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TOWARDS SEISMIC RESILIENCE OF INDUSTRIAL FACILITIES: THE CASE STUDY OF AN OIL REFINERY

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Abstract: *Crude oil refineries are high-importance infrastructure that play a key role in the energy supply chain. Securing the operational and structural integrity of refineries in the aftermath of an earthquake is crucial for avoiding the undesirable consequences of a Natural-Technological (NaTech) incident, such as injuries, environmental pollution, business interruption, and monetary losses. Refineries are designed, constructed, maintained, and operated under a strict framework of standards and regulations. Still, seismic-related NaTech incidents are occurring. Thus, to assess with more confidence and consequently improve, if needed, their seismic resilience, a coherent performance-based framework needs to be utilised, that accounts for the refinery as an integrated system comprising a variety of structural typologies, such as buildings, tanks, and high-rise stacks. These structures have very diverse dynamic properties and hence seismic responses. Towards this objective, a virtual crude oil refinery is examined herein as a case study. The aim is to showcase the steps of a seismic risk assessment framework when applied to such infrastructures, focusing on the evaluation of the seismic hazard, the development of the exposure model, the numerical analysis of the structures, and the preliminary damage assessment of the facility using different earthquake scenarios.*

Introduction

Crude oil refineries are among the most important energy infrastructure since they are located in the core of the energy supply chain. Crude oil extracted at oil rigs, is transported to refineries (upstream part), then processed to produce liquid and gaseous fuels (midstream part), which are then delivered to costumers (downstream part). The large amount of oil and oil products being circulated in a refinery, which are flammable, hazardous, and potentially explosive materials, dictates the need to secure the operational and structural integrity of the facility in the aftermath of an earthquake event. In fact, a potential failure may result in undesirable events, spanning from business disruption to uncontrolled leakage and/ or major fire incidents, as well as injuries and event casualties (Cruz and Steinberg 2005). The devastating consequences of such seismic-triggered NaTech events have been reported, among others, in the aftermath of the 1999 Izmit earthquake in Turkey, the 2003 Tokachi-Oki and the 2011 Tohoku earthquakes in Japan.

The standard practice is the refinery operators to work closely with regulatory authorities to improve the existing as well as to develop more reliable frameworks for the seismic risk assessment of refineries in order to cope with the consequences of earthquakes and ensure continuous operation in case of a NaTech event (Camila et al. 2019). Still, most existing frameworks are qualitative tools based on risk analysis (Girgin et al. 2019), risk evaluation (Theocharidou and Giannopoulos, 2015), and risk rating (Krausmann et al. 2011). These tools are in fact very useful for the development of preliminary mitigation strategies, as well as for developing emergency response plans and mitigation actions on account of predefined scenarios. Yet, they cannot offer a reliable computation of the actual expected seismic loss and consequently contribute to the improvement of the seismic resilience of the facility. It is, thus, necessary to develop a comprehensive framework for the seismic risk assessment of such facilities by considering the aleatory and epistemic uncertainties stemming from the seismic hazard, the

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structures' modelling approaches, the structures' seismic performance, etc. via exploiting the Performance-Based Earthquake Engineering framework (Cornell and Krawinkler 2000).

The preliminary framework for the seismic risk assessment of a crude oil refinery that is developed in this study, consists of (1) the seismic hazard calculation, (2) the development of the exposure model, (3) the analysis of the structures via simplified and surrogate numerical models, and (4) the damage assessment. A virtual typical mid-size refinery located in a highly seismic active area in Greece is considered as a case study, in order to showcase the process and present scenario-based results, as a first step towards identifying the most critical assets at risk.

Seismic hazard

The case-study refinery is located within a major industrial area in the west of Athens, Greece. The open-source platform OpenQuake (Pagani et al. 2014), developed by the Global Earthquake Model Foundation, was employed to compute the seismic hazard for the area of interest. The seismic hazard calculations were based on the results of the Eu-funded SHARE Project (Woessner et al. 2015) area source model and the Ground Motion Prediction Equation of Boore and Atkinson (2008).

