2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

ESTIMATING SEISMIC FRAGILITY OF A SEMI-BURIED SQUARE RC WATER TANK USING EXPERT JUDGMENT

Ioanna IOANNOU[1], Willy ASPINALL[2] & Tiziana ROSSETTO[3]

Abstract: *The assessment of the seismic fragility of water networks is the key to characterizing their risk exposure to strong earthquakes. In the HORIZON2020 IMPROVER project, we focused our attention on the water network of Barreiro, a municipality close to Lisbon, Portugal. To determine vulnerability to ground shaking, the seismic fragility of each key component of the network needed to be determined. To exemplify our approach, we concentrate here on assessing the fragility of a semi-buried RC square water tank; previous studies have overwhelmingly focused on the seismic fragility of cylindrical (and mainly steel) water tanks. Relevant fragility parameters are inevitably uncertain, and our study made use of a sample of experts' judgements, pooled using the Cooke's Classical Model. This structured approach derives performance weights for experts' abilities to quantify uncertainty in a statistically accurate sense and informatively, and then applies these weights to their uncertainty judgements on modelling parameters of concern. The unique empirical control in this procedure ensures an objective, rational consensus is obtained on the uncertainties to ascribe to different contributory factors. The main challenge in our study is to construct a suitable discrete damage scale, and to explore the possibility the tank might suffer liquefaction damage, given its proximity to the River Tagus and groundwater conditions at site. Provisional findings from the exercise are presented here and compared to existing fragility curves constructed for cylindrical RC tanks. The square tank was found to be more vulnerable than a cylindrical one.*

Introduction

There is an increasing interest in the resilience of networks such as the potable water networks, whose operation is critical to the function of a nation. IMPROVER, a HORIZON2020 project, developed a methodology to assess the resilience of such networks and demonstrated its usefulness on the potable network of Barreiro, a municipality of 78,764 people (according to 2011 Census) located on the south bank of Tagus river estuary and is part of the Lisbon Metropolitan Area. Key in the developed framework is the risk assessment of the examined network. An earlier elicitation (Ioannou et al., 2015) of the stakeholders of Barreiro's potable water network identified earthquake as the natural hazard with the highest risk. The seismic risk assessment of the network is based on the fragility assessment of its main components, which include the water source, the transmission network and the distribution network, to the main earthquake-induced hazards, most notably for Barreiro's network: ground shaking and liquefaction. The present study focuses on the fragility assessment of a semi-buried RC square water tank, built in 1974.

In general, the seismic behaviour of water storage tanks is determined by their construction material, foundation and anchorage type, size and seismic design. The relevant literature concentrated on the study of fragility of cylindrical steel water tanks. By contrast, there is very little work on the fragility of RC water tanks and, in particular, those which are not cylindrical in shape. In particular, only two studies (i.e., HAZUS (2010) and ALA (2001)) were found to have produced fragility curves for RC water tanks and in both the tanks were cylindrical in shape.

Given the lack of suitable existing fragility curves and the lack of post-disaster data for the type and shape of RC water tank examined here, the present study focuses on the construction of fragility curves based on expert judgement. This approach accounts for the parameter uncertainties relating to the structural system, the construction material, the geometry of the studied water tanks, as well as the soil conditions at the site where the tank is located. Cooke's classical model is adopted in order to pool the various opinions using a performance-based weighting scheme. This method has been used in the past to construct fragility curves for buildings exposed to earthquakes (Jaiswal et al., 2012), as well as fire (Ioannou et al., 2017).

[1] Dr, UCL, London, UK, ionna.ioannou@ucl.ac.uk
[2] Prof, University of Bristol, Bristol, UK
[3] Prof, UCL, London, UK

In what follows, more information regarding the water tank is provided together with a brief description of the two earthquake induced hazards considered in this study and damage scale adopted for the elicitation. Cooke's method is presented next, followed by the provisional results by the application of the Classical Model to assess the fragility of the studied water tank.

Semi-buried water tank in Barreiro, Portugal

The studied water tank is located 1.2km from the Tagus River and is approximately 80m above sea level. The water tank has a square shape with dimensions 40mx40m and 5m height (see Figure 1). The tank is subdivided in two equal size compartments with capacity 3,000m^3 each and supplies with treated water the nearby elevated water tank, which has capacity 750m^3. The two compartments are separated by a 2m-high wall, depicted in Figure 1. The tank is buried into the ground by 1.5m. The green roof (depicted in Figure 1) rests on prefabricated slabs. The load of the roof is taken by beams, which rest on a 5mx5m grid of columns internally and a wall externally. There is missing information regarding the properties of the materials. Nonetheless, given its construction age, the characteristic strength of the concrete is more likely to be equal to 22MPa and the strength of the reinforcement bars equal to 392MPa. In 2016, inspections detected no deficiencies in the reservoir.

