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An integrated model for the seismic risk assessment of an oil refinery

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ABSTRACT

Oil refineries play a key role in the energy supply chain. Safeguarding the integrity of such high-importance facilities against natural hazards is crucial because a potential failure may result in a sequence of unwanted events, spanning from business disruption to uncontrolled leakage and/or major accidents. Despite the strict criteria enforced during the design, construction, maintenance, and operation of an oil refinery, Natural-Technological events caused by earthquakes still occur.

Oil refining is a complex process that involves a variety of structural typologies, such as buildings, tanks, chimneys, pipe-racks, pressure vessels, and process towers. These structures have fundamentally different dynamic properties and seismic responses. A comprehensive seismic risk assessment framework is thus required to account for the refinery as an integrated system and provide information about both the structural and operational integrity of the individual assets and the system. In the present study, a virtual crude oil refinery is examined as a case study to demonstrate the steps of a preliminary seismic risk assessment framework, consisting of the seismic hazard calculation, the development of the exposure model, the analysis of the structures at risk, and the damage assessment of the facility. Scenario-based results are presented for the refinery and the critical assets are identified.

Keywords: Oil refinery, seismic hazard, risk assessment, exposure model

INTRODUCTION

Refineries are critical infrastructures because a large amount of fuel is produced, stored, and delivered to power the economy and society. Safeguarding the structural and operational integrity of those facilities against natural hazards is of paramount importance, given that the impact of a failure is likely to result in a sequence of unwanted events, spanning from business disruption to uncontrolled leakage and/or major fire incidents. The design, operation, and maintenance of refineries are performed within a strict legislation framework but industrial disasters are still occurring. For earthquakes, in particular, the so-called Natural-Technological (NaTech) events, constitute a major threat for every community, in view that the associated aftermath could be related to fiscal factors, such as direct monetary loss and downtime (Cruz & Steinberg, 2005), as well as casualties, injuries, and psychological disorders (Önder et al., 2006). Recent major seismic events, such as the Izmit earthquake (Kocaeli, 1999) in Turkey and the Tohoku earthquake (2011) in Japan, have resulted in significant damages to refineries that led to leakage of fuel products, widespread fire, and collapses for a series of structures (Hatayama, 2008, 2015; Sezen & Whittaker, 2006). Thus, the international community has acted and developed the Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015) that offers a risk reduction strategy for critical infrastructures.

The refinery designers and operators and the regulatory authorities are working closely to update the existing and develop more sophisticated frameworks for the risk assessment of refineries against NaTech events (Camila et al., 2019). However, these frameworks are at the most qualitative based on tools, such as risk analysis (Girgin et al., 2019), risk evaluation (Theocharidou & Giannopoulos, 2015), and risk rating (Krausmann et al., 2011). These tools are unquestionably useful for developing a preliminary mitigation strategy but insufficient for computing the actual expected seismic loss and consequently the seismic resilience of the facility. It is thus necessary to develop a comprehensive framework for the seismic risk assessment by taking into account the pertinent aleatory and epistemic uncertainties, based on the Performance-Based Earthquake Engineering framework (Cornell & Krawinkler, 2000).

A preliminary framework for the seismic risk assessment of an oil refinery is developed that consists of (1) the seismic hazard calculation, (2) the development of the exposure model, (3) the structural analysis of the assets, and (4) the damage assessment. A virtual typical crude oil refinery is examined as a case study to demonstrate the process and scenario-based results are presented for the critical assets at risk.

SEISMIC HAZARD

A site close to Athens, the capital of Greece is selected, being located in the Elefsina Gulf, a major industrial area, where the three major crude oil refineries of Greece are established. The seismic hazard calculations are performed using the open-source OpenQuake engine (Pagani et al., 2014) and are based on the EU-funded SHARE Project (Woessner et al., 2015) area source model and the Ground Motion Prediction Equation of Boore & Atkinson (2008).

A variety of structural typologies is encountered in an oil refinery with essentially different geometry and dynamic properties and consequently, a variety of Engineering Demand Parameters (EDP) is required to assess the behavior of these structures. Thus, the selected Intensity Measure (IM) for the analysis should be a reliable and sufficient predictor for "all" EDPs of interest (Kohrangi et al., 2017). The mean of the log spectral acceleration at a set of periods ($AvgS_a$), being an asset-aware IM, is selected as the appropriate IM for a range of periods spanning from 0.1sec to 1.0sec. The seismic hazard curve for the site of interest is presented in Figure 1. A set of 30 records from the PEER-NGA database (Ancheta et al., 2013) was selected using the procedure discussed by Kohrangi et al. (2017), which is based on the Conditional Spectrum-based ground motion record selection using $AvgS_a$. Moreover, the Peak Ground Acceleration (PGA) has been considered as an asset-agnostic IM. It is noted that the same ground motion is applied uniformly to all refinery structures, assuming that the area of the facility is limited to neglect any ground motion differentiation with it.

