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Derivation of Seismic Risk Function for Critical Infrastructures

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Abstract

Critical infrastructures importance to the society and the economy is constantly rising due to the increasing dependency of the private and public sector on the services they provide. Critical infrastructures are complex and interdependent systems; thus, damage to one component in the system can lead to a total failure of the CI and consequently lead to disruptions of other CIs. Therefore, there is an utmost importance to ensure reliable performance of critical infrastructures on a continuous basis and particularly after the occurrence of earthquakes. With the understanding that it is unfeasible (economically or physically) to ensure full robustness of the system for all possible scenarios, decision makers are required to plan the upgrade of the systems accordingly to the most efficient strategies and corresponding to the economic limitations.
In this study, a methodology is developed to appraise the risk that CIs are exposed in case of earthquakes and to act as a decision support tool for decision makers to manage efficiently the courses of action to mitigate this risk. In this methodology, Probabilistic Seismic Hazard Analysis (PSHA) approach is used in order to reflect a variety of possible seismic scenarios and overcome the uncertainties regarding to the timing, the location, and the magnitude of an earthquake. The seismic vulnerability of the component is evaluated by fragility curves and Fault-Tree-Analysis.
The seismic risk function of the system is derived by an aggregation of the occurrence probabilities of the earthquake, seismic vulnerability of the different components, and the expected consequences. The derived risk function expresses the expected risk of the system for a given ground motion intensities that reflect different possible earthquake scenarios. Using this methodology, different mitigation strategies can be examined and prioritized accordingly to their contribution to the risk reduction and relatively to each strategy cost.

Keywords: critical infrastructures; earthquakes; fragility curves; risk assessment

1. Introduction

Critical Infrastructures (CI) 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, water supply, communications, etc.

As was observed in previous studies, there is a significant gap between the stability and the preparedness level of CIs for seismic events and the actual damage that those facilities are exposed to in a case of a seismic event [1-3]. The consequences of the latest seismic events emphasize the importance to mitigate the seismic risk by increasing the preparedness of CIs and ensuring reliable and robust performance on a continuous basis, particularly during and after the occurrence of extreme events. Implemented mitigation strategy is derived accordingly to the financial limitation and depends on decision makers' policy. Therefore, at first, in order to clarify the actual risk that CIs are exposed to in case of seismic event the risk should be quantified. Subsequently, in case the risk is not acceptable, different mitigation strategies must be examined in order to select the most optimal strategy, respectively to the financial feasibility.

The major objective of this research is to develop a probabilistic methodology that examines the preparedness of critical infrastructures through an appraisal of the risk that CIs are exposed in case of seismic events and provide a decision support tool for risk mitigation. Prior methodologies for risk appraisal [4-6] presented procedures that

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offer tools such as fragility curves, fault tree analysis, logic tree in order to appraise the risk of different components. Those methodologies presented tools to appraise the risk for existing generic infrastructures based on empiric data. However, those studies didn't examine different mitigation strategies and their effectiveness on the risk reduction and didn't conclude to the optimal strategy. Moreover, those methodologies are mainly used in order to appraise the risk as a result of a specific earthquake event.

This methodology is intended to expand prior risk appraisal tools such as fragility curve and fault tree analysis and implement them as a decision support tool for policy makers. This methodology intended to quantify the seismic risk by a probabilistic seismic analysis of a variety of possible seismic scenarios and examine different mitigation strategies in order to conclude the most optimal mitigation strategy under the given financial constraints.

2. Methodology

The proposed methodology is composed of five main steps; each one of the steps produces values or curves which are essential for the overall risk appraisal process.

2.1. *Seismic Hazards Identification*

The seismic threat for each CI's component is identified according to the location of the facility according probabilistic seismic hazard analysis (PSHA) as presented by [7]. The PSHA approach is intended to consider all possible scenarios according to geological data about the possible earthquake sources, and the probability of magnitude and intensity occurrence that is associated with those events. The PSHA approach requires ground-motion attenuation models that estimate the expected ground-motions at a given site as a result of different intensity and location earthquakes. This step yields an Annual Rate of Exceedance curve (PE_A) as a function of a given ground motion intensity measure (IM); when in most cases, for above-ground structures the IM is expressed in term of peak ground acceleration (PGA) [8-10].