Figure 1. Photographs from the interior and exterior of the studied water tank.

The water tank was built using the then seismic design code of 1967. According to this code, the seismic design of the structure is based on a uniform static horizontal load equal to the 0.15 of the structure's weight. This provides a rather poor resistance to earthquakes.

With regard to the water loading, two extreme cases are considered in this study. According to the first case, the water tank is considered full of water, which means that there is water 4m high in both compartments. According to the second case, the water tank is considered closed for maintenance. In this scenario, the one compartment is completely empty and, in the second compartment, there is water 2m high.

Seismic hazard

Seismic hazard is considered a real danger for Barreiro, which is located in the lower Tagus river valley, and the water network in particular, as highlighted by a stakeholder elicitation facilitated as part of the IMPROVER project (Ioannou et al., 2015). The densely populated valley has historically sustained significant damage and causalities from strong earthquakes most notably the 1755 event as well as the 1344, the 1531 and the 1909 earthquakes (Cabral et al., 2013). In recent times, Barreiro was hit by the 1969 Azores - Cape St Vincent earthquake with magnitude

7.8. During this latter event, Barreiro's water network suffered damage due to ground shaking as well as liquefaction.

For the needs of this study, detailed investigations of the faults likely to produce earthquakes affecting Barreiro is not required as the focus here is on the performance of the water tank affected by ground shaking or liquefaction for all plausible events. In what follows, the likelihoods that the two aforementioned earthquake-induced hazards will affect the studied tank are discussed, and suitable intensity measures are identified for characterizing each hazard.

Ground shaking

During an earthquake, ground shaking is considered to be the most likely cause of damage to the water tank, which is a large structure with inadequate seismic design. When focussing on the fragility assessment of water tanks, shaking intensity has been expressed in terms of Peak Ground Acceleration (PGA) (e.g., HAZUS (2010)) or spectral acceleration at 5% damped horizontal response spectra at a particular impulsive mode frequency (ALA, 2001). PG is also used here to express the ground shaking intensity as it is considered the most familiar by the experts.

Ground failure

The likelihood of ground failure, and in particular liquefaction, under the water tank has been examined in the past by drilling a borehole next to the water tank. The borehole showed sandy soils present in the top 2 meters and clayey soils to lie below. To further investigate liquefaction potential, a new borehole sample has been acquired from the top soil layer (4m depth). The sample was stored in four 4-meter tubes (i.e., 0-1m, 1m-2m, 2m-3m; 3m-4m) and shipped to UCL for further tests. Sieve analyses showed that the liquefaction in the first 2m poses a realistic threat in case of a strong enough earthquake. The drawing plans of the water tank show that the top 1 meter was removed before construction and substituted with compact soil. This means that liquefaction is more likely in the layer of soil between 1m and 2m deep.

Given the weight and size of the water tank, as well as the fact that the water table is 80m below the tank, the potential for liquefaction capable to cause damage to the water tank is considered negligible by experts. Despite this, the likelihood of damage of the water tank due to liquefaction is examined here. This scenario could be considered likely to occur if, due to tank's degradation, there is water leakage under the water tank. For the scenario considered, the weight of the water tank is reduced by assuming that during the seismic event, which triggers liquefaction, the tank is closed for maintenance. In the literature (e.g., HAZUS (2010), the intensity of liquefaction is commonly expressed in terms of permanent ground displacement. For the needs of this study, the liquefaction is expressed in terms of the mean vertical tank settlement.

Damage states	**Name**	**Description for the purpose of this study**
ds_0	*None*	No disruption, the water tank remains intact.
ds_1	*Slight*	Minor damage without loss of content or functionality. Minor damage due to sloshing, minor surficial cracks in RC tanks. The damage is repairable.
ds_2	*Moderate*	Considerable damage but only minor loss of content.
ds_3	*Extreme*	Severe damage and going out of service.
ds_4	*Near Collapse*	The tank has entirely, partially or very close to collapsed and lost all content. The water tank is considered beyond repair and needs to be replaced. Possible failure modes: 1. Overall differential settlement can compromise the slab's integrity. 2. At least 20% reduction in the maximum moment capacity of the external walls. 3. Uplift of tank floor slab when tank is empty due to liquefaction. 4. Unseating of the roof significantly damaging columns and walls. 5. Shear failure of floor slab.

Table 1: Adopted damage scale for the needs of this study (modified from HAZUS (FEMA, 2010)).

