Flat-based wine tank buckling predictions using NZSEE recommendations and 2016 Kaikōura earthquake damage observations

Mohsen Yazdanian[1], Jason M. Ingham[2], W.J. Lomax[3], Christopher Kahanek[4], Dmytro Dizhur[5]

1. Corresponding Author. PhD student. Department of Civil and Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
   E-mail: myaz864@aucklanduni.ac.nz

2. Professor. Department of Civil and Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
   E-mail: j.ingham@auckland.ac.nz

3. Director. Structex Consultant Company, New Zealand
   E-mail: WLomax@structex.co.nz

4. CPEng, IntPE(NZ), CMEngNZ, Associate Principal - Thornton Tomasetti, Los Angeles, USA
   E-mail: CKahanek@thorntontomasetti.com

5. Lecturer. Department of Civil and Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
   E-mail: ddiz001@aucklanduni.ac.nz

Abstract

It has been frequently observed that cylindrical wine storage tanks sustain varying levels of damage during earthquake induced shaking. Typical wine tank failure modes include elephant foot-buckling, diamond shaped buckling, and anchorage system failures. The seismic action loads and allowable structural response to prevent the possibility of such failure modes are suggested by the New Zealand Society of Earthquake Engineers (NZSEE) recommendations for seismic design of storage tanks. Using the collected damage data following the 2016 Kaikōura earthquake and the NZSEE recommendations, elephant-foot and diamond shaped buckling was investigated herein. Comparison of the obtained results and the allowable responses based on the NZSEE recommendations showed that the tank wall thickness and the behaviour of the anchorage system had the most dominant effects on these failure modes. Post-earthquake damage observations of the wine tanks showed that the occurrence of elephant-foot buckling was 1.8 times more frequent than the diamond shaped buckling failure mode.

Keywords: Cylindrical wine storage tanks; elephant foot-buckling; diamond shaped buckling; anchorage system; NZSEE.

1 Introduction

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

Winemaking facilities typically consist of four important elements including buildings, barrel racks, wine storage tanks, and catwalks. Following previous earthquakes in New Zealand, engineering teams have inspected the affected wineries and collected detailed damage data. Based on these observations and the collected data it was established that wine storage tanks sustained the largest proportion of damage within the winery (Dizhur *et al.*, 2017). It was initially estimated by the New Zealand Wine Institute that approximately 20% of tank capacity in Marlborough was impaired to some extent following the 2016 Kaikōura earthquake, with at least 1,000 tanks having sustained some level of damage (New Zealand Wine, 2016).

The New Zealand Society of Earthquake Engineers (NZSEE) provided guidelines in 2009 for the seismic design of storage tanks (NZSEE, 2009), with these guidelines generally being used to design wine tanks in New Zealand. Based on the NZSEE guidelines, liquid storage tanks are to be designed against several limit states, including: hydrodynamic hoop stress, uplift, base plate stress, buckling, freeboard, shear, and overturning stability mechanisms.

Based on post-earthquake observations it was established that elephant-foot buckling, diamond shaped buckling, and anchorage system failure were among the most commonly observed failure modes. As part of the study reported herein a parametric analysis based on NZSEE 2009 was undertaken on predictions of elephant-foot buckling and diamond shaped buckling, which was then compared against post-earthquake damage observations.

2 Background of NZSEE Recommendations

A series of design guidelines were developed by the New Zealand Society of Earthquake Engineering (NZSEE) for liquid storage tanks. In 1986 NZSEE published guidelines for the seismic design of storage tanks (for Earthquake Engineering and Priestley, 1986), which were later updated in 2009 (NZSEE, 2009) to allow determination of seismic design actions in accordance with NZS 1170.5 (Standard, 2004). Wine storage tanks in Marlborough were typically constructed between 2001 and 2013, and it is estimated that 70-80% of those tanks were designed using the 1986 version and that 10-15% were designed using the 2009 version (Rosewitz and Kahanek, 2014). Au et al. (Au, Walker and Lomax, 2015) recommended that while the NZSEE 2009 guidelines provide an excellent procedure for the design of liquid storage tanks, the document must be used with caution when applied to the design of wine cylindrical tanks due to the difference in sloshing behaviour of liquid for closed top and open-top tanks. For example, K_h and K_v are period coefficients that are important for calculating impulsive modes and vertical modes but the graphs can only be used for tanks with a height/radius ratio up to H/R= 4, whilst flat-based wine tanks typically have a higher H/R ratio. Catwalks are another element in the wineries that provides access to the cone part of the tank and are typically designed in two types: (i) self-supported; (ii) tank supported. Catwalks are either not connected or flexible enough to not have a substantial impact on the behaviour of the tank. whilst NZSEE 2009 (NZSEE, 2009) does not make much comment on the design of the catwalks and their connection to the wine storage tanks. Following the 2016 Kaikōura earthquake, a number of tanks were affected due to the catwalk indent.

