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RELATIONSHIPS BETWEEN EARTHQUAKE-INDUCED DAMAGE AND MATERIAL RELEASE FOR LIQUID STORAGE TANKS

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***Abstract**: Liquid storage tanks are critical components in the industrial sector, as large amounts of toxic, volatile, or flammable substances are stored in them. Motivated by their underlying vulnerability to physical damage caused by earthquakes, an empirical relationship is proposed to link the specific type of earthquake-induced structural damage with the extent of material release that can potentially be triggered. To achieve this goal, an extensive database of recorded seismic-related failures of industrial tanks is examined and suitable damage states are identified. For each tank in the database, material release levels consistent with industry standard procedures for risk assessment are associated with the pertinent damage states. This is done with the consideration of characteristics that affect the seismic behaviour of tanks, such as aspect ratio and filling level. As a result, we propose a series of event trees for industrial liquid storage tanks that associate damage states and combinations thereof with material release levels. These event trees can be exploited for consequence analysis (e.g., to analyse the propagation of damage, or potential domino effects) within the context of seismic risk assessment for industrial facilities.*

1. Introduction

Several types of structures are typically involved in every industrial process. Within these processes, certain industrial components that contain a considerable inventory of toxic, volatile and/or flammable substances are vulnerable to earthquake-induced damage. Furthermore, some level of damage in a component (e.g., crack of some sizable width) may result in a certain degree of material release, which in turn may trigger physical consequences (e.g., fire, explosion) potentially impacting the nearby components, the entire facility, as well as the community in their proximity. Therefore, to evaluate the risk in a quantitative manner it is necessary to find how much material may be released when a component experiences a given level of damage after an earthquake. More precisely, we seek to establish an empirically-based relationship between earthquake-induced damage states (DSs) of a component and possible material release levels (RLs). Typically, in industrial seismic risk assessment studies, the association of DSs to RLs is assumed to be deterministic [(Cozzani *et al.* (2014), Caputo (2016), Alessandri *et al.* (2018)]; in other words, a given DS (e.g., elephant's foot buckling in a liquid storage tank) always produces a certain RL (e.g., major material release). There are some studies [e.g., Caputo and Vigna (2017)] that propose a probabilistic relationship between damage and material release by assigning weights to each RL given the occurrence of a DS, but these are mostly based on expert opinion and engineering judgement without an explicit consideration of empirical data.

Given the hazardous substances they usually contain, liquid storage tanks are one of the most critical and seismically vulnerable components within an industrial facility. Therefore, it is no surprise that tanks have been the focus of many analytical studies [Housner (1963), Malhotra and Veletsos (1994), Paolacci *et al.* (2015), Bakalis *et al.* (2017), Vathi *et al.* (2017), Caprinozzi *et al.* (2021)] that proposed numerical models and analysed the damage states that may occur. Some empirical studies [Cooper *et al.* (1997), O'Rourke and So (2000), Eidinger J. M. *et al.* (2001), Berahman and Behnamfar (2017), D'Amico and Buratti (2019), Yazdanian *et al.* (2021)] have also compiled and utilised databases of observed seismic-triggered failures of tanks to develop empirical fragility curves.

Herein, we explore an extensive earthquake-induced industrial tank damage database developed by D'Amico and Buratti (2019). Contrary to other studies, we aim to exploit this database to propose a direct association between DSs and RLs in the form of an event tree instead of conventional fragility curves that associate earthquake intensity levels either with DSs or RLs, but not both at the same time. To achieve this goal, we identified within the tanks of the database four DSs typical for earthquake-induced damage in liquid storage tanks, namely elephant's foot buckling, sloshing damage, base plate damage, and anchorage damage. Each of the tanks experiencing one (or a combination) of the aforementioned DSs is associated to an RL, that is, no release, minor release, major release, or catastrophic release of the contained material. Based on these data, we propose a series of event trees associating DSs (and combinations of DSs) and RLs for liquid storage tanks, which can be adopted for consequence analysis within the general framework of seismic risk assessment of industrial facilities.

2. Database preliminary exploration

The database of earthquake-induced damages for steel cylindrical liquid-storage tanks, which are the focus of our study, developed by D'Amico and Buratti (2019), includes damage data suffered by a total of 5829 tanks in 24 earthquake events occurred worldwide between 1933 and 2014. The authors focused on atmospheric tanks located in chemical and process industrial facilities, thus excluding, for example, wine tanks. Only well-documented cases with full understanding of the tank's seismic response were included in the database, while cases of liquefaction or foundation failure where excluded. Therefore, after this screening process a total of 3026 tanks were left, as shown in Table 1. This table shows the number of tanks per seismic event along with the estimated Peak Ground Acceleration (PGA) range at the tank sites.

Table 1. Events included in the tank database after D'Amico and Buratti (2019).

