Wine industry implementation of the NZSEE guidance on the seismic design of liquid storage tanks

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ABSTRACT: The New Zealand Society for Earthquake Engineering (NZSEE 2009) *Seismic design of liquid storage tanks* guidelines provide excellent procedures for analysing the seismic performance of tanks and determining design actions. However given the wide scope of the document, there is a lack of specific guidance that deals with the subtle nuances of the New Zealand wine industry and the wine tank configurations which are commonly used. The recent 2013 Seddon earthquake sequence resulted in significant damage to wine tanks and associated infrastructure, highlighting many deficient design details resulting from poor design. There is an apparent knowledge gap between the use of the NZSEE guidance and its implementation into the wine industry. This paper summarises the types of damage observed and provides indications of likely causes. This information goes on to outline loadpaths and mechanisms which should be checked to provide a robust wine tank system, introducing some aspects which are not explicitly covered by the NZSEE guidance.

1 INTRODUCTION

The seismic assessment and design of liquid storage tanks is not well covered in the New Zealand loadings and materials standards. In lieu, the New Zealand Society for Earthquake Engineering (NZSEE 2009) guidance document provides excellent procedures for determining design actions and analysing the performance of tanks.

Whilst the NZSEE document is assumed to be utilised 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 recent 2013 Seddon earthquake sequence resulted in significant damage to wine tanks and associated infrastructure, highlighting the inadequacy of many design details common in the industry.

The New Zealand wine industry contributes over $1.5 billion to the country's GDP and supports over 16,500 full-time equivalent jobs (NZIER 2009). Thus the seismic risk posed by poor tank design is not something that should be ignored.

This paper begins by briefly describing aspects of wine tank design that the NZSEE (2009) document covers well. This is followed by a summary of damage observed to wine tanks in Marlborough following the 2013 Seddon earthquake and the common design deficiencies which caused them. The paper then finishes by describing the load-paths and mechanisms that are not explicitly covered by the NZSEE document, which should be considered in the seismic design of tanks for the New Zealand wine industry.

2 COVERAGE OF NZSEE (2009) GUIDANCE DOCUMENT

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. Wine tanks are generally sealed vertical cylindrical tanks, with height to radius ratios on the order of 3-5, and constructed from 2-6mm thick stainless steel. Smaller 5,000-60,000 litre tanks are typically supported on mild steel base-frames, with or without diagonal bracing (Figure 1), and with the frame feet either fixed to the slab or left unbolted. Larger 40,000-270,000 litre tanks are typically mounted on concrete plinths, and usually anchored to the slab. Methods used to anchor plinth-mounted tanks are wide ranging, and include shear bolts anchored into the plinth through the tank skirt (Figure 2a), 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 (Figure 2b-f).

(a) Diagonally-braced base-frame

(b) Un-braced base-frame

Figure 1. Examples of base-frame mounted tanks.

For vertical cylindrical steel wine tanks, the NZSEE (2009) document provides excellent guidance for the 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), 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).

(a) Shear bolt anchors (b) Chair mounted un-necked tension anchors


(c) Chair mounted un-necked tension anchor (d) Chair mounted un-necked tension anchor


(e) Chair mounted necked tension anchors (f) Chair mounted necked tension anchors

Figure 2. Examples of plinth-mounted tank anchorages.

For elevated tanks mounted on base-frames, the NZSEE (2009) document does not make much comment on the design of the supporting frame. Once seismic design actions have been obtained, a frame should be able to be designed in accordance with good engineering practice and the New Zealand steel structures standard, NZS3404:1997. In spite of this, deficient base frame details have managed to emerge, as will be seen in the following section.

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.

Given the wide scope of the document, it is understandable that it would not cover all the subtle details which are unique to the wine industry and the tank configurations which are used. Subtle differences in liquid-storage tanks which are unique to each industry need to be carefully evaluated using basic engineering principles and judgement.

3 OBSERVATIONS FROM THE 2013 SEDDON EARTHQUAKES

Damage observed to wine tanks in Marlborough following the 2013 Seddon earthquakes have been well-documented by others (Morris, Bradley, Walker, Matuschka 2013), but are described again herein to highlight the importance of detailing on seismic performance, and the subtle details which need to be considered with wine tanks.