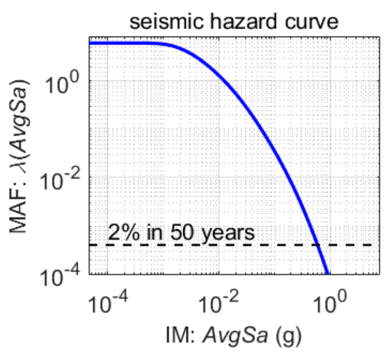


Figure 1. *Seismic hazard curve on site of interest*

EXPOSURE MODEL

A virtual oil refinery is examined as a case study. The examined refinery is typical in terms of functionality and roughly the size of those located in the Elefsina Gulf but with different details due to confidentiality reasons. The plan view is illustrated in Figure 2 and covers a rectangular area with dimensions 1,850m × 1,250m. The main structures identified are (1) the atmospheric tanks for storing liquid fuel products (crude oil, naphtha, diesel, marine oil, jet oil, gasoline, slops, asphalt), (2) the spherical pressure vessels for storing gases (propane, butane), (3) the flare for burning gaseous wastes, (4) the truck loading station, and (5) the refining areas. Liquid and gas fuels are circulated in the refinery via a dense buried, on-ground, and above-ground piping network.

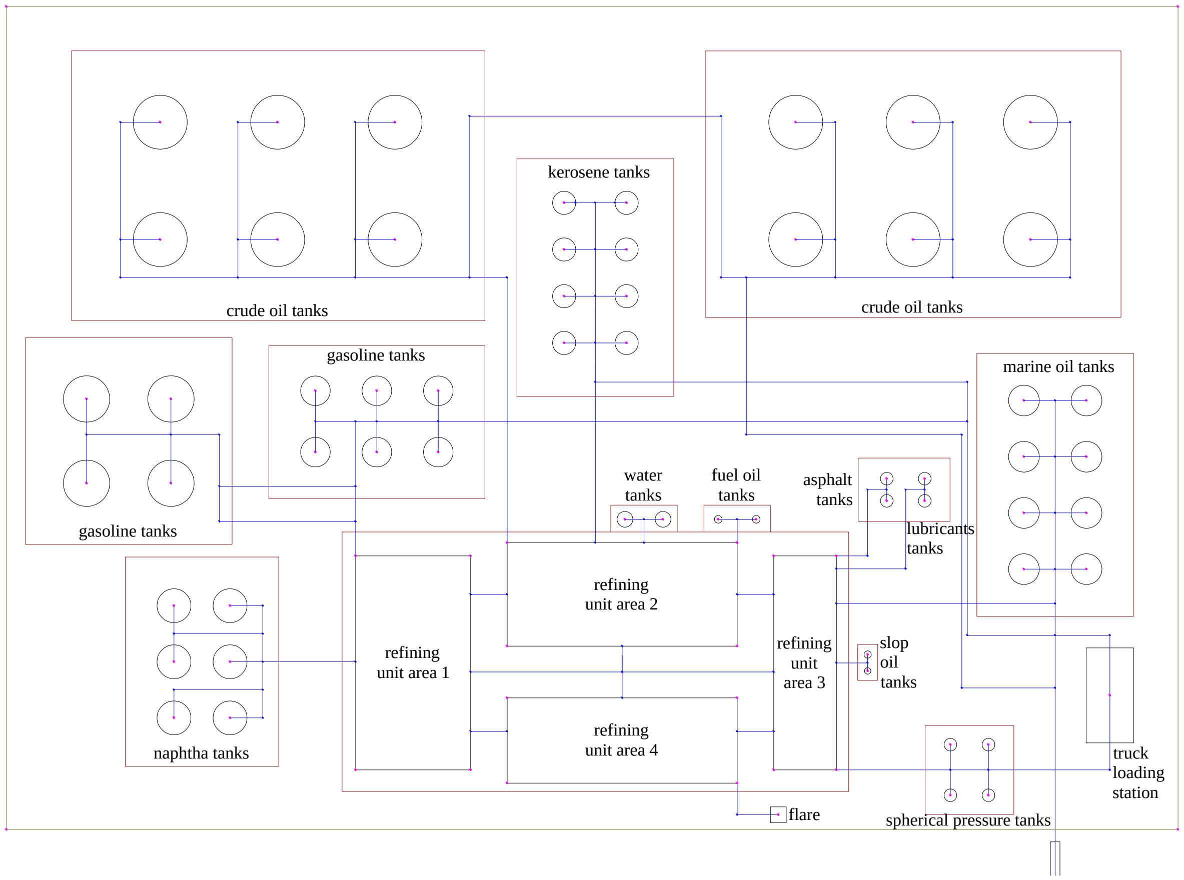


Figure 2. *Refinery plan view*

Crude oil is imported via pipelines from marine or land terminals and stored in crude oil storage tanks. Then, it is transported to the refining areas for processing. Final products are stored in liquid storage tanks and spherical pressure vessels for export. The refining areas (Figure 3) are the core of the facility and include (1) process towers, where chemical and physical processes, such as atmospheric distillation, vacuum distillation, alkylation, isomerization, etc. (Ancheyta, 2011) take place, (2) steel and reinforced concrete chimneys for the disposal of non-hazardous gases, (3) open-frame steel and reinforced concrete building that support process equipment, such as pressure vessels, heat exchangers, pumps, reactors, vacuum chargers, etc. (Sullivan et al., 2015), and (4) various pressure vessels.

