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SEISMIC VULNERABILITY ASSESSMENT FOR LIQUID STORAGE TANK FARMS

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ABSTRACT

A seismic vulnerability estimation procedure is developed for liquid storage tank-farms, specifically ensembles of atmospheric tanks that are interconnected to provide enhanced storage capacity for a given liquid product. All pertinent sources of uncertainty are considered together with associated intra- and inter-structure correlations, while particular attention is paid to the effect of uncertainty on damage state threshold values. Appropriate decision variables are defined in view of enabling decision-making for the mitigation of seismic losses at the level of the system, rather than the individual structure, focusing on (a) the leakage of stored product and (b) the loss of storage capacity. A case study of nine tanks, evenly split in three types, is undertaken. Whenever uncertain damage state thresholds are considered, Monte-Carlo simulations reveal a significant potential for loss of containment for average spectral accelerations ($AvgS_a$) of 0.30g. While storage capacity is proportionately impacted, a remarkable 30% of the total farm storage volume can survive an $AvgS_a$ of 0.5g, thus leaving considerable room for the drainage and repair of damaged tanks in typical operation scenarios.

Keywords: Liquid storage Tanks; Tank farm; Seismic vulnerability; Uncertainty

1. INTRODUCTION

Oil & Gas industry products are normally stored in large-capacity atmospheric tanks. Safeguarding the integrity of such industrial facilities against earthquakes is vital not only for maintaining the flow of essential products and energy resources, but also for preventing any associated socioeconomic consequences. Ensuring an "appropriate" level of safety tantamount to the importance of liquid storage tanks, mandates the use of state-of-the-art techniques that take into account all possible sources of uncertainty, in the form of Performance-Based Earthquake Engineering [PBEE, Cornell and Krawinkler (2000)].
The assessment methodology typically undertaken by engineers is based on the design code and can be summarised in a prescriptive approach that may only deliver some acceptable (but actually unknown) level of accuracy by engaging in a deterministic process, where the associated dispersion is either inadequately defined or completely missing. It appears that current design codes and guidelines have not fully adopted the PBEE concept, while its application to industrial facilities is very limited and usually dependent on the respective client.
Despite the devastating outcome of recent earthquake events such as Kocaeli (1999) and Tohoku (2011), little attention has been paid to industrial facilities even from an academic point of view. Previous research efforts may be summarised to a fragility-based methodology using either computer-intensive finite element models (Buratti and Tavano, 2014; Talaslidis et al., 2004), or available empirical data as shown by O'Rourke and So (2000). Along these lines, a systematic PBEE methodology based on a surrogate (i.e., reduced-order) modelling approach was recently developed by Bakalis et al. (2017a; b), thus offering an alternative to the existing procedures. Still, this only concerns a single tank rather than an ensemble.
Modern refineries accommodate a variety of industrial components that blend harmoniously to deliver

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high quality oil and gas products. The component topology is normally very strict and follows certain design criteria to meet health and safety measures. Large-capacity atmospheric tanks are normally constructed according to specific requirements to suit the volume produced and the physical characteristics of each liquid product in the refinery. Each design is typically constructed in multiples to avoid design and procurement iterations. Still, even for the same product, one may find adjacent liquid storage tanks that do not share similar geometric characteristics, either due to different year of construction, or due to the varying demand in fluid capacity prescribed by the client. Such a topology is presented in Figure 1 where the difference between the group on the left (indicated by yellow arrows) and the group on the right (indicated by red arrows) is evident.

This study aims to extend the existing framework by evaluating the seismic vulnerability of a set of liquid storage tanks. A typical tank-farm within a modern refinery is examined in view of defining the correlation of damage between adjacent structural systems with varying geometric characteristics, subject to the same ground excitation. Several scenarios are considered, taking into account the intra- and inter-structure correlations that befit a system of closely-spaced and constructionally related tanks.

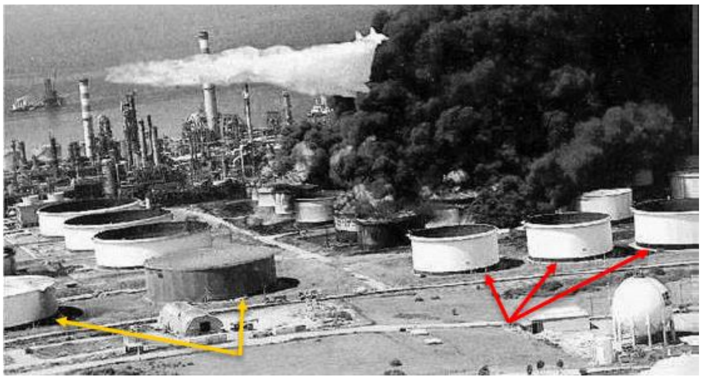


Figure 1: Damage on the Izmit refinery during the Kocaeli (1999) earthquake.

