Sensitivity analysis in seismic loss estimation of urban infrastructures

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\begin{abstract}
Iran, as a seismic country, is situated over the Himalayan-Alpied seismic belt and has faced many destructive earthquakes throughout history. Therefore, it is very important to evaluate the possible damage to the existing infrastructure based on statistical and spatial analysis. In this study, a new model is developed to analyse seismic damages based on seismic hazard assessment and extraction of the vulnerability function for all features of fuel infrastructure. To consider uncertainty analysis in the model, Monte Carlo simulation is used based on 10,000 iterations. The results of hazard analysis indicated that peak ground acceleration is about 0.18 g and there is slight to moderate damages to the desired fuel infrastructure in the study area. Moreover, sensitivity analysis is also performed to determine how median, standard deviation (or beta), grid size, attenuation relationships, liquefaction and landslide susceptibility impact the seismic loss. Last but not least, the effect of input parameters of earthquake scenarios including magnitude, focal depth and focal distance are also analysed in conjunction with regression analysis. The results of the study show that magnitude and focal distance are the most sensitive parameters in which the expected damage to the fuel infrastructure is reduced by about 25% if the epicentre of the earthquake is moved from 10 to 25 km.
\end{abstract}

\section{Introduction}

Earthquakes are one of the most destructive natural hazards and cause casualties as well as financial and environmental damage every year around the world. As Iran is a seismic country located over the Himalayan-Alpied seismic belt, there is a high possibility of earthquake occurrence (Yazdani and Kowsari 2011). In modern societies, the civil infrastructure and utility systems are very important to support daily activities and achieve socio-economic prosperity. Because these services are necessary for emergency services and are critical for survival, the loss of utility systems can have calamitous consequences for a community who is trying to recover after a seismic event. Relevant networks, such as the water, electricity, communication and transportation systems, which are often termed lifelines, are inherently complex and like most man-made structures, often prone to seismic events.
Any earthquake loss models should ideally include ground shaking (GS), landslides, liquefaction and faulting hazards (Calvi et al. 2006). Although in the previous studies, the concurrent effects of GS and ground failure (GF) are partially covered in the damage analysis of the infrastructure, whereas, a comprehensive algorithm is developed to incorporate both primary and secondary hazards (such as liquefaction, lateral spreading and landslides) of an earthquake in the computation in the study.

In general, vulnerability assessment methods are divided into two groups: experimental and analytical methods. The empirical methods for the seismic vulnerability assessment can be divided into two main groups: (1) damage probability matrices (DPM) and (2) vulnerability functions (Calvi et al. 2006). Various models such as HAZUS 99 (FEMA 1999), Risk-Ue Project (Mouroux and Le Brun 2006), JICA (2000), LESSLOSS (2007), etc. based on vulnerability functions were presented. Also many researchers have studied earthquake damage analysis for complex infrastructure systems (Tan and Shinozuka 1982; Vanzi 1996; Hwang et al. 1998; Davis et al. 2000; Cagnan and Davidson 2003; Shinozuka et al. 2007). In general, there is a lack of consideration of the existing uncertainties in the estimation of seismic damage in the previous studies.

The usage of geographic information systems (GIS) has been used for a wide number of different types of vulnerability assessments and analyses. Some researchers such as Karlson (2012), Rezaie and Panahi (2015), Armaz (2012), Hizbaron et al. (2012), Servi (2004) and Sinha et al. (2016) have used geospatial information system GIS-based multi criteria decision-making methods.

The development of statistical methods and computer simulations provide a useful insight into network designs, and help to predict network behaviour in response to internal or external disturbances in recent years (Goda and Ren 2010). Selcuk-Kestel et al. (2012) developed a GIS-based model to show the seismic reliability of lifelines. In another study, a software package (computational intelligence applications to power systems) incorporating metaheuristic algorithm for assessing the vulnerability of electric networks was developed by Haidar et al. (2010).