The geometry and dynamic properties of the structures encountered in an oil refinery are essentially very different. A variety of Engineering Demand Parameters (EDPs) is therefore required to assess the structural performance of such assets. 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 ($AvgS_a$), that is in fact an asset-aware IM, is selected herein as the appropriate IM considering for its evaluation a range of periods that span between 0.1sec to 1.0sec. The seismic hazard curve for the site of interest is presented in Figure 1. Additionally, the typical asset-agnostic PGA is also adopted as an IM.

A set of 30 hazard-consistent natural ground motion records was selected for undertaking the time-history analyses of the assets. The non-pulse-like and non-long-duration records were selected from the NGA-West2 database (Ancheta et al. 2013) using the Conditional Spectrum-base method of Kohrangi et al. (2017). More details on the selected ground motion records are presented by Bakalis et al. (2018) and Karaferis et al. (2022).

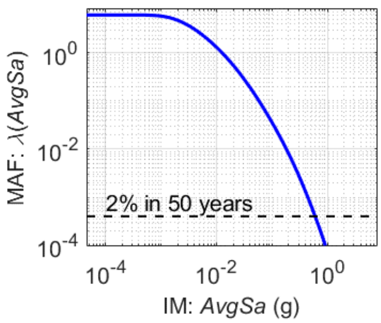

Figure 1. Seismic hazard curve for the case-study refinery site.

Exposure model

The examined facility is a typical mid-size crude oil refinery in terms of functionality, covering an area of 1850m x 1250m. The plan view of the refinery is shown in Figure 2. The identified critical assets at risk are (1) the atmospheric liquid storage tanks (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 main refinery flare, and (5) the refining areas, where process towers, chimneys, and equipment-supporting building-type structures are located.

Crude oil is imported in the refinery via pipelines from marine or land terminals and stored in crude oil tanks. Then, it is transported to the refining areas for processing. Intermediate and final products (liquid and gaseous fuels) are stored in tanks. Fuels and gases are circulated within the refinery via a dense piping network, consisting of buried, on-ground, and rack-supported pipes. An overview of the entire refining process can be found in Ancheyta (2011).

