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SLIDING RESPONSE OF UNANCHORED STEEL STORAGE TANKS SUBJECTED TO SEISMIC LOADING

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ABSTRACT

Steel storage tanks are critical components of an industrial installation due to their high seismic vulnerability and containment of hazardous materials. Failure of a which, may lead to loss of containment (LOC) triggering domino effects such as explosion, environmental pollution, loss of functionality and disruption of business. Past earthquakes have demonstrated different type of failure modes in steel storage tanks. Although there are plenty of studies related to different failure modes like elephant foot buckling or tank uplifting, there are very few efforts on the sliding behavior of tank. Large displacements caused by the tank sliding can lead to pipe detachment and release of hazardous material which might cause damage propagation. Consequently, this damage state is very important for the Quantitative Seismic Risk Assessment of industrial plants.

In order to enumerate the sliding displacement of unanchored steel storage tanks, a simplified numerical model realized with OpenSees platform is proposed. The friction model used in OpenSees is calibrated with the results obtained from ABAQUS FE model. Sliding response of tanks with different D/H ratio is analyzed using the simplified model. Fragility curves for the tank sliding damage state are analytically evaluated for different D/H ratio of the tank using the "cloud method". Finally, a parametric study is conducted in order to comprehend the influence of different parameters on the sliding behavior such as friction coefficient, tank filling level and the influence of the vertical component of ground motions.

INTRODUCTION

Industrial plants are the second most dangerous plants after nuclear power plants, due to their high seismic vulnerability and containment of hazardous material. Past earthquake has shown their high vulnerability e.g. Koaceli earthquake 1999, where a 7.4 magnitude caused important damages in 30% of industrial plants [1], some of them induced domino effects due to release of hazardous material.

Nowadays, interest in the quantitative seismic risk analysis (QsRA) is increased amongst researchers. Modification of traditional QRA of industrial facilities has been proposed by [2], [3], [4], [5] taking into account damage caused by natural events, randomness of initial damage scenario and damage propagation due to loss of containment (LOC).

Steel storage tanks are one of the most vulnerable components of petrochemical plants due to containment of hazardous material and the large masses involved, for these reasons LOC from this component during earthquakes is possible. There are several damage states possible in tank pertaining to LOC, induced from: i) detachment of pipes due to tank sliding, ii) tank shell fracture due to buckling and excessive hoop stresses, iii) excessive motion of floating roofs. A methodology to assess LOC in a probabilistic way is proposed in [6].

While there are plenty of simplified models of steel storage tanks in literature, [7], [8], [9], almost all researchers neglect the sliding of unanchored tanks by focusing only in rocking motion. An analytical model for tank sliding using one dimensional lumped mass [10] could be found in literature. Past earthquakes has shown several sliding failure of unanchored steel storage tanks, so it is important to take it into consideration especially when QsRA has to be conducted.

In this paper, a simplified numerical model in OpenSees [11] will be presented. First, the friction element of simplified model will be calibrated based on 3D numerical model in ABAQUS [12]. In the second part, after the calibration of the friction model, sliding response of steel storage tanks with different H/D ratio are presented. Furthermore, fragility curves using cloud method are estimated. Finally, sensitivity analysis for the influence of different parameters such as coefficient of friction, tank filling level and vertical earthquake motion, are conducted.

CALIBRATION OF FRICTION PROPERTIES OF SLIDER

In order to have a proper sliding model in simplified 2D numerical model, the friction properties must be calibrated with the refined model of ABAQUS. A steel block, having a length and width of 2m, and a height of 0.5m is used as specimen.

ABAQUS 3D FE block model

The block is modeled by a SS304 stainless steel material. The stainless steel has a Young's modulus of 210 GPa, a Poisson's ratio of 0.3, and a density of 7,900 kg/m3. The yield strength of steel in tension is 290 MPa. The steel block is unanchored and is rested on a rigid surface. Ground motions were applied at the rigid base of the block. In Figure 1 the FE model from ABAQUS is shown.

Lagrangian solid elements are used to discretize the block. The C3D8R solid elements which are explicit, 8-node linear brick, reduced integration with hourglass control are used. A fine mesh of 1 mm is chosen for sample steel rectangle of the model based on a mesh convergence analysis. Rigid surface is modelled with shell elements which are meshed with R3D4, 4-node bilinear rigid quadrilaterals.