2. CASE STUDY DESCRIPTION

In an attempt to capture the seismic vulnerability involved in a modern industrial complex, a simple 3x3 layout is adopted, as shown in Figure 2. Three different structural systems are considered: Tanks A have a radius (R_A) equal to 13.9m and a total height (h_{tA}) of 16.5m. The bottom course wall (t_{wA}) is 17.7mm thick, while the corresponding base plate (t_{bA}) and annular ring (t_{aA}) thickness are 6.4mm and 8.0mm respectively. In the same sense the geometric characteristics for Tanks B may be summarised as R_B=23.47m, h_{tB}=19.95m, t_{wB}=22.23mm, t_{bB}=6.4mm and t_{aB}=10.0mm, while for Tank C as R_C=6.1m, h_{tC}=11.3m, t_{wC}=9.6mm, t_{bC}=4.8mm and t_{aC}=4.8mm.

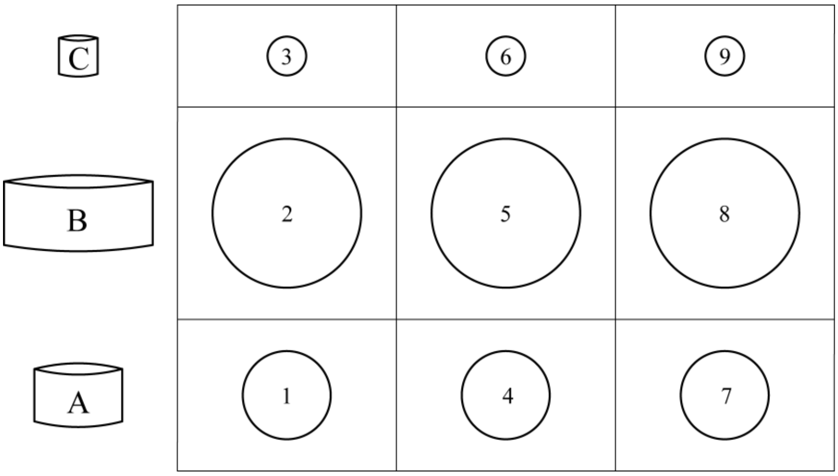


Figure 2: Case study layout of liquid storage tanks.

3. STRUCTURAL ANALYSIS

The surrogate modelling approach developed by Bakalis et al. (2017a) is adopted in view of offering a balanced "computational efficiency versus accuracy" compromise for nonlinear time-history analysis (Figure 3). The modelling approach is based on the work of Malhotra and Veletsos (1994) for liquid storage systems, where the uplift mechanism of unanchored tanks is modelled in detail. The response is defined using two decoupled masses that represent the rigid-impulsive motion of the tank on one hand and the sloshing of the fluid (convective mass) on the other. The latter is considered to offer very little in terms of overturning action on the tank (at least of the dimensions that are of interest herein), which means that it may be neglected during the modelling process, and that sloshing response may individually be obtained through a simple response spectrum analysis (CEN 2006; Malhotra 2000; Vathi and Karamanos 2017).

Figure 4(a) presents the associated response for unanchored tanks A, B and C at their maximum fill level, under varying levels of earthquake loading. Single-record and median Incremental Dynamic Analysis (IDA) curves (Vamvatsikos and Cornell 2002) are plotted for a set of 30 pairs of records that have been selected using the conditional spectrum approach (Kohrangi et al. 2017; Lin et al. 2013). The base uplift is adopted as the engineering demand parameter (*EDP*), while the geometric mean of spectral accelerations [i.e. the so-called average spectral acceleration, $AvgS_a$, (Cordova et al. 2001; Eads et al. 2015; Kazantzi and Vamvatsikos 2015; Kohrangi et al. 2016; Vamvatsikos and Cornell 2005)] is employed as a suitable intensity measure (*IM*). Relevant research conducted by the authors (Bakalis et al. 2017b) has revealed the superiority of $AvgS_a$ over traditional (scalar) intensity measures such as the peak ground acceleration (*PGA*), while it has also shown that the range of low and high periods [T_L, T_H] that should be considered for it is [0.1s, 4.5T_i], where T_i is the impulsive mass vibration period of the liquid storage tank.