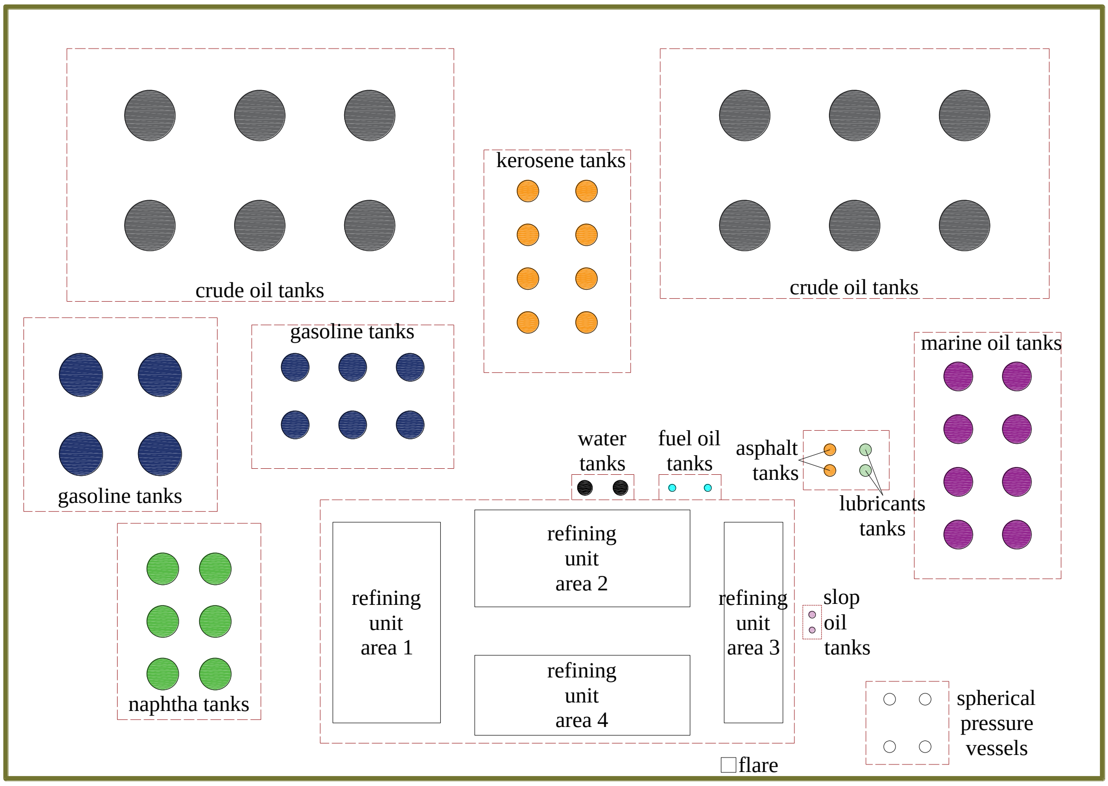

Figure 2. Exposure model: Plan view of the case-study crude oil refinery.

Fragility analysis

A comprehensive description of the considered structures and the corresponding numerical models is offered in Table 1.

Structure	Description	Model	Reference
Liquid storage tanks	Anchored and unanchored tanks with diameter raging from 11.6m to 85.4m	Surrogate model	Bakalis et al. (2017)
Steel buildings	1 and 2 story steel open-frame buildings with rectangular plan	Elastic nonlinear models with diaphragms modelling slabs	Kazantzi et al. (2022)
RC buildings	1, 2, and 4 story RC open-frame buildings with rectangular plan	Elastic nonlinear models with diaphragms modelling slabs	Kazantzi et al. (2022)
Process towers	Pressurized steel tower with height 33m	Multi degree-of-freedom nonlinear model with elastic beam-column elements	Karaferis et al. (2022)
RC chimney	Reinforced Concrete chimney with height 87m	Multi degree-of-freedom nonlinear model with fibre elements	Karaferis et al. (2022)
Steel chimney	Steel chimneys with height 30m and 80m	Multi degree-of-freedom nonlinear model with elastic beam-column elements	Karaferis et al. (2022)
Flare	Steel lattice tower with height 68m and rectangular plan	Nonlinear 3D model with elastic beam-column elements	Karaferis et al. (2022)
Spherical pressure vessels	Spherical pressure vessels (tanks) with diameter 20.22m, supported by braced legs	Spherical shell represented by a concentrated mass, legs modelled with elastoplastic beam-column elements, and braces modelled with tension-only elements	

Table 1. Refinery structures analysed: Brief description and numerical models.

The numerical models were developed using the open-source software OpenSees (McKenna and Fenves 2000). The seismic demand of the refinery structures was evaluated by means of Incremental Dynamic Analysis (Vamvatsikos and Cornell 2002) for the selected set of 30 records. Both aleatory and epistemic uncertainties were considered. The former stem from the record-to-record variability, while the latter from the analysis assumptions.

Fragility curves are employed to quantify the structure's susceptibility to damage. The fragility for the considered structures is computed as:

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

where $F_{LS}(IM)$ is the fragility at a given IM level, $P[\cdot]$ is the probability of its arguments, D is the structural demand, and C is the capacity.

The structure-specific damages states (DSs) are homogenized in order to formulate a set of global DS for the refinery system as per ATC-20 (1989), namely DS0: No damage, DS1: Low damage, DS2: Medium damage, DS3: Extensive damage, and DS4: Near collapse. The failure modes of each refinery structure with reference to the global DSs are presented in Table 2.

Structure	**DS0**	**DS1**	**DS2**	**DS3**	**DS4**
Liquid storage tanks	–	Sloshing	Sloshing, base plate rotation	Elephants' foot buckling, base plate rotation	
Steel/RC buildings	–	Structural elements: low intestory drift	Structural elements: medium intestory drift	Structural elements: high intestory drift	
		Components: failure of low importance	Components: failure of medium importance	Components: failure of high importance	
Process towers	–	Top displacement			Shell local buckling
RC chimney	–	Top displacement	Cross-section yielding		Cross-section failure
Steel chimney	–	Top displacement	Interstory drift		Shell local buckling
Flare	–	Top displacement	Interstory drift		Buckling of structural members
Spherical pressure vessels	–	First yielding of braces	Most braces have yielded	Brace fracture	

Table 2. Refinery structures analysed: Brief description and numerical models.