The critical structures/assets examined in this study are the liquid storage tanks, the buildings, the process towers, the chimneys, and the flare. An indicative schematic overview of these structures is shown in Figure 4. It is noted that the auxiliary building, the pier, the truck loading station, and the piping network are not investigated.

Figure 3. *Refining units areas*

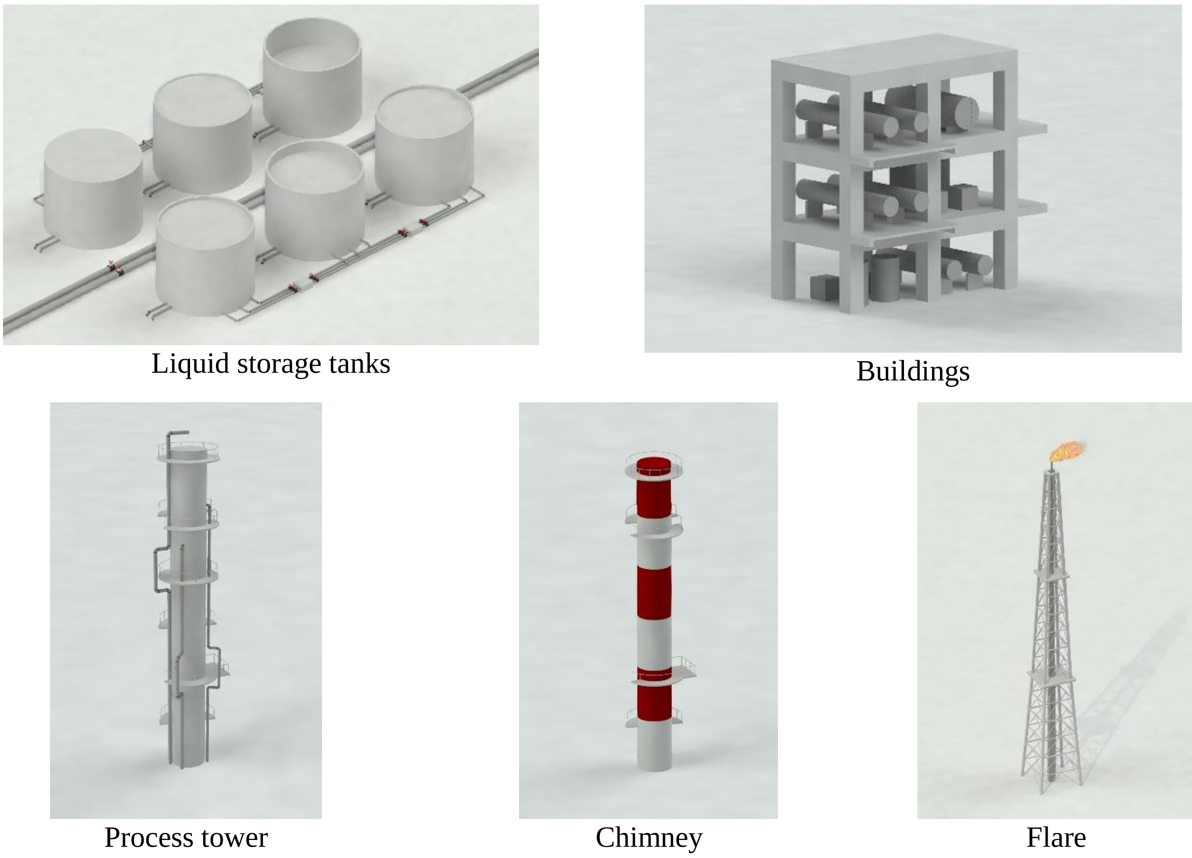


Figure 4. *Indicative structural typologies examined*

FRAGILITY ANALYSIS

The seismic demand of the structures was evaluated through Incremental Dynamic Analysis (Vamvatsikos & Cornell, 2002) for the selected suite of 30 records (section SEISMIC HAZARD). Reduced-order numerical models were developed for each structure using the open-source software platform OpenSees (McKenna & Fenves, 2000). Both aleatory, stemming mainly from the record-to-record variability, and epistemic uncertainties were considered. A brief description of the structures and the developed models analyzed are presented in Table 1.