The Damage Scale

The damage scale adopted for the needs of this study is based on the five-state damage scale proposed by HAZUS (FEMA, 2010). The states vary from no damage to complete failure. To reduce the number of target questions, the elicitation concentrates on constructing fragility curves corresponding to two damage states: ds_1, ds_4. A detailed description of these two states is updated through discussions with the experts (see Table 1). It should be noted that the average of these two curves results in fragility curves corresponding to moderate damage (ds_2), which is also constructed in this study.

Structured Expert Elicitation Methodology

Expert elicitation is adopted here in order to assess the seismic fragility of a square, semi-buried RC water tank. The main challenge in any elicitation is how to combine the experts' judgments. In general, for a complex and uncertain problem like this one, if an individual expert is asked to provide their judgment concerning the expected value of a variable and to quantify their uncertainty, they typically provide an estimate of the mean that is not necessarily very accurate, accompanied by an uncertainty estimate - expressed here in terms of the expert's 90% credible interval around the mean - that understates the real variability of the parameter. By contrast, if a large group of experts is elicited and their opinions are weighted equally, a good estimate of the mean of the variable is typically obtained, but the associated uncertainty is typically very wide.

Cooke's Classical Model (Colson and Cooke, 2018), adopted herein, offers a rational means of quantifying the uncertainty by an optimized weighting of experts according to their demonstrated ability to quantify uncertainty concerning particular relevant variables. Generally, although not always, the Cooke method produces an outcome distribution with formally quantified uncertainty that falls somewhere between the two extremes. In what follows, an introduction to the Cooke's method is presented as well as a description of the expert elicitation workshop.

The Classical Model

The Classical Model ranks the experts according to their ability to judge uncertainty distributions. Their ability is assessed by their answers to a series of seed questions, usually comprising of 10 or more questions. The true value for each question is not known by the experts, but an informed expert is expected to be able to accurately judge a credible interval which capture this value for a majority of the seed questions.

In application, each expert is required to provide their judgement regarding the median and marker values corresponding to the upper and lower bounds of a 90% credible interval that contains the unknown quantity, in their judgment. From their responses, the ability of each expert to gauge the uncertainty around an unknown quantity is assessed by determining how well-calibrated and informative their judgments are overall, as presented in Figure 2. The "statistical accuracy" (or calibration) of each expert can be measured from their responses. If most of the 'true' values of the seed questions fall within the expert's 90% intervals, then that particular expert is considered well calibrated. It should be noted that the number of 'true' values above and below the median value should be approximately equal for a well-calibrated expert.

In addition, the informativeness of the expert can also be measured from their responses to the seed items. In Figure 2, it can be noted that the more an expert's uncertainty distribution approximates a uniform distribution, the less informative the expert is. The Classical Model combines these two metrics, statistical accuracy and informativeness, into a product with which to score and weight the judgments of the individual expert. This scoring formulation punishes badly-calibrated and over-opinionated experts, as well as less-informative experts (see Figure 2).

As just mentioned, the Classical Model scores a performance-based weight for each expert by combining the two aforementioned objective metrics, namely: their calibration (statistical accuracy) and information scores. Estimation of the two scores requires determination of the information term, $I(s, p)$, which indicates how informative the sample density distribution of a given seed variable s, provided by expert e_j, is compared to the reference uniform or log-uniform density distribution, p:

$$I(s,p) = \sum_{i=1}^{4} s_i \ln\left(\frac{s_i}{p_i}\right) \tag{1}$$

where i is the number of intervals defined for the distribution. For example, i = 4 if three values are elicited for each seed variable, corresponding to 5%, 50% and 95% probability distribution markers.

Information score

The information score $\Lambda(e_j)$, for expert e_j, represents the degree to which the sample distribution proposed by the expert is concentrated with respect to a reference uniform distribution:

$$\Lambda(e_j) = \frac{1}{n}\sum_{k=1}^{n} I\left(s_{k,e_j}, p_k\right) \tag{2}$$

Calibration score

The calibration score $\Theta(e_j)$, of expert e_j, is determined by testing the null hypothesis H_{ej}, that this expert is well-calibrated, as:

$$\begin{aligned} &\Theta(e_j) = P\left(\chi_3^2 > \chi^2(e_j) \mid H_{e_j}\right) \\ &\textit{with} \\ &\chi_3^2 = 2\cdot n\cdot I\left(s,p\right) \sim \chi^2 - \text{distribution with} \\ &\qquad\qquad\qquad\qquad \text{3 degrees of freedom} \\ &\chi^2(e_j) = 2\cdot n\cdot \sum_{i=1}^{4} s_i(e_j)\ln\left(\frac{s_i(e_j)}{p_i}\right) \end{aligned} \tag{3}$$

where $\Theta(e_j)$ is equal to the p-value of the statistical test. This score quantifies the 'statistical accuracy' of the expert's set of distributions.