Seismic event	Number of tanks	PGA range (g)	Number of tanks used
Long Beach, 1933	52	0.358-0.448	52
Kern County, 1952	64	0.113-0.351	64
Alaska, 1964	40	0.20-0.384	40
Niigata, 1964	189	0.16	0
San Fernando, 1971	35	0.12-0.86	35
Managua, 1972	3	0.39	3
Miyagi, 1978	73	0.29	73
Imperial Valley, 1979	29	0.378-0.467	29
Greenville, 1980	177	0.167	1
Coalinga, 1983	52	0.187-0.45	52
Chile, 1985	168	0.23-0.28	163
Adak, 1986	3	0.20	3
New Zealand, 1987	11	0.3-0.5	11
Loma Prieta, 1989	1824	0.065-0.55	1824
Costa Rica, 1991	38	0.24	37
Landers, 1992	33	0.19-0.553	33
Northridge, 1994	105	0.23-0.90	104
Kobe, 1995	426	0.36-0.74	0
Tokachi-oki, 2003	177	0.10	177
Bam, 2003	7	0.413-0.497	7
Central Peru, 2007	104	0.34-0.427	104
Chile, 2010	202	0.24-0.334	202
Tohoku, 2011	1927	0.11-0.91	0
Napa Valley, 2014	96	0.23-0.65	12
Total	5829	0.065-0.90	3026

In their analysis, D'Amico and Buratti (2019) classified the data of each damaged tank according to two properties: a) the structural damage expressed in terms of DSs; b) the level of material released expressed in terms of RLs. For structural damage, five DSs related to the structural condition of the tank were identified, as shown in Table 2. It should be noted that in the context of standard fragility concepts, as e.g., expressed in the FEMA Seismic Performance Assessment of Buildings Methodology, FEMA P-58 (FEMA, 2018), the five DSs are not sequential. Thus, the occurrence of elephant's foot buckling in DS4 or DS5 does not imply that damage to piping (DS3) or to the upper part of the shell (DS2) has already happened. Furthermore, they are not mutually exclusive, as for example, elephant's foot buckling and sloshing damage may both happen in the same tank during ground shaking [Bakalis *et al.* (2017)]. In addition, when progressing from DS1 to DS5 the severity in terms of structural consequences generally increases, with the exception of DS2. This is based on the nature of the tank's response, that is, DS2 is strictly related to the sloshing motion of the liquid contained, while DS3 to DS5 are related to the impulsive motion of the liquid (i.e., the liquid moving in synch with the tank's wall).

Regarding material release, three RLs were proposed, as shown in Table 3. It is noted that spillage from the top of the shell is not considered as material release by D'Amico and Buratti (2019).

Table 2. Damage state (DS) definition after D'Amico and Buratti (2019).

Damage State	Description	Number of tanks
DS1	No damage or slight damage to tank wall, bottom plate, minor damage to piping system	2786
DS2	Damage to roof and upper part of the shell due to sloshing	72
DS3	Damage to piping system	59
DS4	Slight elephant's foot buckling, damage to the shell-bottom plate junction	59
DS5	Extensive elephant's foot buckling, damage to the shell-bottom plate junction, severe damage to the shell or bottom plate, total failure, tank collapse, overturning	50

Table 3. Release level (RL) definition after D'Amico and Buratti (2019).

Release level	Description	Number of tanks
RL1	No release, spillage from roof	2893
RL2	Minor leaks from shell tearing or damaged piping	41
RL3	Major leaks from shell rupture or broken pipe, inlet/outlet pipe or outflow pipe disconnected from tank. Leaks from tearing in correspondence to bottom-shell junction	92

3. Damage states and release levels for industrial components

A certain level of damage in a component, such as cracks' opening size, which in our work is considered as a DS, can induce a certain degree of material release leading to an RL. Traditionally, quantitative risk assessment (QRA) methodologies [see, for example, the Purple Book (Uijt De Haag and Ale, 2005)] simplify the number of considered material release levels and rely on a few, predefined release events. For example, the standard RLs for stationary vessels (e.g., liquid storage tanks and pressure vessels as opposed to tanks on vehicles) in decreasing order of severity are (Uijt De Haag and Ale, 2005): Instantaneous release of complete inventory (G.1), release of complete inventory in 10 min at a constant rate (G.2), and continuous release from a hole with an effective diameter of 10 mm (G.3). It should be noted that these conventional RLs are associated to human error or equipment failure and not to structural damage due to natural hazardous events (e.g., earthquakes, floods, hurricanes). Therefore, in a seismic assessment, regardless of their definition, RLs should be correlated to the amount of structural damage sustained by a component due to seismic excitation.

Comparing the release levels from D'Amico and Buratti (2019) with the conventional release level events from QRA, the following observations can be made:

- Conventional RLs for atmospheric tanks in QRA do not cover failure of pipes connected to the vessels and tanks. Pipe failures need to be evaluated separately, using a different set of QRA analyses and a separate set of RLs (e.g., full bore rupture, leak).