2.2. *System's Seismic Vulnerability*

In this step, the expected damage state as a result of a seismic event is formulated in terms of fragility curve. The fragility curve expresses the probability of reaching or exceeding certain damage states for a given level of IM [11-14]. This function is fully defined by determination of two parameters: median capacity of the component to resist the damage state (θ) and standard deviation of the capacity (β).

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

Eq. 1 expresses a formulation of a fragility function. When P stands for 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 (IM). 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_{ds}	The median capacity of the component to resist damage state ds measured in terms of IM
β_{ds}	Logarithmic standard deviation of the uncertain capacity of the component to resist damage state ds

2.3. *Damage Assessment due to seismic Extreme Events for different components*

This step associates a damage ratio (DR_i) with each damage state; the DR_i expresses the percentage of the total replacement value of a component corresponding to damage state i. Subsequently, since the damage ratio is associated directly to the damage state, the expectant damage ratio of a component (DR_c) can be calculated as follows:

$$DR_c = \sum_{ds} DR_i * P(ds_i|IM) \quad (3)$$

Where

DR_i	Damage rate of the damage state i
$P(ds_i \mid IM)$	Conditional probability of being in a certain damage state i for a given IM

Furthermore, the expected repair cost (RC_c) of the component for a given IM can be calculated regarding to the replacement value (RV_c); when the RV_c expresses the total replacement cost of the component. Thus, one can calculate the expected direct damage of the component for any given IM as follows:

$$RC_c(IM) = RV_c * \sum_{ds} DR_i \cdot P(ds_i|IM) = DR_c * RV_c \quad (4)$$

2.4. *Risk Appraisal according to expected damage*

The product of this step is a seismic risk curve, that present the expected annual risk for any given value of IM. Since risk represents the potential impact and loss and it is defined as the product of the occurrence probability and the expected consequences, this curve is constructed by multiplying the annual rate of exceedance curve with the direct damage curve by matching between the PGA values in both curves and link the expected consequence and its probability to occur. This matching produces a curve that correlated between the expected damage in terms of annual expectancy of risk and the PGA.

$$R_A(IM) = RC_c(IM) \cdot PE_A(IM) \quad (5)$$

Where

$\mathrm{R_A}(IM)$	Annual risk for a given IM
$RC_c(IM)$	Replacement cost of the component for a given IM
$P\mathrm{E_A}(\mathrm{IM})$	Annual rate of exceedance of a given IM

2.5. *Risk Mitigation*

In this step, different mitigation strategies are examined in order to predict the effectiveness of the mitigation strategy on the preparedness level of the CIs by quantifying the reduction of risk followed by implementation of each strategy. Each examined mitigation strategy has different effects on the robustness and the resilience of the system which is reflected in different parameters of the fragility curve; those changes will effect on the level of risk. Subsequently, the optimal strategy is selected according to the level of reduction of risk and economic considerations.

3. Case study

The annual rate of exceedance curve depends on the specific location of the facility. Therefore, in this case, the facilities are assumed to be located in Beer-Sheva, Israel. As well, the cases are performed according to a simplified annual rate of exceedance curve (Figure 22), which was derived based on the values that were published by the Geophysical Institute of Israel report [15]. In this report, the attenuation is based on the model of [16] which has a good correlation to the middle east seismic patterns. This attenuation model considers a sufficient range of magnitudes (4-8.5) and allows to consider the effects of weak seismic areas. Moreover, this attenuation considers main parameters of site effect such as: Magnitude (M), distance from rupture (R), fault mechanism, and soil stiffness. In this chapter, two example cases of implementation of the methodology for CIs components are presented: (A) steel storage tank and (B) Oil pumping plant.

