SURROGATE MODELLING AND SENSITIVITY ANALYSIS

OF STEEL LIQUID STORAGE TANKS

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1. ABSTRACT

Large-capacity atmospheric tanks are widely used to store liquids, such as oil or liquefied natural gas. The seismic risk of such industrial facilities is considerably higher compared to ordinary structures, since even some minor damage induced by a ground motion may have uncontrollable consequences, not only on the tank but also on the environment. Recent earthquakes have shown that heavy damage on tanks may lead to temporary loss of function, usually followed by leakage and/or fire. Therefore, a Performance-Based Earthquake Engineering (PBEE) framework should be employed for the seismic design and performance assessment of such critical infrastructure. Current design codes and guidelines have not fully adopted the performance-based concepts, while their application to industrial facilities is still under research. The proposed PBEE framework consists of a series of nonlinear response history analyses based on a simplified modelling of the tank. Our aim is to improve upon the existing body of work by offering a surrogate model that can be implemented with minimum effort for both anchored and unanchored tanks, for application within a PBEE framework using either static or dynamic analysis methods. In that sense, a robust sensitivity analysis is presented to acknowledge the uncertainties involved in the model presented.

2. INTRODUCTION

Recent earthquakes have highlighted the need for innovative engineering concepts in order to mitigate the devastating consequences of strong ground motions on structures of the chemical industry. PBEE concepts currently form the state-of-the-art for evaluating the seismic risk on structures, but still their extension to other critical infrastructures, such as the liquid storage tanks, is under research.

Various performance-assessment approaches, ranging from simplified deterministic to comprehensive probabilistic may be adopted. In the latter case, the structural model is a critical parameter for the successful performance evaluation due to the computational time required during the analysis. This remark is highlighted for the case of atmospheric liquid storage tanks, where the simulation of the fluid-structure-interaction may result in complex finite element models (FEM) that require a considerable amount of time even for a single response history analysis [1]. Similar studies have developed numerical approximations for the contained liquid [2,3], in an attempt to minimise the estimated computational time. Although the aforementioned FEM-based procedures may be able to capture complex modes of failure such as buckling, their use within a probabilistic framework may become computationally prohibitive.

It has been widely accepted within the Earthquake Engineering community that the response of liquid storage tanks can be idealised using a two-degree-of-freedom (2DOF) system, where the two masses (impulsive and convective) are considered decoupled [4–6]. The geometric and modal characteristics of the hydrodynamic problem are determined using equivalent parameters for the impulsive and convective masses. For the purpose of this study, the recommendations of EC8 [7] are adopted featuring Part 4 [8], where the design of tanks is discussed in detail. Under the assumption that the impulsive pressure is acting on the tank walls only, one may obtain estimates for parameters such as the natural period coefficients (C_i and C_c), the masses (m_i and m_c) and the effective height components (h_i and h_c). These parameters are distinguished with the aid of subscripts "i" and "c" denoting "impulsive" and "convective", respectively. Other studies, however, have shown that the contribution of the convective mass to the overall response of the structure can be ignored, as the impulsive mass is held responsible for the majority of the damage that tanks suffer during a strong ground motion event [2,9]. Decoupling shall form the basis of the procedure adopted, thus providing the ability for a robust simulation tool that is easy to implement compared to the time-consuming three-dimensional finite element models.