- RL3 in D'Amico and Buratti (2019) is related to major material release and thus may be associated to an instantaneous release of complete inventory (G.1). Nevertheless, RL3 may also be associated to a continuous release of the complete inventory in 10 min at a constant rate of release (G.2) because for a large-diameter tank, a continuous release of material in 10 min is actually a significant release.
- RL2 in D'Amico and Buratti (2019) is related to minor material release and thus may be associated to a continuous release from a hole with an effective diameter of 10 mm (i.e., G.3).

Taking these considerations into account, RL events from pipe failure were excluded from our analysis. Regarding the tank-specific RLs, achieving a one-to-one association between RLs from the tank database and conventional RLs from QRA requires the addition of a fourth level (herein denoted as RL3), related to the cases for which a complete failure of the shell or base plate of the tank occurs (i.e., an immediate release of the complete inventory of material). In light of all these considerations, the proposed RLs in this study are described in Table 4.

Table 4. Definition of Release Level (RLs) proposed in this study.

Release level	Description
RL0	No material release
RL1	Minor material release, associated to G.3 (i.e., continuous release from a hole with an effective diameter of 10 mm)
RL2	Major continuous material release, associated to G.2 (i.e., continuous release of the complete inventory in 10 min with a constant release rate)
RL3	Catastrophic material release, associated to G.1 (i.e., instantaneous release of complete inventory)

4. Proposed damage states

Given the limitations of the DS1-DS5 states proposed by the original study, we have slightly reworked said DSs to adopt only four beyond the no-damage state:

- Base plate and wall-to-base connection damage (BP).
- Anchorage damage (AN).
- Sloshing damage (SL).
- Elephant's foot buckling (EFB).

These have been long identified as potential seismic failure modes of liquid storage tanks and have been widely adopted in the literature [see, for example, Bakalis *et al.* (2017), Vathi *et al.,* (2017)]. Note that we avoid numbering them, as these DSs are neither sequential nor mutually exclusive, as discussed earlier. Therefore, to describe the seismic response of liquid storage tanks we adopt the "simultaneous" DS logic (i.e., these potential damage states may occur, but need not necessarily occur, at the same time) from the FEMA Seismic Performance Assessment of Buildings Methodology, FEMA P-58 (FEMA, 2018).

Note that even though SL has been proven to cause physical consequences such as fire in floating roof tanks [see, for example, Hatayama (2008)], traditional QRA release levels do not explicitly consider material release due to sloshing (e.g., oil spillage from the top of a tank), while dispersion models, i.e., models developed to predict the intensity of physical consequences at a distance from a source, are not readily available in the QRA literature. Moreover, it is well known that the convective period (responsible for SL) of tanks is significantly longer than the impulsive period (responsible for BP and EFB). Therefore, there is little correlation between SL and BP or EFB as the convective and impulsive components of the fluid inside a tank are excited by ground motions with energy content in significantly different period ranges. Hence, as in D'Amico and Buratti (2019), we decided to exclude material release due to SL from the analysis. This entails that the cases in the database where there was spillage from the roof were disregarded for our purposes, that is those cases were assigned to RL0 instead of to RL1, RL2, or RL3.

5. Database statistics and event tree analysis

5.1. Frequency of release levels per damage state

The statistics of DSs of the tanks included in the database are graphically summarized in

Figure 1. Again, our interest in this study is not to predict whether damage occurs to tanks but to propose probabilistic relationships that link DSs to RLs. Therefore, we focus only on the tanks experiencing one or a combination of the DSs.