3.1 Damage to plinth-mounted tanks

Typical damage observed to plinth-mounted tanks included:

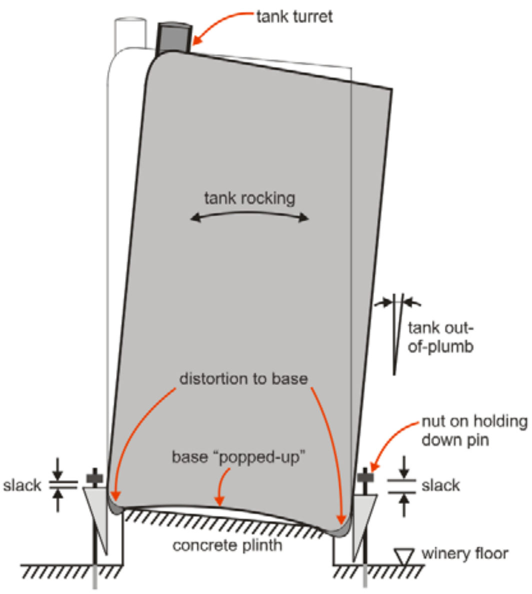
- Tensile anchor bolt failure, whether by steel fracture, pull-out through the epoxy, or concrete cone failure (Figure 3a). Concrete failure modes occur when the anchorage has insufficient capacity to develop the overstrength of the steel cross section. Steel fracture occurs when the material has insufficient ductility for the displacement demand, which may occur with tension-only anchors when an event larger than the chosen design level occurs (described later in section 5).
- Shear failure of shear bolts (Figure 3c).
- Lateral sliding of the tank on top of the plinth, leading to bending of hold-down anchors (Figure 3d). For older wine tanks, there can be a 20-80mm gap between the tank skirt and concrete plinth to provide tolerance for the construction method used. As such, the only available shear mechanism between the tank and plinth is friction between the tank floor and plinth. When this is exceeded, sliding occurs.
- “Knuckle-squash” (also referred to as guttering of the knuckle) as depicted in (Figure 3e), which occurs due to a lack of a complete engineered loadpath. Tension anchors provide hold-down to resist overturning. Conversely, there is a compression reaction on the opposite side which must be resisted. In cases where the tank skirt did not bear on the slab, this loadpath did not exist and rocking of the tank resulted in deformation of the knuckle. In cases where hold-down anchors had a nut to the underside of the chair and could take compression, anchors buckled resulting in milder-deformation of the knuckle.
- Diamond-shaped or elephant foots’ wall buckling (Figure 3b), which occurs due to insufficient wall thickness to resist axial wall stresses.
- Local skirt damage. In the case of Figure 3f, the skirt did not extend to the slab and the loadpath for the compression reaction was via the hold-down chair. The skirt had insufficient thickness or support to resist the concentration of stresses, resulting in local buckling around the chair.

(a) Combined concrete cone-pull-out failure

(b) Buckling of tank wall

(c) Steel shear bolt failure

(d) Lateral sliding on top of plinth



(e) Illustration of "knuckle-squash"

(f) Local buckling of skirt

Figure 3. Examples of damage observed to plinth-mounted tanks (Source of figures d-f: Morris et al. 2013).

3.2 Damage to base frame-mounted tanks

Typical damage observed to base frame-mounted tanks included:

- Bending of legs for un-braced frames (Figure 4a). Where frames are un-braced, they are required to act as moment-resisting frames to resist lateral loads. However, often beam to leg joints were not detailed to act as fully-rigid connections.
- Buckling of braces for braced base frames. In these cases, braces were too slender to resist the applied loads (Figure 4b).
- Bending of adjustable feet (Figure 4a). Winery floors are often sloped to provide drainage. To accommodate this, base frame-mounted tanks often have threaded adjustable feet. These connections were observed to act as weak points leading to failure.
- Fracture or damage to welded-straps/tags connecting the tank to the base frame. For ease of construction, often the base frame perimeter did not align with the tank wall, such that tags ended up being welded to the curved knuckle of the tank. This created an eccentric loadpath which resulted in fracture of the weld or deformation of the knuckle. In some cases, damage was sufficient to rupture the knuckle resulting in a loss of contents.