In our work, a simplified model based on previous work of Malhotra and Veletsos [10–12] is proposed [13]. The model combines beam elements and elastic multilinear springs in order to simulate the response of liquid storage tanks. The modelling approach presented herein consists of two distinct steps. The first step considers the analysis of a single base plate strip (Fig. 1(b)) in order to determine its uplifting resistance. Axial and rotational springs are used to simulate the interaction between the tank wall and the base plate. The second step evaluates the response of the entire base plate (Fig. 1(c)). The latter step uses the outcome of the first as an input through vertical springs placed along the edges of the plate. The results provided by the first step may also be used for the evaluation of both the static and the dynamic response of the full tank model shown in Fig. 1(d). The model is able to simulate both anchored and unanchored liquid storage tanks. When anchored tanks are considered equivalent "edge springs" are used which are assumed to carry a number of bolts, equally distributed along the circumference of the plate.
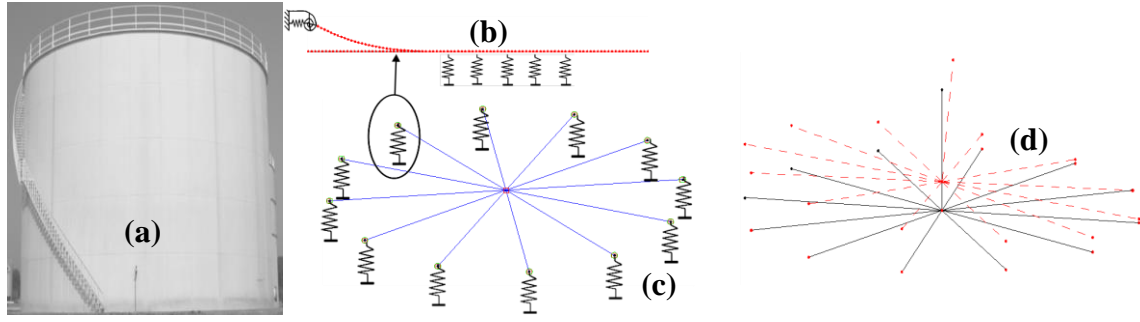
Fig. 1: (a) Atmospheric tank, (b) Strip model, (c) Base plate model, (d) Simplified model of the entire tank

3. SENSITIVITY ANALYSIS

A sensitivity analysis is carried out in order to assess the sensitivity of your model to the modelling assumption made during analysis and also to determine the parameters that introduce a level of epistemic uncertainty in our model. The most important parameters considered are the steel elastic Young's modulus (E) and the expected yield strength (f_y). Other geometric parameters, namely the tank wall (t_w), the annular ring (t_a) and the base plate thickness (t_b) are also evaluated along with the contained fluid height (h_f). The edge rotational ($k_{\theta\theta}$) and axial springs (k_{uu}) suggested by Malhotra & Veletsos [10] are also considered a potential source of modelling uncertainty and hence are both included in the sensitivity analysis matrix shown in Table 1. Finally, the bolts' yield strength (f_b) and the ductility of the anchored connections (δ_u) are evaluated for the case of anchored systems. The aforementioned parameters are summarised in Table 1, where the coefficients of variation (CoV) adopted provide reasonable high and low estimates for the problem variables. For the case of the anchored connection ductility only, no CoV is assigned and every connection is assumed to reach its ultimate displacement within the range of 1÷20cm.

The sensitivity analysis employs both static (*Pushover*) and dynamic (*Incremental Dynamic Analysis, IDA*) analysis procedures, as discussed in [8]. A set of three static Pushover analyses is performed for each parameter, in order to evaluate the response corresponding to the mean, high and low estimates of each parameter. Although the pushover has drawn a lot of criticism regarding its performance estimation abilities, it is here adopted in order to assess the behaviour of the model against monotonic loading and also to identify its most critical parameters. Having eliminated parameters that introduce minor levels of uncertainty to the model, the IDA method is subsequently adopted in order to assess sensitivity of the model using seismic ground motion records.

*Table 1. Sensitivity analysis matrix*

Parameter	Notation	Mean (μ)	CoV
Young's Modulus (GPa)	E	210	0.03
Yield Stress (MPa)	f_y	235	0.07
Edge Springs	$k_{\theta\theta}/k_{uu}$	-	0.3
Bolts' Strength (MPa)	f_b	900	0.07
Anchorage ductility (cm)	δ_u	-	-
Wall thickness (mm)	t_w	13.1	0.1
Base plate thickness (mm)	t_b	6.4	0.1
Annular ring thickness (mm)	t_a	8.0	0.1
Fluid height (m)	h_f	$0.75h_f$	0.3

3.1 Static pushover sensitivity

Fig. 2 presents the sensitivity of the model in terms of pushover curves for the parameters of Table 1. The effect of the material is shown in Fig. 2(a) and (b). It is evident that the material effect is of minor importance as both the higher and the lower estimated curves are perfectly aligned to the mean estimates of the model. The sensitivity analysis for both the rotational and the axial edge springs is given in Fig. 2(c) and (d) respectively. Although the rotational spring does not introduce a considerable sensitivity to the model, the axial component affects the response for large uplift deformations, namely above 0.20cm.