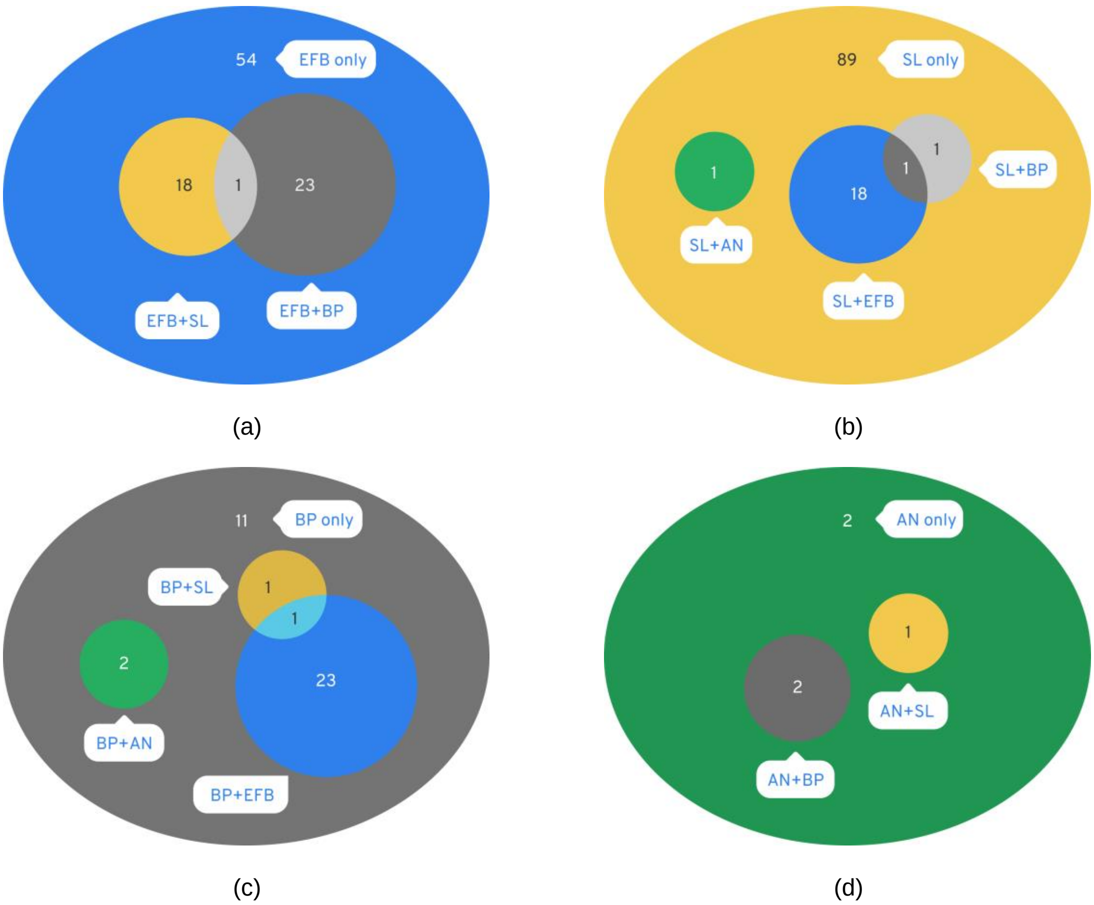

Figure 1. Venn diagrams of DSs for the liquid storage tanks in the database: (a) Tanks experiencing EFB; (b) Tanks experiencing SL; (c) Tanks experiencing BP; (d) Tanks experiencing AN.

As shown in Figure 1a, 54 out of the 96 EFB-damaged tanks experienced only EFB, 23 suffered EFB+BP, 18 showed EFB+SL, and one tank experienced EFB+BP+SL. On the other hand, no tanks experienced EFB+AN, or any more complex combination. From Figure 1b, one can note that a total of 89 out of the SL-damaged tanks experienced only SL, 18 experienced SL+EFB, one had SL+BP, and another SL+AN. In Figure 1c, it is shown that 11 out of the 38 BP-damaged tanks experienced only BP, 23 showed BP+EFB, two BP+AN, and one BP+SL. Finally, Figure 1d shows that out of the 5 AN-damaged tanks, two experienced only AN, two got AN+BP, one AN+SL. No AN damaged tanks experienced a combination of more than two DSs. However, because of the small amount of data, such conclusions for AN should not be generalized. The results extracted from the analysis of DS combinations are summarised in Table 5.

Given the scarce information on anchorage failure and the exclusion of sloshing-related material release, we focus on material release due to three possible damage state combinations: BP only, EFB only, and BP+EFB. Consequently, BP+SL, BP+AN, and BP only cases were merged into BP only, EFB+SL and EFB only cases were merged into EFB only, BP+EFB and BP+EFB+SL cases were merged into BP+EFB. All the remaining SL only, AN only, and SL+AN cases were merged into a single category. Since no release was observed (corresponding to RL0) for this last category, it is excluded from further analysis. The statistics after the merging operations are shown in Table 6.

Table 5. Number of tanks in database experiencing different RLs based on combination of DSs.

Damage state(s)	RL0	RL1	RL2	RL3	Total
BP only	2	2	5	2	11
EFB only	34	2	10	8	54
SL only	89	0	0	0	89
AN only	2	0	0	0	2
BP+EFB	4	5	6	8	23
BP+SL	0	0	1	0	1
BP+AN	2	0	0	0	2
EFB+SL	11	0	5	2	18
EFB+AN	0	0	0	0	0
SL+AN	1	0	0	0	1
BP+EFB+SL	0	0	0	1	1
Total	145	9	27	21	202

Table 6. Number of tanks in database experiencing different RLs based on combination of DSs (merged).

Damage state(s)	RL0	RL1	RL2	RL3	Total
BP only	4	2	6	2	14
EFB only	45	2	15	10	72
BP+EFB	4	5	6	9	24
Excluded: SL only, AN only, or SL+AN	92	0	0	0	92
Total	145	9	27	21	202

5.2. Event trees

Based on the database analysis results of Section 5.1, an event tree to map RLs to single DSs and to DS combinations was built after Table 6. Figure 2 shows the event tree for different RLs for BP only, while Figure 3 and Figure 4 show the same for EFB only and for the combination of BP+EFB, respectively. For example, in the case of only EFB-damaged tanks (see second row in Table 6), the weights associated to the RL0, RL1, RL2, and RL3 branches are 45/72 (0.63), 2/72 (0.03), 15/72 (0.21), and 10/72 (0.14), respectively (Figure 3). These weights are derived from the number of occurrences of each RL caused by the DS under consideration (EFB only, in this example).