The computed fragility curves of two liquid storage tanks are shown in Figure 3, while the corresponding ones for two typical steel high-rise stacks, namely a 30m high chimney and a process tower are presented in Figure 4.

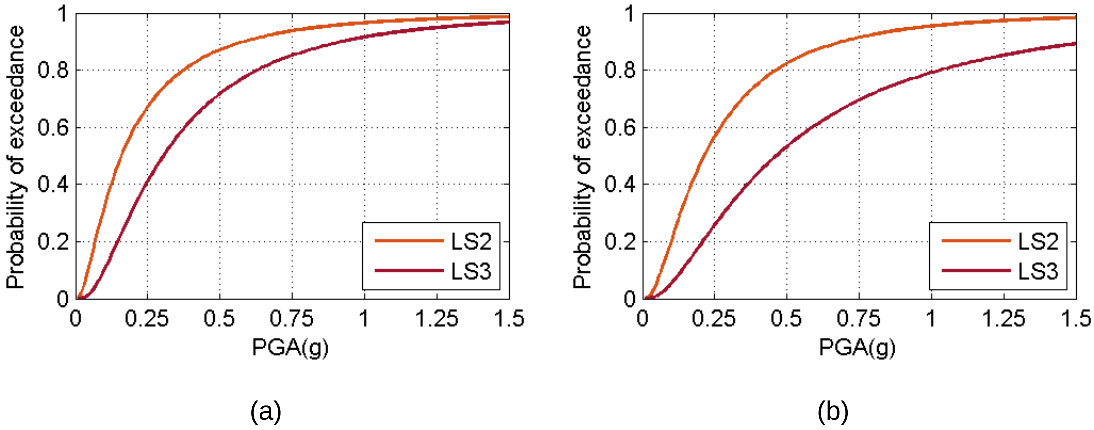

Figure 3. Fragility curves: (a) crude oil tank and (b) gasoline tank [LS2: sloshing base plate rotation, LS3: elephants' foot buckling, base plate rotation].

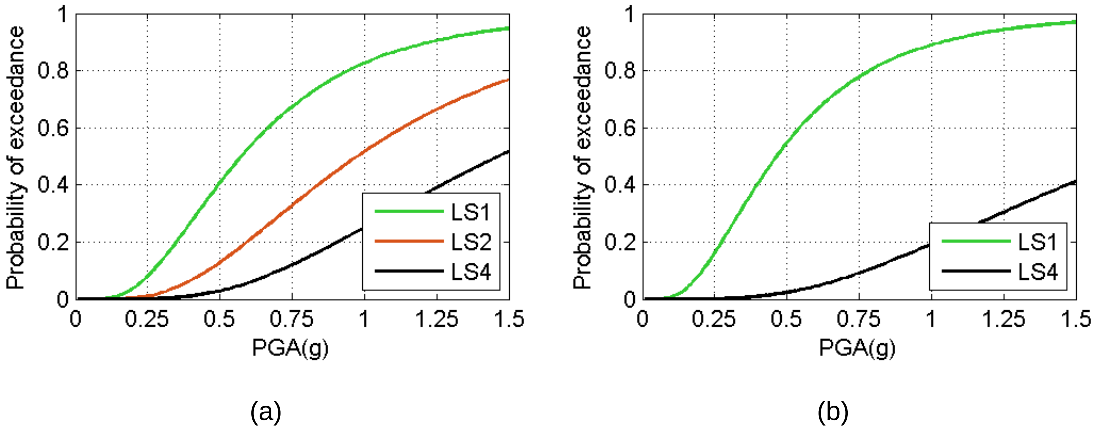

Figure 4. Fragility curves: (a) 30m high steel chimney and (b) a process tower [LS1: top displacement, LS2: Interstory drift, LS4: shell local buckling].