However, the relationships between seismic damage analysis of lifelines and spatial information systems have not been adequately investigated and only a few models to assess the damage of lifelines based on GIS are available. Hence, a well-developed model is presented for both engineering and spatial analysis due to the large number of mathematical calculations required and the effort needed to increase the accuracy of the calculations. Also to determine the effect of input parameters on the desired model, the system is analysed using various input data. In addition, to investigate the sensitivity analysis of the model, sensitivity analysis, which has received little attention in the previous research, is performed on the model.

### 2. Materials and methods

The descriptive and spatial information related to geology and seismicity play an important role in the seismic damage analysis of the infrastructure. Hence, developing a model in an appropriate environment, such as the geo-spatial information system, is an essential requirement.

Modelling can be defined as a simplification of the real world and is accomplished using GIS to provide a set of map layers and the relations between them. All the necessary steps to implement this model in the seismic loss estimation of the infrastructure are shown in Figure 1 and the procedures are explained in the following.

#### 2.1. Implement the database

The required criteria to select the database of the management system should be able to support spatial data (including vector and raster), work with big data, communicate with programming environment and simultaneously service multiple users.

According to the above-mentioned criteria, the local database of ESRI, termed the geo-database, is used in this study. On this basis, the fuel infrastructure data for a city in Iran with a high potential
Earthquake are collected to be applied in damage analysis. In addition, seismic data in the area with a radius of 150 km is also considered to better evaluate the seismicity of the region (Figure 3) (Falcon 1983; Mirzaei et al. 2002; Berberian 2014). It is important to note that the fuel infrastructure is assumed as a lifeline system and the digital database is completed, updated and verified based on the collected data from the Statistical Center of Iran (2014). Afterwards, data are compiled into GIS for both single-site and network lifeline utilities.
2.2. Seismic hazard analysis

Seismic hazard analysis is an essential step in the analysis of seismic damage to build critical infrastructures. In this regard, the earthquake hazards can be divided into two main categories as GS and GF. GF is further divided into three different types including faulting, landslide and liquefaction. It should be mentioned that the liquefaction failure is also further divided into two categories as lateral spreading and ground settlement (FEMA 2011). Based on the model that is used in this study, the GS and GF are discussed, and the necessary steps to estimate the seismic hazard are presented in the following.

2.2.1. Earthquake scenario preparation

In this step, after the preparation of seismic data, the values of the earthquake scenario are selected as follows:

- Earthquake magnitude: a number of historical and instrumental earthquakes in the range of 5–7.5 degree on the Richter scale within a distance of less than 150 km from the city of study are recorded over the last years (Mirzaei et al. 2002). Hence, the possible magnitude is randomly selected in the range of 5–7.5 on the Richter scale based on a uniform distribution function to cover the majority of earthquakes in the study area.
- Focal depth: given that more than 83% of the previous earthquakes in this region occurred at a depth between 5 and 25 km (Mirzaei et al. 2002), the focal depth of the earthquake is selected at random intervals in the range of 5–25 km based on a uniform distribution function.
- Location of the earthquake: the location of the earthquake is selected as the extent on the map with a radius of 150 km around the city.

2.2.2. Hazard analysis for ground shaking using attenuation relationships

Many factors, including the fault mechanism, site geological conditions, thickness and type of overburden, affect the attenuation of ground motion, and the most recent attenuation laws also take these effects into account. In this study, the Zare et al. (1999), Ghodrati et al. (2007) and Campbell and Bozorgnia (2008) relationships are used for hazard analysis.

2.2.3. Amplification of ground shaking based on local site conditions

Amplification of GS is based on the site classes and soil amplification factors proposed for the 1997 NEHRP Provisions to consider the local site conditions. The NEHRP Provisions define a standardized site geology classification scheme and specify soil amplification factors for most site classes. Based on their classification, soil amplification factors are categorized as A, B, C, D and E classes. The methodology amplifies rock’s peak ground acceleration (PGA) (Class B) with the short-period (0.3-second) spectral acceleration (Equation (1)) and rock’s PGV (Class B) with the 1.0-second spectral acceleration (Equation (2)) (FEMA 2011):

\[
\text{PGA}_i = \text{PGA} \times F_{Ai} \\
\text{PGV}_i = \text{PGV} \times F_{Vi}
\]

In which, \(\text{PGA}_i\) is peak ground acceleration for Site Class i (g), \(F_{Ai}\) is the short-period amplification factor for Site Class i, \(\text{PGV}_i\) is peak ground velocity for Site Class i (m/s), \(F_{Vi}\) is the one-second period amplification factor for Site Class i.