From the event trees, it is interesting to note that, given the BP-only DS, the most probable RL is RL2, which means that the BP-only DS would be frequently mapped to a continuous release of the entire content of the tank in 10 min with a constant release rate. For the EFB-only DS, the most probable RL is RL0, which means that the EFB-only DS would be frequently mapped to no material release, even though there is a significant probability (0.35) that tanks that suffered EFB cause RL2 or RL3, that is, a continuous release of the entire content of the tank in 10 min with a constant release rate or an instantaneous release of the entire content, respectively. As expected, for the BP+EFB DS the most probable RL is RL3, whereas the least probable RL is RL0.

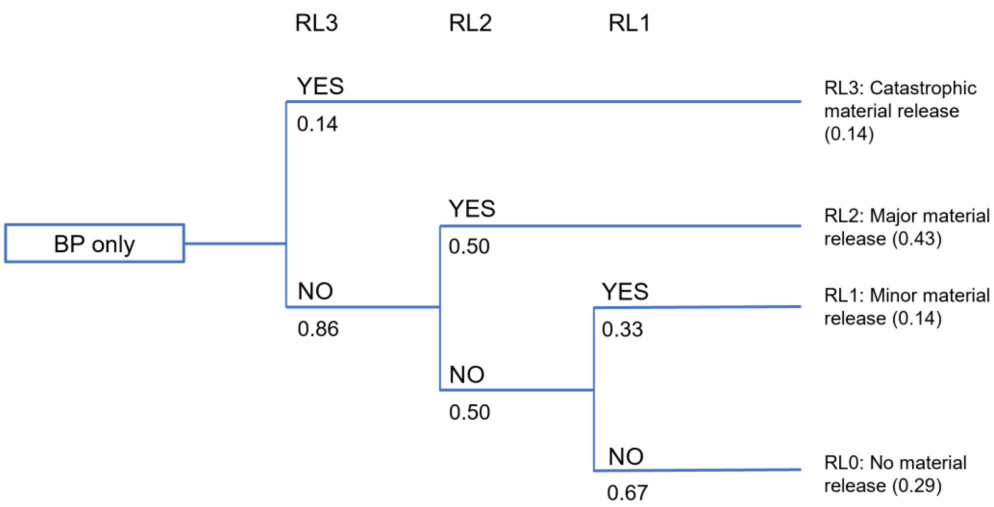

Figure 2. Event tree for RLs of liquid storage tanks that are in the BP-only DS after an earthquake.

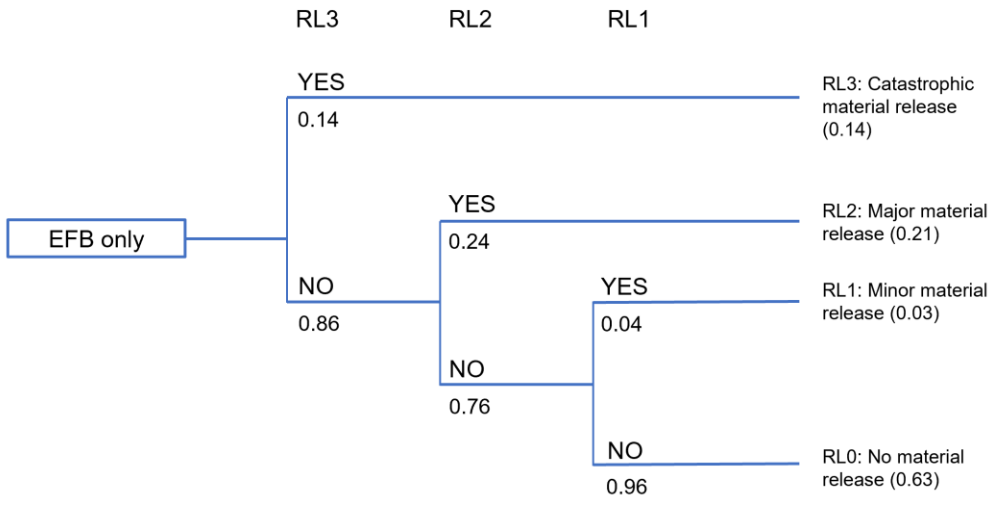

Figure 3. Event tree for RLs of liquid storage tanks that are in the EFB-only DS after an earthquake.