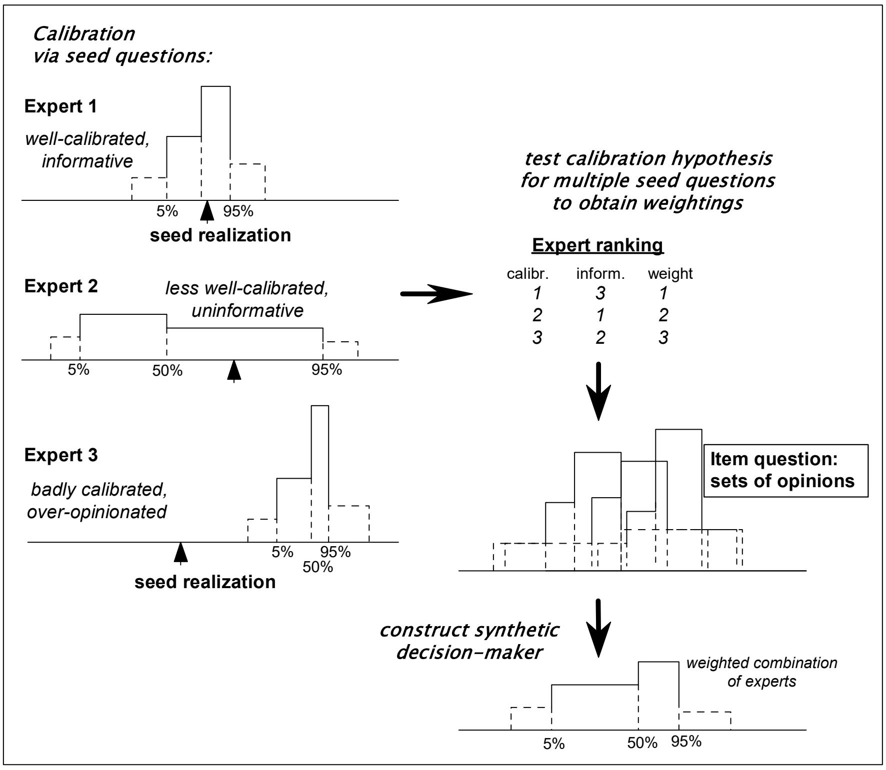

Figure 2. Schematic ranking of experts based on their information and calibration scores, and combination of weighted judgments on a target item to form a "decision-maker" solution.

Combining experts judgments

The weight assigned to each expert is the product of the expert's calibration score with their information score:

$$W_\alpha(e_j) = \chi_{(a,\infty)}\left(\Theta(e_j)\right)\cdot\Theta(e_j)\cdot\Lambda(e_j) \tag{4}$$

These weights are then used to combine the experts' judgments on target question items using linear pooling. Expert weights can be either global or item weights: the former are obtained from the responses to the complete set of seed questions, and are applied uniformly to all target questions. By contrast, item weights are calculated for each target question per expert based on a combination of their calibration score from the seed items and their informativeness on that particular target question. In this study, experts' opinions are pooled according to the item-weighting scheme and the results are compared with their counterparts obtained by an equal weighting scheme, according to which the judgments of all experts are ascribed the same weight. A key feature of the Cooke Classical Model approach is that its scoring scheme validates the experts' judgments by means of this form of empirical testing – and, in structured elicitation terms, is unique to the method.

The workshop

For this study, the expert elicitation took place during a workshop. Prior to the workshop, the experts were approached though a survey aiming to introduce them to the principles of the method as well as to consult them over important issues such as suitable measures of ground motion and liquefaction intensity and appropriate damage scales.

The workshop was divided into two parts. In the first session the experts were provided with 13 seed questions and were asked to provide a range which reflected each expert's confidence that it would encompass the 'true' average recurrence interval. For this study, the working 'credible range' was defined by three values:

- the point at which the '5%-ile value' (5th percentile) would fall, and
- the point at which the '95%-ile value' (95th percentile) would be found. Put another way, these upper and lower values are chosen such that there is less than 10% chance that the proper value falls outside this range, in the judgement of the expert.
- the third value elicited was the 50%-ile or median value.

The chosen values for the 5%ile and 95%ile do not have to be symmetrical about this median - but can be chosen to reflect any skewness the expert thinks is likely to be present in such a distribution. To encourage experts to state their own independent judgments, responses to the seed and target questions were received and processed confidentially by the facilitator.