The geometric characteristics is another source of potential uncertainty, especially for the case of liquid storage tanks, where the corrosion determines the effective tank wall and base plate thickness. According to Fig. 2(e), the base plate thickness does not present any significant change in the response for the given range of variation. The annular ring thickness on the other hand is significant, due to the post-yield response modification shown in Fig. 2(f). Decreasing t_a reduces strength for our model. At the same time, when thickness exceeds the mean value the response becomes stiffer and the plastic hinge formation on the base plate shifts to slightly higher base shear estimates. In general, the base plate thickness modifies the post-yield behaviour of the model for uplift values less than 0.20cm. One may notice the significance of the annular ring over the base plate thickness, even though the thickness of the latter traditionally presents smaller design (t_b) estimates. The truth is that there cannot be a solid prediction on the sensitivity response among these two parameters, as both of them are strongly influenced by the annular ring indentation towards the centre of the tank. In general, the annular ring is expected to be important for the majority of tanks, while the base plate sensitivity increases as its radius approaches the tank radius. API-650 [14] may provide a minimum annular ring length, but still the base plate sensitivity cannot be neglected a priori. The tank wall sensitivity shown in Fig. 2(g) does not present any considerable modification on the response, except for large uplifts where some minor changes take place on the pushover curves. The contained liquid height shown in Fig. 2(h) summarises the geometric properties evaluation. The fluid height given as a fraction of the total height of the tank, is by far the most influential parameter examined so far, as the discrepancies found between the 50% and the 99% fluid height curves, for a given uplift, reach almost 50% following the first plastic hinge formation. Reducing the fluid stored in the tank results in stiffer models, while, as it approaches the tank roof, the liquid storage system's strength is significantly compromised, increasing its vulnerability.

Finally, for the case of anchored tanks, the yield strength of the bolts is also examined. According to Fig. 2(i) the effect of the yield strength of the bolts is negligible, for the case study, here considered. A further parametric investigation is conducted using a range of ultimate displacements for the anchored connections (δ_u =1cm to δ_u =20cm). According to Fig. 2(j), as the ultimate displacement of the anchorage increases, the capacity of the system also increases. At the same time, the response of the anchored system seems to change significantly once the anchors begin to fail. For low ultimate displacement values, the majority of anchors fail almost simultaneously, whereas as δ_u approaches 20cm, a progressive fracture of the connections (followed by associated drops of the system's stiffness) takes place until the response becomes similar to that of the unanchored tank.
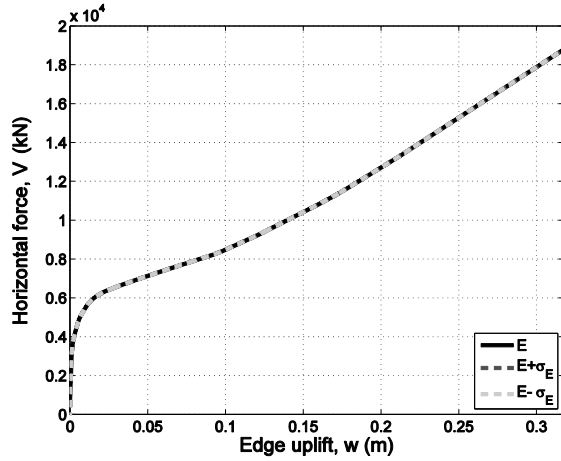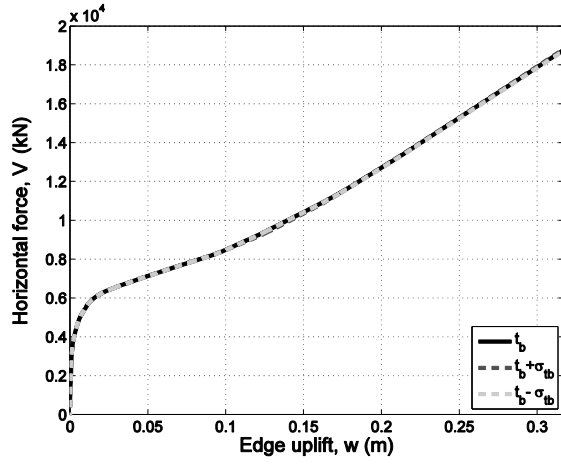

