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Probabilistic risk assessment of oil and gas infrastructures for seismic extreme events

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Abstract

Modern economy and society are constantly highly dependent on a variety of critical infrastructures (CIs) over the last decades. However an observation and review of the extreme events that occurred during the last two decades reveal that while the interdependencies between the CIs are growing and getting more complex there is an increasing gap between the growing risk and the actual preparedness. Therefore, there is an utmost importance to ensure reliable and robust performance of critical infrastructures on a continuous basis, particularly during and after the occurrence of extreme events. A decision support tool for decision makers to appraise and mitigate the risk of CIs after the occurrence of seismic events is developed. The methodology analyzes the damage of critical infrastructure components by Fault-Tree-Analysis, Decision Trees and Fragility Curves. Though the methodology is suitable for a variety of critical infrastructures, this study will focus on critical Oil and Gas Network Systems, which are vital to the energy supply infrastructure of Israel. In order to assess the risk that Oil and Gas Critical Infrastructures are exposed to in case of seismic extreme events, fragility curves are derived and adjusted to different components of the Oil and Natural Gas systems. Subsequently, a variety of possible seismic scenarios are examined and analyzed in order to determine the damage of the components. The overall expected damage of the Oil or Gas system is assessed by considering the damage state of all components of the system. The expected damage states of the components disclose and emphasize the most vulnerable parts of the system. Also discussed are guiding principles for decision makers for risk informed mitigation on benefit-cost-ratio analysis.

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Keywords: critical infrastructures; fragility curves; risk assessment; seismic events

1. Introduction

Critical Infrastructures (CIs) play a crucial role in the normal performance of the economy and society. Over the last decades the amount and the variety of critical infrastructures grew rapidly, and the interdependency between them increased constantly; consequently more and more essential services depend on the continuous performance of one, two or even more critical infrastructures such as power and water supply, communications, etc. An observation

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and review of the extreme events occurred during the past two decades reveal that while the interdependencies between the CIs are growing rapidly and getting more complex there is a large gap between the increasing risk and the actual preparedness of critical infrastructures to extreme events [1-3]. After the Izmit earthquake in 1999, the electricity power supply failed for several days within minutes of the earthquake, few highway bridges collapsed, and water distribution system was interrupted. A fire that broke out at refineries of Turpas, which were responsible for the refining of major part of Turkey's oil, endangered industrial sites in the area for days until it was turned off [4-7]. The Indian Ocean earthquake and tsunami at 2004 and the Haiti earthquake in 2010 demolished most of the CIs in those areas, beyond the high death toll. CIs such as educational facilities, medical centers, government facilities, and water distribution system were completely destroyed and arduous the rescue and rehabilitation efforts [8-11]. The Fukushima- Daiichi event exhibited insufficient preparedness of the Nuclear Power Plant (NPP) in aspects such as robustness (height of breakwater walls), resilience, and redundancy (power supply) [12-15] and demonstrated the failure in the hazardous scenarios detection.

The review of extreme events over the last two decades shows that loss and damage of CIs that developed countries suffer from, is significantly higher than the damage developing countries witness. This trend is stimulated by the density of critical infrastructures and the growing consequences of events due to higher risks. Therefore, there is an utmost importance to ensure reliable and robust performance of critical infrastructures on a continuous basis, particularly during and after the occurrence of extreme events.

2. Methodology and Objectives

This manuscript presents a preliminary probabilistic methodology that examines the preparedness of critical infrastructures through an appraisal of the risk CIs are exposed to in case of seismic extreme event. The goal of this research is to establish a quantified model to assess the total risk of CIs to extreme earthquake events and allow the decision makers to manage the course of actions in order to mitigate the risk. The methodology will include risk assessment of CIs components and guiding principles to mitigate the risk using benefit-cost-ratio analysis. The methodology analyzes the damage of infrastructures components by fragility curves, fault-tree-analysis, and decision trees. Though the methodology is suitable for a variety of critical infrastructures, this research will focus on critical Oil and Gas Network Systems, which are vital to the energy supply infrastructure.

The proposed methodology is composed of seismic hazard identification, components seismic vulnerability function adjustment, damage assessment due to seismic extreme events of different components, and a risk appraisal procedure.

