Methods for defining the seismic loadings of liquid storage tanks: an experimental comparison

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ABSTRACT: Storage tanks are essential structures but there is no explicit procedure to scale ground motions for time-history analysis of liquid storage tanks. Current standards and design codes minimise the difference between the response spectra of the chosen records and the target spectrum in a range of periods central to the response of a tank. The limits of the period range are related to the fundamental translational period in the direction being considered. However, the design specifications have important differences in scaling procedures that may affect the seismic response of the structure analysed. Additionally, these procedures were not specifically formulated for performing time-history analysis of storage tanks whose fundamental period is generally much shorter than other structural types.

This paper reports on a series of experiments, using a shake table, of a model PVC tank that contains water. A comparison is presented of the seismic response of a fixed base system (tank with anchorage) by using the procedures of three codes in international use to determine the applicable time history of loading. The experiments were performed using ground motions recorded from the Christchurch sequence of earthquakes. Measurements of the stresses in the tank shell are presented. The main differences between the scaling procedures and the consequences are discussed.

KEY WORDS: Storage Tanks, Seismic standards, ASCE/SEI 7-05, NZS 1170.5, Eurocode 8, shake table test, record scaling

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 [1-3] and standards and design guides have been established [4-6] and compared [7]. Despite the importance of storage tanks, there is no 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 [8]. One of these ways is to use actual records obtained from databases of previous events [9-11]. The other way is to use ground motions stochastically generated by using physical or numerical models [12, 13]. Current design specifications [14-16] 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. [17] provides a list of ground motions to be used in the North Island of New Zealand. Iervolino et al. [18] and NIST [19] state the criteria for selecting ground motions for using the Eurocode 8 [16] and ASCE/SEI 7-10 [15] procedures, respectively.

Contrarily to the criteria for selecting records, where there is agreement between the standards and codes, the scaling procedures given by these specifications differ in very important aspects. Those procedures define different frequency ranges of interest to scale the records and different approaches to match the target spectrum for general structures. In the case of storage tanks, there are no specific rules to perform time history analysis known to the authors in any of the worldwide currently available design documents.

To the authors knowledge a comparison of the selection criteria and scaling procedures in these three well-used design specifications has not been reported for liquid storage tanks. The objective of the work is to evaluate the consequences of the procedures for the assessment of the seismic performance of storage tanks and reveal any deficiencies or inconsistencies from using the methods in the specifications considered.

2 METHOD FOR SCALING RECORDS

All these specifications define how to compute a factor with which to multiply the recorded ground motion for matching the target spectrum over a certain period range. However, this
factor is computed in different ways. A summary of the main points of the procedures is presented below.

2.1 New Zealand Standard (NZS 1170.5)

The New Zealand Standard NZS1170.5 [14] 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.

\[
\log(k_1 \cdot \frac{S_{A_{component}}}{S_{A_{target}}}) = 0
\]

(1)

where \( S_{A_{component}} \) : 5% damped spectrum of one of the components of the record; and \( S_{A_{target}} \) : 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):

\[
k_2 = \frac{S_{A_{target}}}{\max(S_{A_{principal}})}
\]

(2)

where: \( S_{A_{principal}} \) : 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 restrictions apply to the scale factors:

\[
0.33 < k_1 < 3.0 \\
1.0 < k_2 < 1.3
\]

2.2 U.S.A. Standard (ASCE/SEI 7-10)

ASCE/SEI 7-10 [15] requires the use of at least three ground motions. Each ground motion shall consist of pairs of appropriate horizontal components that shall be selected and scaled from recorded events. The selected ground motions shall have magnitudes, fault distance, and source mechanisms consistent with the expected maximum earthquake considered in the analysis. Note that no mention is made of site geology. Appropriate simulated ground motion pairs can be used to make up the total number of ground motions when the required number of recorded ground motions is not available.

The square root of the sum of the squares (SRSS) of the 5% damped response spectrum of each ground motion must be computed from the scaled pairs that form the record. The same scale factor shall be applied to both components of the record, i.e., each record has a unique scale factor. The SRSS of the response spectrum of each record shall not be less than the target spectrum in the period range of interest defined by [15], which is between 0.2 \( T_1 \) and 1.5 \( T_1 \), where \( T_1 \) is the fundamental period of the structure in the direction analysed.