The analytical calculation of fragility curves via response-history analysis has been thoroughly discussed in numerous studies (e.g. Bakalis & Vamvatsikos, 2018; Kazantzi et al., 2011; Kwon & Elnashai, 2006). The fragility is a function of structural demand (D) at a given IM level, exceeding an associated capacity (C) threshold for a given limit state (LS):

$$F_{LS}(IM) = P[LS \text{ violated}|IM] = P[D > C|IM] \quad (1)$$

Fragility curves are employed to quantify the damage potential of the structures and consequently, the probability of exceeding a given LS is equivalent to the probability of being in a particular damage state (DS). A set of global DS is defined for all refinery structures to assess the damage severity on the refinery scale as per Table 2. The failure modes of each refinery structure with reference to the global DSs are presented in Table 3.

Table 1. *Brief description of refinery structures and numerical modeling approach*

Structure	Structure	Numerical model
Flare	Steel lattice tower with height 68m and rectangular plan	Nonlinear 3D model with elastic beam-column elements
Spherical pressure vessels	Spherical pressure vessels (tanks) with diameter 20.22m, supported by braced legs	Spherical shell represented by a concentrated mass, legs modeled with elastoplastic beam-column elements, and braces modeled with tension-only elements
Liquid storage tanks	Various unanchored and anchored atmospheric tanks with diameter from 11.6m to 85.4m	Model after Bakalis et al. (2017)
Steel buildings (structure)	1 and 2 story steel open-frame buildings with rectangular plan	Elastic nonlinear models with diaphragms modeling slabs
RC buildings	1, 2, and 4 story RC open-frame buildings with rectangular plan	Elastic nonlinear models with diaphragms modeling slabs
Process tower	Pressurized steel tower with height 33m	Multi degree-of-freedom nonlinear model with elastic beam-column elements
RC chimney	Reinforced Concrete chimney with height 87m	Multi degree-of-freedom nonlinear model with fiber elements
Steel chimney	Steel chimneys with height 30m and 80m	Multi degree-of-freedom nonlinear model with elastic beam-column elements
Pressure vessels	Horizontal and vertical pressure vessels after The PEC project consortium (2016)	— [published fragility curves undergone IM-transformation]

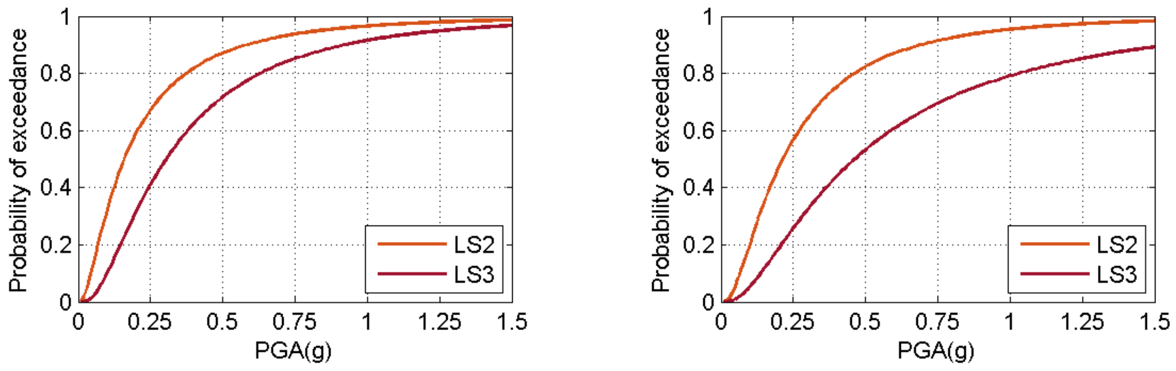
Table 2. *Global Damage States colored as per ATC-20* (Applied Technology Council, 1989) *for increasing seismic damage severity*

DS0	DS1	DS2	DS3	DS4
No damage	Low damage	Medium damage	Extensive damage	Near collapse

Table 3. *Failure modes of refinery structures at each global DS*

Structure	DS0	DS1	DS2	DS3	DS4
Flare	—	Top displacement	Interstory drift		Buckling of elements
Spherical pressure vessels	—		Yielding of braces	Yielding of columns	Failure of columns
Liquid storage tanks	—	Sloshing	Sloshing, base plate rotation	Elephants' foot buckling, base plate rotation	
Buildings (structure)	—	Interstory drift	Interstory drift	Interstory drift	
Buildings (components)	—	Failure of low importance	Failure of medium importance	Failure of high importance	
Process tower	—	Top displacement			Shell local buckling
RC chimney	—	Top displacement	Cross-section yielding		Cross-section failure
Steel chimney	—	Top displacement	Interstory drift		Shell local buckling
Pressure vessels	—	First leakage and minor structural damage			Complete release of content and global structural failure

The seismic performance of two liquid storage tanks and two high-rise steel stacks in terms of fragility curves is illustrated in Fig. 5 and Fig. 6, respectively.