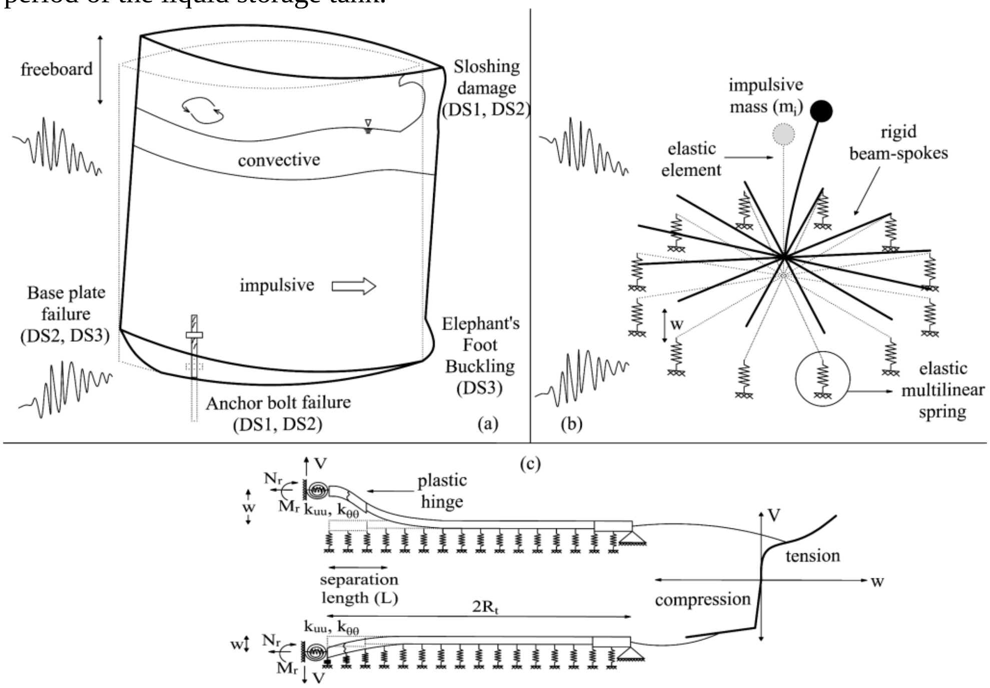
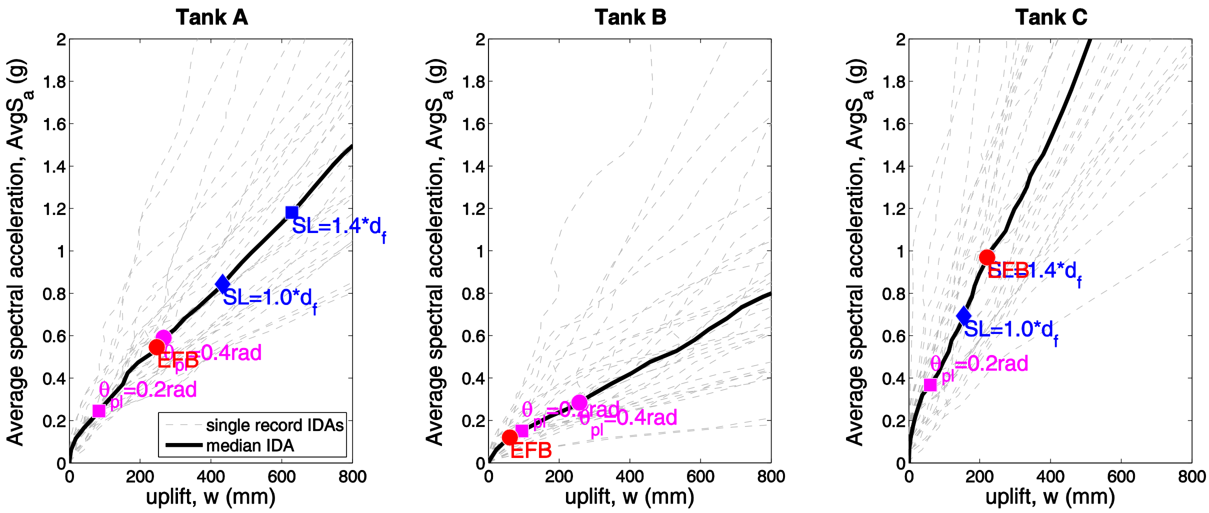


Figure 3: (a) Impulsive versus convective fluid component, failure modes, and system-level damage state classification on a fixed roof liquid storage tank. Depending on the presence of anchors, the system is either anchored or unanchored. (b) The "Joystick" surrogate model and its deflected shape. (c) The strip model under tensile and compressive loading (Bakalis et al. 2017c).

