Assessment of New Zealand scaling procedure of ground motions for liquid storage tanks

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ABSTRACT: Liquid storage tanks are critical lifelines on a local and regional basis. Hence, the integrity of these tanks must be ensured. However, there is a lack of a specific scaling procedure for time-history analysis for these structures. The only available procedures are those provided by seismic design documents for general structures. This brings about a problem for New Zealand designers because there is a restriction in the minimum value of the fundamental period of the structure when scaling ground motions. Storage tanks are very stiff structures and their fundamental periods are in most cases below the limit imposed. This paper presents a comparison between the shake table seismic response of storage tanks using the New Zealand standard to scale ground motions both with and without the restriction of a minimum value for the fundamental period. The results of a series of experiments using a shake table and a model PVC tank containing water are presented, along with numerical comparisons. The experiments and the numerical comparisons were carried out using actual records scaled to the New Zealand design spectrum contained in NZS1170.5 (2004). Stresses in the tank shell and the horizontal displacement of the top of the tank were recorded. The results show that the restriction in the fundamental period underestimates the axial stresses in the tank shell.

1 INTRODUCTION

Storage tanks are essential structures that provide basic supplies to the community such as water and fuel. For this reason it is essential that these structures remain operational. Because of the importance a lot of studies have been carried out (Housner 1957, Wozniak and Mitchell 1978, Veletsos 1984) and standards and design guides have been established (NZSEE recommendations 2009, API 650 2007, Eurocode 8 Part 4 2004). Despite the importance of storage tanks, there is not a specific procedure to perform time-history analysis to estimate the actual behaviour of this structure. Current practice only provides seismic loading coefficients based on a pseudo dynamic method, and hence it is impossible to examine the successive plastic excursions of the structural elements (shell and base plate) using the current methods provided by the design specifications. To understand the plastic behaviour of a tank it is essential to have an appropriate method to perform time-history analysis that requires an appropriate selection criteria and scaling procedure of the ground motions. The selection criteria would include such information as earthquake magnitude, fault mechanism, source distance and site geology for example.

To select ground motions for time history analysis there are two different ways (Oyarzo-Vera and Chouw 2008). One of these ways is to use actual records obtained from databases of previous events (COSMOS, 1999, EQC and GNS Science, 2004, PEER, 2005). The other way is to use ground motions stochastically generated by using physical or numerical models (Chouw and Hao 2005, Boore 2003). Current design specifications (NZS 1170.5 2004, ASCE/SEI 7-10 2010, Eurocode 8 2004) recommend the use of records of previous events. However, if there are insufficient records with suitable characteristics available, current specifications allow the engineer to generate appropriate simulated ground motions to make up the total number of records required. All these documents agree with the requirements for choosing the records to be used, e.g. the ground motions should have compatible seismological characteristics to the expected earthquake at the site analysed (magnitude, distance, fault mechanism and soil conditions). Studies have been carried out to obtain ground motions that meet the requirements imposed by the design specifications. Oyarzo-Vera et al. (2012) provides a list of ground motions to be used in the North Island of New Zealand. Iervolino et al. and NIST state the criteria for selecting ground motions for using the Eurocode 8 and ASCE/SEI 7-10 procedures, respectively.

Because of a lack of specific procedures for storage tanks, the design documents for general structures are utilised to scale ground motions for time-history analysis. The procedures given by those documents define different frequency ranges of interest to scale the records and different approaches to match the target spectrum for general structures. This period range or frequency range depends on the fundamental period of the structure to be analysed. In this matter, NZS 1170.5 differs from the other design documents establishing a minimum value of the fundamental period to determine the period range of interest. Storage tanks are very stiff structures with fundamental periods of a few tenth of seconds in most practical cases (Larkin 2008) and, therefore, the limit imposed by NZS 1170.5 leaves these structures out of the period range of interest.