(a) *(b)*

Figure 5. *Fragility curves of (a) a crude oil tank and (b) a gasoline tank [LS2: sloshing base plate rotation, LS3: elephants' foot buckling, base plate rotation]*

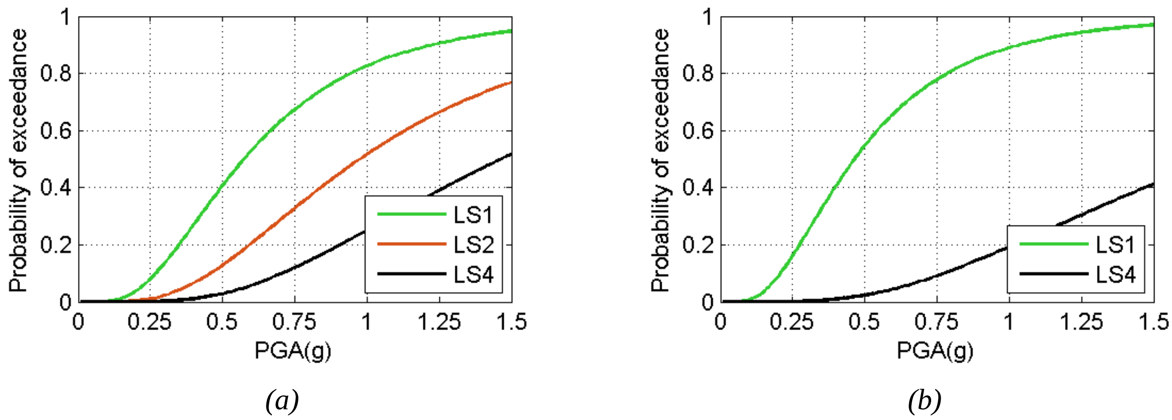


Figure 6. *Fragility curves of (a) a steel chimney and (b) a process tower [LS1: top displacement, LS2: Interstory drift, LS4: shell local buckling]*

SCENARIO-BASED RESULTS

Scenario-based results are typically included in risk assessment studies and are used for planning post-disaster emergency actions and designing risk mitigation strategies. The output of scenario-based analysis provides the distribution of damage to assets throughout the refinery given an earthquake of specific magnitude at a specific distance has occurred. The level of damage is typically imaged using the color tagging of ATC-20 (Applied Technology Council, 1989) as shown in Table 2. It should be noted that scenario-based results lack any information on the likelihood of the earthquake scenario in a given time period, as well as the distribution of the most probable damage in the refinery.

As an example, two earthquake scenarios are considered: (1) a magnitude 6.4 earthquake at the Loutraki fault, located southwest of the refinery, and (2) a magnitude 6.0 earthquake at the Ag. Theodoroi fault, located west of the refinery. The accelerograms were produced using the EXSIM (https://www.seismotoolbox.ca/) software taking into consideration the effects of the source, the propagation path of the seismic waves, and the local geotechnical conditions at the site of interest. The seismic sources are modeled by rectangular planes that are divided into discrete sub-faults, which are then considered to be point sources. The energy produced by these sub-faults propagates radially with a constant velocity and triggers neighboring sub-faults, leading to the rupture of the entire fault surface. The path effects are represented by empirical attenuation relationships. The site effects are considered via empirical amplification functions or factors (Giannaraki et al., 2018). The produced accelerograms for both scenarios are illustrated in Fig. 7.

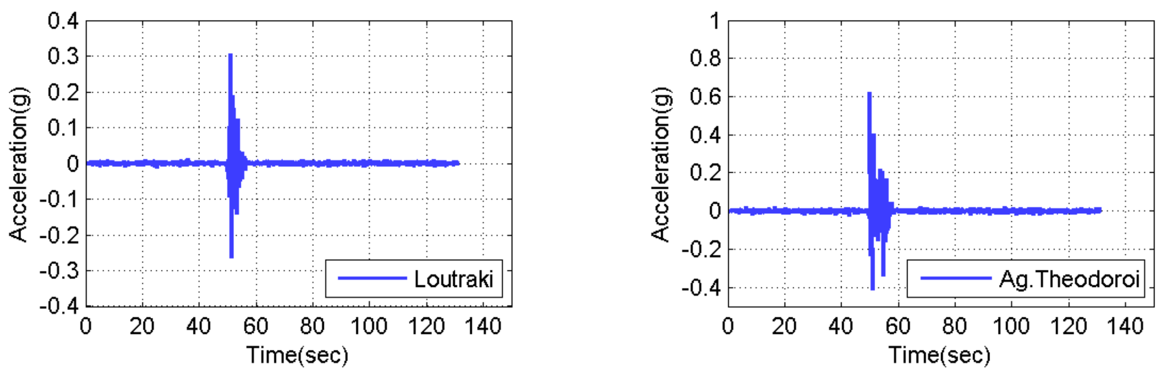


Figure 6. *Accelerograms for earthquake scenarios at Loutraki (maximum acceleration 0.307g) and Ag. Theodoroi (maximum acceleration 0.621g) faults [courtesy of Dr. V. Karastathis, Research Director at the National Observatory of Athens]*

The consequences of each earthquake scenario to the refinery are illustrated in Fig. 7 for scenario (1) and Fig. 8 for scenario (2). The most severe scenario (2) in terms of the maximum acceleration leads to significant damage of most refinery structures and especially liquid storage tanks, as well as buildings and pressure vessels located in the refining areas.