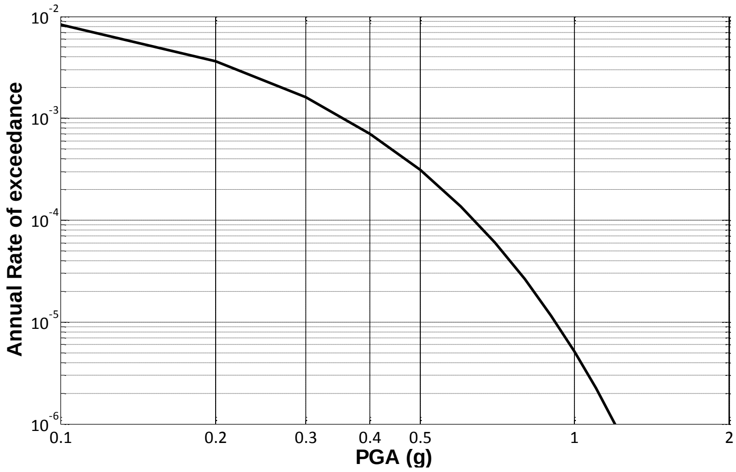


Figure 22 - Annual rate of exceedance curve for west Beer-Sheva region

3.1. *Case study A –Steel storage tank*

This case study implements the proposed methodology on an oil steel storage tank. Oil storage tanks are used for storage of different petroleum products for a long or a short time; often, several storage tanks ate concentrated under the envelope of an oil farm. The modern oil storage tanks are varying from 12-76m in diameter with heights to diameter ratio (H/D) is mostly lesser than one. The most common design type of tanks is cylindrical ground-supported tank due to their efficient resistance to hydrostatic pressure and can be easily constructed [5, 10, 17, 18]. In addition, most of the oil storage facilities are composed of welded steel with floating roof.

Several fragility parameter sets are offered by the literature based on empirical data [19]. [4] provides data for steel tanks categorized the tank only whether it is anchored or unanchored. In addition, [6, 8, 20] suggest to consider parameters such as H/D ratio and fill level.

In this case, the fragility parameters are based on the values proposed by [8] for tank with H/D ratio lesser than 0.7, since most of the storage tanks in Israel are complying with these criteria. According to those values the fragility curves are composed (Figure 23). The damage ratio of the tank is based on the best estimate damage ratio that proposed by HAZUS [4]. In addition, the full replacement cost of a single tank is estimated at 800 thousand US$.

Table 20. Damage states description and parameters of a steel tank as proposed by [8] and damage ratio values based on [4]

Damage state (Ds_i)		Damage Description	θ	β	DR_i
Ds_1	Slight/minor	No damage to tank or inlet/outlet pipes	0.67	0.50	0.20
Ds_2	Moderate	Damage to roof other than buckling, minor loss of contents, minor damage to piping, but no elephant's foot buckling	1.18	0.34	0.40
Ds_3	Extensive	Moderate Elephant's foot buckling with minor loss of content, buckling in the upper course	1.56	0.35	0.80
Ds_4	Complete	Elephant's foot buckling with major loss of content, severe damage, broken inlet/outlet pipes	1.79	0.29	1.00

Following those parameters (Table 20), the risk function is derived by an integration of the annual rate of exceedance curve with the fragility curve, DR_c and RV_c. The risk curve (Figure 24) shows that the intensity ground motion PGA at a range of 0.25-75 has a major contribution to the total annual risk expectancy. However, the risk expectancy is relatively low, as could be expected due to the low probabilities to exceed PGA over 0.6g at the site and the values of the fragility curve that express low vulnerability of the steel tank for low-moderate ground accelerations.