The objective of the work is to evaluate the consequences of the limit imposed by NZS 1170.5 to the fundamental period of the structure analysed. A comparison between the results obtained from a shake table test of a PVC tank following the NZS 1170.5 procedure with and without the restriction is presented. The experimental results are compared to those obtained by numerical analysis.

2 NEW ZEALAND STANDARD (NZS 1170.5)

A summary of the most important points of the procedure for scaling ground motions given by NZS 1107.5 is presented in this section.

The New Zealand Standard NZS1170.5 requires the use of a family of at least 3 recorded ground motions. Each record must have at least both orthogonal horizontal components. Vertical component should be included when the structure analysed is sensitive to the action of vertical acceleration. The records shall have similar seismological signatures (magnitude, fault mechanism, source-to-site distance and site geology) to the characteristics of the events that mainly contributed to the target design spectrum of the site over the period range of interest. When there is insufficient recorded ground motions for the site, simulated ground motion records may be used to make up the family.

The period range of interest defined by this standard is between 0.4 T_1 and 1.3 T_1, where T_1 is the fundamental period of the structure in the direction analysed, but cannot be less than 0.4 s. In this range, the records should match the target spectrum after multiplying the records by two factors, k_1 and k_2. k_1 is known as the record scale factor and it is different for each record. k_2 is called the family scale factor and is common for the records within the family. k_1 is the value that minimises in a least mean square sense the function defined in Equation 1 in the period range of interest.

$$log(k_1 \cdot SA_{component} / SA_{target}) \tag{1}$$

where $SA_{component}$: 5% damped spectrum of one of the components of the record; and

SA_{target} : target spectrum.

In this way, k_1 is computed for each horizontal component of the record and the smallest value is chosen for the record scale factor. The component that corresponds to the value of the chosen k_1 is called the principal component.

The family scale factor k_2 is the maximum of 1.0 and the value computed from Equation 2:

$$k_2 = SA_{target} / max(SA_{principal}) \tag{2}$$

where: $SA_{principal}$: 5% damped spectrum of the principal component of the record.

In this way, the principal component of at least one record spectrum scaled by its record scale factor k_1, exceeds the target spectrum.

Additionally, the following limits apply to the scale factors:

$$0.33 < k_1 < 3.0$$

$$1.0 < k_2 < 1.3$$

3 STORAGE TANKS

Current standards and design codes for the seismic design of storage tanks are based mainly on the spring-mounted masses analogy proposed by (Housner 1957). This analogy proposes that the tank-liquid system can be represented by two vibration modes (Wozniak and Mitchell 1978, Veletsos 1984). The portion of the liquid contents which moves together with the tank shell is known as the impulsive mass. The portion of the contents which moves independently of the tank shell and develops a sloshing motion is called the convective mass. The predominant mode of vibration of tall slender liquid storage tanks during an earthquake is the impulsive mode (Larkin 2008, Veletsos et al. 1992) and its fundamental period is very short, generally a few tenths of a second. The impulsive period of vibration will be considered as the fundamental period in the analysis presented in this work.

4 EXPERIMENTAL METHODOLOGY

4.1 Tank Model

A PVC tank is utilised to model a prototype steel tank (Fig. 1). An aspect ratio of 3 (H/R: Liquid height to radius) was studied. The properties of the model and prototype are shown in Table 1. Two anchor bolts fixed the model to the shake table (Fig. 2). The dynamic properties were computed using NZSEE recommendations 2009 and the scale factors determined from similitude requirements are shown in Table 2.

Figure 1. PVC tank model

4.2 Setup

Strain gauges were implemented on the external face of the tank to measure the axial distribution of stresses. A wire-line transducer was attached to the top of the tank to measure the horizontal displacement of the top of the tank shell. Figure 3 shows the setup used.