3. Seismic Scenarios

The first step of the risk appraisal process is the definition of the threat scenarios (Hazardous scenarios) that Critical Infrastructures (CIs) components are exposed to. The main effects of an earthquake are ground shaking and faulting which are the major causes of failure of gas and oil infrastructure during an earthquake event [16, 17]. When computing the risk of critical infrastructures, there is an upmost importance of the ground shaking intensity and site effects across different areas, as opposed to standard structures in which resilience will be determined according to its local ground shaking and site effect. Critical infrastructure components such as oil and natural gas systems deployed on a wide range area and distances of hundreds of kilometers from each other. Therefore the resistance of critical infrastructures systems to seismic events will be determined in accordance with the site effects and ground shaking measures of each component at different locations which are obtained by different soil conditions that affect on site response and at different distances from the epicenter.

A main issue related to the seismic risk analysis of CIs components is the selection of the earthquake intensity measure (IM) which correlates the best with the response of each component. In most cases for aboveground structures, the PGA is directly correlated to the expected damage, because of its proportionality with inertial effects due to the seismic loadings. On the other hand, when in case of pipelines or underground structures, the damage effects are generally proportional to the Peak Ground Velocity (PGV) which is related to ground strain that is the main cause of pipeline damage [18-22]. The most commonly used intensity measures for Oil and Gas systems are; Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak/Permanent Ground Displacement (PGD), and Peak ground strain [22, 23].

4. Oil and natural gas systems

In general Oil and Gas transportation and distribution system components can be divided into three main groups[24]: the first group consists of pipelines elements (buried or above ground), the second group consists of storage structures (Tank Farms) and the third group consists of processing/operational facilities (i.e. Pressure control, pumping).

4.1. Pipelines

Pipelines are categorized as transportation/transmission network that are generally used to transfer from the production site to the industrial plants or urban distribution system or to distribution network for urban users. However, for the research approach the difference between transportation and distribution systems is essentially related to the nominal diameter of pipelines. According to the HAZUS methodology [25] pipelines can be categorized according to their diameter (D) into (a) $D \geq 400$mm for high pressure transmission system and (b) $D \leq 400$mm for distribution and low pressure transmission systems. Damage patterns in pipelines are largely dependent on the material and joint type and many possible combinations of material and joints were divided by in two categories [18, 26]; continuous pipelines (CP) and segmented pipelines (SP). A similar approach has been proposed by [25], where the pipelines are categorized into brittle (SP) and ductile (CP).

4.2. Storage facilities

Modern oil storage tanks included in lifeline systems vary from 12m to 76m in diameter with heights that are nearly always less than the diameter. Storage tanks are designed as elevated, partly buried or underground and mostly are circular cylindrical. [17, 27]. The most common classification of storage tanks is based on the following features [27-29]:

- Material: steel or reinforced concrete
- Construction type: underground, at grade or elevated
- Anchored or unanchored subcomponents
- Roof type: fixed-roof, floating roof
- Shape factor: height-on-diameter ratio (H/D)
- Amount of content in the tank: full, half-full, empty

Finally, it should be noted that tanks are just part of the storage facilities, and that most of those facilities are composed of several storage tanks which includes also components such as inlet/outlet pipelines or mechanical equipment.

4.3. Processing plants/stations

Processing stations such as compression, metering or pressure reduction and pumping plants are located along the pipelines to maintain the flow over long distances. Most of these plant/stations are housed in low-rise buildings and often classified as anchored or unanchored subcomponents [25] or within low-rise buildings, made of masonry or reinforced concrete structure [24].

5. Damage assessment

Several uncertainties regarding to earthquake events are still exist; the exact location and timing of the upcoming earthquake isn't known, as well as the full scope and the magnitude of the event. Therefore, in this research, a probabilistic approach is put forward and probabilistic technics are implemented. This methodology is intended to assess the expected damage of different components of the gas and oil system with multiple Fragility Curves/Functions and by Fault-Tree-Analysis for complex systems.

