a nut to the underside of the chair and could receive a compression demand, this mechanism frequently lead to the buckling of anchors.
- Localized stress to tank skirt associated with poor distribution of anchors around the tank (Fig.4 (f)).
- In extreme cases, buckling of tank walls, both in elephant's foot and diamond shaped buckling modes (reference Fig.4 (g-h)). The elephant's foot buckling appeared to be constrained by the coolant bands. Buckling appears to have occurred when the tank settled so far down the plinth that the skirt makes contact with the slab forcing the tank wall to resist excessive compressive loads.

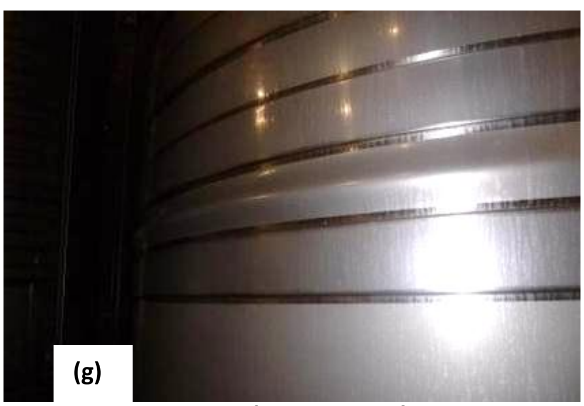
Some older tanks were simply fixed by a number of bolts drilled horizontally into the plinth around the perimeter of the skirt. Shear failure of the majority of bolts fixed into the plinth had occurred at some facilities.

A number of older tanks were not fixed to the slab with any form of anchor and these appear to have performed well. It is likely that the large mass of the wine provided a re-centering force to resist overturning and the relatively thick walls (compared to modern designs) were sufficient to resist the compressive forces. It is anticipated that the lack of anchorage led to larger than expected deflections and that while these tanks performed well in these events, they are exposed to a notably higher risk of failure in larger seismic events.

2.2.2 Catwalks and Services

In the direction along a row of tanks, the cleat orientation is such that bending about the plate's weak axis results in cleat flexibility. Some distortion of plates was observed, however, there was no evidence of connection failure due to displacement in this direction. Across two rows of tanks, in the orthogonal direction, the connections are often stiffer and some displacement induced failures have been observed where the tolerance of the slot has been used up and bolts have failed in shear. Other examples of catwalk damage included the distortion of box-type cleats that are welded to the tank wall.

Anchorage failure by pullout, bolt tensile fracture and bolt shear failure



Elephant's foot buckling of tank

Diamond shaped buckling

Fig.4 (a-h) -Various damage observations for plinth mounted wine storage tanks.

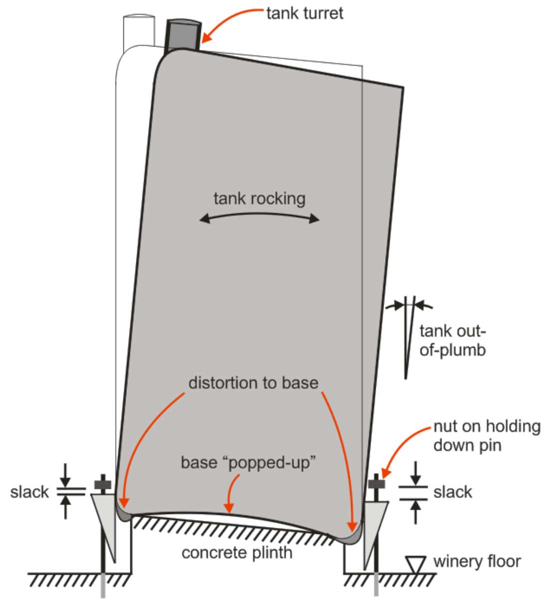


Fig.5 - a characteristic damage state for plinth mounted tanks is tank settlement and "knuckle-squash" at the tank floor (Source: Morris et al. 2013)