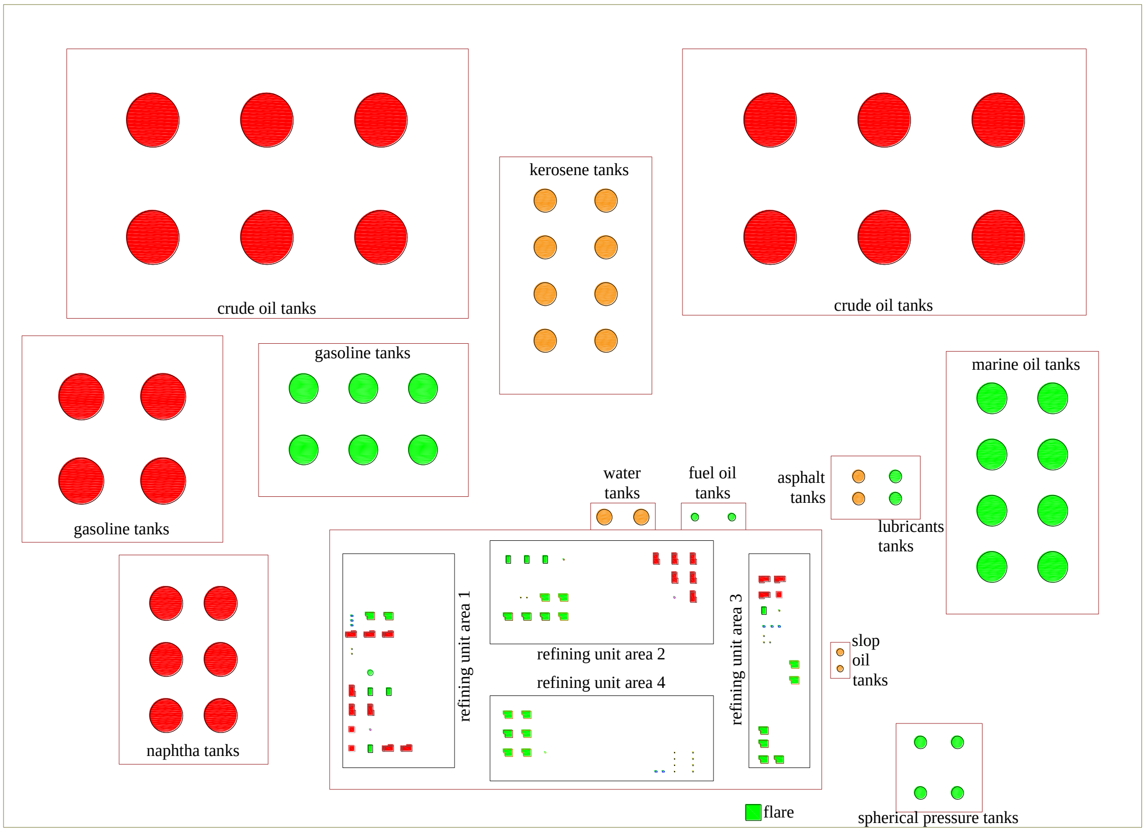


Figure 7. *Consequences of seismic scenario (1) on refinery*

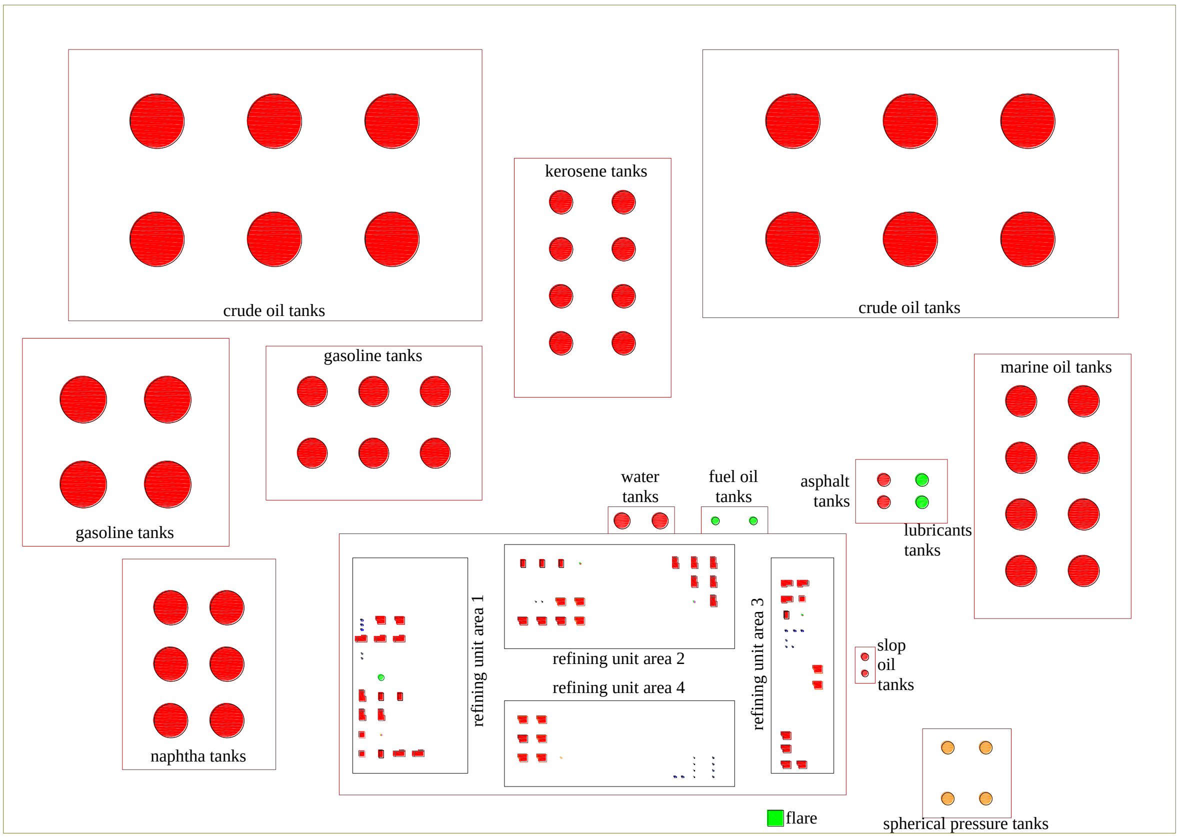


Figure 8. *Consequences of seismic scenario (2) on refinery*

CONCLUSIONS

Crude oil refineries are strategic infrastructure and safeguarding their structural and operational integrity in case of an earthquake event is crucial. A comprehensive framework for the risk assessment of refineries is required to achieve this goal reliably. A preliminary seismic risk assessment of an oil refinery has been presented in the present study. At first, the critical assets of the facility, namely liquid storage tanks, buildings with nested mechanical equipment, pressure vessels, process towers, chimneys, and the flare, were identified and the exposure model of a virtual but realistic refinery was developed. The seismic hazard for the site of interest was calculated using the 2013 European Seismic Hazard Model. Reduced-order numerical models for the assets were developed and the structures were analyzed via Incremental Dynamic Analysis. A set of global damage states was defined and the fragility curves of the assets were calculated. Finally, the seismic consequences for two seismic scenarios were evaluated and the assets more susceptible to damage were identified. These results are typically included in risk assessment studies and offer information to stakeholders and engineers for the design and planning of post-disaster emergency actions, but are not useful for the insurance.

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REFERENCES