The interaction between the steel sample and rigid surface is realized by standard coulomb friction model, a surface-based contact modeling algorithm in the ABAQUS software. In the basic form, two contacting surfaces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to one another; this state is known as sticking. The model defines this critical shear stress at which sliding of the surfaces starts as a fraction of the contact pressure between the surfaces. The stick/slip calculations determine when a point transitions from sticking to slipping or from slipping to sticking. In the model the friction coefficient is defined as a function of the equivalent slip rate and contact pressure.

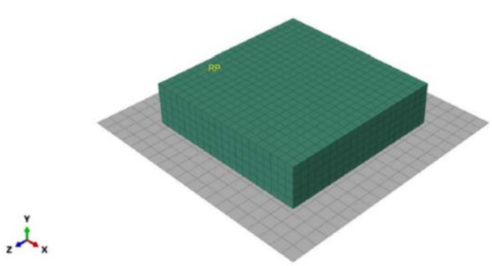

Figure 1. Block FE model in ABAQUS.

OpenSees simplified block model

In OpenSees, the block is modeled as a concentrated mass of 15 ton. A flatSliderBearing element with zero length, is used to model the contact between the block and the ground surface. A Coulomb friction is assigned to flatSlideBearing. A coefficient of friction (μ) and initial elastic stiffness (K_{int}), or in other words the maximum elastic slip (Δ_E), should be defined. The Coulomb model used in OpenSees is shown in Figure 2. The ideal friction model should have zero elastic slip, but such a model would have convergence problems. On the other hand, a low elastic stiffness (big elastic slip), would give slightly big displacements, and for the case where small displacement values are governing element limit state [6], the output of results would be unrealistic. Definition of an optimum elastic slip would be necessary.

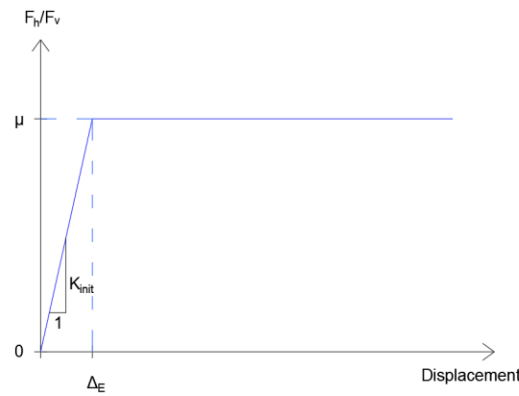

Figure 2. Coulomb friction model.

Calibration of results.

A set of 7 strong ground motions are selected as shown in Table 1. Different ground motions have been chosen, with different frequency and magnitude strong enough to produce sliding. Based on sensitivity analysis an initial stiffnesses, corresponding to an elastic slip of 0.1mm is selected as optimal match with ABAQUS model. A friction coefficient of 0.2-0.4 is used in analysis which corresponds to the typical coefficient of friction of unanchored steel storage tanks.

In Figure 3 are shown the numerical results obtained from the refined and the simplified model respectively, for the block displacement under the selected ground motions. The response from both models have a good match with a mean difference on maximum displacement of ~7.7%, as per Table 2.

UNACHORED TANK NUMERICAL MODEL

Steel storage tanks can be modeled as single degree of freedom system (SDOF), considering impulsive and convective modes of vibration which can be calculated as per [13]. In Figure 4 is shown the simplified numerical model of tank used in OpenSees. Two cantilevers, representing the impulsive and convective modes are fixed on a rigid plate. The plate is free to move for a force bigger than friction force. An impulsive and convective mass are assigned to the top of each cantilever representing the water mass involved in each mode.

Case study.

A real tank farm located in Priolo Gargallo, consisting of ten unanchored steel storage tanks, is selected as case study. The tank farm has five different typologies of unanchored tanks with D/H ratio varying from 2.71 to 4.76. Tanks, filled with crude oil, have the dimensions and properties as given in Table 3. A coefficient of friction μ=0.3 is used to represent the friction properties between tank and foundation.

Dynamic properties of each tank are given in Table 4, where the characteristics of impulsive and convective components of the liquid motion are calculated using existing methods [13].

Table 1. Set of ground motion records used for calibration of friction model.

GM Label	GM Number	Event	Country	Date	Magnitude	Soil	Comp	PGA (g)
124	963/2	Northridge-01	USA	1994	6.69	B	2	0.667
128	10414	Kalamata	GREECE	9/13/1986	5.9	B	2	0.353
129	10593	Umbria Marche	ITALY	9/26/1997	5.7	B	1	0.377
132	763	Loma Prieta	USA	1989	6.93	B	1	0.462
134	963/1	Northridge-01	USA	1994	6.69	B	1	0.737
135	741	Loma Prieta	USA	1989	6.93	B	1	0.32
138	250	Mammoth Lakes-06	USA	1980	5.94	B	2	0.436

Table 2. Block maximum sliding displacement.