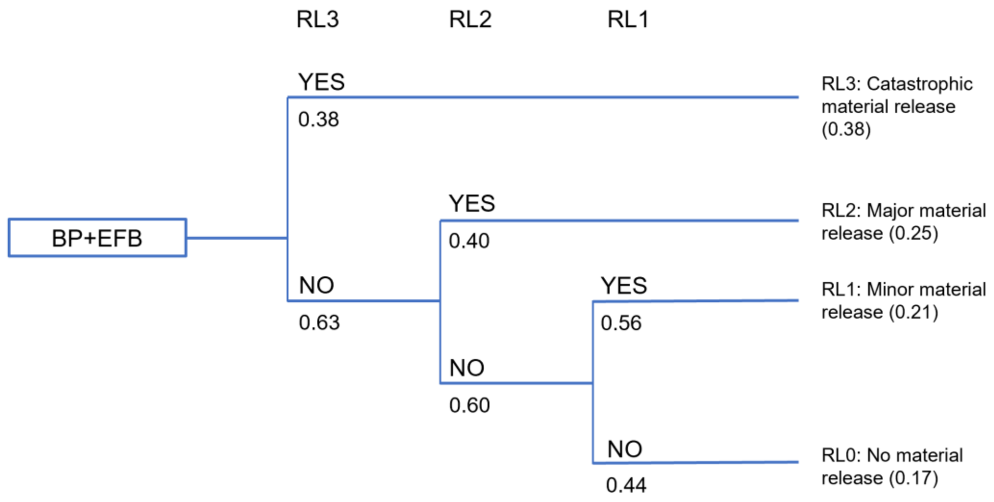

Figure 4. Event tree for RLs of liquid storage tanks that are in the BP+EFB DS after an earthquake.

5.3. Factors affecting the seismic response of tanks

The seismic response of liquid storage tanks depends on a series of factors, such as the aspect ratio (i.e., the height-to-diameter ratio), the filling level, the anchorage system, the fluid type, the roof system, and the construction material. In this study, we focus only on the influence of the aspect ratio and filling level in the relationship between DSs and RLs.

Aspect ratio effect

Aspect ratio, that is, the height-to-diameter ratio, is known for 44% of the tanks in the D'Amico and Buratti (2019) database (1336 out of 3026 tanks). However, for tanks experiencing one or a combination of DSs, the aspect ratio is available for all 202 damaged tanks considered in our analysis. The percentage of damaged tanks with different aspect ratios is shown in Figure 5a. Overall, 87% of the damaged tanks have an aspect ratio lower than, or equal to, 1.0 (177 out of 202). Based on this distribution, one could state that the proposed event trees are more representative of squat/shallow tanks, which is the type of liquid storage tank usually found in industrial facilities.

Figure 5 shows an additional set of histograms with the aspect ratio of the tanks damaged according to the three DSs considered in the event trees of Figures 2-4, that is, BP only, EFB only, and BP+EFB. It is interesting to note from Figure 5b that most tanks experiencing BP only have a significantly low (i.e., lower than 0.5) aspect ratio. In the EFB only case (Figure 5c), damaged tanks are almost evenly distributed with aspect ratios between 0.3 and 1.3. Tanks experiencing BP+EFB (Figure 5d) mostly have aspect ratios lower than 1.2, but also a small fraction of tanks with higher aspect ratios failed in this combination of modes. Based on these findings, one may argue that the tanks with lower aspect ratios tend to experience BP-only more frequently than more slender tanks.