2.2.4. Hazard analysis for ground failure

The following steps need to be taken when considering GF in hazard analysis. It should be noted that the GF is divided into three main categories as faulting, landslide and liquefaction.
2.2.4.1. Liquefaction. Liquefaction happens when a saturated soil loses a substantial amount of strength due to the high excess pore-water pressure generated and accumulated during strong earthquake GS. In order to consider the damage caused by soil liquefaction, the following steps are taken in this study:

- Preparing the geological map
- Determining liquefaction susceptibility (Youd and Perkins 1978)
- Determining liquefaction probability as follows (FEMA 2011):

\[
P \left[ \text{Liquefaction SC} \right] = \frac{P \left[ \text{Liquefaction SC} \mid \text{PGA} = a \right]}{Km \times Kw} \times Pml
\]  

where \( P \left[ \text{Liquefaction SC} \mid \text{PGA} = a \right] \) is the conditional liquefaction probability for a given susceptibility category at a specified level of peak ground acceleration, \( Km \) is the moment magnitude correction factor, \( Kw \) is the ground water correction factor (National Research Council 1985; Seed et al. 1985) and \( Pml \) is the proportion of map unit susceptible (Liao et al. 1988).

- Determining the peak ground displacements of lateral spreading due to liquefaction as follows (Boore 1987):

\[
E[\text{PGD}_{SC}] = K_{\Delta} \times E\left[ \text{PGD}\left(\frac{\text{PGA}}{\text{PL}_{SC}}\right)\right]
\]

where \( E[\text{PGD}\left(\frac{\text{PGA}}{\text{PL}_{SC}}\right)] \) is the expected permanent ground displacement (PGD) for a given susceptibility category under a specified level of normalized GS (Youd and Perkins 1978; Sadigh et al. 1986), and \( K_{\Delta} \) is the displacement correction factor (Seed et al. 1985).

- Determining the peak ground displacement of ground settlement due to liquefaction: ground settlement along with the liquefaction is related to the susceptibility category and is specified for any area (Tokimatsu and Seed 1987).

2.2.4.2. Landslide. The landslide of a hillside slope due to earthquake occurs when the sum of the static and inertia forces within the slide mass make the safety factor less than 1. Calculation of the PGD due to a landslide is as follows:

- determination of liquefaction susceptibility (Keefer and Wilson 1989);
- determination of critical accelerations based on susceptibility categories (Keefer and Wilson 1989);
- determination of percentage of map area with a landslide-susceptible deposit (Wieczorek et al. 2013); and
- determination of PGDs:

\[
E[\text{PGD}] = E\left[ d / a_{is} \right] \times a_{is} \times n
\]

where \( E\left[ d / a_{is} \right] \) is the expected displacement correction factor (Makdisi and Seed 1977), \( a_{is} \) is the induced acceleration and \( n \) is the number of cycles (Seed et al. 1985).

2.2.4.3. Faulting. The median maximum displacement (MD) is given by the following relationship in which \( M \) is the moment magnitude (Wells and Coppersmith 1994):

\[
\text{Log } (\text{MD}) = -5.26 + 0.79 \times M
\]
After meshing the region with equal sizes, this process is repeated for all grids in the system and ultimately it provides the PGA, PGV and PGD outputs, PGD due to lateral spreading, ground settlement and landslides for each grid.

2.3. Estimation of seismic vulnerability

The seismic vulnerability of a structure is defined as its susceptibility to damage by GS or GF with a given intensity (Omidvar and Kivi 2016). The main aim of a vulnerability assessment is to obtain the probability of a given damage state for infrastructures due to an earthquake scenario. In this regard, there are two well-known methods as DPM in which the conditional probability of obtaining a damage level is expressed in a discrete form due to a ground motion of intensity and (2) vulnerability functions, which are continuous functions and express the probability of exceeding damage at a given function of the earthquake intensity (Calvi et al. 2006).