2.2.3 Key Learnings

The observations presented in this section should provide an increased awareness of the types of damage states for stainless steel tanks used for wine storage. The following sections of this paper discuss the history of tank design in New Zealand and present further detail on how the design process can be modified in light of these post-earthquake lessons, culminating in the presentation of the Onguard anchor system, which utilizes ductile and capacity design approaches and incorporates anchor hardware that has the ability to resist cyclic earthquake forces to protect the tanks and their valuable contents. Future considerations for new design, or the repairs of existing tanks, and associated infrastructure may include:

- Acceptance of tension-only yielding anchors' lack of ability to withstand cyclic loading.
- More reliable ductility provided by anchors may be achieved by using mild steels or equivalent. Measures would also have to be taken to mitigate corrosion issues.
- Replaceability of anchors or other yielding elements.
- Eliminating potential tank settlements around the plinth by better consideration of load paths and improved awareness of potential increases in compressive loads in the tank walls.
- Improved specification and monitoring of epoxy anchors. The occurrence of this failure both in Marlborough and previously in Gisborne has highlighted a potential area of improvement.
- Better consideration of likely displacements in catwalk design

3. Basis of tank design in New Zealand

Definitive standards for the seismic design of wine storage tanks in New Zealand (i.e., directly referenced by the New Zealand Building Code) do not exist [5]. The seismic loading standard for structures (NZS1170.5) specifically excludes liquid storage tanks from its scope [6]. In lieu, the New Zealand Society for Earthquake Engineering (NZSEE) 2009 guideline *Seismic Design of Liquid Storage Tanks* [7] guidance document provides excellent procedures for determining design actions and analyzing the performance of tanks. This document provides information that is consistent with changes in legislation, the NZS1170.0:2002 targeted performance criteria [8], and the NZS1170.5:2004 seismic design actions.

This guideline document references the American Petroleum Institute 650 [9], NZSEE *Recommendations for Seismic Design of Storage Tanks* (known as the "Red Book") (1986) [10], and Crawford *Standard Seismic Resistant Details for Industrial Tanks and Silos* (1990) [11]. The latter of these references reviewed relevant guidelines for tank seismic design including the Red Book and API650, making recommendations for several aspects of tank design, including appropriate ductility factors for different anchorage types and details to resist seismic overturning.

Whilst the NZSEE document is assumed to be utilized in the design of tanks for the New Zealand wine industry, there is a lack of specific guidance that work with the nuances of the wine industry and the common tank configurations which are used.

The scope of NZSEE (2009) guidance is rather broad and appears to cover a wide range of tanks and configurations, including steel and concrete tanks, vertical or horizontal cylindrical tanks, rectangular tanks, elevated tanks and tanks on grade, anchored and unanchored tanks, sealed tanks and tanks where the contents can slosh.

Tanks used for wine storage in New Zealand form a much smaller subset, the typical construction of which has been described previously. Methods used to anchor plinth-mounted tanks are wide ranging, and include shear bolts anchored into the plinth through the tank skirt, or necked and un-necked tension bolts epoxied into the slab that are connected to the tank via brackets/chairs, which themselves vary in configuration.

For vertical cylindrical steel wine tanks, the NZSEE (2009) document provides excellent guidance for determining seismic design actions in accordance with NZS1170.5. It considers the convective (sloshing) mode, rigid and flexible impulsive modes, and provides design charts and worked examples for choosing the respective modal periods, masses, mass heights and damping. Guidance is given to the designer on appropriate ductility factors depending on the tank configuration, anchorage and critical failure mechanism. Prescriptive guidance is given for combining said modes and resolving the actions into base shear and overturning moment.

As wine tanks are usually sealed, the convective mode is usually constrained and the total wine mass acts in the impulsive mode. Whilst the guidance document mentions this, little explanation is given for how modal mass heights are to be increased to account for the full mass acting in the impulsive mode. This is left to the designer to interpret and apply in a rational manner.