(a) Bending of un-braced leg (b) Buckling of braces

Figure 4. Examples of damage observed to base frame mounted tanks (Source: Morris et al. 2013).

3.3 Attached catwalks and services

In the New Zealand wine industry, catwalks and piped services are often supported off wine tanks. In some cases, these secondary structures were rigidly fixed to several tanks, creating an unintentional loadpath between tanks. Resulting force transfer between tanks often resulted in local damage at catwalk to tank connections.

4 DESIGNING TANKS FOR THE NEW ZEALAND WINE INDUSTRY

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.

4.1 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 Figure 5. 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. Further allowance will be needed for overstrength if a capacity design approach is used.

$$R = \frac{8M_{OT}}{6D} + W_{rw} \tag{1}$$

where M_{OT} = overturning moment; D = tank diameter; and W_{rw} = total weight of tank roof and wall.

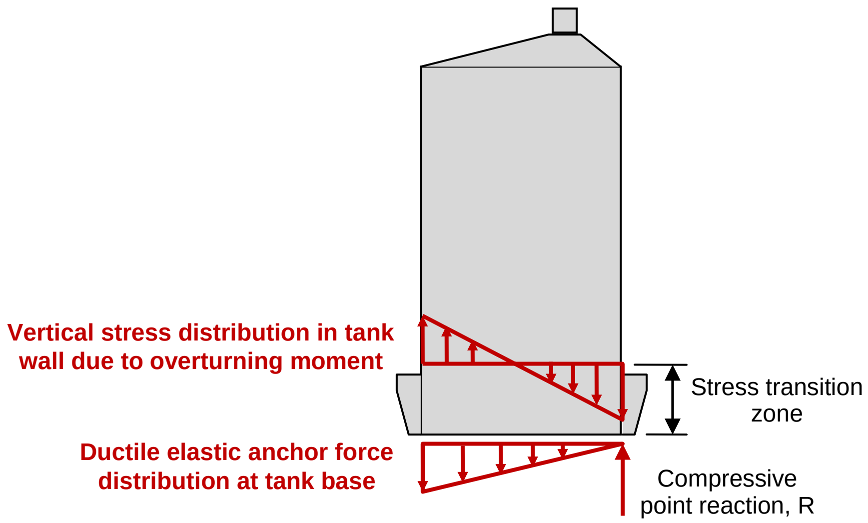


Figure 5. Stress distribution in tank wall and at base for tanks with ductile hold-down anchors.

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 to avoid that seen in Figure 3f.

Further up the tank, NZSEE (2009) assumes an elastic flexural stress distribution in the tank walls, as shown in Figure 5. 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.

4.2 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.

4.3 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.

4.4 **Hold-down anchors**

In the New Zealand wine industry, tanks are often relocated to suite winery expansions or reconfigurations. Because of this, most hold-down anchors are post-installed, as oppose 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 (Figure 6). 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 cracks widths do not compromise the integrity of the anchors. Overseas guidance within the last decade, such as EOTA (2007, 2013a, 2013b), have included the design of epoxied anchors within cracked concrete.

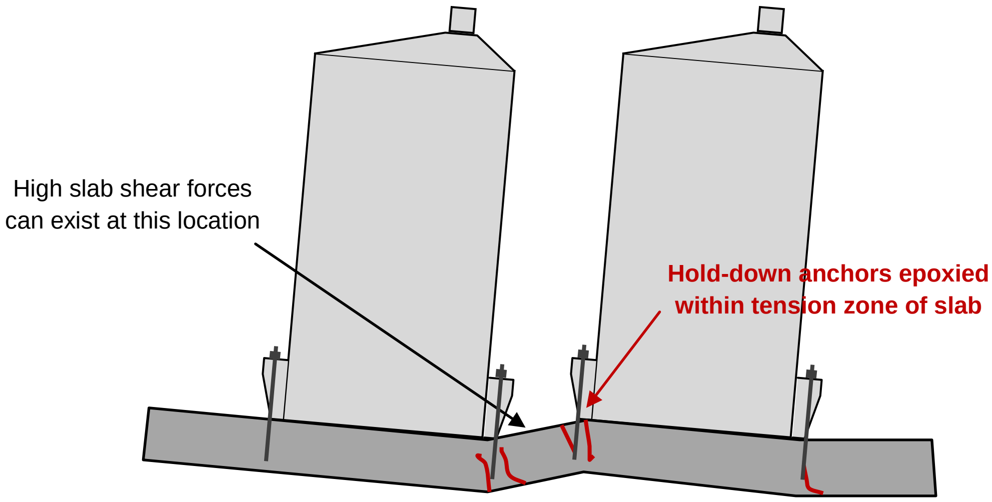


Figure 6. Wine tank and foundation slab interaction.