3 Observed buckling of wine tanks

There are typically two types of wine tanks that are commonly categorised according to their ground supporting conditions: (i) legged wine tanks; (ii) flat-based wine tanks. Based on the collected damage data, flat-based wine tanks typically have a larger capacity (ranging from 30 kL to 300 kL) than legged wine tanks (80 kL maximum capacity). Only flat-based tanks were considered in the study reported herein for damage analysis and buckling prediction using NZSEE (NZSEE, 2009). Most of the wine storage tanks are closed-top, still some red wine tanks have open-tops and their seismic behaviour is different from the closed-top tanks.

The buckling phenomenon of storage tanks can typically be categorised as: (i) elephant-foot buckling; (ii) diamond shape buckling. Elephant-foot buckling generally occurs in tanks that are mostly fully filled, is an elastic-plastic type of instability (NZSEE, 2009), (Sobhan, Rofooei and Attari, 2017), (Spritzer and Guzey, 2017), and can be described as an outward bulge of the tank shell. Due to the cyclic nature of seismic loading, elephant-foot buckling often extends around the full circumference of the tank wall. Diamond shaped buckling is a type of elastic instability (NZSEE, 2009), (Sobhan, Rofooei and Attari, 2017), (Spritzer and Guzey, 2017). Sobhan et al. (Sobhan, Rofooei and Attari, 2017) stated that elephant-foot buckling of the steel tank wall is caused by the interaction of both circumferential tensile stress close to the yield strength and by axial compressive stress exceeding the critical stress, whilst diamond shaped buckling is caused by severe axial compressive stresses.

Wine tanks are typically composed of different parts, including the barrel, top cone, turret and skirt (see Figure 1). Examples of elephant-foot buckling and diamond shaped buckling to three of the tanks in a Marlborough region winery following the 2016 Kaikōura earthquake are shown in Figure 2. Tank #1 (see Figure 2) sustained both elephant-foot and diamond shaped buckling, with elephant-foot buckling as observed in Tank #1 and shown in Figure 2 likely being due to variations in tank wall thickness up the tank height. Wine tanks may be insulated, and in some cases the exterior insulation of tanks may prevents direct visual inspection of tank wall buckling such that an interior tank inspection is required (see Figure 3). Skirt elephant-foot buckling is similar to elephant-foot buckling in barrels and typically occurs above the anchorage system (see Figure 4).

Detailed post-earthquake damage assessment from five inspected wineries following the 2016 Kaikōura earthquake revealed that of 802 flat-based tanks in the collected inventory, 11.0% (88 tanks) sustained elephant-foot buckling and 6.1% (49 tanks) sustained diamond shaped buckling (see Figure 5). A much larger proportion of wine tanks sustained anchorage and skirt related damage (23%). Damage data was classified into four different categories based on the severity; (i) minor (no repair), (ii) moderate (localised repairs), (iii) major (localised replacement), (iv) severe (section replacement). Damage data collected following the 2016 Kaikōura earthquake showed some cases where tanks having minor or no damage to their anchorage system sustained both types of buckling, with damage occurring in different shell courses up the height of the barrel (see Figure 2). Alternatively, in some cases, tanks with major damage to their anchorage systems did not sustain any type of visible buckling. Buckling in different parts of the barrel may lead to substantial repair costs because several shell courses of the barrel will need to be replaced. In limited cases, buckling may lead to loss of contents due to the excessive induced stress. The barrels are typically surrounded by refrigerant lines (Au, Walker and Lomax, 2015). During the site inspection, elephant-foot buckling between the refrigerant channels was common.

