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# Evaluation of seismic ground motion scaling procedures for linear time-history analysis of liquid storage tanks

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ABSTRACT

Liquid storage tanks are vital life-line structures, especially following destructive seismic events. However, at present there is no accepted procedure to scale ground motions to perform time-history analysis for these very short period structures. Current standards and design codes e.g. ASCE/SEI 7-10, Eurocode 8 and NZS 1170.5, for conventional structures, e.g. buildings and bridges, minimise in a pre-defined range of periods the difference between the response spectra of chosen records and the target spectrum. This period range has limits related to the fundamental period of the structure in the excitation direction being considered. However, these design specifications have important differences in their scaling procedures and consequently affect the calculated seismic response of the structure. Additionally, these procedures were not formulated for time-history analysis of liquid storage tanks. This is evident in the case of the restriction imposed by NZS 1170.5 for very stiff structures, which includes most tanks. This restriction leads to reduced structural loading giving non-representative results. The research reported here concerns the seismic response of storage tanks, in terms of base shear, overturning moment and wall stresses, when subjected to scaled ground motions using the procedures of three design specifications. It was found that the Eurocode 8 approach produces the highest seismic response on storage tanks. ASCE/SEI 7-10 gives intermediate results in terms of applied load and seismic response compared to the other two specifications. The study also shows that the restriction imposed by NZS 1170.5 for tanks, produces an underestimate of the seismic load on storage tanks.



## 1. Introduction

Storage tanks are essential structures that provide basic supplies such as water and fuel. It is very important that this kind of structure remain operational after a destructive seismic event to facilitate rapid recovery. Because of the importance of these structures many studies have been carried out [e.g. 1–3] and standards and design guides have been established [4–6] and compared [7]. Yet despite the importance of storage tanks, there is no specific widely accepted procedure for time-history analysis to enable an estimation of the behaviour of storage tanks under a specific seismic excitation. Current design practice only provides seismic coefficients based on a pseudo-dynamic method of assessment. Using this design method it is impossible to see the potential for successive plastic incursions of the structural elements of storage tanks (shell and base plate). It has been shown [8] that such plastic behaviour will lower the impact of earthquake loading whilst imposing ductility requirements. Thus, it is essential to have an appropriate selection criteria and scaling procedure of the ground motions.

There are two distinctly different sources of obtaining ground motions for time-history analysis [9]. The first is to use recorded ground motions from databases of previous events [10–12]. The second source is to use ground motions stochastically generated using physical or numerical models [e.g. 13,14]. Standards and codes, e.g. NZS 1170.5 [15], ASCE/SEI 7-10 [16] and Eurocode 8 [17], recommend the use of recorded motions from previous events. However, if there is insufficient recorded data the three design specifications above [15–17] allow the use of supplementary simulated ground motions to make up the total number of records required. All three documents agree in the requirements for choosing the records to be used. The ground motions should have compatible seismological characteristics, i.e. magnitude, distance, fault mechanism and soil conditions, to the tectonics of the region and the site of the structure. Studies have been carried out in a number of locations to obtain ground motions that meet the requirements imposed by standards and codes. Oyarzo-Vera et al. [18] provide a list of ground motions to be used in the North Island of New Zealand for time-history analysis. Iervolino et al. [19]

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and Cooper [20] state the criteria for selecting ground motions for using the Eurocode 8 [17] and ASCE/SEI 7-10 [16] procedures, respectively.

Contrary to the criteria for selecting records, where there is agreement between the standards and codes, the scaling procedures to apply to the chosen records differ substantially in important ways. The procedures defined in the three design specifications implemented here specify different period ranges of interest. Over these ranges the chosen record should be matched as close as possible to the target spectrum.

To the authors' knowledge a comparison of the application of the three main design specifications to liquid storage tanks has not been reported. The objectives of the work is to evaluate the consequences of the procedures for the analysis of the seismic performance of liquid storage tanks and to reveal the differences and similarities of the outcomes resulting from application of the specifications. The selection of records for time-history analysis is not part of the scope of this study. However, some important points about the criteria for selecting records are provided in the discussion of the results.