GM Label	GM Number	Displacement OpenSees (mm)	Displacement ABAQUS (mm)	OpenSees/ABAQUS
124	963/2	101.4	102.5	0.989
128	10414	4.9	4.8	1.021
129	10593	5.2	4.6	1.130
132	763	2.8	2.6	1.077
134	963/1	42.6	40.9	1.042
135	741	29.4	27	1.089
138	250	11	9.2	1.196

Table 3. Tanks geometry and properties.

Tank Nr.	Diameter (m)	Height (m)	Filling Level (m)	Steel Yield strength (Mpa)	Shell eq. thick. (m)	Shell base thick. (m)	Annular plate thick. (m)	T slab (m)	D/H
1	37.96	14	11.3	345	0.013	0.02	0.008	0.009	2.71
2	41.26	15	12	345	0.013	0.02	0.008	0.009	2.75
3	54.86	18	15.3	345	0.0185	0.0295	0.008	0.009	3.05
4	64.4	14	10	345	0.014	0.0295	0.008	0.009	4.60
5	81.46	25	21.6	345	0.026	0.04	0.016	0.018	3.26

Table 4. Tanks dynamic properties.

Tank	mi (ton)	hi (m)	Ti (sec)	Ki (KN/m)	ξi (%)	mc (ton)	hc (m)	Tc (sec)	Kc (KN/m)	ξc (%)
1	4206	13.42	0.21	3740560	2	7521	13.25	7.33	5527	0.5
2	5166	14.66	0.23	3685564	2	9547	14.57	7.70	6362	0.5
3	11198	19.68	0.29	5104064	2	21965	19.84	8.99	10721	0.5
4	5428	25.49	0.3	2558350	2	24441	32.58	11.63	7128	0.5
5	33230	29.59	0.43	6937178	2	69999	30.42	11.14	22282	0.5

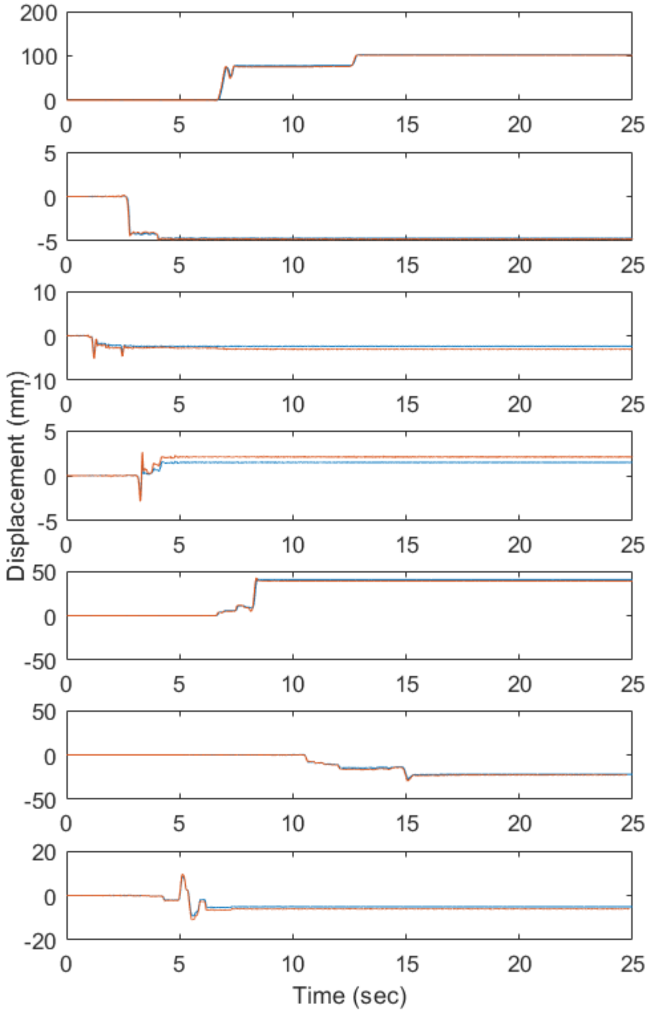

Figure 3. Sliding response of block (red line - ABAQUS; blue line - OpenSees).

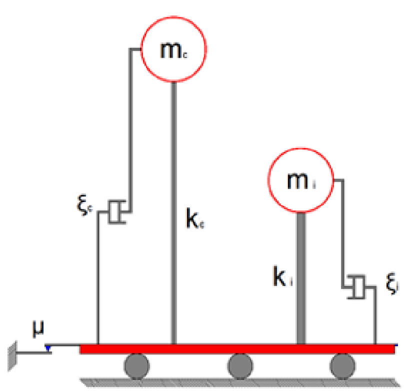

Figure 4. Simplified numerical model of unanchored tank.