At a tank design level, good guidance is given for determining and checking hoop and bending stresses in the tank wall, and checking vertical wall stresses against diamond-shaped and elephant's foot (elastic-plastic) buckling. For wine tanks which are sealed, a method is provided for determining the impact loads on the roof cone from the constrained sloshing. However, no method is given for assessing the strength of the roof cone for resisting such loads. For this, the designer will need to refer elsewhere, such as API-620 (2008) [12], or undertake software-assisted 3-dimensional shell analysis.

For the design of hold-down anchors, equations are provided to calculate tensile demands based on an anchor force distribution which is dependent on the chosen ductility. Beyond this, the designer is left to design the anchor and connection to the tank based on the computed demand and applied overstrength (if applicable).

For the design of foundations, the guidance document conceptually covers site investigation, strength reduction factors for soil, and special ground cases (e.g. slope stability and liquefaction). Although not in-depth, much of the expectation is the same as for normal building structures.

The NZSEE recommendations state a 50-year design life should be adopted but the selection of Importance Level is open to the designer with some guidance on appropriate selection. From the author's experience, many tanks in Marlborough have been designed to an Importance Level 1 in recent years. Ductility factors of up to μ=2.0 are permitted in the NZSEE recommendations.

3.1 Design Recommendations

Despite the availability of the NZSEE (2009) guidance document, damage observed in the 2013 Seddon earthquakes highlighted many design deficiencies, and there is a clear need for better wine tank design. There appears to be a knowledge gap between the use of the NZSEE guideline and its implementation into the wine industry. This section outlines some of the loadpaths and mechanisms, not explicitly covered by the NZSEE document, which should be checked as part of the seismic design of wine tanks.

3.1.1 Point bearing reaction and transition zone

For plinth-mounted tanks with ductile hold-down anchors, NZSEE (2009) allows a ductile elastic anchor force distribution to be assumed, as shown in Fig.6. This creates a compressive point reaction at the tip of the tank and a loadpath must be provided to resist this. The magnitude of this point reaction, R, is given in equation 1.

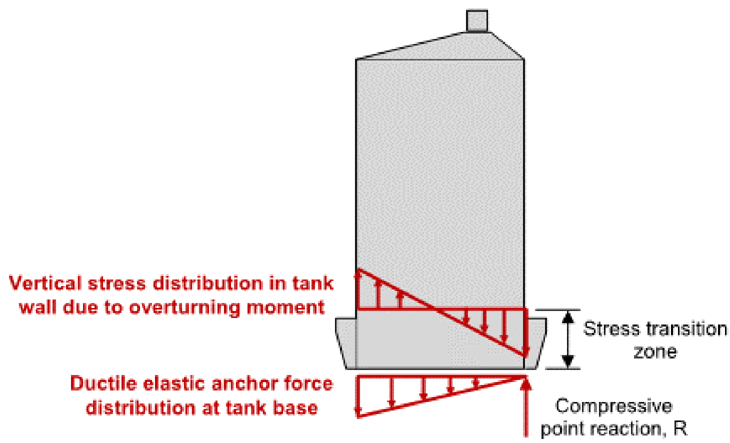


Fig.6 - Stress distribution in tank wall and at base for tanks with ductile hold-down anchors (Source: Au et al. 2015)

If the loadpath is provided by continuing the tank skirt down to the slab, the skirt and concrete bearing must be appropriately checked to prevent buckling of the skirt or bearing failure of the concrete slab. If chairs are being relied upon to transfer some of this reaction, local buckling above the chair should also be considered.

Further up the tank, NZSEE (2009) assumes an elastic flexural stress distribution in the tank walls, as shown in Fig.6. It then follows that there must be a transition zone between this and the base of the tank where the stress distribution changes to the ductile elastic anchor force distribution. It makes sense that the increased axial compression in the tank wall above the compression reaction also be considered.