In the second session, the experts were elicited on values for the unknown target questions. The elicitation of the target questions was based on two thought experiments, which aimed to help the experts conceptualise the problem. The thought experiments used for the needs of this study is modified from the one used by Dr Kishor Jaiswal (2012) in his Lisbon Workshop as part of the Global Earthquake Model (GEM) project, which aimed to construct fragility curves corresponding to the collapse of various buildings classes due to ground shaking.

The first thought experiment aimed to help experts conceptualise the likelihood of damage sustained by the water tank due to ground shaking. According to this hypothetical approach, there are 100 identical water tanks which are placed on a shake table. Each shake table test is driven by representative ground motions with 3 components (2 horizontal ad 1 vertical component). All 100 ground motions have the same maximum Peak Horizontal Acceleration, considered to be equal to 0.05g. The maximum horizontal direction of the ground motion does not necessarily align with the tanks major axis. Each tank is subjected to the motion and then left to rest. The tanks that have been undamaged at 0.05g are then exposed to a new ground motion with maximum peak horizontal acceleration equal to 0.06g. In order to ignore the cumulative damage, the buildings that have suffered some level of damage are not exposed to further shaking. The experiment is repeated, increasing the maximum horizontal PGA by 0.01g for each subsequent run. The experts are invited to use their judgement to decide the maximum horizontal PGA level at which 5, 10, 25, 50, 75 and 95 water tanks are expected to suffer: 1) At least some level of damage (i.e., $DS \geq ds_1$); and 2) Near collapse or Collapse (i.e., $DS \geq ds_4$). Two separate scenarios were considered according to which the tank was a) full (termed 'F'), or b) closed for maintenance (termed 'CfM').

Similarly, the second expert thought experiment aims to conceptualise the likelihood of damage due to liquefaction. According to this experiment, 100 identical water tanks are affected by mean vertical tank settlement caused by an earthquake equal to 0.01m. Each tank is subjected to the same mean vertical tank settlement and then left to rest. The tanks that have been undamaged at 0.01m are then exposed to a new mean vertical tank settlement equal to 0.02m. In order to ignore the cumulative damage, structures that are judged to have suffered some level of damage are not retained and exposed to further settlement. The experiments are repeated iteratively increasing the mean vertical tank settlement by 0.01m. Similar to the first experiment, the experts are asked to determine the mean vertical tank settlement level for which 5, 10, 25, 50, 75 and 95 water tanks are expected to suffer: 1) At least some level of damage (i.e., $DS \geq ds_1$); or 2) Near collapse or Collapse (i.e., $DS \geq ds_4$). For this case, the water tank was considered closed for maintenance only.

Given the novelty of the task, it is likely there will be substantial uncertainty around the probabilities the experts are asked to estimate, but the aim of this study is the quantification of this uncertainty. To accomplish this, the experts were invited to provide a range defined by the aforementioned three uncertainty distribution values based on their own individual engineering judgment about each value. The experts were told that this uncertainty should account for the variability in the structure's known (and unknown) characteristics, their personal certainty regarding the seismic performance of the type of water tank in question, as well as the variability in the vertical tank settlement or the variability in the frequency content, duration etc of the ground motions with identical maximum horizontal PGA.

Results

Three experts provided complete sets of responses to both the seed and target questions. These were input data for EXCALIBUR software (1990), a software package for analysing expert judgment elicitations. The software estimated the weights for each of the three expert who participated in the study based on their performance on the seed questions according to the mathematical principles embodied in the Classical Model. Due to the small number of participants, the analysis of provisional results presented here concentrates on the median fragility curves, leaving aside considerations of the uncertainty in the shape of the fragility curves corresponding to each damage state.

The median value of each point of a fragility curve is fitted to a lognormal distribution in the form:

$$P\left(DS \geq ds_i \mid IM = x\right) = \Phi\left(\theta_1 \ln\left(x\right) + \theta_0\right) \quad (5)$$

where θ_1 and θ_0 are the slope and intercept of the statistical model. The values obtained from the elicitation can be found in Table 2.

IM	Liq.	Tank	DS	*Cooke*		IM	Liq.	Tank	DS	*Cooke*	
				θ_1	θ_0					θ_1	θ_0
PGA in g	No	F	ds_1	1.05	2.39	Vert. Settl in m	*Yes*				
			ds_2	1.01	1.57						
			ds_4	1.00	1.14						
		CfM	ds_1	1.21	2.32			CfM	ds_1	0.99	4.87
			ds_2	1.06	1.21				ds_2	0.99	4.35
			ds_4	1.02	0.73				ds_4	1.01	4.01

Table 2: Provisional parameters of median fragility curves based on the weighted opinions of three experts.