The most common failure modes are depicted on the median IDA curves (solid lines) in Figure 4, where θ_{pl} corresponds to the plastic rotation that may be developed on a tank's base plate when uplift is allowed, and EFB stands for the well-studied elastic-plastic buckling failure, known as the elephant's foot buckling. A third mode of failure, related to convective mode sloshing damage (SL) to the top of the tank wall is also considered. Still, as shown in Figure 4(b), this may occasionally appear at excessive $AvgS_a$ values due to the ultra-long convective period (T_c). Similarly, excessive plastic rotation at the base (i.e. order of 0.4rad), may also be difficult to reach for slender tanks such as Tank C. For the purpose of the vulnerability estimation presented below, a system-level damage state (*DS*) classification is adopted, similar to the one proposed by Vathi et al. (2017). The definition follows an increasing severity pattern, where *DS*0 represents no damage, *DS*1 slight damage, *DS*2 severe damage without leakage and *DS*3 loss of containment. For the case of unanchored systems, *DS*1 may be controlled by the sloshing response of the contained liquid only, *DS*2 though, is governed by the exceedance of either a sloshing wave height capacity equal to 1.4 times the available freeboard or a plastic rotation of 0.2 rad at the base plate. *DS*3, finally, provides information on the loss of containment either through the EFB formation, or the exceedance of a base plate plastic rotation capacity equal to 0.4 rad [Figure 3(a)].



(a) (b) (c)

Figure 4: Single-record and failure mode capacities on the median IDA curves for Tanks (a) A, (b) B and (c) C at their maximum filling level.

4. VULNERABILITY FRAMEWORK

Predicting the seismic loss has been a major challenge for the earthquake engineering community. Complex structural systems may cause additional difficulties due to the increased level of uncertainty that requires even more runs to determine median and dispersion response estimates (Fabbrocino et al. 2005; Salzano et al. 2003). Fragiadakis and Vamvatsikos (2010) have extensively discussed the issues associated with uncertainty estimation not only through Static Pushover procedures, but also using Incremental Dynamic Analysis (Vamvatsikos and Fragiadakis 2010), where the computational time is significantly increased. Recently, Bakalis et al. (2017a) investigated the potential sources of uncertainty for the surrogate model used herein. Parameters such as the ground motion uncertainty, the tank wall (t_w), the base plate (t_b) and annular ring (t_a) thickness were found to be of some importance, yet, the fluid height (h_f) serves as the one parameter that could critically modify the response of the system.

The sources of uncertainty associated with the case study considered may be summarised into the seismic load (i.e. the ground motion record to occur), and the structural properties (i.e. plate/shell thickness, fluid height). Structural elements may suffer a significant loss of thickness, mostly due to the chemical composition of liquids stored in a tank. Oil products typically contain sulphides or other substances (e.g. seawater in crude oil) that can severely corrode steel plating, having a significant impact on the structural capacity both locally and globally. Fluid height on the other hand is highly depended on the operation of the storage facility (e.g. within a refinery). Thus, it is evident that significant uncertainty will be present in any tank assessment.

Having established a performance-based framework where the structural variability is well defined,