Figure 1. Different parts of typical flat-based wine tanks

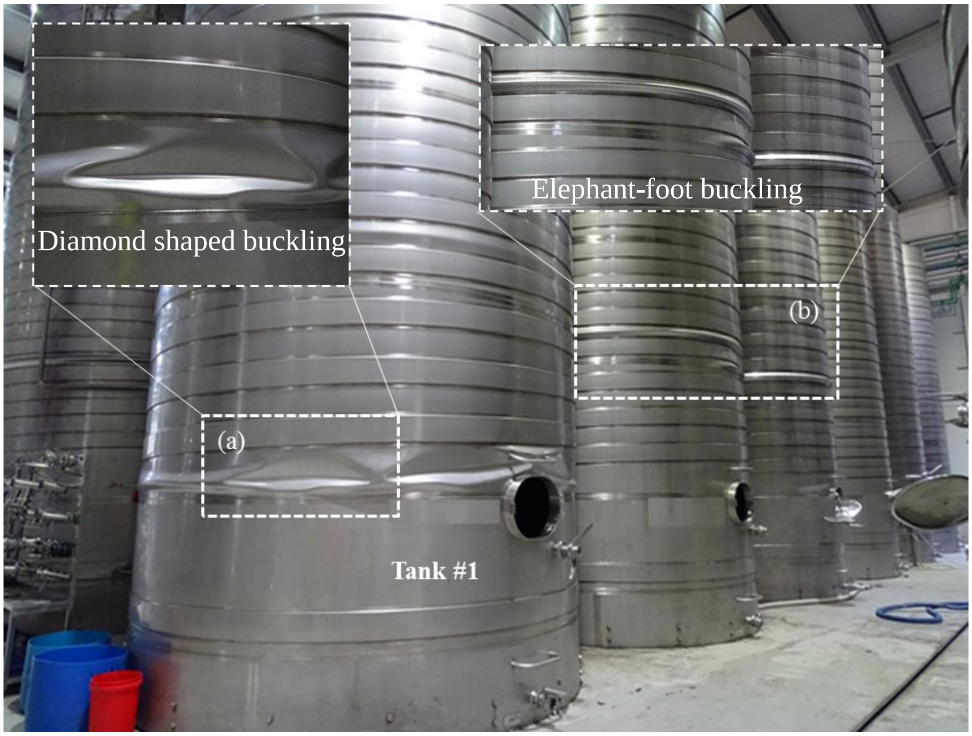


Figure 2. Example of buckling in flat-based tanks (capacity of 100 kL): (a) diamond shaped buckling; (b) elephant-foot buckling

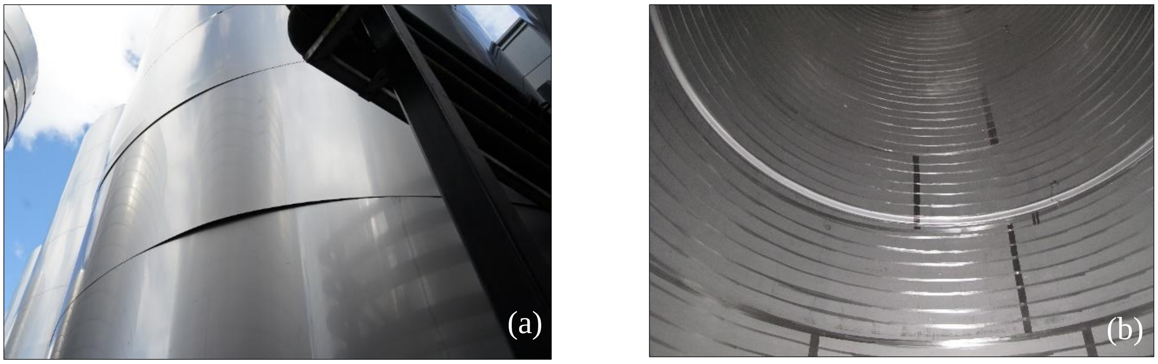


Figure 3. Damage to the insulation due to elephant-foot buckling in the interior shell course (capacity of 240 kL): (a) exterior insulation; (b) interior view of the tank