It is important to note that vulnerability functions comprise two parameters: (1) median for any component that reaches the threshold of damage state, and (2) beta or standard deviation. These are identified for the model based on the type of hazard GS or GF, having anchored or unanchored, and the type of component (median and beta parameters). In addition, the damage states of fragility curves include five states including $d_{s1}$ (non-damage), $d_{s2}$ (slight), $d_{s3}$ (moderate), $d_{s4}$ (extensive) and $d_{s5}$ (complete) (FEMA 2011).

2.4. Seismic loss estimation

The proposed loss estimation methods provide damage estimations and service outages for lifelines with minimum operations. The direct output (damage estimate), based on using the fragility curves as an input for the model, calculates the probability of damage exceeding a damage state for the given level of GS. Then, this output will be used directly as an input in the loss estimation method or combined with inventory information to predict the distribution of damage as a function of the type of facility and geographical location.

The hard and heavy components of the networks (such as CGS, gas station, tank farm oil, etc.) not only are more vulnerable to maximum ground acceleration (PGA), but are vulnerable to PGD as the region faces the potential hazards of liquefaction, landslides, etc. The probability of damage exceeding a damage state is modelled as a cumulative lognormal distribution. In the case of structural damage, considering the PGA or PGD, the probability of exceeding a damage state, $d_s$, is modelled as follows (Omidvar and Kivi 2016):

$$P_{\text{GroundShaking}}[d_s|\text{PGA}] = \varphi \left[ \frac{1}{\beta} \ln \left( \frac{\text{PGA}}{\bar{\text{PGA}}} \right) \right]$$

(7)

$$P_{\text{GroundFailure}}[d_s|\text{PGD}] = \varphi \left[ \frac{1}{\beta} \ln \left( \frac{\text{PGD}}{\bar{\text{PGD}}} \right) \right]$$

(8)

Here $\text{PGA}$ and $\text{PGD}$ are the median value of the PGA and PGD of any infrastructure component reaching the threshold of the damage state ($d_s$), $\beta$ is the standard deviation of the natural logarithm of the spectral displacement of the damage state ($d_s$) and $\varphi$ is the standard normal cumulative distribution function.

It is assumed that the GS damage is not dependent on the GF, and the damage state probability for GF is assumed to be the maximum of the three types of GFs as liquefaction, landslide and lateral spreading. Thus, after assessing the failure probability, the integrated probabilities of exceeding given damage states due to the occurrence of GF or GS are calculated as follows:

$$P_{\text{COMB}}[\text{DS} \geq S] = P_{\text{GF}}[\text{DS} \geq S] + P_{\text{GS}}[\text{DS} \geq S] - (P_{\text{GF}}[\text{DS} \geq S] \times P_{\text{GS}}[\text{DS} \geq S])$$

(9)

$$P_{\text{COMB}}[\text{DS} \geq M] = P_{\text{GF}}[\text{DS} \geq M] + P_{\text{GS}}[\text{DS} \geq M] - (P_{\text{GF}}[\text{DS} \geq M] \times P_{\text{GS}}[\text{DS} \geq M])$$

(10)
\[ P_{\text{COMB}}[DS \geq E] = P_{\text{GF}}[DS \geq E] + P_{\text{GS}}[DS \geq E] - (P_{\text{GF}}[DS \geq E] \times P_{\text{GS}}[DS \geq E]) \]
\[ P_{\text{COMB}}[DS \geq C] = P_{\text{GF}}[DS \geq C] + P_{\text{GS}}[DS \geq C] - (P_{\text{GF}}[DS \geq C] \times P_{\text{GS}}[DS \geq C]) \]

where DS is the damage state, and S, M, E and C indicate slight, moderate, extensive and complete damage, respectively. It should be noted that COMB indicates the combined probability for the damage state due to the occurrence of GF or GS. The discrete probabilities are given as follows:

\[ P_{\text{COMB}}[DS = \text{Noun}] = 1 - P_{\text{COMB}}[DS \geq S] \]
\[ P_{\text{COMB}}[DS = \text{Slight}] = P_{\text{COMB}}[DS \geq S] - P_{\text{COMB}}[DS \geq M] \]
\[ P_{\text{COMB}}[DS = \text{Moderate}] = P_{\text{COMB}}[DS \geq M] - P_{\text{COMB}}[DS \geq E] \]
\[ P_{\text{COMB}}[DS = \text{Extensive}] = P_{\text{COMB}}[DS \geq E] - P_{\text{COMB}}[DS \geq C] \]
\[ P_{\text{COMB}}[DS = \text{Complete}] = P_{\text{COMB}}[DS \geq C] \]

The sequential systematic procedures for earthquake damage assessment are programmed by integrating the sub-modules (Figure 2).