Ancheta, T. D., Darragh, R. B., Stewart, J. P., Seyhan, E., Silva, W. J., Chiou, B. S. J., Wooddell, K. E., Graves, R. W., Kottke, A. R., Boore, D. M., Kishida, T., & Donahue, J. L. (2013). *PEER NGA-West2 Database, Technical Report PEER 2013/03*. https://apps.peer.berkeley.edu/publications/peer_reports/reports_2013/webPEER-2013-03-Ancheta.pdf

Ancheyta, J. (2011). *Modeling and simulation of catalytic reactors for petroleum refining*. Wiley & Sons, Inc.

Applied Technology Council. (1989). *ATC-20 Procedures for postearthquake safety evaluation of buildings*. www.ATCouncil.org

Bakalis, K., Fragiadakis, M., & Vamvatsikos, D. (2017). Surrogate modeling for the seismic performance assessment of liquid storage tanks. *Journal of Structural Engineering*, *143*(4), 1–13. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001667

Bakalis, K., & Vamvatsikos, D. (2018). Seismic fragility functions via nonlinear response history analysis. *Journal of Structural Engineering*, *144*(10), 1–15. https://doi.org/https://doi.org/10.1061/(ASCE)ST.1943-541X.0002141

Boore, D. M., & Atkinson, G. M. (2008). Ground-Motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra*, *24*(1), 99–138. https://doi.org/https://doi.org/10.1193/1.2830434

Camila, S.-P. M., Perreur, M., Munoz, F., & Cruz, A. M. (2019). Systematic literature review and qualitative meta-analysis of Natech research in the past four decades. *Safety Science*, *116*(2019), 58–77. https://doi.org/https://doi.org/10.1016/j.ssci.2019.02.033

Cornell, C. A., & Krawinkler, H. (2000). Progress and challenges in seismic performance assessment. *PEER Center News*, *3*(2), 1–4. https://apps.peer.berkeley.edu/news/2000spring/index.html

Cruz, A. M., & Steinberg, L. J. (2005). Industry preparedness for earthquakes and earthquake-triggered hazmat accidents in the 1999 Kocaeli earthquake. *Earthquake Spectra*, *21*(2), 285–303. https://doi.org/https://doi.org/10.1193/1.1889442