Sliding response of tanks.

The displacement of tanks for two different ground motions are shown in Figure 6 and 7. First one GM-124 has PGA around 0.67g and around ten peaks bigger than 0.3g in a duration of 10 seconds, while GM-132 has a PGA around 0.46g and six peaks bigger than 0.3g in a very short period around 2 seconds as shown in Figure 5.

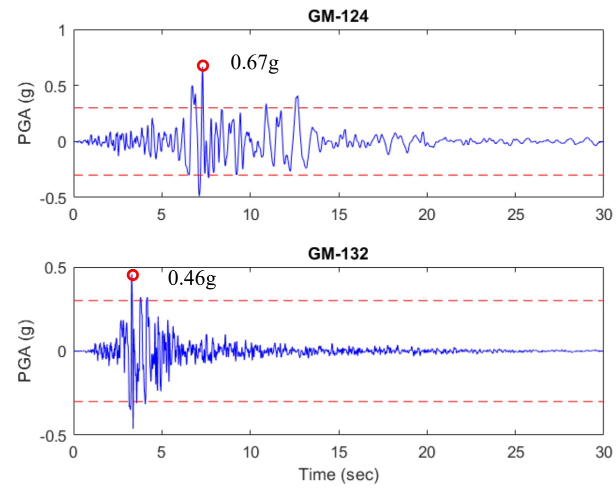

Figure 5. Time history of GM-124 & GM-132.

As shown Figure 6, tank 5 has the biggest displacement during GM-124 around 25cm, while tank 4 has the smallest displacement around 12.5cm. In terms of residual displacement tank1,2,5 have almost same residual displacement around 22.5 cm while tank 3 and 4 have smaller one. In case of GM-132 the picture is different, where the biggest displacement befalls to tank 3, which is around 3.4cm. In term of residual displacement, they are different in each tank, and the biggest 1.8cm occurs in tank 2.

For different ground motion the sliding response of different tanks changes a lot with no consistency. In order to understand better the vulnerability of tanks related to sliding under different ground motions we will calculate their fragility curves using cloud analysis.

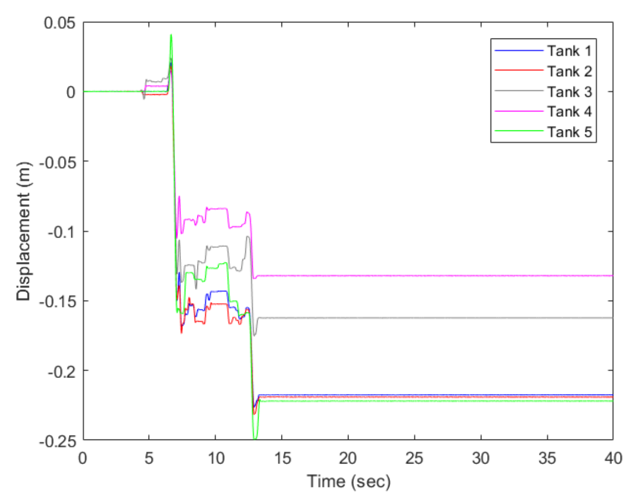

Figure 6. Sliding response of tanks due to GM-124.

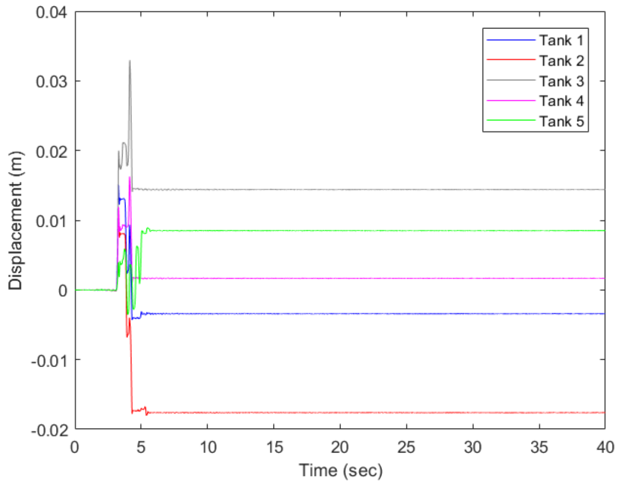

Figure 7. Sliding response of tanks due to GM-132.