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 suits the mixing and fermentation process. 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.

4.5 **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 Figure 6, there can be large shears 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, 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.

4.6 **Steel base-frames**

Steel base-frames should be designed for the seismic loadcase which includes both gravity and earthquake actions simultaneously. The authors have come across existing tanks, where member sizes are just sufficient for the gravity loads, suggesting that lateral earthquake loads had not been considered.

Where frames are required to act as moment-resisting frames to provide lateral resistance, connections need to be appropriately detailed as rigid joints. In many joints the authors have seen, CHS legs are simply fillet welded to the underside of RHS beams. A better solution would be for RHS beams to be butt-welded to the CHS, with horizontal stiffeners provided to the CHS which align with RHS flanges.

Where frames are braced, additional flexural actions in the legs created by eccentricities in the alignment of braces (such as that in Figure 1a) should be considered. From the author's assessment of some existing frames, it is apparent this has not been done.

Failures observed in Marlborough highlight the importance of aligning straps/tags connecting the base-frame to the tank with the tank wall and ensuring sufficient weld is provided. In addition, threaded adjustable feet require improvement, if they are to remain in use, to ensure these are not a weak point.

4.7 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 level as the tank, and this should be discussed with the winery. For catwalks which are frequently used, higher design 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 much of these issues 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.

4.8 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, crumpling of the roof cone knuckle 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.

5 FUTURE RESEARCH NEEDED

Numerical studies have shown that liquid-storage tanks with energy dissipating anchors experience a significant reduction in base shear and overturning moment when compared to fully anchored tanks, and exhibit smaller levels of base uplift and floor plate deformation when compared to unanchored tanks (Malhotra 1998).

Designing tanks with energy dissipation results in numerous benefits. Firstly, cost savings will arise from a reduction in tank wall thicknesses and foundation size. Secondly, smaller overturning moment allows more slender tanks, which are desirable from a winemaking and land utilisation perspective. Thirdly, reliable energy dissipation introduces a level of resilience to the system which currently does not exist with traditional tension-only anchored tanks. When tension-only anchored tanks experience earthquake actions larger than designed for, the result is base uplift and floor plate deformations on a similar order to that of an unanchored tank, and base shear and overturning actions of similar magnitude to a fully anchored tank (Malhotra and Veletsos 1995) – effectively the worst of both worlds.

Unfortunately the design and analysis of partially uplifting tanks with energy dissipation is limited to nonlinear methods such as that proposed in Malhotra (2000). To encourage the development and design of such systems, further research is required to produce design guidance of similar vein to the current NZSEE (2009) document. The authors envisage that this could be achieved via design charts produced from a series of numerical studies, considering tanks of different aspect ratios, partial hold-down anchorage ratios and damping.

Future research should also include investigating whether it is possible to introduce reliable capacity design to wine tanks to limit damage to replaceable fuses. Whilst the 'capacity design' term is used in the NZSEE guideline, the authors do not believe the 'capacity design' method described therein provides the same protection as provided in capacity designed building structures. When a tension-only anchored tank is overloaded, the tank will uplift, essentially increasing its hold-down capacity by picking up the weight of the contents as the floor peels from the plinth. As such, the overturning capacity of the tank will continue to increase as required, increasing the likelihood of buckling of the tank wall. The opportunity to limit loads to prevent wall buckling and isolate damage to replaceable fuses would protect the winery's produce and allow continued operation following seismic events.

6 CONCLUSION

The NZSEE (2009) guidelines for the seismic design of liquid storage tanks provide excellent procedures for determining design actions and analysing 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.

Numerical studies have shown that designing tanks with energy dissipation results in several benefits in terms of cost, land utilisation and performance. To encourage the development and use of such systems, further research is needed to develop guidance for tanks with energy dissipation on similar vein to the existing NZSEE guidance.

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