Table 1. Dimensions and properties of tank model and prototype

	Model	Prototype
Material	PVC	Steel
Young's modulus (MPa)	$1.6*10^3$	$2.068*10^5$
Diameter (m)	0.50	10.00
Height (m)	0.75	15.00
Wall and base thickness (mm)	4	10
Mass of the contents (kg)	147	1178097
T_1 (s)	0.036	0.167

Table 2. Scale Factors

Dimension	Scale Factor
Length	20
Mass (liquid content only)	8000
Time	4.64
Stiffness	369.5
Acceleration	0.93
Force	7440

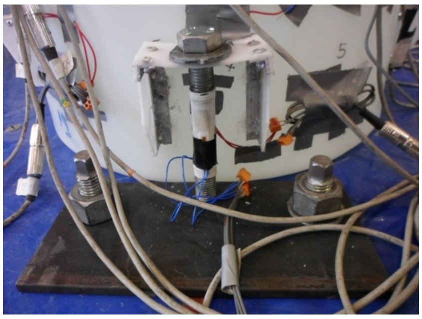

Figure 2. Anchor bolt

4.3 Ground Motions

The ground motions records used in this study were obtained from the database of GNS Science and are part of the sequence of Christchurch earthquakes (2011). The Christchurch earthquake occurred on February 21st, 2011 with a magnitude of 6.3 and the hypocentre was located at a depth of 5 km.

Both horizontal components of each record are used in this study. The results of 3 ground motions are presented here from a set of ten ground motions used to compute the calibration factors of each scaling procedure. The list of ground motion records and their characteristics used to determine the results presented here are shown in Table 3.

The target spectrum selected in this study was determined using NZS 1170.5 in conjunction with NZSEE recommendations, for the specific case of a liquid storage tank at Christchurch City with a site classification of C.

Table 3. Ground motions records of Christchurch earthquakes (2011)

ID	Christchurch earthquake records	PGA (m/s2)	Distance (km)
EQ1	Hospital (CHHC)	3.521	8
EQ2	Cashmere High School (CMHS)	3.895	6
EQ3	Lyttelton Port Company (LPCC)	8.645	4

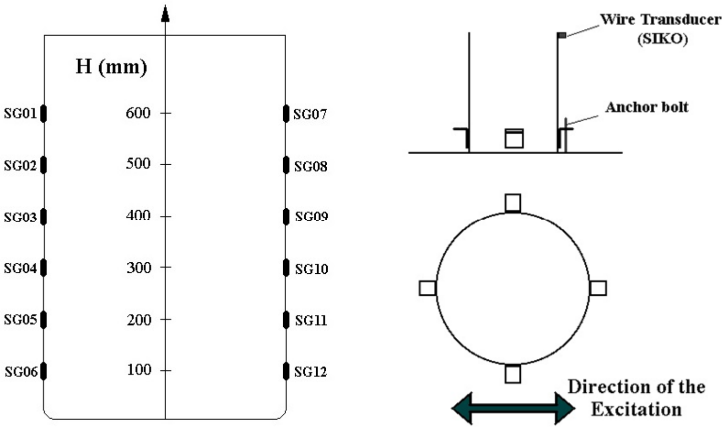

Figure 3. Experimental setup. Strain Gauge distribution (right), location of the devices and plan view (left).

5 RESULTS

All the ground motion records were scaled to the target spectrum, defined in the previous section, using the procedures given by NZS 1170.5 with and without the frequency restriction imposed by this standard. Figure 4 shows the unscaled response spectra of the records and the target spectrum.

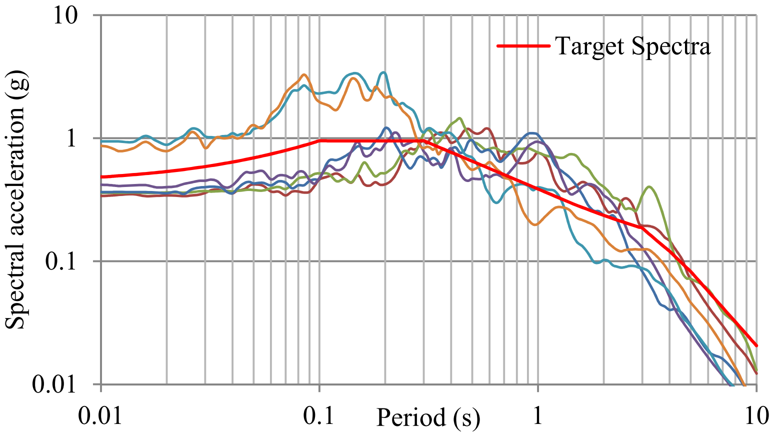

Figure 4. Target spectrum and response spectra of the unscaled ground motion records.