FRAGILITY ANALYSIS

Fragility functions are generally derived using different approaches such as an expert judgement, damage observations in field, or static structural analyses, but in the field of earthquake engineering the focus is mostly on analytical fragility functions which are developed from dynamic structural analysis. From the structural point of view, fragility can be defined as the conditional probability that the response of the structure exceeds a certain limit state (LS) of interest or the collapse, for a given intensity measure (IM). Usually a lognormal cumulative distribution function (CDF) is often used to define a fragility function.

Cloud Analysis.

The cloud method is particularly effective due to ease of performing non-linear analysis of the structure subjected to the ground motion time histories which are unscaled. When the seismic demand (Engineering Demand Parameters EDP) and the structural limit states (LS) are assumed to follow a lognormal distribution, the probability of exceeding a specific damage state can be estimated with [13]:

$$P(D_{EDP} > LS|IM) = 1 - \Phi\left(\frac{\ln(LS_m) - \ln(D_m)}{\sqrt{\beta_{d|IM}^2 - \beta_{LS}^2}}\right) \quad (1)$$

where $\Phi(.)$ is the standard normal cumulative distribution function, LS_m is the median estimate of the structural limit state, D_m is the median estimate of the demand, $\beta_{d|IM}$ is the dispersion of the demand conditioned on the IM, and β_{LS} is the dispersion of the structural limit state.

The estimate of the median demand can be predicted by a power function [15]:

$$D_m = a(IM)^b \quad (2)$$

In the log form the equation can be rewritten as:

$$lnD_m = \log(a) + b\, log(IM) \quad (3)$$

where a and b are regression coefficients based on the collection of maximum displacement d_i and IM_i from the *i-th* time history seismic analyses of the analyzed tank and from the selected suite of n ground motions. While standard deviation can be calculated according to eq. (4).

$$\beta_{d|IM} = \sqrt{\frac{\sum_{i=1}^{n}[\ln(d_i) - \ln(aIM_i^b)]^2}{n-2}} \quad (4)$$

For this case study a suitable set of 140 ground motion are selected according to criteria [4]. PGA is used as intensity measure. Occasionally tanks, are connected with short pipes which are fixed on ground, in that case even a small displacement of tank could be very crucial for the plant as it can result in loss of containment from bolted flange joint [6]. Experimental testing of bolted flange joint has shown that leakage can start for small displacement, even less than 1mm [16]. Based on engineering judgement, experimental results and accounting for some pipe deformation, a displacement of 1mm will be considered as LS to define tank sliding. Fragility curves are constructed for different D/H ratio as shown in Figure 8.

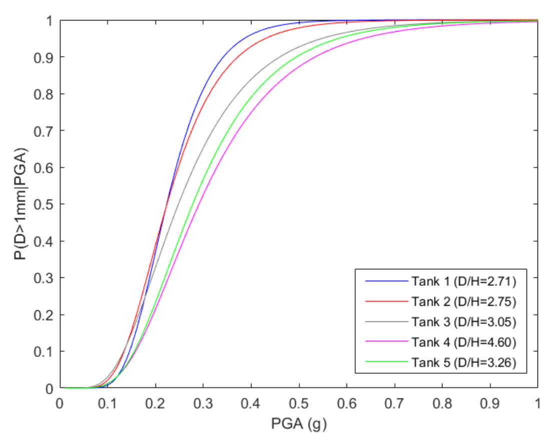

Figure 8. Fragility curve of tank sliding LS.

Tank 1 and 2 are the most vulnerable tanks, for a PGA of 0.3g they have 50% probability of sliding. From the results, it is possible deduce that smaller the D/H ratio of unanchored steel storage tanks, higher is the vulnerability of sliding failure.

PARAMETRIC STUDY

A parametric study is done using the most vulnerable tank (in this case Tank 1), varying coefficient of friction, tank filling level and effect of vertical component of ground motion.

Coefficient of friction.

Three values of coefficient of friction (CoF) are analyzed 0.2, 0.3 and 0.4 respectively. Tank 1 is modeled assumed to be fully filled up to maximum design level.

Sliding response of Tank 1 with varying coefficient of friction is shown in Figure 9. For μ=0.4, the tank experiences around 46% smaller displacement comparing to the case of μ=0.3, while for the CoF μ=0.2, maximum displacement reduces by 33% comparing to the case of μ=0.3.