one may argue that the vulnerability estimation is only a few calculations away. That may be true for the case of a single liquid storage unit, but the application of the procedure on a tank-farm becomes more complex, as correlations regarding uncertainty both in the structure considered (intra-structure) and the farm (inter-structure) need to be considered. Bradley and Lee (2010) have already highlighted the component correlation significance by offering a structure-specific seismic loss procedure, where different correlation assumptions can significantly affect the results for certain cases. It appears that correlation has drawn a lot of attention since, as research efforts such as Kazantzi et al. (2014) and Vamvatsikos (2014) also take it into account in view of an accurate seismic performance estimation. Furthermore, interconnectivity of infrastructure is a topic of considerable importance that has grown considerably in the literature (e.g., Pitilakis et al. 2014). The fire hazard due to leakage ignition is a significant issue (Alessandri et al. 2017; Fabbrocino et al. 2005), which however, is not tackled herein.
Regarding the different variables within a tank (i.e. intra-structure), zero intra-structure correlation is assumed. Plate/shell thicknesses may serve as the primary source of uncertainty, due to the effect they may have on the predefined failure mode capacities such as EFB and θ_{pl}. Following the sensitivity analysis results found in Bakalis et al. (2017a), it is reasonable to assume that the demand is not affected. The steel plates are already extremely thin compared to tank dimensions, and as a result, a reduction of thickness at the order of 30% is not expected to significantly modify either the local or the global demand for the tank. This observation reduces the computational load by far, as the model cases that must be considered correspond to tanks with varying fluid height only. Even damage state capacities that could be construed to be correlated due to similar corrosion damage, e.g. tank wall buckling resistance and base plate plastic rotation, are actually modelled uncorrelated as design codes stipulate a thickness-independent limiting value for θ_{pl}. Similarly, sloshing damage is only a function of the available freeboard (CEN 2006; Malhotra 2000).
For the case where two adjacent tanks are examined (i.e. inter-structure), the correlation may be deemed perfect across all tanks (types A, B and C) under the assumption that they are used to store the same product and filled/drained uniformly. Apparently, this is highly depended on the operating procedures within the refinery, thus implying strong correlation for sloshing damage states as they are a function of the available freeboard and hence the fluid height. Zero correlation may be assumed for the damage state capacities of different tanks, bearing in mind that parameters such as the year of construction and the inspection/repair schedule will reduce any dependence: To avoid a significant reduction in storage capacity of the tank-farm, repairs are performed serially rather than in parallel, resulting in tanks with different corroded states at the time of the earthquake. However, for a very large storage facility that could afford to inspect and repair tanks in parallel, strong correlation may be a better option. As far as ground motion records are concerned, they may be applied uniformly on the entire tank-farm, given the same site conditions and the relatively small distance between them, thus implying full correlation. To be more precise, perfect correlation can only be achieved among structural systems that share the same dynamic properties, i.e. the impulsive (T_i) and convective (T_c) periods of vibration. Even for the same type of tanks, the aforementioned variables are strongly tied to the fluid height ratio (i.e. a certain percentage of the maximum allowable fluid height prescribed for a liquid storage system), leading to a strong but not necessarily perfect correlation.

4.1 Monte Carlo Sampling

With the basis of the vulnerability framework adequately defined, the sample matrix may be formed in a few steps. A series of assumptions that define both intra and inter-structure correlation is more than necessary at this point in order to come up with realistic scenarios at the minimum computational cost. Fluid height levels of interest are defined to describe common practice scenarios. h_f is assumed to be uniformly distributed in [$0.5h_{f,max}$, $1.0h_{f,max}$], where $h_{f,max}$ is the maximum allowable fluid height for each tank type. Stratified sampling is performed on the aforementioned fluid heights of interest, resulting in five different structural systems for each tank that need to be subjected to Incremental Dynamic Analysis, based on the associated j^{th} sample of fluid height ($h_{f,j}$). For the case study examined, it is assumed that all nine tanks are uniformly filled to same fluid height ratio at any given time. Obviously, the amount of the liquid in a tank is affected by the operations performed within a

refinery, yet some uniformity of the filling height is a plausible assumption, given that the same product is assumed to be stored in all tanks. Table 1 shows the sample matrix with all the available scenarios considered when no damage state uncertainty is employed. Therefore, only scenarios associated with fluid height and ground motion uncertainties are presented.
A more realistic representation is possible if the damage states are examined from a probabilistic point of view, where their capacities are considered lognormally distributed around their median estimates (EDP_c). Bearing in mind the zero correlation already assumed, Table 1 may be augmented following a random permutation pattern (due to zero inter-structure correlation) of the uncertain capacities for each tank. A reasonable sample size (i.e. N_p=8) is considered for the Monte Carlo simulation and stratified sampling is performed in order to define equiprobable damage state capacities, as shown in Table 2.

Table 1: Sample matrix without *DS* threshold uncertainty. All possible combinations of 5 fluid heights times 30 record pairs are considered for each tank.