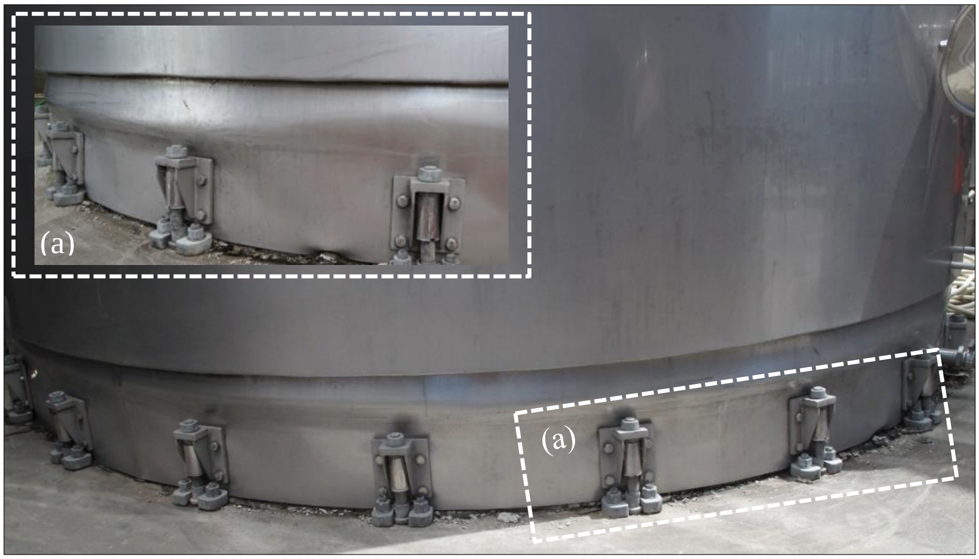


Figure 4. Skirt elephant-foot buckling (capacity of 240 kL): (a) zoomed in image showing skirt buckling

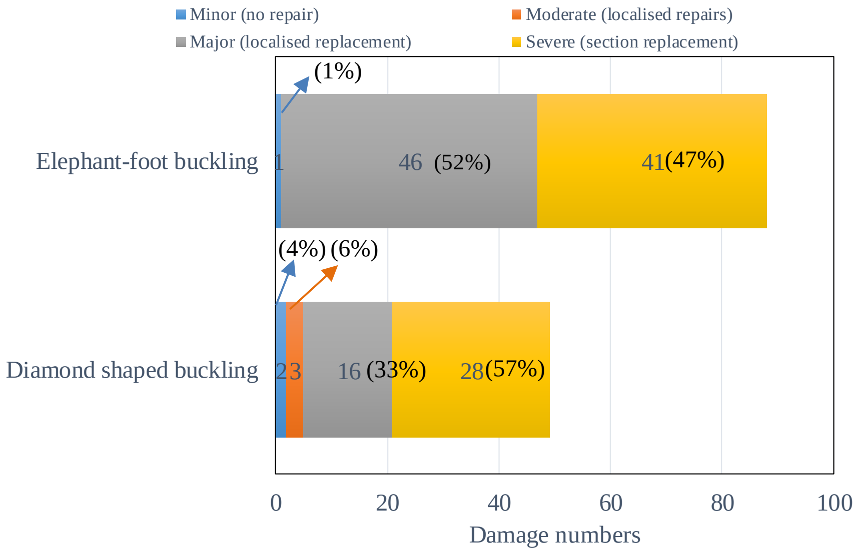


Figure 5. Elephant-foot and diamond shaped buckling among 802 flat-based tanks (showing the extent of damage levels)

4 Buckling predictions using NZSEE

The recommendations in section 5.5.2 of NZSEE (NZSEE, 2009) are for stress limits of buckling in vertical cylindrical steel tanks, and are based on an extensive review of experimental results and on the theory of cylindrical shell buckling by Rotter (Rotter, 1985). The equations give an accurate assessment of the stress required to initiate elastic-plastic collapse, or elephant-foot buckling. Based on the NZSEE guidance, the vertical membrane compression stress for a tank with internal pressure (f_m) shall not exceed the allowable diamond shape buckling stress (F1) and the elephant-foot buckling stress (F2). f_m, F1, F2 can be defined as follows:

$$\sigma_T = \frac{W_s}{2\pi RT} \tag{1}$$

$$\sigma_O = \frac{M_{rw}}{Z_T} \quad (2)$$

$$f_m = \sigma_T + \sigma_O \quad (3)$$

Where σ_T is the axial membrane stress in the shell wall due to shell and roof weight; σ_O is the axial membrane stress in the shell wall due to overturning; w_s is the total compression reaction in the shell for an uplifting circular tank at base; R is the radius of the tank and T is the tank wall thickness; M_{rw} is the ring wall moment and Z_T is the section modulus for the tank shell. It should be noted that based on NZSEE (NZSEE, 2009), anchor chairs and their connection to the tank wall shall also be designed using a capacity design approach. It was unclear that the tank was designed initially for the overstrenth of anchors or not. During the analysis considered herein the tank wall was assumed for the overstrength of anchors and tank wall design loads are calculated herein based on the anchor overstrength moment.