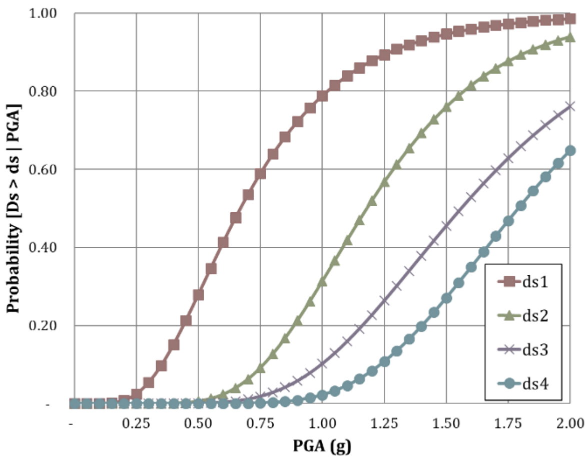


Figure 23 - Fragility curve for steel tank

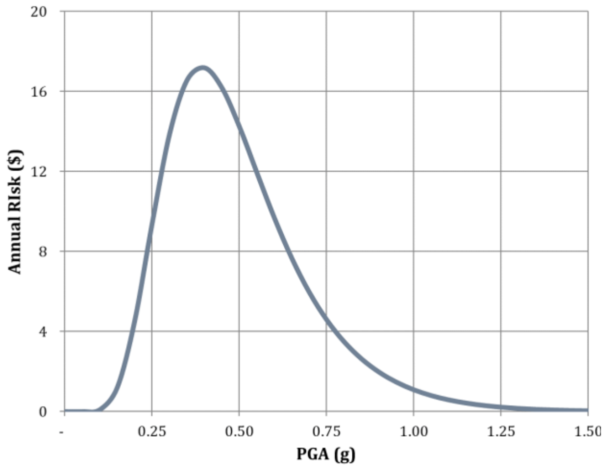


Figure 24 - Risk curve for steel tank

3.2. *Case study B – Oil pumping plant*

Pumping stations serve to maintain the flow of oil across pipeline system. They are located at certain intervals along the pipeline network to ensure the transport over long distances and around the storage facilities when the pressure must be increased due to friction losses. In addition, Pumping is also required to transport oil uphill wherever this is required by topographic conditions.

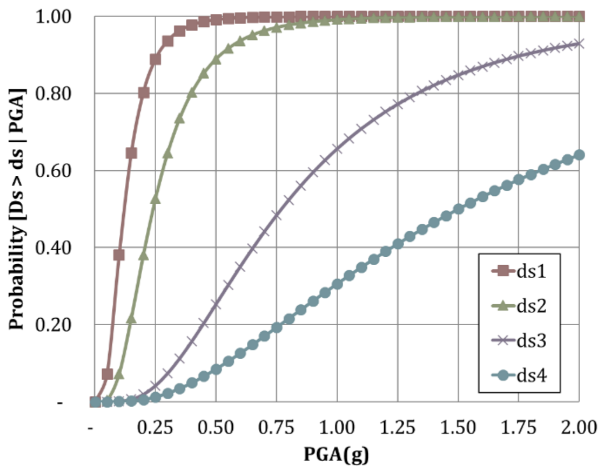
According to [6] the failure of a pumping plant is most likely to occur as a result of damage to one of its main sub-components: the building, one or more pumps, electrical equipment, and electric power and backup systems. Regarding to pumping stations, the anchorage of the subcomponents is a key point, as unanchored equipment can lead to breaks of the equipment and the piping.

In this case, the fragility parameters are based on the values proposed by [4] for unanchored pumping plant (Figure 25). The damage ratio of the tank is based on the best estimate damage ratio that proposed by [4] and the full replacement cost for a pumping plant is estimated at 1M US$.

Table 21.Damage states description and parameters of an oil pumping plant and the damage ratio values as proposed by [4]

Damage state (Ds_i)		Damage Description	θ	β	DR_i
Ds_1	Slight/minor	Defined by light damage to building	0.12	0.60	0.08
Ds_2	Moderate	Defined by considerable damage to mechanical and electrical equipment, or considerable damage to building	0.24	0.60	0.40
Ds_3	Extensive	Defined by the building being extensively damaged, or pumps badly damaged.	0.77	0.65	0.80
Ds_4	Complete	Defined by the building being in complete damage state	1.50	0.80	1.00

Following the above parameters (Table 21), the risk function is derived by an integration of the annual rate of exceedance curve with the fragility curve, the damage ration (DR_c), and the replacement value (RV_c). The risk curve analysis shows that low-moderate ground accelerations, where the exceeded PGA is lesser than 0.8, have a major contribution to the total annual risk of the pumping station (Figure 26).



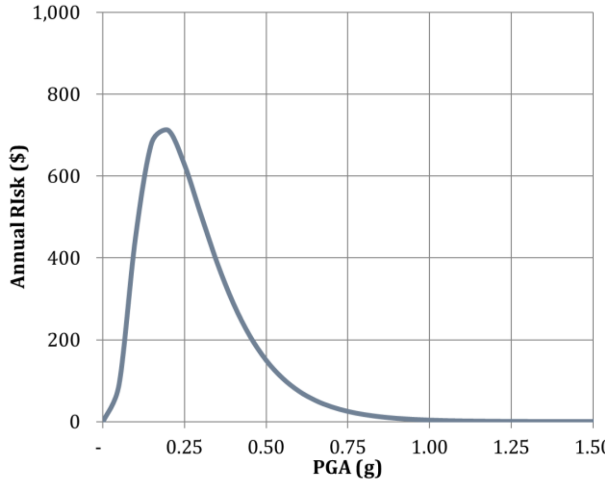
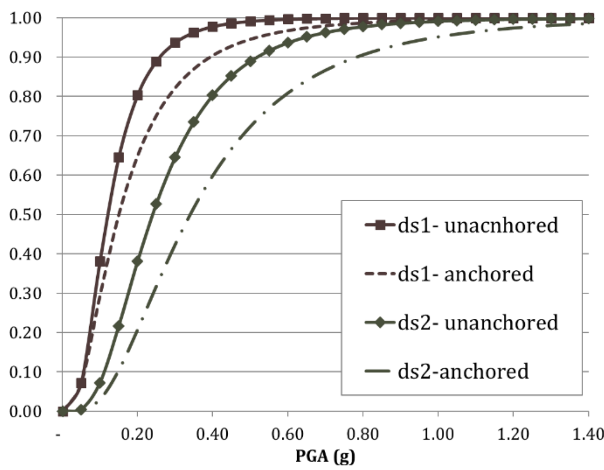