5.1. Fragility Curves

In our methodology fragility functions represent the probability that a component will be damaged or disrupted to a given or worse damage state as a function of an intensity parameter. Fragility functions for Oil and Gas system components other than pipelines are modeled as a lognormal cumulative distribution function (CDF) that expresses the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA, PGV, and PGD) [30-32] as presented in Eq. 1.

$$[DS \geq ds|IM = x] = \Phi\left(\frac{ln(x/\theta_{ds})}{\beta_{ds}}\right) \quad ; ds \in \{1,2, \dots N_D\} \tag{1}$$

$P[DS \geq ds|IM = x]$ Represents a conditional probability of being at or exceeding a particular Damage State (DS) for a given seismic intensity x defined by the earthquake Intensity Measure. Where,

DS	Uncertain damage state of a particular component. {0,1,... Nn};
ds	A particular value of DS;
N_D	Number of possible damage states;
IM	Uncertain excitation, the ground motion intensity measure (i.e. PGA, PGD, or PGV);
x	A particular value of IM;
Φ	Standard cumulative normal distribution function.;
θ_d	Median capacity of the asset to resist damage state ds measured in terms of IM;
β_d	Logarithmic standard deviation of the uncertain capacity of the asset to resist damage state ds.

In sequential damage states, the damage states are ordered in ascending order and the probability of being in the specified damage state is calculated as follows:

$$(DS = ds_i|IM) = \begin{cases} 1 - P(DS \geq ds_i|IM) & i = 0 \\ P(DS \geq ds_i|IM) - P(DS \geq ds_{i+1}|IM) & 1 \leq i \leq n-1 \\ P(DS \geq ds_i|IM) & i = n \end{cases} \tag{2}$$

Another way to present the damage function, that is important to notice, is by Damage Probability Matrices (DPM). The DPM presents the probability of a level of damage being reached at a specific intensity measure level for a given component [23].

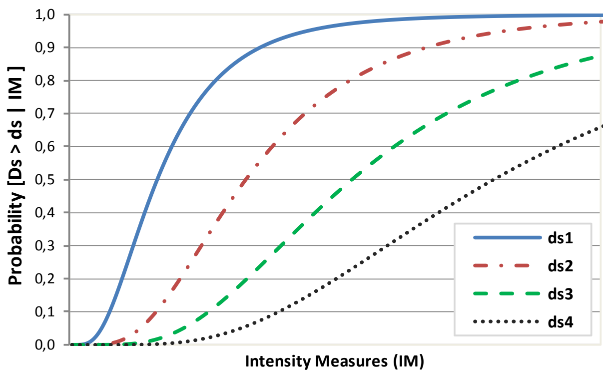

Figure 1 - Fragility curve

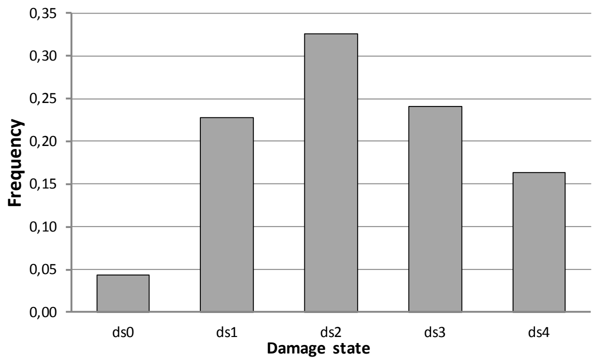

Figure 2 - Illustration of PDM

For pipelines components the fragility functions are described as the expected Repair Rates (RR) due to ground motion (quantified in terms of PGV) or ground failure (quantified in terms of PGD). The RR function represents the expected number of repairs needed per a determined length of pipe, it is usually defined as a power function as described in Eq. 3 below, where *b* and *c* represent coefficients set using the standard linear least squares method.

$$RR = b \cdot IM^c \qquad (3)$$

In general, four types of fragility curves are proposed [30, 31, 33]: Empirical, Analytical, Expert judgment, and Hybrid. The empirical method is based on recorded data of past earthquakes and an observation of actual damage on exposed components, the analytical method is based on structural simulation and examination of the component's response to different seismic ground motion, the Expert judgment method is based on the experts opinion that estimated the damage probabilities for different levels of seismic loading, and the Hybrid method combines the above-mentioned techniques in order to compensate for their respective drawbacks. The process and the approach of the fragility curves development is based mainly on the type, the quantity, and quality of the available data. It should be noted, that fragility functions can be derived with high reliability when there is a large quantity of appropriate test data available on the behavior of the component of interest at varying levels of intensity.