$$F1 = f_{cl} \times (0.19 + \left(0.81 \times \frac{f_p}{f_{cl}}\right)) \quad (4)$$

$$f_p = (f_{cl} \times (\sqrt{1 - \left(1 - \frac{\bar{p}}{5}\right)^2 \times \left(1 - \left(\frac{f_0}{f_{cl}}\right)^2\right)})) \leq f_{cl} \quad (5)$$

$$f_{cl} = 0.6E\frac{T}{R} \quad (6)$$

$$\bar{p} = \frac{pR}{Tf_{cl}} \leq 5 \quad (7)$$

$$F_2 = f_{cl} \times (1 - \left(\frac{pR}{Tf_y}\right)^2) \times (1 - \frac{1}{1.12 + s^{1.5}}) \times (\frac{s + \frac{f_y}{250}}{s+1}) \quad (8)$$

$$s = \frac{(\frac{R}{T})}{400} \quad (9)$$

Where f_{cl} is the classical membrane compression buckling stress for a perfect elastic cylinder under axial load; f_0 is the membrane compression buckling stress for a tank without internal pressure, subject to uniform compression; p is the internal pressure of liquid; E is the modulus of elasticity; T is the tank wall thickness; R is the radius; $\bar{p}$ is a condition that is checked for the tank wall design and f_y is the material yield stress. It should be noted that the attained axial stresses due to the overturning moment are varied based on the tank height, this variation provided an opportunity to investigate the impact of different parameters based on the height variations. Details on how to calculate the overturning moments are reported in section 3.5 of NZSEE (NZSEE, 2009).

5 Case study analysis

A prototypical cylindrical closed-top wine tank was selected as a case study to investigate the effects of various parameters on the tank design and its seismic performance. The case study tank was in operation prior to the 2016 Kaikōura earthquake (the exact construction date of the case study tank is unknown). General geometrical and material properties of the case study tanks are reported in Table 1. During the 2016 Kaikōura earthquake the case study tank sustained severe elephant-foot buckling (see Figure 6) and was later retrofitted using new energy dissipation devices, with the buckled parts of barrel sections being replaced with new shell courses. The exterior view of the tank in Figure 6.b shows the extent of retrofitting works undertaken for the subject tank. The wall thickness of the case study tank varies with height, with the thickest part of shell being in the skirt portion of the tank (5.0 mm) and the thinnest portion (2.0 mm) being in the upper shell course near to the cone part of the tank. Wall thickness, return period (Ru), site hazard (Z factor), and height-to-radius ratio (H/R) are the most critical inputs in the design of a steel wine tank. The influence of variations of these inputs on diamond shaped and elephant-foot buckling of the steel wine tank was investigated.

Figure 6. The case study tank (240 kL) showing elephant-foot buckling (indicated with arrows) following the 2016 Kaikōura earthquake. (a) Inerior view of the tanks showing elephant-foot buckling, (b) Exterior view showing the extent of buckling when the external insulation layer was removed.

Table 1. General geometry and properties of the selected tank

Capacity (L)	Height (mm)	Radius (mm)	Wall thickness (mm)	# of anchors	Modulus of Elasticity (GPa)	H:R	Material yield stress (MPa)	Tank material	Soil class
245955	13,600	2,440	2-5	20	200	5.6	210	Stainless steel	D

5.1 Seismic zone hazard factor (Z) and Return period (Ru)

The seismic zone hazard factor (site hazard), Z has a significant effect on the earthquake actions. Z shall be taken from Table 3.3 or interpolated from Figures 3.3 or 3.4 of NZS 1170.5 (2004). The minimum value of Z shall be 0.10 in the Northland Regional Council area and shall be 0.13 for the rest of New Zealand. The case study tank considered herein is located in Blenheim, New Zealand. Based on NZS 1170.5 (2004), Z for Blenheim is equal to 0.33. To compare the effect of hazard factor on tank wall buckling, it was assumed that the tank was constructed in a low seismic zone such as Auckland (Z = 0.13). The seismic return period factor, Ru, is selected based on treatment of consequences of failure including life safety, environmental exposure, community significance and design working life (NZSEE, 2009). R_u for the return period or probability of occurrence for the limit state can be obtained from Table 3.5 of NZS 1170.5 (2004) as presented in Table 3.3 of AS/NZS 1170.0 (2002).