Figures 6 shows response spectra of the records scaled by NZS 1170 with (left) and without (right) the frequency restriction respectively, along with the target spectrum.

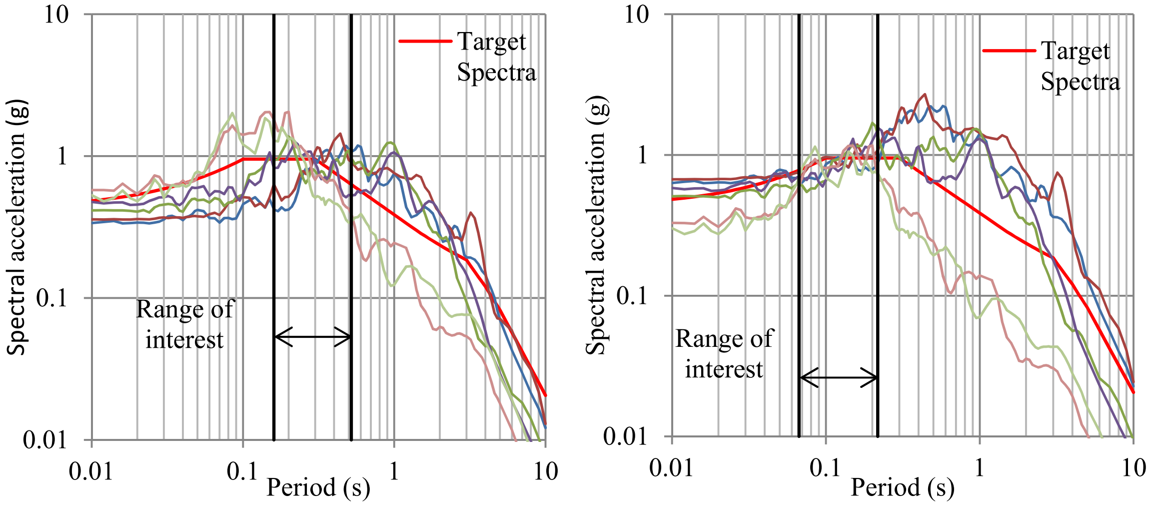

Figure 6. Target spectrum and response spectra of the scaled ground motion with the restriction.

It is noticeable from Figure 6 that whether considering or not the minimum value for the fundamental period changes the period range of interest and, therefore, affects the scale factors calculated for the ground motions. Table 4 shows a summary of the scale factors computed using the two procedures.

Table 4. Scale factors computed using the three procedures

ID	With frequency restriction	Without frequency restriction
EQ1	0.994	1.866
EQ2	1.137	1.397
EQ3	0.613	0.349

Figure 7 shows the distribution of the maximum axial stresses obtained from a component of ground motions EQ1, EQ2 and EQ3 for the two scaling procedures.