Comparison: Cooke's vs Equal weights

The influence of two alternative schemes of pooling expert judgement on the shape of the fragility curves is explored by comparing the curves based on the performance-based Cooke's weighting scheme to the ones based on assigning equal weights to all experts. The comparison is depicted in Figure 3. Differences in the two weighting schemes can be noted, depending on the earthquake-induced hazard concerned. With regard to the fragility on seismic shaking, the weighted combination of opinions produces systematically flatter fragility curves than the equal weighting scheme. This indicates that if the best performing experts are considered, the fragility curves predict higher likelihood of damage for small levels of PGA and smaller likelihood for higher PGA levels. By contrast, for fragility curves for liquefaction, the curves based on Cooke's method are shifted to the left, highlighting that if the weighted judgments of the experts are accepted then the structure is considered more vulnerable to liquefaction than if the whole group equal weights solution is adopted.

Comparison: closed for maintenance vs full to capacity

The influence of the volume of water on the seismic performance of the studied water tank can be explored in Figure 4. The comparison of the fragility curves for the full water tank with their counterparts for a tank closed for maintenance indicate that there is little or no perceptible difference in the likelihood of the tank sustaining any level of damage (≥ ds_1). By contrast, the best-performing experts highlight that the full tank is more likely to suffer moderate or extreme damage than when it is closed for maintenance. This can be attributed to the added impact of water sloshing in the roof, which is simply resting on the interior columns and external wall. The same conclusion was reached in other studies (e.g., O'Rourke & So, 2000; Salzano et al., 2003) in their study of empirical fragility of unanchored cylindrical steel tanks.

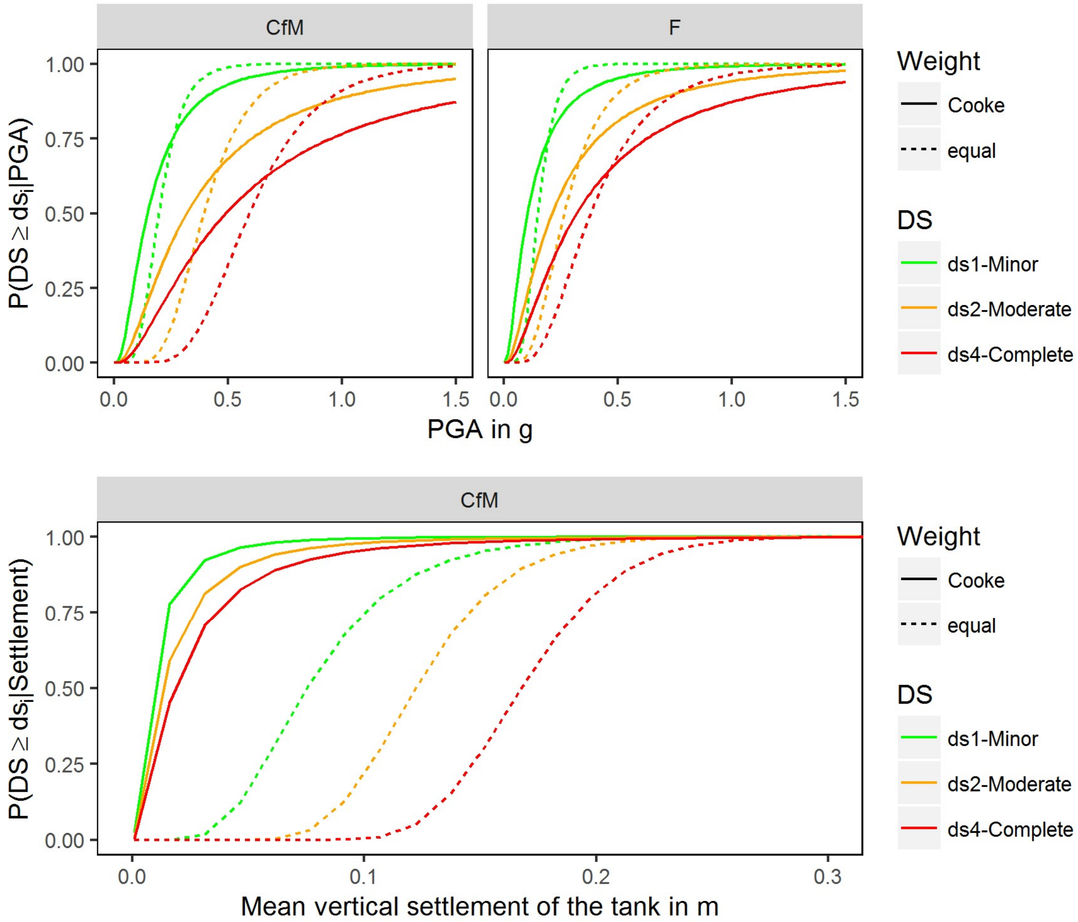

Figure 3. Median fragility curves of the water tank based on seismic excitation only.