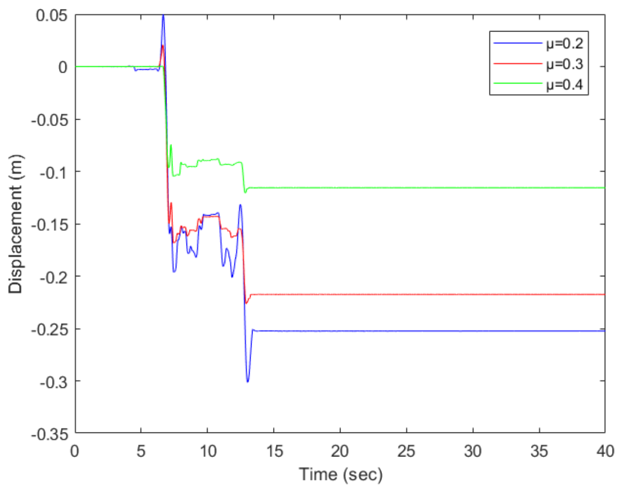

Figure 9. Tank-1 sliding response under GM-124 varying μ.

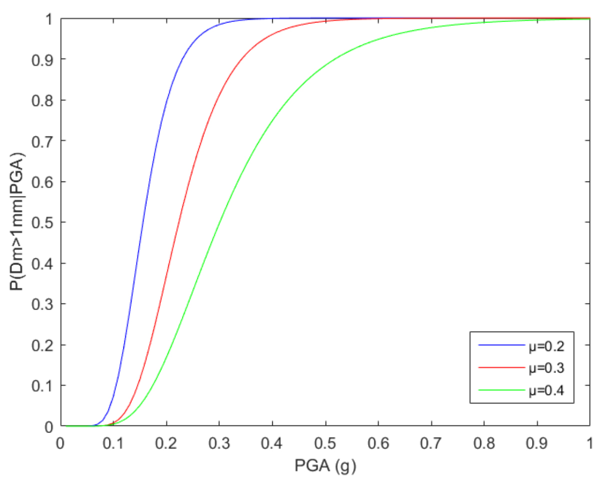

Figure 10. Tank-1 fragility curves for different μ.

Figure 10 shows the influence of coefficient of friction in fragility curves, it is safe to extract that smaller the friction coefficient, bigger the vulnerability of the tank to get damaged.

Tank filling level.

Three different filling level of reference Tank 1 with a CoF μ=0.3 is considered for this parametric study. In the first case the tank is fully filled which corresponds to maximum design filling level around 80%, in second case 50% of tank height and in the third case 25% of the total height

Figure 11 shows the displacements of Tank 1 for aforementioned filling levels. It can be observed that the displacements become smaller with lowering the filling level.

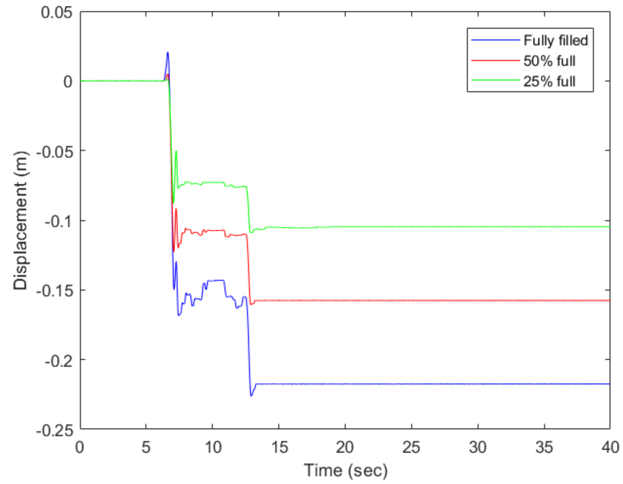

Figure 11. Tank-1 displacement due to GM-124 for different filling level.

Similarly, Figure 12 shows the fragility curves of tank 1 for the three different filling levels. It can be seen than tank will be more vulnerable to sliding when it will be filled up to maximum design level.

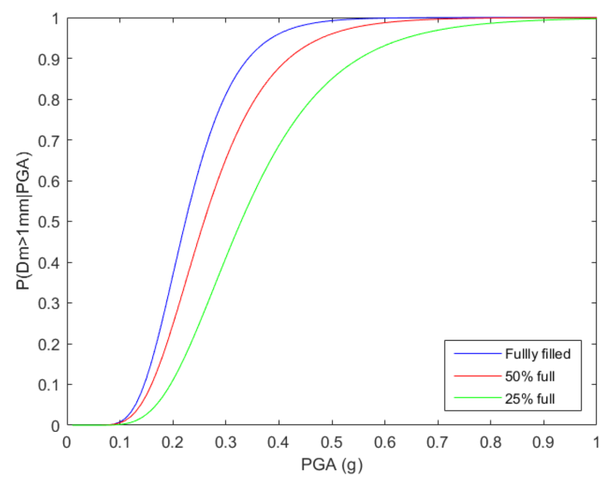

Figure 12. Tank-1 fragility curve for different filling level.