Giannaraki, G., Kazantzidou-Firtinidou, D., Kassaras, I., Roumelioti, Z., Ganas, A., Karakostas, C. Z., Mourloukos, S., Stoumpos, P., & Tsimi, C. (2018). Scenario-based seismic risk assessment in the city of Aigion (Greece). *16th European Conference on Earthquake Engineering*. http://papers.16ecee.org/files/16ecees Aigion Giannaraki final.pdf

Girgin, S., Necci, A., & Krausmann, E. (2019). Dealing with cascading multi-hazard risks in national risk assessment: The case of Natech accidents. *International Journal of Disaster Risk Reduction*, *35*(2019), 101072. https://doi.org/https://doi.org/10.1016/j.ijdrr.2019.101072

Hatayama, K. (2008). Lessons from the 2003 Tokachi-Oki, Japan, earthquake for prediction of long-period strong ground motions and sloshing damage to oil storage tanks. *Journal of Seismology*, *12*(2), 255–263. https://doi.org/https://doi.org/10.1007/s10950-007-9066-y

Hatayama, K. (2015). Damage to oil storage tanks from the 2011 Mw 9.0 Tohoku-Oki tsunami. *Earthquake Spectra*, *31*(2), 1103–1124. https://doi.org/https://doi.org/10.1193/050713EQS120M

Kazantzi, A. K., Righiniotis, T. D., & Chryssanthopoulos, M. K. (2011). A simplified fragility methodology for regular steel MRFs. *Journal of Earthquake Engineering*, *15*(3), 390–403. https://doi.org/https://doi.org/10.1080/13632469.2010.498559

Kohrangi, M., Bazzurro, P., Vamvatsikos, D., & Spillatura, A. (2017). Conditional spectrum-based ground motion record selection using average spectral acceleration. *Earthquake Engineering & Structural Dynamics*, *46*(10), 1667–1685. https://doi.org/https://doi.org/10.1002/eqe.2876

Krausmann, E., Cozzani, V., Salzano, E., & Renni, E. (2011). Industrial accidents triggered by natural hazards: An emerging risk issue. *Natural Hazards and Earth System Science*, *11*(3), 921–929. https://doi.org/https://doi.org/10.5194/nhess-11-921-2011

Kwon, O. S., & Elnashai, A. (2006). The effect of material and ground motion uncertainty on the seismic vulnerability curves of RC structure. *Engineering Structures*, *28*(2), 289–303. https://doi.org/https://doi.org/10.1016/j.engstruct.2005.07.010

McKenna, F., & Fenves, G. L. (2000). *Open System for Earthquake Engineering Simulation*.

Önder, E., Tural, Ü., Aker, T., Kılıç, C., & Erdoğan, S. (2006). Prevalence of psychiatric disorders three years after the 1999 earthquake in Turkey: Marmara Earthquake Survey (MES). *Social Psychiatry and Psychiatric Epidemiology*, *41*(11), 868–874. https://doi.org/https://doi.org/10.1007/s00127-006-0107-6

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M., & Vigano, D. (2014). Openquake engine: An open hazard (and risk) software for the global earthquake model. *Seismological Research Letters*, *85*(3), 692–702. https://doi.org/https://doi.org/10.1785/0220130087

Sezen, H., & Whittaker, A. S. (2006). Seismic performance of industrial facilities affected by the 1999 Turkey earthquake. *Journal of Performance of Constructed Facilities*, *20*(1), 28–36. https://doi.org/https://doi.org/10.1061/(ASCE)0887-3828(2006)20:1(28)

Sullivan, D., Metro, S., & Pujadó, P. R. (2015). Handbook of Petroleum Processing. In S. A. Treese, P. R. Pujadó, & D. S. J. Jones (Eds.), *Handbook of Petroleum Processing*. Springer International Publishing. https://doi.org/https://doi.org/10.1007/978-3-319-14529-7

The PEC project consortium. (2016). *Deliverable D.B.1 - Definition of the structural models and seismic fragility analysis techniques available for the specific case study*. http://www.pec-echo.eu/wp-content/uploads/2017/02/D.B.1_Fragility-curves-for-seismic-risk-.pdf

Theocharidou, M., & Giannopoulos, G. (2015). *Risk assessment methodologies for critical infrastructure protection . Part II : A new approach*. Publications of the European Union. https://doi.org/https://doi.org/10.2788/621843

United Nations. (2015). *Sendai Framework for Disaster Risk Reduction 2015 - 2030*. www.unisdr.org

Vamvatsikos, D., & Cornell, C. A. (2002). Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, *31*(3), 491–514. https://doi.org/https://doi.org/10.1002/eqe.141

Woessner, J., Laurentiu, D., Giardini, D., Crowley, H., Cotton, F., Grünthal, G., Valensise, G., Arvidsson, R., Basili, R., Demircioglu, M. B., Hiemer, S., Meletti, C., Musson, R. W., Rovida, A. N., Sesetyan, K., & Stucchi, M. (2015). The 2013 European Seismic Hazard Model: key components and results. *Bulletin of Earthquake Engineering*, *13*(12), 3553–3596. https://doi.org/https://doi.org/10.1007/s10518-015-9795-1