Comparison: existing vs existing studies

The fragility curves constructed in this study are bespoke to the unique water tank examined. Nonetheless, their comparison with existing fragility curves for other types of water tanks will provide a deeper insight into whether the fragility of this type of tank is higher or lower than other RC water tanks.

With regard to the fragility to ground motion, the fragility curves constructed in this study using Cooke´s weighting scheme are compared with the HAZUS (2010) curves for anchored and unanchored cylindrical RC water tanks, which are also expressed in terms of PGA. The curves proposed by ALA (2001) are not suitable for comparison as they used a different intensity measure and their damage states adopted are associated with specific failure modes that cannot be used to in the seismic risk context.

With regard to ground shaking fragility, the comparison of the fragility curves is depicted in Figure 4. With regard to HAZUS (2010), the fragility curves for anchored RC water tanks appear to be shifted to the right of their counterparts obtained for unanchored water tanks for the three damage states examined here. This indicates that the unanchored curves are more vulnerable than their anchored counterparts, which is intuitively expected. Moreover, the comparison of the curves constructed for HAZUS and IMPROVER shows that the present expert elicitation highlighted that irrespective of whether the studied water tank is full to capacity or closed for maintenance the curves are notably steeper and more shifted to the left than the HAZUS ones. Moreover, the differences with the HAZUS curves increase with the increase in the extremity of the damage. They appear to be very small for minor damage and are substantial for collapse. This suggests that the studied water tank is overall more vulnerable than an at-grade RC cylindrical water tank and it is by far more likely to collapse.