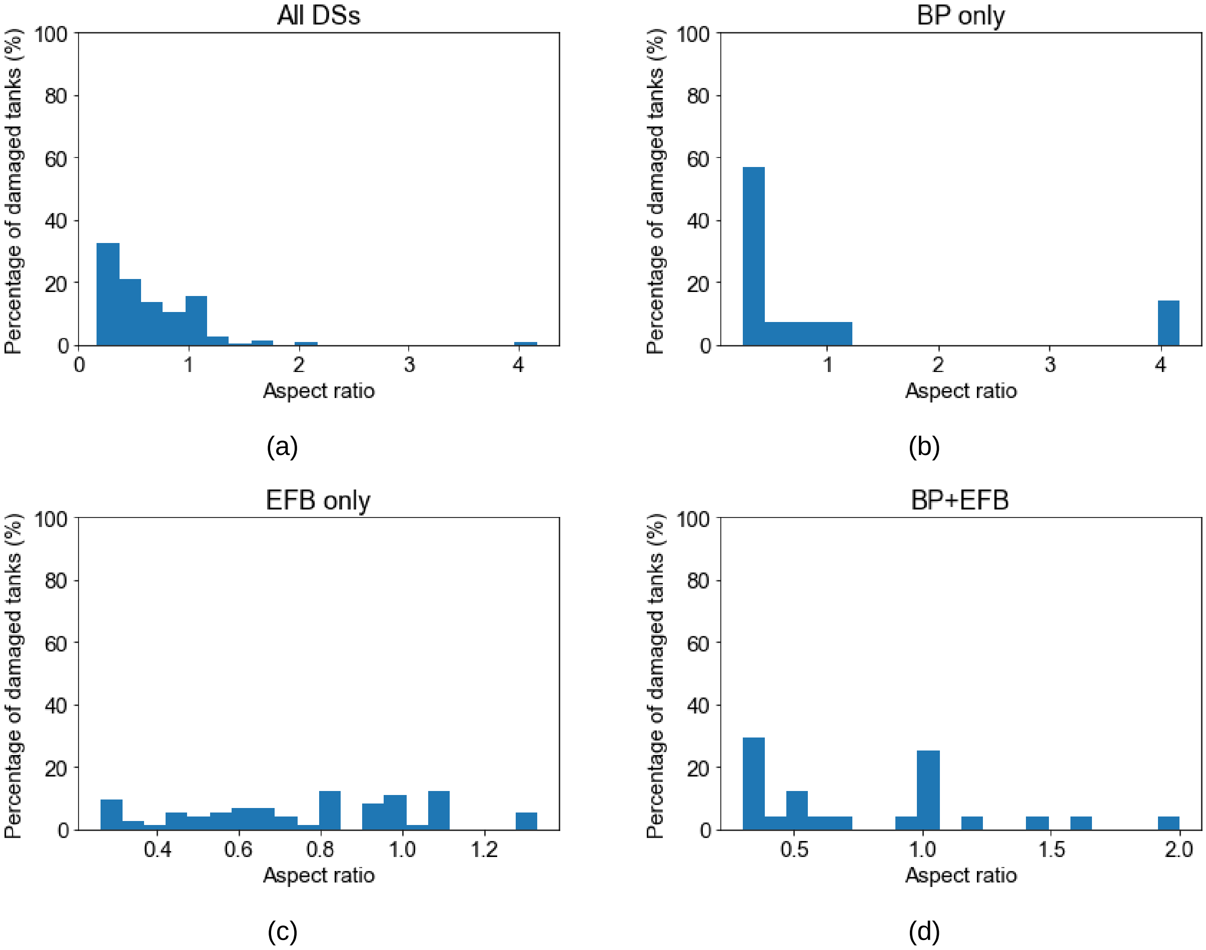

Figure 5. Percentage of tanks by aspect ratio that were damaged according to the following DSs: (a) All DSs; (b) BP only; (c) EFB only; (d) BP+EFB.

Filling level effect

Filling level is not always a readily available information from tank damage reports due to practical and operational reasons. In the D'Amico and Buratti (2019) database, filling level is available for only 14% of the tanks (422 out of 3026 tanks). However, for the damaged tanks experiencing one or more of the DSs considered in our analysis, the filling level is available in 78% of the cases (158 out of 202 tanks). An inspection of the percentage of damaged tanks with filling level available (Figure 6a) reveals that the majority of damaged tanks had a filling level greater than or equal to 0.6 (135 out of 158 tanks, about 85%) and that, within this range, there was a significant contribution from tanks with filling level greater than or equal to 0.8 (106 out of 158 tanks, about 67%). These findings could be interpreted in two ways: first, that tanks with high filling levels are more prone to be damaged in case of earthquake or, second, that the filling level was reported only for tanks that were almost full. We give more credit to the former interpretation.

Like the aspect ratio effect, the additional set of histograms in Figure 6 shows the percentage of tanks with different filling levels that were damaged in the three DSs considered for the event trees. Interestingly, Figure 6b shows, contrary to expectation, that a significant fraction of tanks that experienced BP only had a relatively low filling levels (i.e., lower than 0.3). On the other hand, tanks experiencing EFB only (Figure 6c) were for the most part full or almost full (i.e., filling levels greater than 0.7). Finally, all the tanks that suffered BP+EFB (Figure 6d) had filling levels greater than 0.7, with a significant contribution from tanks with filling levels greater than 0.9. Again, these findings can have a twofold interpretation. However, we are inclined to state that EFB is most significant for tanks with filling levels greater than 0.5, but BP can also occur in tanks having filling levels lower than 0.5.