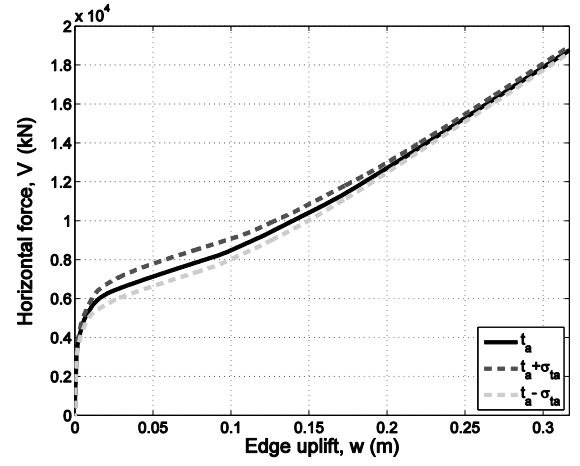*(a) E is of minor importance*
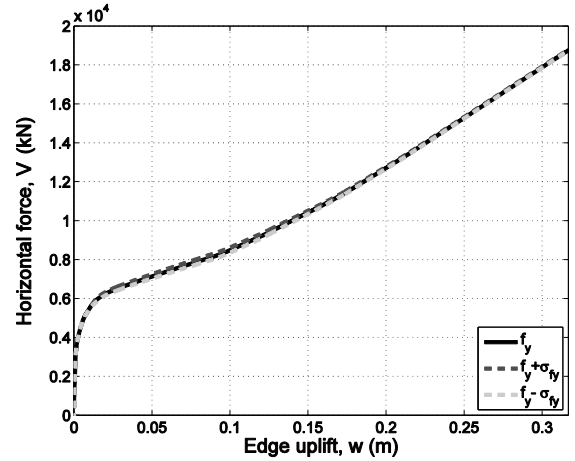
(b) f_y is of minor importance
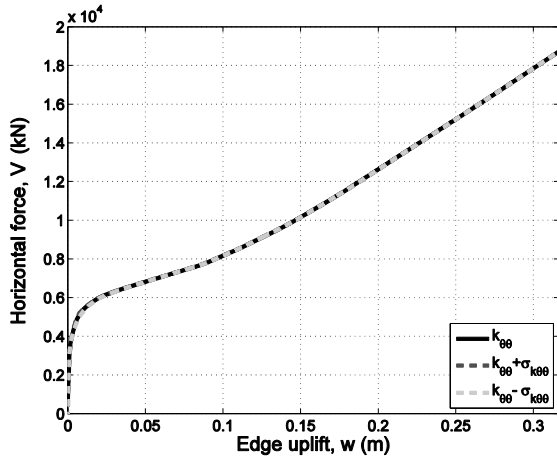
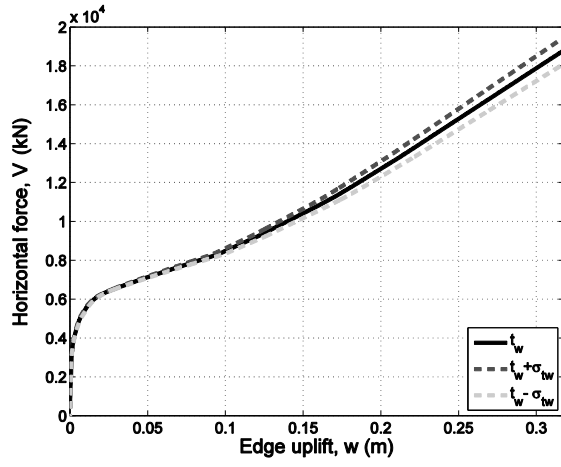*(c) $k_{\theta\theta}$ is of minor importance*
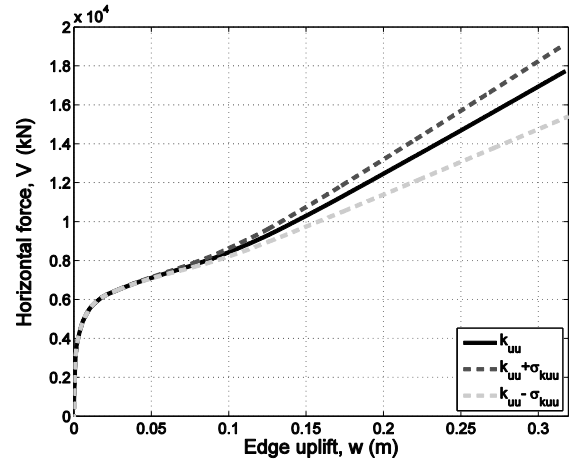
(d) k_{uu} is important for large uplifts
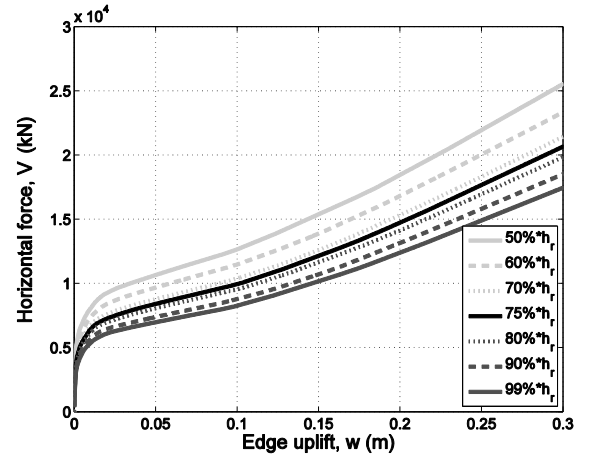
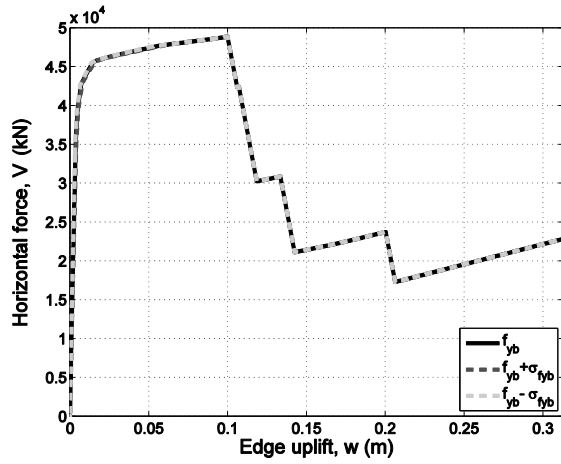*(e) t$_b$ is of minor importance*