5.2 Height-to radius ratio

Based on Wozniak (Wozniak, 1979), the maximum height of the tank can be selected based on the soil bearing capacity at the location where the tank is installed. The H/R ratio of the case study tank is 5.6, while another assumption (H/R=4.3) is considered herein to compare the impact of H/R on the buckling. It should be noted that in both cases, the volume and other inputs of the tanks are equal to the value reported in Table 1, except H and R which for the tank with H/R=4.3 are equal to 12 m and 2.765 m.

5.3 Wall thickness

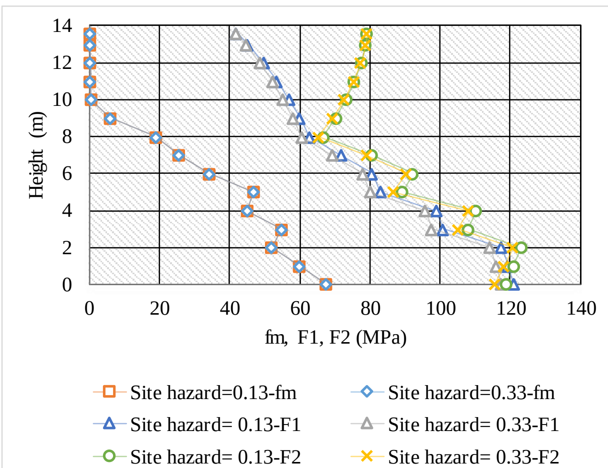
Wine tanks usually have a varying wall thickness that decreases with height. Based on the cost, height, radius, liquid density, and allowable unit stress, tank wall thickness is chosen. Wozniak (Wozniak, 1979) recommended the following equation as an initial estimation for the selection of wall thickness:

$$T = (\gamma \times H \times 2R)/(2fe) \tag{10}$$

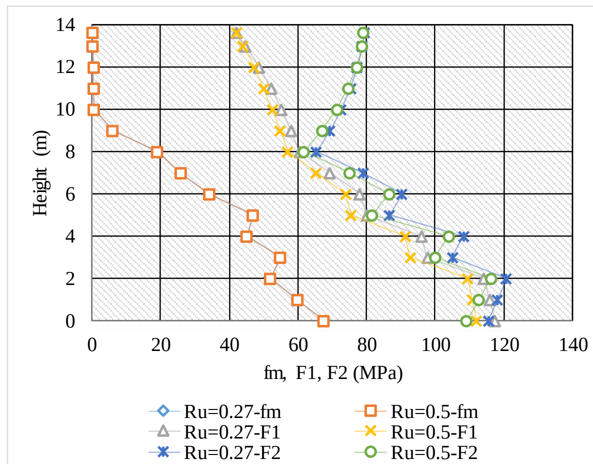
Where γ is liquid density, H is tank height, R is radius, f is allowable unit stress, and e is joint efficiency (strength of weld over the strength of base material). API 650 (American Petroleum Institute (API), 2007) recommended the minimum required shell thickness based on the nominal tank internal diameter. API 650 (American Petroleum Institute (API), 2007) table for the minimum required shell thickness is also presented in the NZSEE (NZSEE, 2009).