Vertical component of ground motion.

In this part, influence of the vertical component of the ground motion to sliding response of tank is investigated. As per Eurocode 8 [17], vertical component is considered as 30% of horizontal component, having a positive or negative sign.

Vertical component of ground motion has a big influence on sliding response of tanks as it influences the friction resisting force, this can be seen also in Figure 13. Depending from the sign, the vertical component can increase the maximum displacement or reduce it, e.g. in case of GM-124. An interesting case is GM-134 where the vertical component increases maximum displacement no matter what its sign is, even more it can change also the direction of residual displacement.

So, it is important to consider the vertical component of ground motion while calculating the sliding response of unanchored tanks.

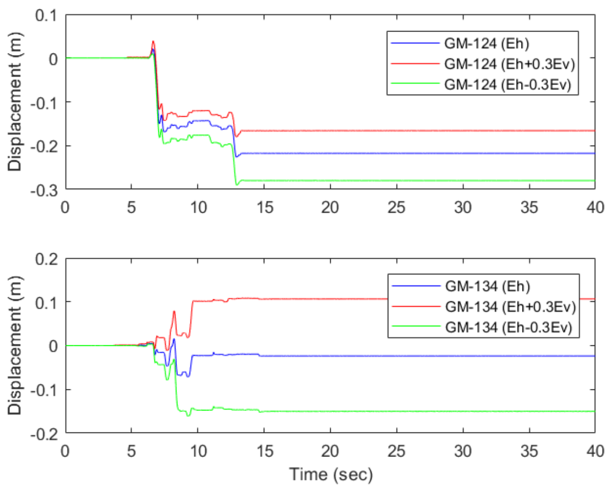

Figure 13. Tank-1 displacement due to GM-124& GM-134 accounting also the vertical component of GM.

Regarding fragility analysis, accounting for vertical component of ground motion will not have big influence in the results as shown in Figure 14. This can also be related with the definition of limit state. In our case the limits state is selected relatively small value (1mm), so the influence of vertical component of GM is small, while for other LS this may not be the case.

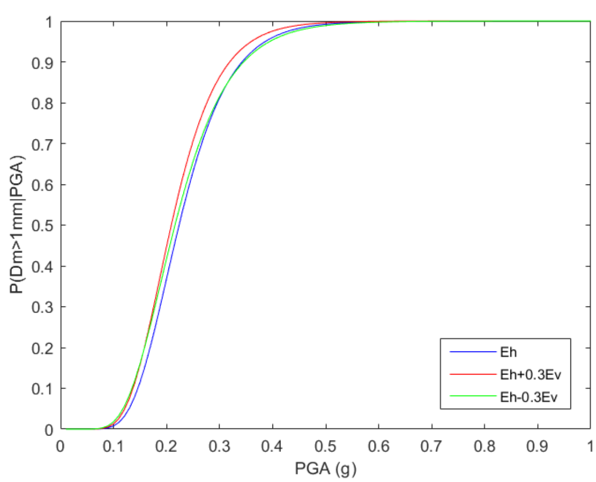

Figure 14. Tank-1 fragility curves accounting also for vertical component of GM.

CONCLUSIONS

This paper deals with sliding response of unanchored steel storage tank. After calibrating the friction properties of simplified model (optimal elastic slip) with 3D model realized in ABAQUS, a simplified 2D numerical sliding model is used to model the tank sliding behavior in OpenSees in order to reduce computational cost and time.

Results following the given methodology and fragility curves as the indicators shows that tanks with the smallest D/H ratio are the most vulnerable to sliding, subsequently leading to damage and LOC.

Moreover, a parametric study is conducted to show the vulnerability of tank on different parameters by varying coefficient of friction, tank filling level and effect of vertical component of ground motion. The tank displacement and vulnerability against sliding decreases with reduction of tank filling level. Coefficient of friction has huge influence on tank maximum displacement, therefore it is important to have a right measure of coefficient of friction between tank and foundation while assessing unanchored tanks. Finally, it is shown that the vertical component of ground motion should be considered into analysis when interested in calculation of maximum sliding or residual sliding.

In future research, the proposed simplified model will be benchmarked against full 3D FEM of steel storage tank in ABAQUS.