#	Tank 1	Tank 2	...	Tank 9
30 records * h_{f1}	0.55$h_{fA,max}$ record 1	0.55$h_{fB,max}$ record 1	...	0.55$h_{fC,max}$ record 1
	0.55$h_{fA,max}$ record 2	0.55$h_{fB,max}$ record 2	...	0.55$h_{fC,max}$ record 2
	…	…	...	…
	0.55$h_{fA,max}$ record 30	0.55$h_{fB,max}$ record 30	...	0.55$h_{fC,max}$ record 30
30 records * h_{f2}	0.65$h_{fA,max}$ record 1	0.65$h_{fB,max}$ record 1	...	0.65$h_{fC,max}$ record 1
	0.65$h_{fA,max}$ record 2	0.65$h_{fB,max}$ record 2	...	0.65$h_{fC,max}$ record 2
	…	…	...	…
	0.65$h_{fA,max}$ record 30	0.65$h_{fB,max}$ record 30	...	0.65$h_{fC,max}$ record 30
… …	… …	… …	… …	… …
30 records * h_{f5}	0.95$h_{fA,max}$ record 1	0.95$h_{fB,max}$ record 1	...	0.95$h_{fC,max}$ record 1
	0.95$h_{fA,max}$ record 2	0.95$h_{fB,max}$ record 2	...	0.95$h_{fC,max}$ record 2
	…	…	...	…
	0.95$h_{fA,max}$ record 30	0.95$h_{fB,max}$ record 30	...	0.95$h_{fC,max}$ record 30

Table 2: Sample matrix with *DS* threshold uncertainty. For each tank, all possible combinations of 5 fluid heights times 30 record pairs, times *Np*=8 damage state capacities are considered.

#	Tank 1	...	Tank 9	...	Tank 9
30 records * h_{f1}*$EDP_{C,j,Np}$	0.55$h_{fA,max}$ record 1 $EDP_{C,1,1}$	...	0.55$h_{fC,max}$ record 1 $EDP_{C,9,1}$	...	0.55$h_{fC,max}$ record 1
	0.55$h_{fA,max}$ record 2 $EDP_{C,1,1}$	...	0.55$h_{fC,max}$ record 2 $EDP_{C,9,1}$	...	0.55$h_{fC,max}$ record 2
	…	...	…	...	…
	0.55$h_{fA,max}$ record 30 $EDP_{C,1,1}$	...	0.55$h_{fC,max}$ record 30 $EDP_{C,9,1}$	...	0.55$h_{fC,max}$ record 30 $EDP_{C,9,Np}$
30 records * h_{f2}*$EDP_{C,j,Np}$	0.65$h_{fA,max}$ record 1 $EDP_{C,1,1}$	...	0.65$h_{fC,max}$ record 1 $EDP_{C,9,1}$	...	0.65$h_{fC,max}$ record 1
	0.65$h_{fA,max}$ record 2 $EDP_{C,1,1}$	...	0.65$h_{fC,max}$ record 2 $EDP_{C,9,1}$	...	0.65$h_{fC,max}$ record 2
	…	...	…	...	…
	0.65$h_{fA,max}$ record 30 $EDP_{C,1,1}$	...	0.65$h_{fC,max}$ record 30 $EDP_{C,9,1}$	...	0.65$h_{fC,max}$ record 30 $EDP_{C,9,Np}$
… …	… …	… …	… …	… …	… …
30 records * h_{f5}*$EDP_{C,j,Np}$	0.95$h_{fA,max}$ record 1 $EDP_{C,1,1}$	...	0.95$h_{fC,max}$ record 1 $EDP_{C,9,1}$	...	0.95$h_{fC,max}$ record 1
	0.95$h_{fA,max}$ record 2 $EDP_{C,1,1}$	...	0.95$h_{fC,max}$ record 2 $EDP_{C,9,1}$	...	0.95$h_{fC,max}$ record 2
	….	...	….	...	….
	0.95$h_{fA,max}$ record 30 $EDP_{C,1,1}$	...	0.95$h_{fC,max}$ record 30 $EDP_{C,9,1}$	...	0.95$h_{fC,max}$ record 30 $EDP_{C,9,Np}$

4.2 Damage Index

Seismic vulnerability is typically illustrated using appropriate decision variables. They may be used to quantify seismic loss in terms of cost or damage, depending on the application. For the case of liquid storage tanks two damage indices (*DI*) are defined.