Figure 25 - Fragility curve for pumping plant

Figure 26 - Risk curve for pumping plant

One of the possible methods to reduce the potential damage of the PP in case of seismic event is anchoring the subcomponents of the station. This strategy is increasing the resistance of the subcomponents to overcome moderate level ground accelerations and subsequently increases the robustness of the pumping plant for seismic events. Implementation of this strategy modifies the fragility curve parameters for ds_1 and ds_2, which gives a relatively high probability to exceed this damage states in case of moderate ground for the unanchored plant while anchoring the subcomponents reduces the probabilities to exceed ds_1, ds_2 in case of moderate ground accelerations (Figure 27). This mitigation strategy reduces the total risk of the pumping plant. The reduction is manly effect the damage that expected as a result of moderate ground motion. A analysis of the derived risk curves for unanchored and anchored plants shows that anchoring the components can reduce the risk by about 27% (Figure 28).



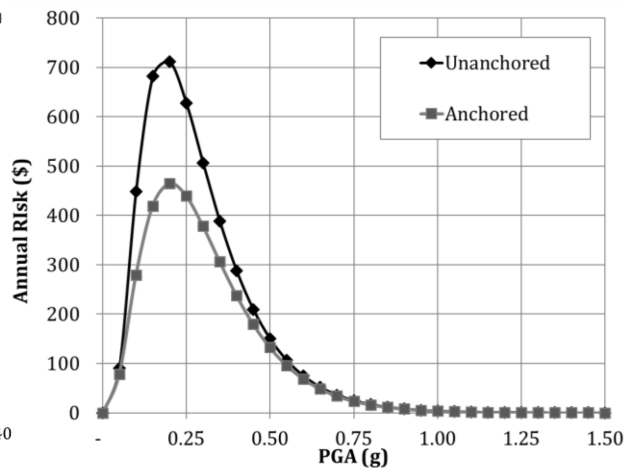


Figure 27 - Comparison of ds_1 and ds_2 for anchored and unanchored pumping plant

Figure 28 - Comparison of the derived risk curve for anchored and unanchored pumping plant

4. Conclusion

In this paper a probabilistic risk appraisal methodology is introduced and presented. The methodology appraises the expected damage to critical infrastructures components using fragility curves. The occurrence probability of different-intensity seismic events is estimated according to probabilistic seismic hazard analysis (PSHA) approach. Then, the annual risk expectancy is calculated as a product of the annual rate of exceedance and the expected damage for a given IM.

This paper presents an implementation of this methodology through two case studies: oil tank and pumping plant. The oil tank case illustrates a good example that the overall risk is determined according to two main factors: seismic vulnerably of the system and probability of occurrence. Since the tank is mainly vulnerable to high ground accelerations on the one hand and the probability to exceed those ground accelerations is low, the risk expectancy of the tank is relatively low. The second case demonstrates the seismic risk expectancy of a pumping plant. In this case, the risk expectancy curve reveals that the majority of the risk is concentrated at the low-moderate peak ground accelerations levels. A possible mitigation strategy was examined and the subsequent reduction of risk was analyzed. It was found that anchoring the subcomponents of the pumping plant can reduce the risk expectancy by over 25% at the most critical range of ground accelerations.

The methodology presented in this paper is intended to be used as a decision support tool in for management and priority setting of mitigation strategies based on the seismic risk expectancy that critical infrastructures are exposed to and according to the level of risk reduction of the mitigation strategy and the Benefit to Cost Ratio analysis.

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