2.5. Uncertainty analysis

To consider uncertainty analysis in seismic damage assessment, the Monte Carlo simulation is used in this study. Monte Carlo simulation, which is based on the iteration and generation of random variables from a specific range, is one of the most widely used numerical methods (Goodarzi et al. 2013). This method is mainly applicable to complex problems with a large number of random values when analytical methods are not applicable (Akkar and Cheng 2016). Monte Carlo simulation requires a number of simulations to achieve a certain level of accuracy and the estimated results may be treated statistically (Bissell 1979). In this study, 10,000 random variables are generated to consider uncertainty in seismic damage analysis.

2.6. Estimate damage state based on damage ratio

As a single damage statement cannot clearly explain the damage condition of each network component, five different damage states as ‘non-damage’, ‘slight damage’, ‘moderate damage’, ‘extensive damage’ and ‘complete damage’ are considered in this study. Afterwards, the FEMA damage ratio is used to obtain the damage state of different types of infrastructure and the results are presented in Table 1.

As the damage ratios for these components are expressed as a fraction of the component replacement cost, the damage ratio for the infrastructure is calculated as sum of damage ratios of all the subcomponents multiplied by their respective percentages of the total component value.

2.7. Case study

A city with the population of 200,000, area of 662 km², and more than 600 subdivisions in the form of counties, districts and rural areas located 70 km south of Tehran has been considered as a case study (Statistical Center of Iran 2014). This city is a major agricultural producer and exporter in the country for a very long time. As it can be seen in Figure 3, there are many active and capable faults in the area of the case study in which three active faults with lengths of 50, 59 and 104 km are placed in the heart of the city and 30 active and capable faults are distributed within a radius of 150 km around the city. Based on the historical records, a number of earthquakes with a high magnitude (at least seven historical earthquakes with magnitudes greater than 7 on the Richter scale, and two earthquakes with magnitudes between 6 and 7 in conjunction with three instru-
mental earthquakes) occurred in less than 200 years at different times around the study area (Figure 3).

Regarding the rapid population growth, and being an industrial city with many tourist attractions, the civil infrastructure and various utility systems have been developed over the last 20 years.

Figure 2. Proposed systematic procedure of earthquake damage assessment.
For instance, in one case there is a buried steel pipe for fuel transportation with a length and diameter of 42 km and 20 inches, respectively. A lateral pipe with a length of 7 km is also used to transfer oil to an oil tank farm with a capacity of 30 million litters in order to supply the necessary fuel for the combined cycle power plant. Other important elements of civil infrastructure in the city are five gas stations, six CGS with an input pressure of 250 Psi, and three buried gas pipes with diameters of 12, 20 and 24 inches, and lengths of 14, 18 and 48 km, respectively. Also, most of the fuel infrastructure of the city is located in downtown areas with high density. Hence, measuring seismic damage is an essential task to reduce the seismic damage as the fuel infrastructure plays an important role in supporting daily activities and achieving socio-economic prosperity, and the loss of utility systems can have calamitous consequences for a community trying to recover after a seismic event (Statistical Center of Iran 2014).