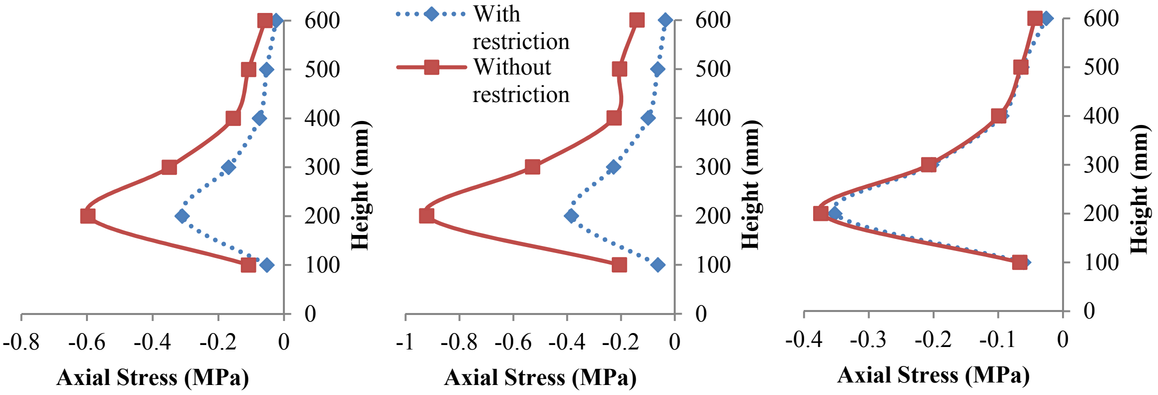

Figure 7. Maximum axial compressive stresses. EQ1 (left), EQ2 (centre) and EQ3 (right).

Generally, the wall thickness of cylindrical tanks is determined by considering the maximum axial compressive stress. To better understand how the scaling procedure affects the compression stresses in the shell, the ratio of the maximum compressive stress without the restriction to that with the restriction, MCSR, as defined in Equation 3, is shown in Table 5.

$$MCSR = \frac{Maximum\ compressive\ stress\ without\ frequency\ restriction}{Maximum\ compressive\ stress\ with\ frequency\ restriction} \tag{3}$$

In a similar way, the ratio of the maximum top displacement without the restriction to that with the restriction, MDR, as defined in Equation 4, is shown in Table 6.

$$MDR = \frac{Maximum\ top\ displacement\ without\ frequency\ restriction}{Maximum\ top\ displacement\ with\ frequency\ restriction} \tag{4}$$

Table 5. MCSR for all the ground motions (both components)

ID	MCSR
EQ1A	1.92
EQ1B	1.51
EQ2A	2.40
EQ2B	4.45
EQ3A	1.06
EQ3B	1.39

Table 6. MDR for all the ground motions (both components)

ID	MDR
EQ1A	1.41
EQ1B	1.47
EQ2A	2.46
EQ2B	1.77
EQ3A	1.09
EQ3B	1.34

Figure 7 and Tables 5 and 6 confirm the same result, the experimental values of axial stresses obtained considering the restriction in the minimum value of the fundamental are lower than those obtained without the restriction. This is a very important fact because the restriction imposed by NZS 1170.5 results in a underestimation of the axial stresses in the tank shell.

Table 7 shows MCSR obtained for the prototype by numerical analysis.

Table 7. MCSR obtained by numerical analysis

ID	MCSR
EQ1	1.88
EQ2	1.23
EQ3	0.57

Table 7 corroborates the experimental results in 67% of the cases and it is 100 % correlated to Table 4.

6 CONCLUSIONS

A series of earthquake records for use in an experimental study have been derived using NSZ 1170.5 with and without considering a minimum for the fundamental period. Ten different ground motions were considered to compute the scale factors. Three of these records were chosen to be utilized in physical experiments using a shake table. The main aim was to evaluate the effects of the restriction imposed by NZS 1170.5 on the measured tank wall compressive stress.

The investigations reveal:

1. The restriction imposed by NZS 1170.5 affects the computation of the period range of interest and, therefore, the scale factors for the ground motions to be used.
2. According to the experimental findings, the restriction imposed by NZS 1170.5 results in a underestimation of the axial compressive stresses in the tank shell.
3. Numerical results are 100 % correlated to the computed scale factor and corroborate in 67 % the experimental results.
4. The authors recommend to reconsider the minimum value of fundamental period to scale ground motions in the case of time-history analysis of storage tanks .

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