5.2. Fault Tree Analysis

In case of complex systems, such as pumping station and tank farm, several components of the system are essential for proper functionality. Thus, a failure of one component can lead to a total failure of the entire system. Thus, each component in these systems affects directly the overall performance of the entire system. For these complex components, Fault-Tree-Analysis (FTA) is a more suitable tool to estimate the expected damage as a result of the seismic event. The FTA presents the functional interrelationships between the sub-components of the system, and describes the contribution of the sub-component to top components by "AND", "OR", and other gates

For example, a pumping station is composed of four main sub-components: electrical and mechanical equipment, pump, power supply, and the structure of the station. In the case that one of those components is damaged, the functionality of the station will be disrupted. The FTA enables to derive the vulnerability of the system from the fragility curve of each component (Gehl et al. 2014; NIBS 2004). Figure 3 below shows a scheme of possible fault tree of a basic pump station.

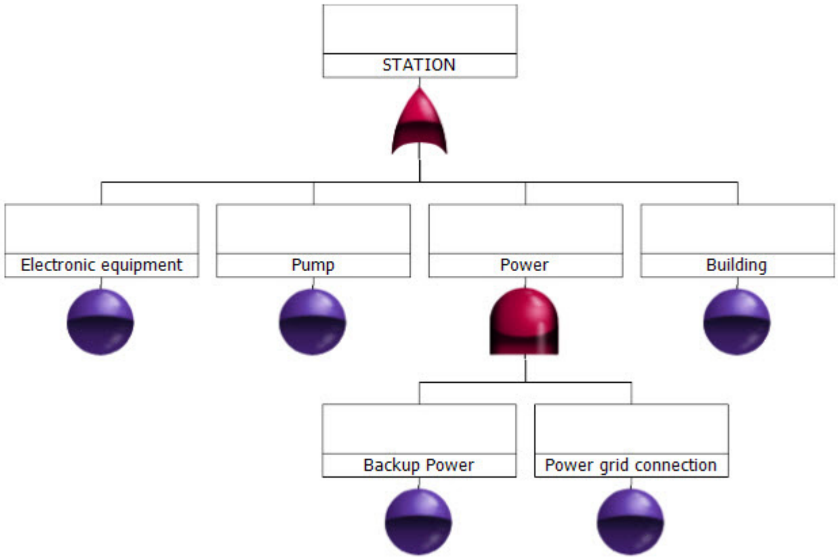

Figure 3 - Example of possible fault tree analysis for Pumping station

6. Damage and risk assessment

In this framework, the damage is calculated in terms of the expected cost as a result of the seismic event. Therefore, the direct economic losses are computed based on three main values:

- The probability that the component exceeded a certain damage state i, defined as P [Ds ≥ ds_i].
- The replacement value of the component which represent the 100% replacement cost of the component, defined as RV.
- The damage ratios for each damage state that represent the percentage of the total RV of the component, defined as DR_i when $0<DR_i<1$.

After the definition of those values, the direct losses of certain damage state are evaluated by multiplying the damage ratio (DR_i) by the replacement value of the component (RV). Additionally, the compounded damage ratio (DR_c), that expresses all defined damage states, is computed as the probabilistic combination of the damage ratios and the probabilities of exceedance for a given IM, as follows [25].

$$DR_c = \sum_{ds} DR_i * P(ds_i|IM) \tag{4}$$

Where,

DR_i	Damage rate of damage state i
$P(ds_i\|IM)$	The probability of being in damage state i given a seismic event at Intensity Measure IM

The total damage of seismic scenario can be calculated with reference to expected indirect losses that iare composed of potential loss due to the shutdown of the service. Furthermore, the total consequences will consider possible environmental impacts and the expected results of them. The risk of seismic event is the product of the occurrence probability and the estimated consequences; therefore the occurrence probability must be defined. In this research, the occurrence probability of different earthquakes intensity, is defined as the annual rate of exceeding function for different potential IMs.

According to the fragility functions (Figure 4) that were developed for CIs components, the damage ratio of components (DR_c), and the repair cost (RC) of the system, one can calculate the repair cost as a function of the intensity measure (Figure 5). Subsequently, combined with the annual rate of exceedance function (Figure 6), the development of the annual risk function can be acquired. The total annual risk of the scenario can be computed as the product of the total damage and the annual probability of the seismic event. One can see that by using the described methodology, it is feasible to calculate the total annual seismic risk that critical infrastructures are exposed to, and integration of this function gives the annual risk expectancy (Figure 7).