6 Results and discussion

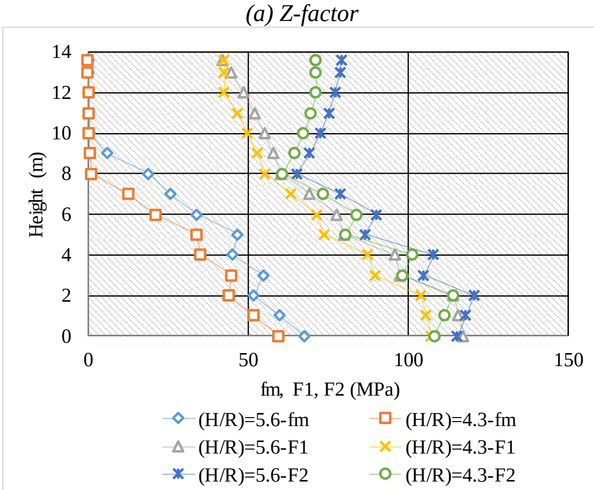
Results of the analysis are reported in two formats: (i) variation of the parameters versus the variable tank wall thickness based on the real design drawings (see Figure 7); and (ii) variations of the parameters versus constant tank wall thickness (uniform, see Figure 8). A distinct difference was obtained between the values of tank stress with variable and uniform thickness due to the differences in thickness. For example, the F2 stress values fluctuated up the tank wall height for the variable tank (see Figure 7), while F2 decreased up the tank wall height for the tank with uniform thickness. Following the 2016 Kaikōura earthquake, inspectors identified that most of the buckling events in the barrel of the tank wall occurred in locations of thickness changes, which is well matched with the changes in stress values shown in Figure 7. A decline in site hazard, R_u, and H/R led to a slight decrease in the values of stress in tanks for both variable and uniform wall thickness. Unlike for the site hazard, R_u, and H/R, thickness contributed greatly in changes of the stress value (see Figure 8.d). Except when changing the wall thickness from 5 mm to 3 mm (see Figure 8d), none of the changes in parameters were associated with both types of buckling prediction. Based on the analysis of the case study tank with actual geometrical characteristics (see Figure 7), no buckling of tank walls was predicted. However, elephant-foot buckling of the case study tank was observed following the 2016 Kaikōura earthquake. The buckling phenomenon is typically due to exceeding of the tank seismic capacity. It is noted that during earthquake induced shaking, the response of the tank is a result of multiple interacting parameters such as the response of the tank anchorage system.



(a) Z-factor



(b) Ru



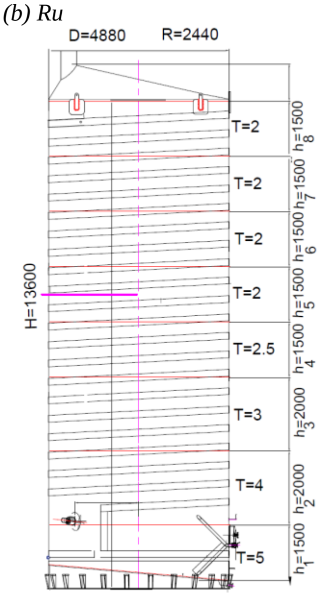
(c) H/R

H= average tank height (mm)

D= diameter (mm)