Preliminary results

Stakeholders and policy makers are typically more familiar with scenario-based results, compared to time-based ones, because the former provide a "straightforward" answer on the expected structural damages given that a specific earthquake scenario has occurred. These results are usually included in risk assessment studies and are used for post-disaster emergency planning and risk mitigation strategies designing, using the colour tagging of ATC-20: DS0 "green", DS1 "yellow", DS2 "orange", DS3 "red", and DS4 "black". In such results, apparently, the likelihood of the earthquake scenario in a given time period and consequently the distribution of the most probable damage throughout the facility is not provided.

Two earthquake scenarios are considered in this study: (1) a M6.4 earthquake event at the Loutraki fault, located 46km southwest of the considered refinery and (2) a M6.0 earthquake event at the Ag. Theodoroi fault, located 32km west of the refinery. The accelerograms at the refinery site 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 modelled 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 neighbouring sub-faults, leading to the rupture of the entire fault surface. The path effects are represented by empirical attenuation relationships. The maximum acceleration at the refinery site resulting from the event at the Loutraki fault is 0.37g, while from the event at the Ag. Theodoroi fault is 0.621g. The consequences are depicted in Figure 5 for the scenario (1) and in Figure 6 for the scenario (2). In both cases, it is identified that the liquid storage tanks and the building in the refining unit areas are the most vulnerable assets.

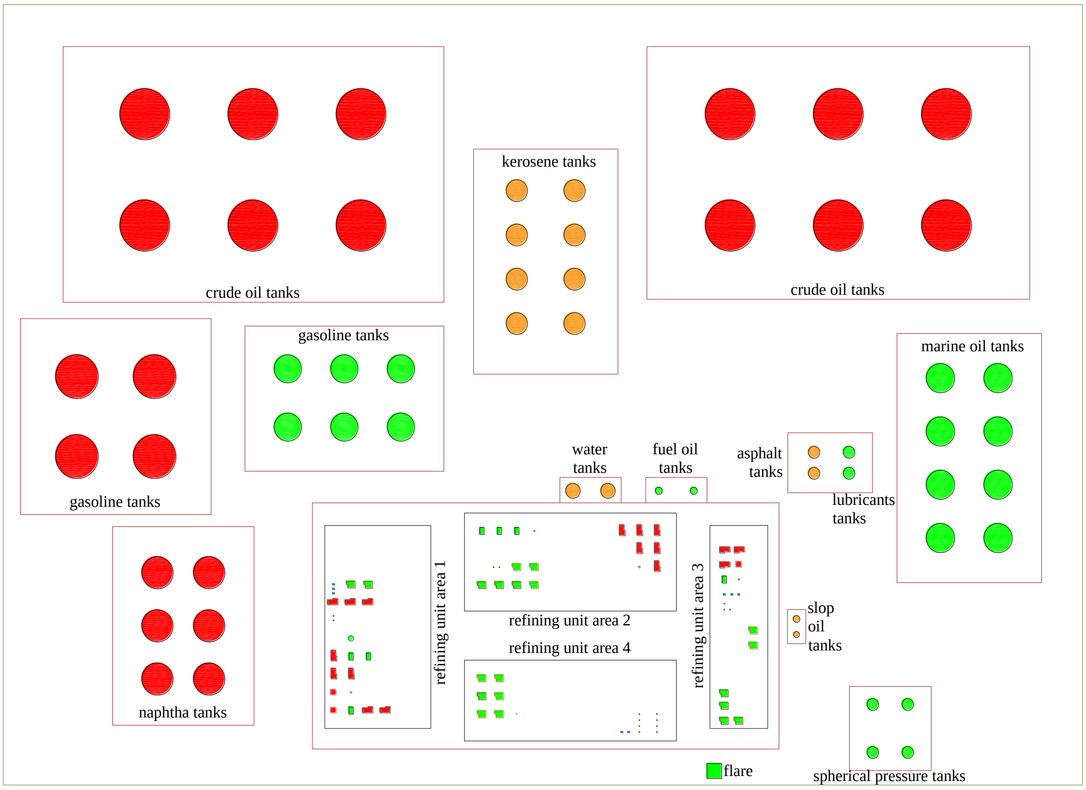

Figure 5. M6.4 earthquake event at the Loutraki fault [scenario (1)]: Consequences in terms of most probable DS.