3.1.2 Shear transfer to plinth

For plinth mounted tanks, shear transfer from the tank to the plinth must be considered. Typical mechanisms include friction between the tank floor and plinth, and hoop stress within the skirt if the plinth is constructed so that it bears against the skirt. If the tank floor is sloped, the effect of this should be considered as part of the shear-friction mechanism, as friction resistance will reduce when shear is directed away from the slope.

3.1.3 Shear transfer to slab

Similarly, shear transfer from the plinth to the slab should be considered, as often the plinth is cast separately from the slab. Typical mechanisms include shear friction, with additional assistance from shear dowels epoxied into the slab and cast within the plinth. Recently the authors have seen hold-down anchors with baseplates, which may also provide shear resistance to the plinth.

In theory, some shear may be transferred via the compressive point reaction, similar to a reinforced concrete shear wall, provided the skirt has sufficient out-of-plane support. Further research and guidance would be helpful on this.

3.1.4 Hold-down anchors

In the New Zealand wine industry, most hold-down anchors are post-installed, as opposed to cast into the slab with anchor plates. Wine tanks are typically arranged in lines of double-rows, with drains and walkways between each double row.

Due to the proximity of adjacent tanks, there is interaction between the tank and foundation slab, which means that hold-down anchors will generally be located within the tension zone of the slab during the earthquake (Fig.7). At this location, the concrete is likely to crack which will affect the performance of epoxied anchors. This should be considered in the design of the hold-downs, and the slab should be appropriately designed so that expected crack widths do not compromise the integrity of the anchors. Overseas guidance within the last decade, such as EOTA (2007, 2013a, 2013b) [14, 15,16] have included the design of epoxied anchors within cracked concrete.

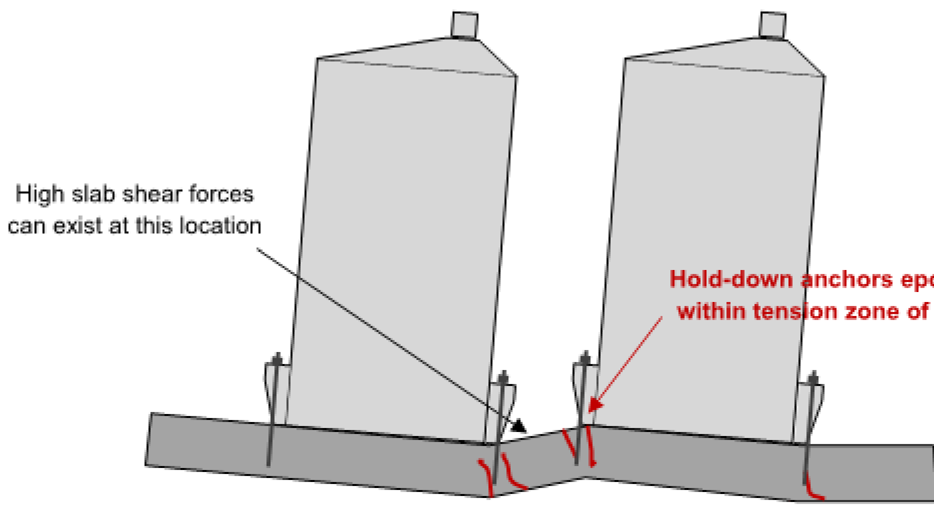


Fig.7 – Wine Tank and foundation slab interaction (Source: Au et al. 2015)

Where hold-down anchors are connected to the tank via brackets/chairs, the prying actions induced from the eccentric connection onto the skirt should be considered. The authors have typically used 3-dimensional shell analysis to determine the expect shell bending and membrane stresses induced. Often compensating plates welded to the skirt are required.

Wine makers generally prefer narrow slender tanks as this better suits the winemaking process and maximizes the efficient use of available floor space. The strength of epoxy anchors generally limits wine tanks in Marlborough to a height to radius ratio of around 4.5, when designed as an Importance Level 1 structure. If designed to a higher level, the tank will generally need to be squatter.