When seven or more ground motions are used to perform the analysis, the average response will be considered for design purposes. If less than seven ground motions are used, then the maximum response of the structure will be considered as pivotal.

2.3 Eurocode 8

This code requires the use of a set at least three records, regardless if they are natural, artificial (generated to match the target spectrum), or simulated (numerical simulation of source and path). The records shall consist of both horizontal components and a vertical component when this is required. The records that make up the set shall be consistent with the magnitude and the “other relevant features” of the seismic event considered.

The average of the 5% damped elastic spectrum, calculated from all time histories, should not be less than 90% of the target spectrum in the period range of interest. The period range of interest defined by Eurocode 8 [16] is between 0.2 \( T_1 \) and 2 \( T_1 \), where \( T_1 \) is the fundamental period of the structure in the direction the accelerogram will be applied. It is worth noting that this procedure, contrary to the previous two, does not apply a different scale factor for every record, the procedure provided by this code applies the same scale factor to the whole set.

There is another requirement that has to be met. The average spectral response acceleration (calculated from the individual time histories) at a period of 0 seconds has to be larger than the value of the target spectrum at the same period.

Seven or more ground motions shall be used to take the average response for design purposes. If less than seven ground motions are used, then the maximum response will be considered as pivotal.

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 [1] (Figure 1). This analogy proposes that the tank-liquid system can be represented by two vibration modes [2, 3]. The portion of the liquid contents
which moves together with the tank shell is known as the impulsive mass \( m_i \). The portion of the contents which moves independently of the tank shell and develops a sloshing motion is called the convective mass \( m_c \). The predominant mode of vibration of tall slender liquid storage tanks during an earthquake is the impulsive mode \([20, 21]\) 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.

![Figure 1. Spring-mounted masses analogy for storage tanks.](image)

4 EXPERIMENTAL METHODOLOGY

4.1 Tank Model

A PVC tank is utilised to model a prototype steel tank (Figure 2). 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 (Figure 3). The dynamic properties were computed using [4] and the scale factors determined from similitude requirements are shown in Table 2.

![Figure 2. PVC tank model](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>Model</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus (MPa)</td>
<td>1.6*10³</td>
<td>2.068*10³</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>0.50</td>
<td>10.00</td>
</tr>
<tr>
<td>Height (m)</td>
<td>0.75</td>
<td>15.00</td>
</tr>
<tr>
<td>Wall and base thickness (mm)</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Mass of the contents (kg)</td>
<td>147</td>
<td>1178097</td>
</tr>
<tr>
<td>( T_1 ) (s)</td>
<td>0.036</td>
<td>0.167</td>
</tr>
</tbody>
</table>

Table 1. Dimensions and properties of tank model and prototype

![Figure 3. Anchor bolt](image)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>20</td>
</tr>
<tr>
<td>Mass (liquid content only)</td>
<td>8000</td>
</tr>
<tr>
<td>Time</td>
<td>4.64</td>
</tr>
<tr>
<td>Stiffness</td>
<td>369.5</td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.93</td>
</tr>
<tr>
<td>Force</td>
<td>7440</td>
</tr>
</tbody>
</table>

Table 2. Scale Factors

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 4 shows the setup used.

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 [14] in conjunction with NZSEE recommendations [4], for the specific case of a liquid storage tank for a Christchurch City with a site classification of C.
Table 3. Ground motions records of Christchurch earthquakes (2011)

<table>
<thead>
<tr>
<th>ID</th>
<th>Christchurch earthquake records</th>
<th>PGA (m/s²)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ1</td>
<td>Hospital (CHHC)</td>
<td>3.521</td>
<td>8</td>
</tr>
<tr>
<td>EQ2</td>
<td>Cashmere High School (CMHS)</td>
<td>3.895</td>
<td>6</td>
</tr>
<tr>
<td>EQ3</td>
<td>Lyttelton Port Company (LPCC)</td>
<td>8.645</td>
<td>4</td>
</tr>
</tbody>
</table>

5 RESULTS

All the ground motion records were scaled to the target spectrum, defined in the previous section, using the procedures given by the three specifications described in Section 2. Figure 5 shows the unscaled response spectra of the records and the target spectrum.