**Table 1. Damage ratios for infrastructure (FEMA 2011).**

| Damage state | Damage ratio | Water treatment | Water storage tank | Wells and pumping station | Substation | Power plant | Oil tank farm | Gas station and CGS |
|--------------|--------------|-----------------|-------------------|--------------------------|------------|-------------|--------------|--------------------|
| Slight       | Best estimate damage ratio | 0.08 | 0.20 | 0.05 | 0.05 | 0.08 | 0.13 | 0.08 |
| Moderate     | Best estimate damage ratio | 0.4 | 0.40 | 0.38 | 0.11 | 0.35 | 0.4 | 0.4 |
| Extensive    | Best estimate damage ratio | 0.77 | 0.8 | 0.8 | 0.55 | 0.72 | 0.8 | 0.8 |
| Complete     | Best estimate damage ratio | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
|              | Range of damage ratios | 0.8–1.0 | 0.8–1.0 | 0.8–1.0 | 0.8–1.0 | 0.8–1.0 | 0.8–1.0 | 0.8–1.0 |

**Figure 3. Faults and previous earthquakes.**
3. Results

In order to run the model, zoning maps for the seismic hazard and seismic damage analysis were prepared for the fuel infrastructure and various analyses were performed on the outputs of the model.

3.1. Map of seismic hazard analysis

The zoning map of liquefaction and landslide susceptibility are shown in Figure 4. Liquefaction is divided into three groups: soil and sediment type, site geological age and depositional environment of the region. Landslide is also considered as a function of three factors including soil and sediment type, slope of the land and ground moisture. It should be mentioned that the liquefaction zoning map shows moderate liquefaction while landslide susceptibility indicates low landslide susceptibility for the desired city.

Figure 5(a–c) shows the zoning map for seismic hazard analysis for PGA, the hazard of lateral spreading, and the hazard of landslide. According to Figure 5(a), zoning in the peak ground acceleration shows changes from 0.16 to 0.19 g in PGA. According to Figure 5(b,c), the PGD caused by the lateral spreading and landslide would be between 0–4.5 inches and 0–0.5 inches, respectively. It can be concluded that the hazard of GF is very low in the area of study. The important role of the liquefaction and landslide susceptibility can be observed in Figure 5(b,C) and also using the available information (Figure 4). For example, the PGD values are certainly zero in Figure 5(b,C) for the locations without susceptibility in Figure 4. Furthermore, the locations with high susceptibility do not necessarily have high PGD values because of the displacement due to lateral spreading and landslide as well as the dependency of liquefaction and landslide susceptibility on the PGA values in each grid.

3.2. Map of seismic loss estimation

After preparing the zoning map for the seismic hazards of the study area, the seismic damage analysis map for all types of infrastructure is prepared. For example, the zoning map of the seismic damage analysis for the fuel infrastructure of this city is shown in Figure 6. Based on Figure 6(a), the
seismic loss estimation can be seen for three components of the fuel infrastructure at five damage states: none, slight, moderate, extensive and complete. The results demonstrate that there is slight to moderate damage in this case. The component with the highest damage is specified in Figure 6(a) and the final loss estimation of fuel infrastructure in the city is specified in Figure 6(b). However, the proximity of the components to each other may make it difficult to display some damage on this map. Accordingly, the outputs of the damage for these components are shown in Table 2.

3.3. Descriptive statistical analysis

After obtaining the damage map for the critical infrastructure in the study area, descriptive statistical analysis is performed on the outputs and a summary of this analysis is shown in Table 2. Based on this table, the average damage probability for each damage state, standard deviation, upper bound and lower bound, confidence interval with $\alpha = 5\%$ are given for three types of fuel infrastructure. In
Table 2. Summary of statistical analysis of damage probability to the fuel infrastructure.