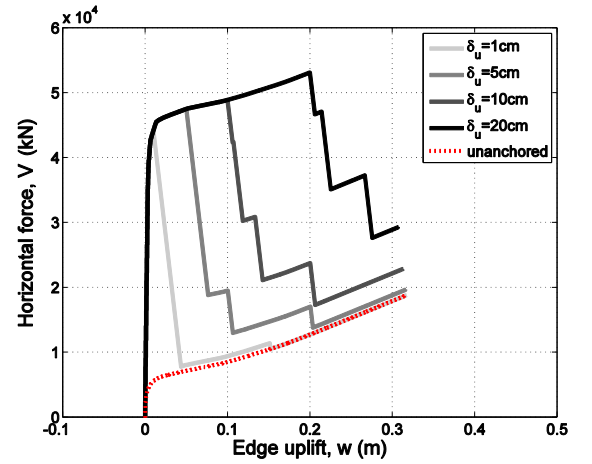*(f) t$_a$ modifies the post-yield response*

(g) t$_w$ is important for large uplifts

(h) increasing h$_f$ reduces strength

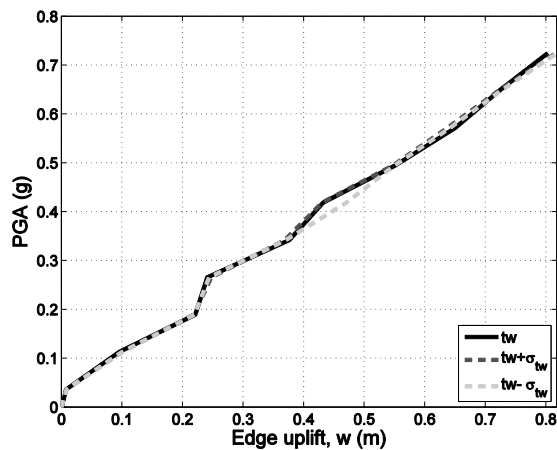*(i) f$_{yb}$ is of minor importance*

(j) increasing δ$_u$ increases strength

Fig. 2: Sensitivity of the static pushover curves to the parameters examined
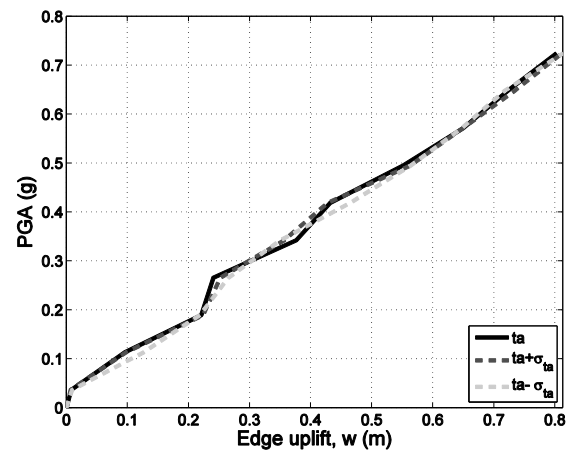
3.2 IDA sensitivity

Sensitivity analysis using monotonic loading has shown that the most influential parameters, are the fluid height, the thickness of the tank wall, the thickness of the annular ring and the strip model axial spring stiffness. A series of Incremental Dynamic Analyses (IDAs) are also performed. A set of 22 pairs of records (far-field ground motion set [15]) is adopted. The uplift (w) is the engineering demand parameter (EDP) adopted, while the peak ground acceleration was chosen as the intensity measure (IM).

Fig. 3 presents the median IDA curves for the sensitivity analysis verification. It is evident that geometric parameters such as the tank wall (Fig. 3(a)) and the thickness of the annular ring (Fig. 3(b)) do not introduce any level of uncertainty to our model after all, as all three lines (mean-model, higher and lower estimates) are almost perfectly aligned. The same outcome applies for nearly the entire given uplift range of the strip model axial spring (Fig. 3(c)). One may notice that the low-value estimate deviates from the mean-model results for uplifts greater than 0.6m, yet the difference may be considered statistically insignificant in view of the significant record-to-record variability. There is no doubt that according to Fig. 3(d), the fluid height introduces a considerable level of uncertainty to the model. Even though the median IDA curves follow the exact same pattern with the static pushover results for a fluid height up to 75% of the tank's height, it appears that as the aforementioned limitation is exceeded, the response alters in a totally different manner. The 80% curve perfectly aligns to the 75% curve, while both the 90% and the 99% curves develop a stiffer/stronger response for PGAs greater than 0.2g, indicating better seismic performance despite the increased mass and the obviously contrary results of static pushovers. In the opinion of the authors this is a manifestation of the different periods associated with the different weights, an effect that PGA cannot capture. The above results imply that further parametric investigation will be necessary
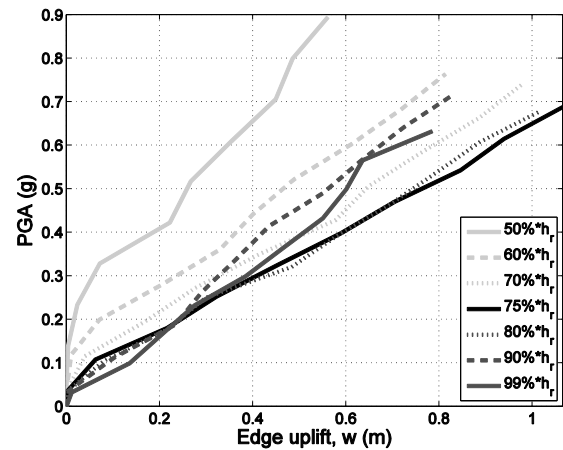