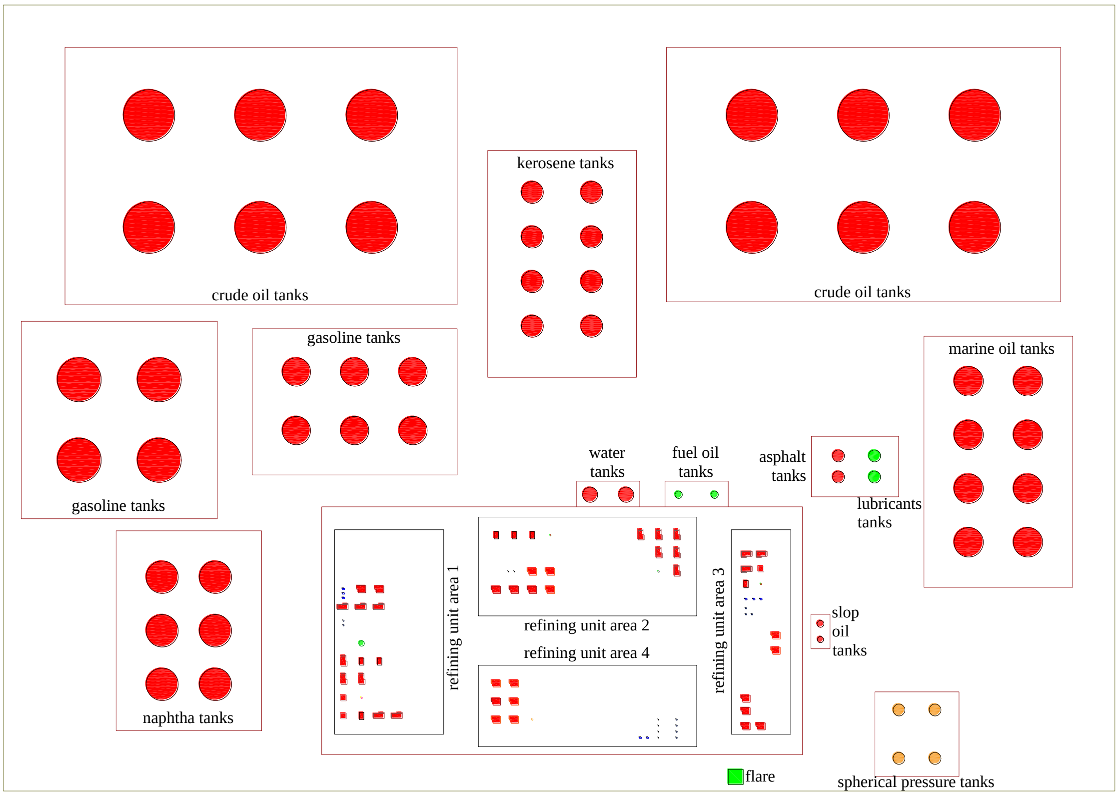

Figure 6. M6.0 earthquake event at the Ag. Theodoroi fault [scenario (2)]: Consequences in terms of most probable DS.

Conclusions

The structural integrity and operational safety of crude oil refineries are critical, especially in the event of an earthquake. To reliably achieve this dual objective, a comprehensive framework for assessing the seismic risk of refineries is necessary. This study presents a preliminary seismic risk assessment of a virtual mid-size oil refinery, which is examined as a case study. Initially, the critical assets of the facility, namely liquid storage tanks, equipment-supporting building-type structures, spherical pressure vessels, process towers, chimneys, and the flare, were identified to formulate the exposure model. The seismic hazard at the site of interest was calculated using the 2013 European Seismic Hazard Model. Reduced-order numerical models for the assets were developed, and Incremental Dynamic Analysis was used to analyse the structures and compute their seismic demands. The fragility curves of the assets were calculated by defining a set of global damage states. Finally, the seismic consequences for two seismic scenarios were evaluated, demonstrating that liquid storage tanks and equipment-supporting building-type structures as the most vulnerable assets. While these results are typically used in risk assessment studies to provide information to stakeholders and engineers for post-disaster emergency planning and design, they may not be applicable for insurance purposes.

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