*DI*1 shall represent the loss of containment ratio,

$$DI1 = \frac{\text{Volume loss post event}}{\text{Volume contained pre event}} \tag{1}$$

under the assumption that the exceedance of the *DS*3 capacity triggers a complete loss of the stored product within the tank. *DI*2 on the other hand shall provide information on the available volume capacity through the following equation:

$$DI2 = \frac{\text{Volume capacity loss post event}}{\text{Volume capacity pre event}} \tag{2}$$

The concept behind the aforementioned damage indices is to enable a decision-making process using parameters that make sense even to non-engineers. They provide information both on the loss of the stored material and on the capacity of the facility following an earthquake event. Both indices are obviously controlled through *DS*3, while *DI*2 is affected by *DS*2 too, in view of the significant damage that may render the tank unusable. *DS*1 is not considered in this calculation, as it represents relatively easy-to-repair damage on the upper course of the tank whose repair may require draining the tank but can be scheduled with relative ease.

Figure 5(a) presents the 16%, 50% and 84% fractiles for *DI*1, without considering *DS* threshold capacity uncertainty. It is evident that the tank farm examined suffers an immediate loss of containment, at the order of 35%, which may be attributed to the exceedance of the θ_{pl}=0.4rad capacity as well as the EFB allowable stress for type ‘B’ tanks (i.e. 2-5-8 in Figure 2). According to Figure 4, the aforementioned capacities are developed for relatively moderate $AvgS_a$ estimates (order of 0.15-0.30g), when the contained liquid reaches the maximum allowable height, thus verifying the results observed in the first ascending branches of Figure 5(a) fractiles. Moreover, both EFB and θ_{pl}=0.4rad capacities of type ‘A’ tanks are slightly higher (order of 0.55-0.60g) compared to the corresponding type ‘B’ values, fully justifying the loss of another 30% of the total volume stored in the facility. Evidently, type ‘C’ tanks are held responsible for the loss of the remaining volume, as the loss of containment damage state capacities are developed for significantly larger seismic intensities. It should be noted that the response of the type ‘C’ tanks never reaches the θ_{pl}=0.4rad limit, and as a result *DI*1 is solely controlled by EFB for that particular case.

The results discussed above are presented from a system capacity point of view in Figure 5(b). 16%, 50% and 84% fractiles are illustrated for *DI*2, thus providing an alternative representation of the system response, where the available capacity suddenly drops (on average) down to (approximately) 30%, once an $AvgS_a$ at the order of 0.30g is reached. The two graphs provide similar, yet not identical information. For instance, one may notice the considerably larger variation among the fractiles in Figure 5(a), which cannot be attributed to the record-to-record variability. In fact, *DI*1 is strongly tied to the fluid height ratio compared to *DI*2 that is only affected by the actual height of the tank. Hence, this extra source of uncertainty appears in the representation of the results.

Damage indices 1 and 2 are reproduced taking the *DS* threshold uncertainties into account. It appears that uncertainty significantly removes the abrupt nature of the previous results for *DI*1 and *DI*2. Comparing the median vulnerability curves of Figure 5(c) and Figure 5(d) for any given *IM* level, reveals that *DS* uncertainty forces the onset of minor loss to appear at lower $AvgS_a$ values, yet significant losses are delayed until much higher intensity levels, at least for *DI*2. Regarding *DI*1, an $AvgS_a$ equal to 0.60g results in a median loss of containment slightly over 60% when the *DS* uncertainties are taken into account, while a 35% loss is estimated for the case that the aforementioned uncertainties are ignored. The inverse conclusions are drawn for *DI*2, as according to Figure 5(b) and Figure 5(d), for an $AvgS_a$ level equal to 0.60g, the median system capacities suffer 75% versus 100%, respectively.

The differences observed among the two different assumptions are significant. There is no question that properly accounting for *DS* uncertainty is important, but at the same time it comes at an additional computational cost. Ignoring this important source of variability may simplify the analysis, yet at the same time it introduces an unknown error that may or may not be conservative, thus degrading the fidelity of one's conclusions.