(a) t_w is of minor importance

(b) t_a is of minor importance
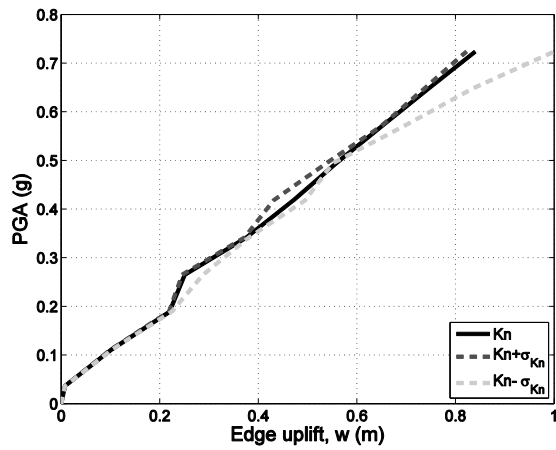
(c) K_N is of minor importance

(d) unexpected response for $h_f > 0.75 h_r$

Fig. 3: Sensitivity of the median IDA curves to the parameters examined

4. CONCLUSIONS

A sensitivity analysis on a typical liquid storage tanks is performed. The assessment has been based on a surrogate, yet robust, beam-element model. An attempt to acknowledge the modelling associated uncertainty is presented through the investigation of a range of parameters that may critically determine the response. The static pushover analysis may develop a good starting point for the sensitivity analysis, however, upon the identification of the most influential parameters, IDA is employed to verify the static analysis results. The median IDA curves reveal that the majority of the parameters examined are of minor importance, with the exception of fluid height and anchorage ductility. Especially for the fluid height, its effect can be counter-intuitive, sometimes showing a beneficial effect for a 90-95%-filled tank compared to some one that is only 75-80% full.

5. ACKNOWLEDGEMENTS

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ΑΔΡΟΜΕΡΗΣ ΠΡΟΣΟΜΟΙΩΣΗ ΚΑΙ ΑΝΑΛΥΣΗ ΕΥΑΙΣΘΗΣΙΑΣ ΑΤΜΟΣΦΑΙΡΙΚΩΝ ΔΕΞΑΜΕΝΩΝ

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ΠΕΡΙΛΗΨΗ

Τα υγρά προϊόντα της χημικής και πετρελαϊκής βιομηχανίας κατά κανόνα αποθηκεύονται σε μεταλλικές ατμοσφαιρικές δεξαμενές μεγάλης χωρητικότητας. Η σεισμική διακινδύνευση των εγκαταστάσεων αυτών είναι πολύ μεγαλύτερη από εκείνη των συμβατικών κτιριακών έργων, αφού ακόμη και μικρής έκτασης βλάβες που μπορεί να προκληθούν κατά τη διάρκεια ενός σεισμού συχνά έχουν ανεξέλεγκτες συνέπειες. Πρόσφατα σεισμικά γεγονότα έχουν προκαλέσει εκτενείς ζημιές σε δεξαμενές αποθήκευσης υγρών καυσίμων έχοντας πολλές φορές ως συνέπεια τη διαρροή υλικών επικίνδυνων για το περιβάλλον καθώς και την πρόκληση πυρκαγιάς. Δεδομένων των περιορισμών των κανονιστικών διατάξεων, η έννοια της σεισμικής επιτελεστικότητας μπορεί να αποτελέσει ένα ισχυρό εργαλείο στο σχεδιασμό και την αποτίμηση αυτών των κατασκευών υψηλής σπουδαιότητας. Για την ορθή και πρακτικώς εφικτή εκτίμηση της επιτελεστικότητας, προτείνεται η χρήση μη γραμμικών δυναμικών αναλύσεων σε συνδυασμό με αδρομερή υπολογιστικά προσομοιώματα. Σκοπός είναι να βελτιωθεί το υπάρχον πλαίσιο και να δημιουργηθεί ένα αδρομερές προσομοίωμα που μπορεί να εφαρμοστεί εύκολα τόσο σε αγκυρωμένες όσο και σε ελεύθερα εδραζόμενες δεξαμενές. Ταυτόχρονα, για τον ακριβή υπολογισμό της σεισμικής επιτελεστικότητας, πραγματοποιείται μία ανάλυση ευαισθησίας ώστε να προσδιοριστεί η αβεβαιότητα που εμπεριέχεται στο εν λόγω προσομοίωμα.