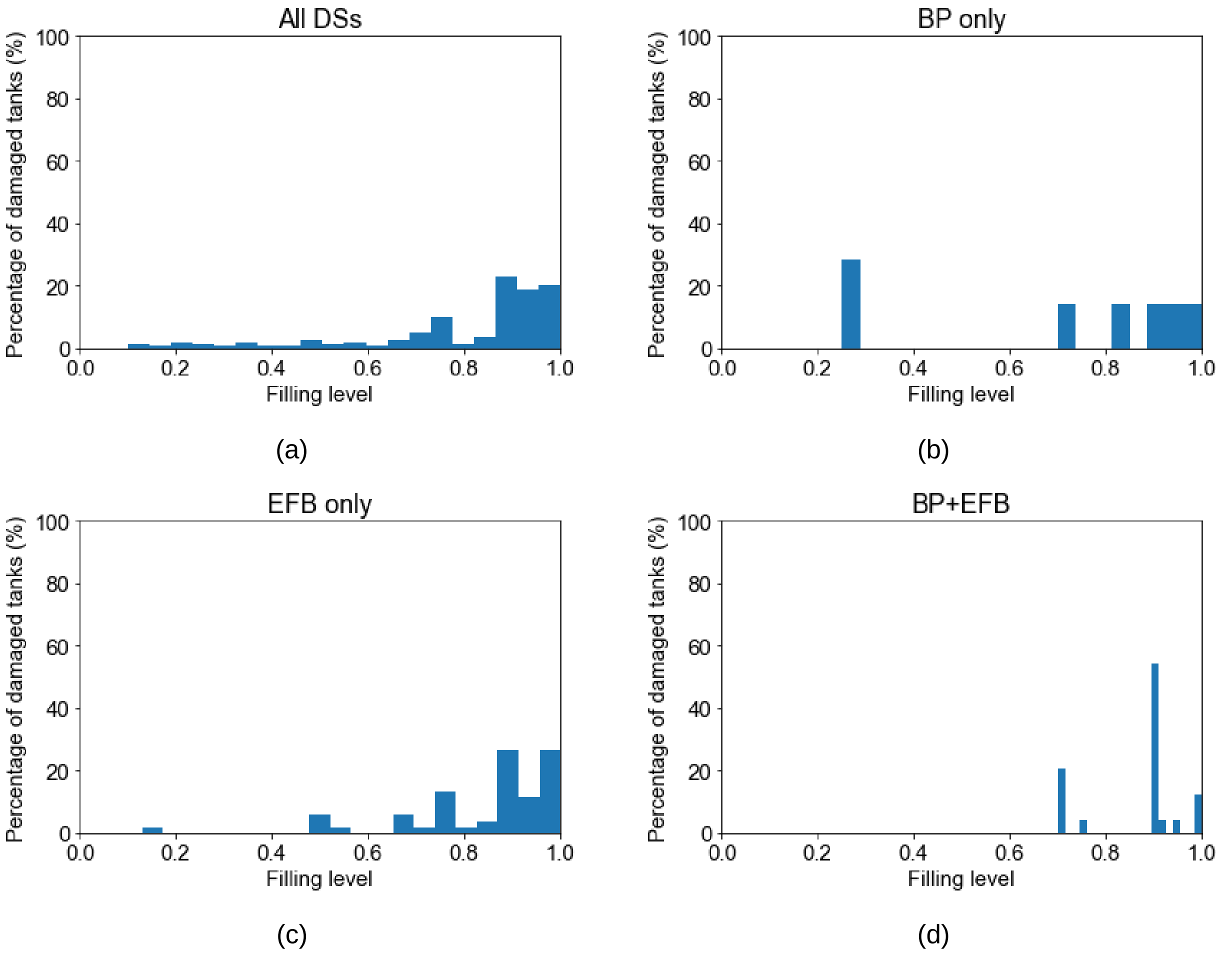

Figure 6. Percentage of tanks by filling level (when available) that were damaged according to the following DSs: (a) All DSs; (b) BP only; (c) EFB only; (d) BP+EFB.

6. Conclusions

A detailed exploration of the extensive earthquake-induced tank damage database developed by D'Amico and Buratti (2019) was performed. Four damage states (DSs) that describe the seismic response of tanks were identified. Also, the initial release levels (RLs) proposed by D'Amico and Buratti (2019) were redefined based on the conventional release levels from industrial Quantitative Risk Analysis. Finally, we propose a relationship between damage states and levels of material released by liquid storage tanks when damaged in different ways: base plate damage, elephant's foot buckling, and the simultaneous occurrence of base plate damage and elephant's foot buckling. The main conclusions are summarised as follows:

- The most frequent damage states identified in the 202 damaged tanks in the available database were sloshing damage and elephant's foot buckling. The least represented damage state, i.e., anchorage damage, was observed in only five tanks.
- Most sloshing-damaged tanks, as expected, did not experience any other type of damage whereas most of the tanks that were base-plate-damaged experienced elephant's foot buckling too. This because it is well known that the convective component, responsible for sloshing damage, and the impulsive component, responsible for base plate damage and elephant's foot buckling, of the fluid in motion inside the tank are excited by ground motions with energy content in significantly different period ranges. Given the scarcity of data, no significant conclusions could be extracted from tanks that experienced anchorage damage.
- As one would expect, the simultaneous occurrence of base plate damage and elephant's foot buckling results in a higher probability of a catastrophic material release and a lower probability of no material release compared to the tanks that suffered base plate only and elephant's foot buckling only damage.

- The proposed event trees are mostly representative of shallow/squat steel liquid storage tanks with filling levels between 0.6 and 1.0. For the time being, in absence of a more representative dataset of damaged tanks, the proposed event trees that were used to develop a link between DSs and RLs can be used more generally for other steel liquid storage tanks in the chemical industry.

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