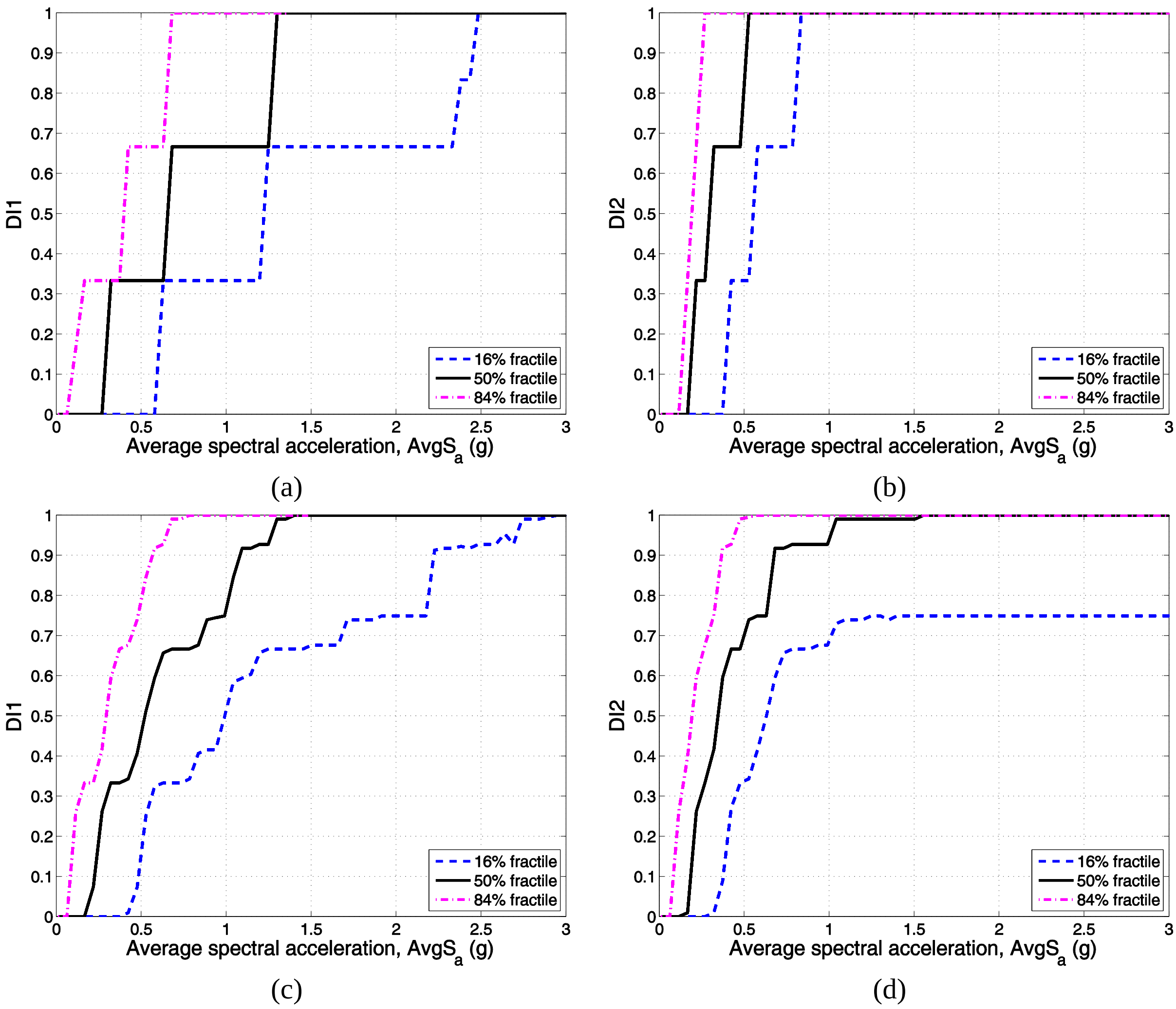


Figure 5: (a) *DI*1 without *DS* threshold uncertainty, representing the system loss of containment, (b) *DI*2 without *DS* threshold uncertainty, featuring the system loss of capacity, (c) *DI*1 with *DS* threshold uncertainty and (d) *DI*2 with *DS* threshold uncertainty.

5. CONCLUSIONS

A seismic vulnerability assessment methodology has been developed for the mitigation of seismic losses within a typical tank-farm. The damage indices developed aim to enable a rapid decision-making process through the estimation both of the loss of containment and the available capacity, following a strong ground motion event. Potential assumptions are discussed in view of defining intra and inter-structure correlation, of the effect of considering or neglecting damage state capacity uncertainty is examined. Although the majority of assumptions are reasonably defined, further modifications to the existing framework could extend the accuracy as well as the applicability of the methodology. Employing a leakage ratio for *DI*1, instead of the assumption that a full loss of containment takes place upon the *DS*3 capacity exceedance, would be a good example to illustrate this. The latter may enhance the quality of the methodology outlined, and it is expected to be covered in a future direction of our research.

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