## 2. Method for scaling records

A summary of the three design specifications used in this study is presented below. All three design specifications require the computation of a multiplication factor to apply to the chosen time history to ensure a match to the target spectrum in the period range of interest. However, this factor is computed differently depending on the standard or code considered.

### 2.1. New Zealand Standard (NZS 1170.5)

NZS 1170.5 requires the use a family of at least three pairs of horizontal ground motions recorded in seismic events. The vertical component shall be included when the structure analysed is sensitive to the action of vertical acceleration. The selected events shall have similar seismological characteristics (magnitude, fault mechanism, source-to-site distance and near-surface soil profile) to the characteristics of the events that mainly contributed to the seismic hazard at the site over the period range of interest. When there is insufficient suitable recorded ground motions available for a site, simulated ground motion records may be used to complete the family of records.

The period range of interest defined by this standard is between $0.4T_1$ and $1.3T_1$, where $T_1$ is the fundamental period of the structure in the direction analysed, but may not be less than 0.4 s. In this range, the records should match the target spectrum as closely as possible by using the multiplication factors, $k_1$ and $k_2$. $k_1$ is known as the record scale factor and is different for each record. $k_2$ is known as the family scale factor and is common to all records in the family. $k_1$ is the value that minimises in a least mean square sense the function defined in Eq. (1) in the period range of interest.

$$\log\left(k_1 \cdot \mathrm{SA}_{\mathrm{component}}/\mathrm{SA}_{\mathrm{target}}\right) \quad (1)$$

where $\mathrm{SA}_{\mathrm{component}}$: 5% damped spectrum value of the chosen horizontal component of the record; and $\mathrm{SA}_{\mathrm{target}}$: corresponding target spectrum value at the same period.

In this way, $k_1$ is computed for each horizontal component of the record and the smallest value is chosen as the record scale factor. The component that yields the value of $k_1$ for a pair of horizontal ground motion components is called the principal component.

The family scale factor $k_2$ is the maximum of 1.0 and the value computed from Eq. (2):

$$k_2 = \mathrm{SA}_{\mathrm{target}}/\max(\mathrm{SA}_{\mathrm{principal}}) \quad (2)$$

where $\mathrm{SA}_{\mathrm{principal}}$: 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 after application of the family factor $k_2$.

Additionally, the following restrictions apply to the scale factors:

$$0.33 < k_1 < 3.0$$
$$1.0 < k_2 < 1.3$$

It is important to realise that the minimum value for $T_1$ = 0.4 s imposed by this standard will affect the time-history analysis of the storage tanks analysed. Liquid storage tanks generally have very short fundamental periods, only a few tenths of second [21], and, therefore, their periods are most likely less than 0.4 s.

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

ASCE/SEI 7-10 requires the use of at least three pairs of ground motions. The selected events shall have magnitudes, fault distance, and source mechanisms consistent with the expected maximum earthquake considered in the analysis. Soil profile similarities are not required explicitly by this standard. 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 pair that forms the records. The same scale factor shall apply to both horizontal components, i.e., each pair has a unique scale factor. The scale factor is determined by the criterion that the SRSS of the response spectrum of each pair shall not be less than the target spectrum in the period range of interest defined by ASCE/SEI 7-10. The period range is specified as being between $0.2T_1$ and $1.5T_1$, where $T_1$ is the fundamental period of the structure in the direction analysed.

When seven or more pairs 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 will be considered.

### 2.3. Eurocode 8

This design specification requires the use of a set at least three pairs, regardless of their origin. 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 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 is between $0.2T_1$ and $2T_1$, where $T_1$ is the fundamental period of the structure in the direction of application of the motion. It should be noted that this procedure, contrary to the previous two, does not provide a specific method to compute the scale factors for the records. The requirement established by Eurocode 8 can be fulfilled in several ways. Even a single unique scale factor for all the records can be used if the average of the 5% damped elastic spectrum of all time histories meets the requirement. Iervolino et al. [19] realised this issue and proposed additional conditions on choosing ground motions to be utilised for time-history analysis. Katsanos et al. [22], present a complete review of the state of art of the selection of records for time-history analysis. They confirmed that there is a high variability in