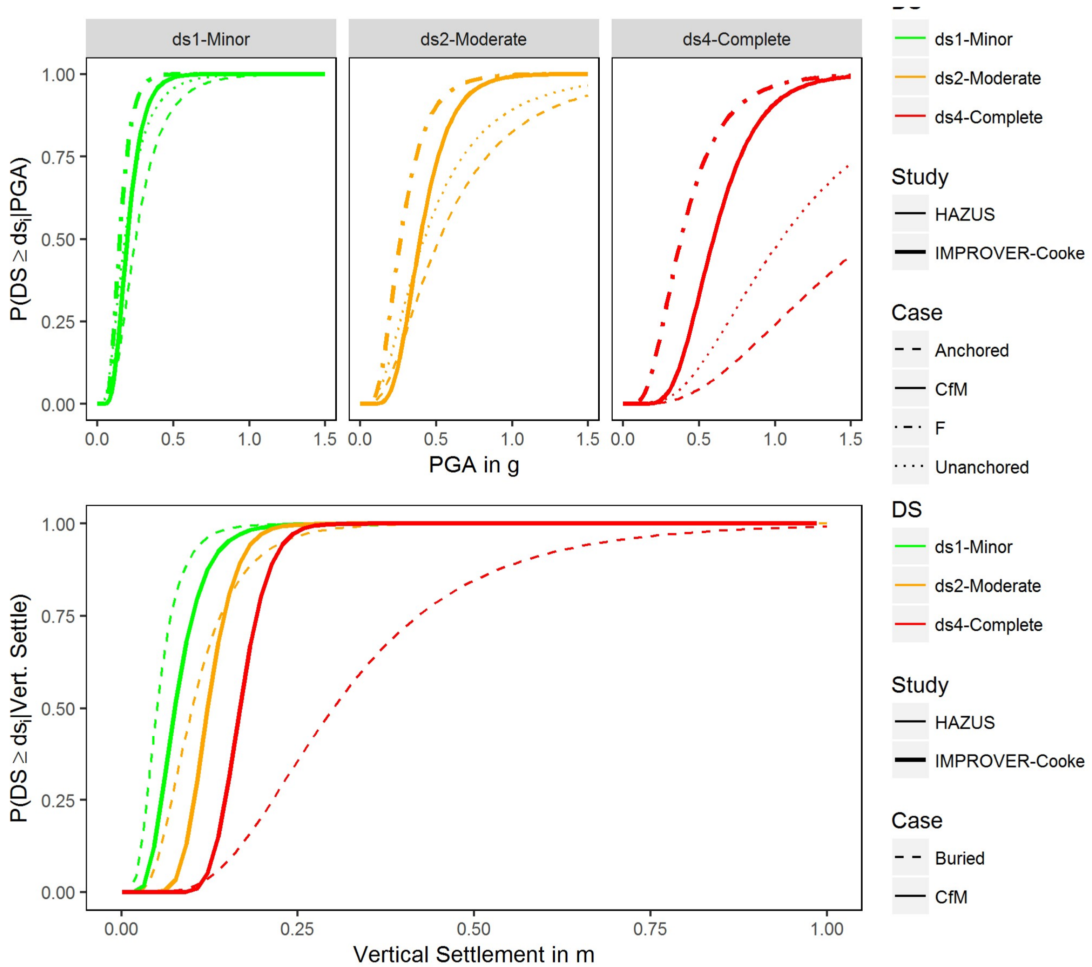

Figure 4. Median fragility curves for the water tank based on seismic shaking, assuming that the tank is full, or closed for maintenance, and on liquefaction, assuming that the tank is closed for maintenance.

With regard to liquefaction vulnerability, the picture in Figure 4 appears more complex with the IMPROVER curves to be shifted to the right of the HAZUS ones for ds_1 and to the left of the HAZUS ones for ds_4. In line with the ground shaking fragility, the studied semi buried water tank is more likely to collapse due to liquefaction than an at-grade RC cylindrical tank.

Concluding Remarks

In this study, the fragility of a semi-buried square water tank in Barreiro, Portugal exposed to ground shaking as well as liquefaction has been assessed using expert elicitation. The details of Cooke's Classical Model adopted here to pool experts' opinions have been described. The provisional results based on the opinions of three experts showed:

- Based on Cooke's Classical Model, the full studied water tank is more likely to suffer moderate or complete damage than if it is partially emptied for maintenance.

- Compared to the fragility curves based on an equal weight of experts opinions, Cooke's Classical Model produced curves which are more likely to suffer a given level of damage or above for lower PGA levels and less likely to sustain a given damage level or above for higher PGA levels. The Classical model also highlighted that the studied water tank is notably more vulnerable to liquefaction.

- The comparison of the fragility curves constructed here with the HAZUS ones showed that the semi-buried square water tank is more likely to sustain complete damage than an at-grade cylindrical if the two are exposed to ground shaking or a buried cylindrical water tank if the two are exposed to liquefaction.

References

Berahman F and Behnamfar F (2007), Seismic fragility curves for un-anchored on-grade steel storage tanks: Bayesian approach, *Journal of Earthquake Engineering*, *11*(2): 166-192.

Cabral J, Moniz C, Batlló J, Figueiredo P, Carvalho J, Matias L, Teves-Costa P, Dias R and Simão N (2013), The 1909 Benavente (Portugal) earthquake: Search for the source, *Natural Hazards*, 69(2): 1211-1227.

Colson AR, Cooke RM (2018), Expert elicitation: using the classical model to validate experts' judgments, *Review of Environmental Economics and Policy*, 12(1): 113-32.

Cooke R and Solomatine D (1990), EXCALIBR software package for expert data evaluation and fusion in risk and reliability assessment, *Department of Mathematics, Delft University of Technology*.

Eidinger J, Avila EA, Ballantyne D, Cheng L, Der Kiureghian A, Maison BF, O'Rourke TD, Power M (2001), Seismic fragility formulations for water systems. *American Lifelines Alliance*, Reston, VA.

Federal Emergency Management Agency (2010), *Hazus-MH MR5 Technical Manual. Multi-Hazard Loss Estimation Methodology Earthquake Model*.

Jaiswal KS, Aspinall W, Perkins D, Wald D, Porter KA (2012), Use of expert judgment elicitation to estimate seismic vulnerability of selected building types, in 15th World Conference on Earthquake Engineering (WCEE), Lisbon, Portugal.

Ioannou I, Willy Aspinall W, Bouffier C, Carreira E, Honfi D, Lange D, Melkunaite L, Reitan NK, Rossetto T, Storesund K, Teixeira R (2015), Methodology for identifying hazard scenarios to assess the resilience of critical infrastructure, *IMPROVER Report*.

Ioannou I, Aspinall W, Rush D, Bisby L, Rossetto T (2017), Expert judgment-based fragility assessment of reinforced concrete buildings exposed to fire. *Reliability Engineering & System Safety*, 167:105-27.

Khakzad N, and Van Gelder P (2017), Fragility assessment of chemical storage tanks subject to floods, *Process Safety and Environmental Protection*, 111: 75-84.

O'Rourke MJ and So P (2000), Seismic fragility curves for on-grade steel tanks, *Earthquake spectra*, *16*(4): 801-815.

Salzano E, Iervolino I and Fabbrocino G (2003), Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis, *Journal of Loss Prevention in the Process Industries*, *16*(5): 403-409.