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REFERENCES

[1] Frederic Masson, Jean-Philippe Pineau, Jean-Jacques Tritsch. Consequences of Izmit (Kocaeli) Earthquake (Turkey, August 17, 1999) on industrial plants and some jetties. International Conference on Safety and Reliability (ESREL 2001), Sep 2001, Turin, Italy. pp.1883-1890, 2001. <ineris-00972226>

[2] Fabbrocino G., Iervolino I., Orlando F., Salzano E., (2005), Quantitative risk analysis of oil storage facilities in seismic areas, Journal of Hazardous Materials, Volume 123, Issues 1–3, 31 August 2005, Pages 61-69, DOI: org/10.1016/j.jhazmat.2005.04.015

[3] Caputo A.C., Giannini R., Paolacci F., (2015), Quantitative seismic risk assessment of process plants. state of the art review and directions for future research, ASME 2015 Pressure Vessels & Piping Conference PVP2015, July 19-23, 2015, Boston, Massachusetts, USA, DOI: 10.1115/PVP2015-45374

[4] Alessandri et al, (2018) Probabilistic Risk Analysis of Process plants under Seismic loading based on Monte Carlo Simulations, Journal of Loss Prevention in the process Industries, Vol 53 - pp. 136-148, DOI: 10.1016/j.jlp.2017.12.013

[5] S. Alessandri, A.C. Caputo, D. Corritore, G. Renato, F. Paolacci, H.N. Phan, (2017), On the use of proper fragility models for quantitative seismic risk assessment of process plants in seismic prone areas, ASME 2017 Pressure Vessels & Piping

Conference PVP2017, July 16-20, 2017, Waikoloa, Hawaii, United States DOI:10.1115/PVP2017-65137

[6] Paolacci F., Corritore D., Caputo A.C., Bursi O.S., Kalemi B., (2018) A Probabilistic Approach for the Assessment of LOC Events in Steel Storage Tanks Under Seismic Loading, ASME 2018 Pressure Vessels & Piping Conference PVP2018, July 15-20, 2018, Prague, Czech Republic DOI: 10.1115/PVP2018-84374

[7] Housner G.W., Dynamic behaviour of water tanks, Bulletin of the Seismological Society of America, vol. 53, pp. 381–387, 1963.

[8] Bakalis K., Kazantzi A., Vamvatsikos D., Fragiadakis M., (2018) Seismic performance evaluation of liquid storage tanks using nonlinear static procedures. Journal of Loss Prevention in the process Industries, Accepted manuscript posted March 19, 2018. DOI:10.1115/1.4039634

[9] Phan H.N., Paolacci F., Alessandri S., (2016), Fragility Analysis Methods for Steel Storage Tanks in Seismic Prone Areas, ASME 2016 Pressure Vessels and Piping Conference PVP2016, July, 2016, Vancouver, British Columbia, Canada, DOI: 10.1115/PVP2016-63102

[10] A. Di Carluccio, G. Fabbrocino (2012), Some remarks on the seismic demand estimation in the context of vulnerability assessment of large steel storage tank facilities. International Scholarly Research Network, Volume 2012, Article ID 271414, 12 pages, DOI:10.5402/2012/271414

[11] F. McKenna, M.H. Scott, G.L. Fenves (2010), Nonlinear Finite-Element Analysis Software Architecture Using Object Composition, J. Comput. Civ. Eng. 24 (2010) 95–107. doi:10.1061/(ASCE)CP.1943-5487.0000002.

[12] ABAQUS®. (2016). "ABAQUS- Dassault Systèmes® 3D Software."

[13] Malhotra PK, Wenk T, Wieland M (2000) Simple procedure for seismic analysis of liquid-storage tanks. Struct Eng Int 10(3):197–201

[14] Nielson, B.G., and DesRoches, R., (2007), Analytical seismic fragility curves for typical bridges in the central and southeastern united states, Earthquake Spectra, Vol. 23, No. 3, pp. 615-633.

[15] Cornell, C., Jalayer, F., Hamburger, R., and Foutch, D., (2002), Probabilistic Basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines, J. Struct. Eng., pp. 526-533 DOI: 10.1061/(ASCE)0733-9445(2002)128:4(526).

[16] V. La Salandra, S. Alessandri, F. Paolacci, R. Di Filippo, O.S. Bursi (2016), Cyclic Response of Enhanced Bolted Flange Joints for Piping Systems, 00032 (2016) V008T08A024. doi:10.1115/pvp2016-63244.

[17] Eurocode 8 (1998), Design Provisions of Earthquake Resistance of Structures, Part 4: Silos, Tanks and Pipelines, European Committee for Standardization, Brussels, Belgium, 1998.