3.1.5 Foundation Slab

Foundation slabs need to provide adequate hold-down against overturning and limit soil bearing to suit site conditions. In addition, any design actions from interaction between adjacent tanks should be considered.

As illustrated in Fig.7, there can be large shear forces in the zone between adjacent tanks. From the authors' experience, shear reinforcement is often required for larger tanks. In addition, the Concrete Structures Standard, NZS3101:2006 [17], requires minimum shear reinforcement to be provided in slabs thicker than 400mm, where the shear force exceeds half the design shear strength provided by the concrete.

3.1.6 Catwalks and Services

Catwalks and services attached to tanks should be connected with sliding joints such that tanks can move laterally independently of each other without the introduction of force transfer between tanks.

Where catwalks are supported by tanks, it follows that the catwalk will have the same seismic design importance level as the tank, and this should be discussed with the winery. For catwalks which are frequently used, higher design importance levels than is typically used for tanks may be appropriate. Options include supporting the catwalks on a separate structure or increasing the design level of the supporting tank. But note the latter may require the tanks to be squatter which has further implications on the tank cost, foundations, wine making and land use.

The foundation slab, tank, catwalks and services are often designed and installed by different parties, and performance issues can arise from a lack of coordination between them. These issues are best dealt with good project management at the beginning of the project, in consultation with the winery.

3.1.7 Roof Cone

Typical roof cones of wine tanks in New Zealand do not appear to have the stiffening girders or large radius knuckles to provide the compression rings described in API-620 (2008). As a result, extensive crumpling of roof cone knuckles was observed in Marlborough following the 2013 Seddon earthquakes. To the authors understanding, no rupture of the knuckle was observed and there was no loss of contents as a result. Further guidance on acceptable performance levels in this area for wineries would be beneficial for the industry.

4. Proprietary performance-based systems

In response to the damage observed to wine tanks following the 2013 Marlborough earthquake the team at Structex, a consulting engineering firm based in Christchurch, New Zealand, have developed the Onguard seismic tank anchor system.

The anchor system integrates a necked anchor that carries load under both tension and compression with a replaceable element. The necked anchor allows a ductile response to be used in the tank design and the determinable overstrength demands are used to apply a capacity design approach to the other components such as the tank walls, tank skirt, and epoxied fixings into the slab, with reserve capacity above overstrength actions.

Unlike the necked wine tank anchor system traditionally found in New Zealand tanks and the welded bracket system traditional in the USA – which only work in a one-pull tension manner – Onguard anchors provide both strength and stiffness in tension and compression to resist cyclic earthquake loads.

The Onguard system is now widely used in new and retrofit tank installations in Marlborough and being implemented in the USA.

5. Conclusion

The NZSEE (2009) guidelines for the seismic design of liquid storage tanks provide excellent procedures for determining design actions and analyzing the performance of tanks. However, given the wide scope of the document, there is a lack of guidance that deals with the wine tank configurations commonly used in New Zealand Wine Industry. This is apparent from observed damage to wine tanks in Marlborough following the 2013 Seddon earthquakes.

There are loadpaths and mechanisms that need to be considered in wine tanks' design, which are not explicitly covered by the NZSEE (2009) guidelines. These include compressive point bearing reactions from overturning, shear transfer to the plinth and slab, prying actions on the skirt where external hold-down chairs are used, foundation shear and the influence of cracks on epoxy anchors, adequate detailing of steel base-frame connections and effects from attached catwalks and services.

Proprietary anchorage systems are now available that give engineers more reliable design procedures and are intended to address the need for increased earthquake performance rather than meeting minimum strength-based design requirements. One such system - the Onguard system - is now widely used in Marlborough and being implemented in USA. This system integrates a ductile yielding mechanism with a replaceable element to allow a capacity design approach to be used in design to exclude damage to other components of the tank and helps minimize disruption to a winery following a major seismic event.

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