| Damage state     | CGS          | Gas station   |
|------------------|--------------|---------------|
|                  | Average      | Std. deviation| Upper bound | Lower bound | Best-fitted distributions | Estimate parameters of fitted distributions | Average | Std. deviation| Upper bound | Lower bound | Best-fitted distributions | Estimate parameters of fitted distributions |
| Non-damage       | 34.5         | 8.0           | 41.9        | 27.2        | Lognormal (3P) | $\sigma = 0.2117 \mu = -1.086$ | 27.3     | 8.5           | 37.9        | 16.7        | Lognormal (3P) | $\sigma = 0.2893 \mu = -1.339$ |
| Slight damage    | 37.5         | 5.1           | 42.2        | 32.7        | Lognormal (3P) | $\sigma = 0.1218 \mu = -0.989$ | 43.1     | 5.8           | 50.2        | 35.9        | Lognormal (3P) | $\sigma = 0.1234 \mu = -0.8495$ |
| Moderate damage  | 25.3         | 5.0           | 29.8        | 20.7        | Lognormal (3P) | $\sigma = 0.0239 \mu = 0.6525 \gamma = -1.668$ | 22.5     | 2.7           | 25.9        | 19.1        | Lognormal (3P) | $\sigma = 4.839 \mu = -6.5 \gamma = 0.2038$ |
| Extensive damage | 1.8          | 0.7           | 2.5         | 1.2         | Lognormal (3P) | $\sigma = 0.019 \mu = -1.067 \gamma = -0.3255$ | 6.0      | 1.7           | 8.0         | 3.9         | Lognormal (3P) | $\sigma = 0.3229 \mu = -2.861$ |
| Complete damage  | 0.9          | 0.3           | 1.2         | 0.6         | Lognormal (3P) | $\sigma = 0.0222 \mu = -1.941 \gamma = -0.1348$ | 2.3      | 0.0           | 2.3         | 2.2         | Lognormal (3P) | $\sigma = 0.0139 \mu = -3.791$ |
| Final damage     | 14.9         | 2.9           | 17.6        | 12.3        | Lognormal (3P) | $\sigma = 0.2009 \mu = -1.921$ | 18.1     | 0.0           | 22.6        | 13.5        | Lognormal (3P) | $\sigma = 0.1868 \mu = -1.727$ |
addition, various statistical analyses are performed on CGS and gas stations, and then, the best-fitted
distribution with distribution parameters are obtained for five different damage states to determine
the best distribution for the outputs (Schittkowski 2002; Mehrannia and Pakgohar 2014). As there is
only one oil tank in the city under study, it is not possible to determine the standard deviation, con-
fidence intervals or the best-fitted distributions. Thus, the gas stations and CGS are only used in this
analysis.

3.4. Sensitivity analysis

The main relationships and parameters that affect the loss estimation model of the infrastructure
and are used in the sensitivity analysis are given in the following.

3.4.1. Median and beta parameters in the fragility curves

By changing the median and beta parameters of the fragility curve in the five different states, the
outputs of the probability of non-damage in the infrastructure of both the CGS and gas station are
estimated and the results are shown in Figure 7. According to Figure 7(a), if the median becomes
half of the normal state (1 M), the non-damage probability of all utilities is lower than that for other
states. As the median is defined as 50% of the utilities facing damage, if that amount reaches half of
its initial value, the probability of damage to the desired state will also increase. The largest change
that occurred between two consecutive medians is between half of the main median (or 0.5 M) and
0.75 times of the main median (or 0.75 M). However, based on Figure 7(b), the variations in the
beta values indicate the smooth gradient of changes in the output results (non-damage probability
of infrastructure).

3.4.2. Changing attenuation relationships

In order to perform the sensitivity analysis of the attenuation relationships, five different cases are
selected, as follows:

- Analysis only based on Zare et al.’s attenuation relationship
- Analysis only based on Ghodrati et al.’s attenuation relationship
- Analysis only based on Campbell and Bozorgnia’s attenuation relationship
- Analysis based on the average of the three above-mentioned relationships
- Analysis based on the maximum of the three above-mentioned relationships

The effect of changing the attenuation on the outputs of non-damage probability for both types
of infrastructure is shown in Figure 8(a). Based on the results, if only the Zare et al.’s relationship is
used, the probability of non-damage is lower than when the other two relations have been applied.
However, if the average of the three relationships is used, the outputs are between the Zare et al. and Ghodrati et al.’s relationships. In addition, the probability of non-damage is less than all cases and is very close to the results of Zare et al.’s relationship when the maximum of the three relationships is used.

3.4.3. Changing liquefaction and landslide susceptibility

Figure 8(b) shows the probability of non-damage versus liquefaction and landslide susceptibility among three different cases: none, moderate and very high susceptibilities. Based on the achieved results it can be concluded that changing the desired variables significantly affects the outcomes, and the liquefaction susceptibility has a greater effect than landslide susceptibility on the probability of damage.