Figures 6, 7 and 8 show response spectra of the records scaled by NZS 1170 [14], ASCE/SEI 7-10 [15] and Eurocode 8 [16], respectively, along with the target spectrum.

The spectra show that Eurocode 8 [16] gives the least uniform scaled response spectra. This is because Eurocode 8 applies a unique scale factor for all the ground motions and, therefore, gives the widest distribution of values in the range of interest.

Table 4 shows a summary of the scale factors computed using the three procedures described above.
Figure 7. Target spectrum and response spectra of the ground motion records scaled by ASCE/SEI 7-10.

Figure 8. Target spectrum and response spectra of the ground motion records scaled by Eurocode 8.

Table 4. Scale factors computed using the three procedures

<table>
<thead>
<tr>
<th>Ground Motion</th>
<th>NZS 1170.5</th>
<th>ASCE/SEI 7-10</th>
<th>Eurocode 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ1</td>
<td>0.994</td>
<td>1.542</td>
<td>1.224</td>
</tr>
<tr>
<td>EQ2</td>
<td>1.137</td>
<td>1.471</td>
<td>1.224</td>
</tr>
<tr>
<td>EQ3</td>
<td>0.613</td>
<td>2.342</td>
<td>1.224</td>
</tr>
</tbody>
</table>

Figures 9, 10 and 11 show the distribution of the maximum axial stresses obtained from ground motions EQ4, EQ5 and EQ8 for the three scaling procedures.

Figure 9. Maximum axial compressive stresses due to EQ4.

Figure 10. Maximum axial compressive stresses due to EQ5.

Figure 11. Maximum axial compressive stresses due to EQ8.
It is noticeable from these three figures that ASCE/SEI 7-10 [15] gives the highest values of axial compressive stresses compared to the other 2 scaling procedures. This corroborates what Table 4 indicates. Table 4 shows the scale factors computed using [15] are higher than those computed using the other two procedures.

Generally, the wall thickness of cylindrical tanks is determined by considering the maximum axial compressive stress, which occurs near the junction of the wall and base of the tank. Those values are shown in Table 5 for both components of the ground motions considered.

Table 5. Maximum axial compressive stress (MPa)

<table>
<thead>
<tr>
<th>Ground Motion</th>
<th>NZS 1170.5</th>
<th>ASCE/SEI 7-10</th>
<th>Eurocode 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ1A</td>
<td>0.065</td>
<td>0.108</td>
<td>0.057</td>
</tr>
<tr>
<td>EQ1B</td>
<td>0.097</td>
<td>0.131</td>
<td>0.083</td>
</tr>
<tr>
<td>EQ2A</td>
<td>0.097</td>
<td>0.108</td>
<td>0.064</td>
</tr>
<tr>
<td>EQ2B</td>
<td>0.099</td>
<td>0.087</td>
<td>0.065</td>
</tr>
<tr>
<td>EQ3A</td>
<td>0.079</td>
<td>0.090</td>
<td>0.079</td>
</tr>
<tr>
<td>EQ3B</td>
<td>0.095</td>
<td>0.099</td>
<td>0.095</td>
</tr>
</tbody>
</table>

Table 5 shows that in 17 of the 18 cases analysed ASCE/SEI 7-10 [15] gives the highest values of axial compressive stress, confirming what Table 4 and Figures 9, 10 and 11 indicate.

6 CONCLUSIONS

A series of earthquake records for use in an experimental study have been derived using 3 different procedures. 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 on the measured tank wall compressive stress resulting from different acceleration scaling procedures given by three design specifications.

The investigations reveal:
1. ASCE/SEI 7-10 gives the highest values of scale factors.
2. Eurocode 8 scaling procedure gives the least uniform results because it applies a unique scale factor to the whole set of earthquake records.
3. ASCE/SEI 7-10 is the most conservative document in terms of axial compressive stress.
4. For the three records used in the experiments Eurocode 8 is the least conservative specification in terms of maximum axial compressive stresses in the tank wall.

ACKNOWLEDGMENTS

The authors wish to thank the Chilean Government for awarding the first author a “Becas Chile” scholarship for his doctoral study at the University of Auckland.

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