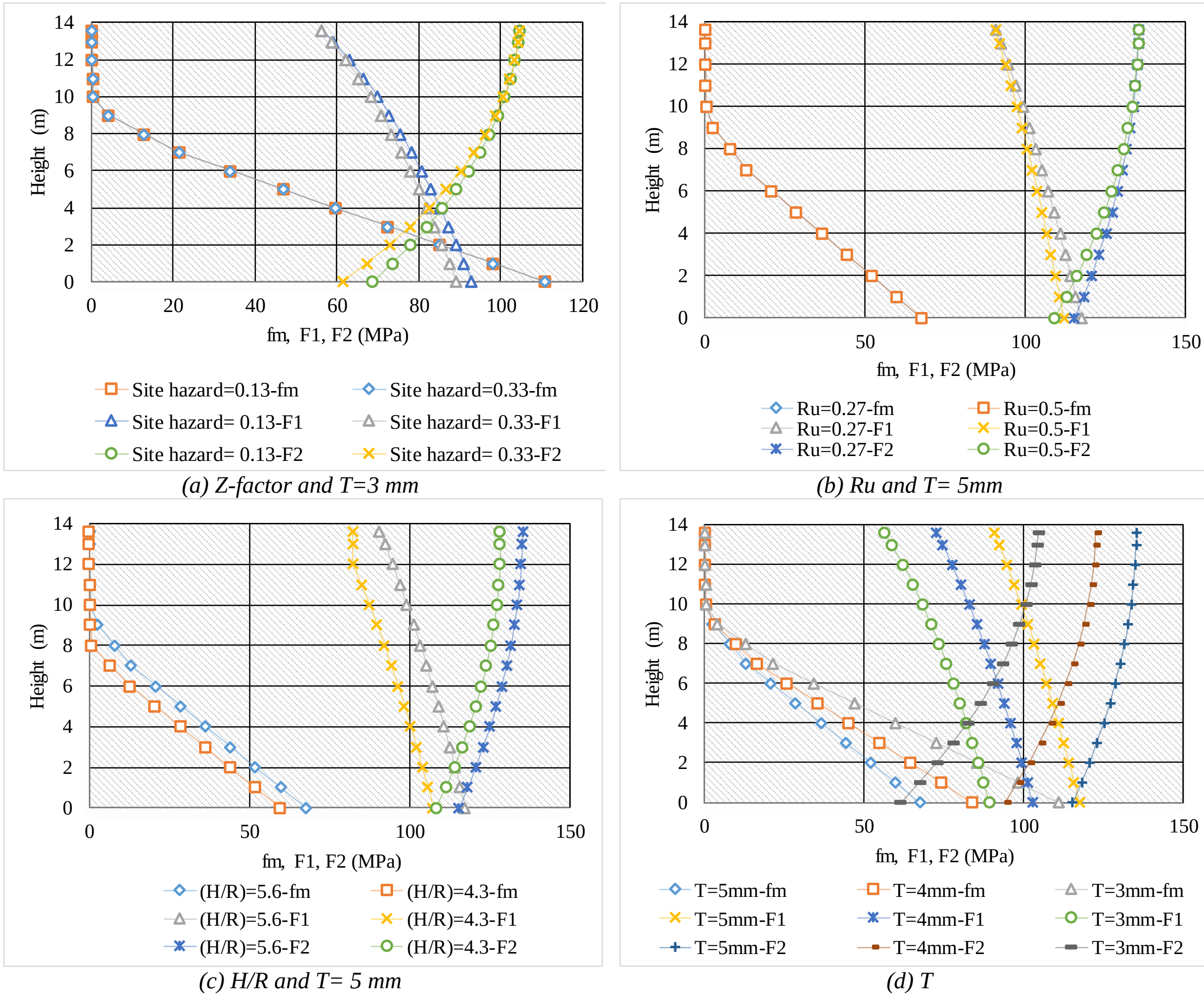
T= thickness (mm)

R=radius (mm)



(d) the geometry charachteristic of the case study tank showing variable wall thickness with increasing height

Figure 7. Variation of parameters according to the height of the tank (variable wall thickness)



[*] *Figure 8. Variation of parameters according to the height of the tank (uniform wall thickness)*

*Note: Except the changes in the parameters written in this figure, the other are based on the Table 1

7 Conclusions

A post-earthquake damage assessment was conducted following the 2016 Kaikōura earthquake and a detailed inventory of the performance of 802 flat-based wine tanks was collected. Analysis of damage data revealed that 11.0% and 6.1% of the flat-based tanks in the collected inventory sustained elephant-foot buckling and diamond shaped buckling respectively. Although the percentage of damage to the anchorage system and skirt (23%) was 5.9% higher than the total damage to the tank wall due to both type of buckling (17.1%), loss of content of the tank was seen due to the severe occurrence of buckling.

A flat-based tank with capacity equal to 240 kL that sustained buckling following the 2016 Kaikōura earthquake was selected as a representative case study and investigated in detail herein. The detailed parametric analysis including site hazard, return period, thickness, and the H/R ratio revealed that wall thickness had the highest impact on stress values, highlighting that changes in the tank wall thickness should be selected with caution to prevent buckling. Buckling prediction using NZSEE showed that the designed tank should perform well against buckling if it was designed for the overstrength of the anchors because the stresses due to hydrodynamic pressure, overturning moment and the shell weight did not exceed the stress required to induce buckling. However, the tank buckled severely following the 2016 Kaikōura earthquake and the buckled layers were replaced as part of the remedial works, suggesting that the earthquake loads transferred to the tank barrels were higher than those attained during design of the studied tank. Difference in analytical results and post-earthquake performance of tanks could be because in the study reported herein, tank wall design moment was calculated based on the anchor overstrength moment. Findings reported herein suggest that there is a direct relation between the anchorage system and the buckling failure mode in the tank wall.

As NZSEE guideline does not make comment about the catwalks design procedure, the calculation reported herein is solely for an isolated tank. Catwalks can make the seismic behaviour of tanks complicated and make a difference in results.

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