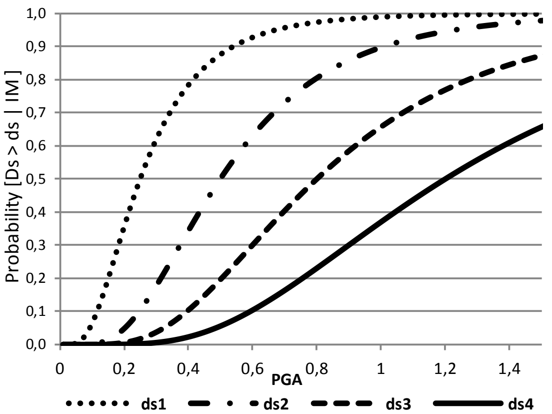

Figure 4 - Fragility Curves

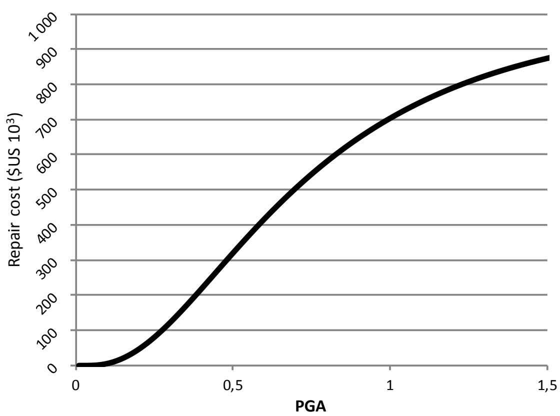

Figure 5 - Repair cost as a function of PGA

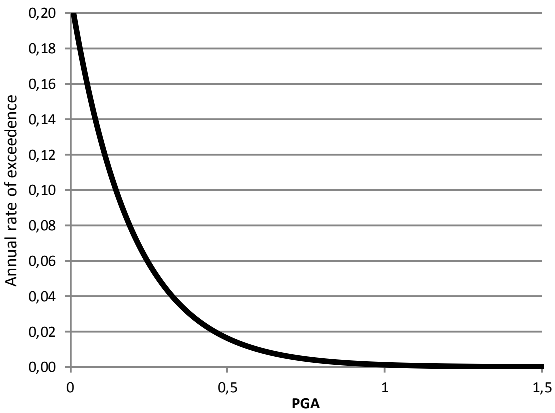

Figure 6 - Annual rate of exceedance function

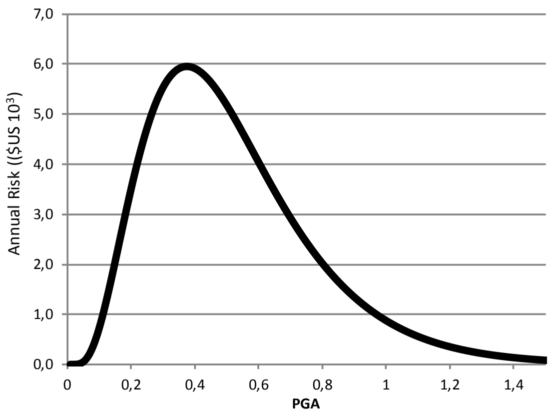

Figure 7 - Annual Risk of Component

7. Conclusion

A significant gap between the level of preparedness of critical infrastructures in case of extreme events and the risk that those infrastructures are exposed is evident. The last decade's extreme events emphasize the importance of proper and suitable preparedness of CI in terms of resilience, robustness and redundancy; most of government, economics, and social services are highly dependent on the continuous and stable performance of CI such as electric power supply, and communication. This research intends to develop a risk appraisal and mitigation methodology for CIs (highlighting oil and gas systems), which will help to optimize the courses of actions for increasing the preparedness of critical infrastructures for seismic extreme events. The presented methodology analyzes the damage of critical infrastructures components using fragility curves and annual rate of exceedance function. This method allows calculating the total annual seismic risk that critical infrastructures are exposed to, and integration of this function gives the expectancy of the total annual risk. Based on those findings, the optimal mitigation strategy may be developed. Further research is needed to investigate the applicability and the effectiveness of various risk mitigation strategies such as robustness, resilience, and redundancy on the preparedness of C.I.s for extreme events at different intensities.

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