3.4.4. Changing the grid size

To consider the effect of distance and geological parameters on each location in seismic hazard analysis, the study area is divided into a number of grids of equal size, and then, for each grid, the hazard parameters – PGA, PGV and PGD – are calculated. In this study, the size of each grid is selected as 2 × 2 km grids, but grids with three other sizes (0.5 × 0.5 km, 1 × 1 km and 5 × 5 km) are also considered to determine the impact of minimizing or enlarging the size of the grids on the results. As shown in Figure 9, the PGA variation does not have any significant impact in terms of grids of different size. However, the accuracy of the calculations is slightly increased by reducing the grid size while the computation time is significantly increased.

4. Discussion

The main input parameters in the earthquake scenarios consist of the magnitude of the earthquake, focal depth and the focal distance. In order to evaluate the effect of each parameter on the output, each input parameter is slightly changed to see its effect on the outcomes.

4.1. Earthquake magnitude effect

Figure 10 shows the variation in non-damage probability distribution by changing the earthquake magnitude and keeping the other factors constant. In the case of both types of infrastructure (CGS and gas station), the gradient of the non-damage probability is almost equal. However, the maximum gradient varies between 5 and 6 Richter. It is important to note that the probability of non-damage is dependent on the earthquake magnitude for both types of infrastructure (Figure 10).
4.2. Focal depth effect

Figure 11(a) shows how changing the focal depth will affect the non-damage probability distribution while keeping the other factors constant. The gradient of the non-damage probability here is also the same, and the probability of non-damage is dependent on the focal depth for both types of infrastructure (Figure 11(a)).

4.3. Focal distance effect

The probability distribution of non-damage state is obtained by changing the distance between the epicentres and every component of the infrastructure while the other variables are kept constant (Figure 11(b)). In this case, the gradient of the non-damage probability is not the same for both types of infrastructure and the maximum gradient also varies between 10 and 25 km. It should be mentioned that the non-damage probability function is dependent on the focal distance for both types of infrastructure (Figure 11(b)).
Figure 10. The impact of magnitude in seismic loss estimation of fuel infrastructure.

![Graph showing the impact of magnitude on seismic loss estimation.]

Figure 11. The impact of (a) focal depth and (b) distance on the seismic loss estimation of fuel infrastructure.

![Graphs showing the impact of focal depth and distance on seismic loss estimation.]

Figure 12. The impact of magnitude and distance in seismic loss estimation of (a) CGS and (b) gas station.

![Graphs showing the impact of magnitude and distance on seismic loss estimation for CGS and gas station.]
Table 3. Damage probability equations as function of components distance to the earthquake epicentre.

| Damage State | Magnitude range (Richter) | Equation | R-squared value \((R^2)\) | Equation | R-squared value \((R^2)\) |
|--------------|---------------------------|----------|----------------------------|----------|----------------------------|
| Non          | 4–5                       | \(y = 0.0004x^2 - 0.082x^2 + 5.25x - 26.8\) | 1 | \(y = 0.0002 \times 3 - 0.04 \times 2 + 3.6x - 19.8\) | 1 |
|              | 5–6                       | \(y = 36.045\ln(x) - 74.742\) | 0.999 | \(y = -0.006 \times 2 + 1.57x - 11.3\) | 1 |
|              | 6–7                       | \(y = -0.0054x^2 + 1.248x - 9.872\) | 0.999 | \(y = 0.0008 \times 2 + 0.67x - 6.54\) | 0.999 |
|              | 7–7.5                     | \(y = -0.0018x^2 + 0.936x - 7.6759\) | 1 | \(y = 0.0035 \times 2 + 0.197x - 2.36\) | 0.999 |
| Slight       | 4–5                       | \(y = 0.0003x^3 - 0.04x^2 + 1.3x + 19.7\) | 1 | \(y = 0.0003 \times 3 - 0.047 \times 2 + 1.67x + 19.1\) | 1 |
|              | 5–6                       | \(y = 0.0005x^3 - 0.08x^2 + 3.67x - 10.68\) | 1 | \(y = 0.0004 \times 3 - 0.072 \times 2 + 3.5x - 9.1\) | 1 |
|              | 6–7                       | \(y = 0.0005x^3 - 0.09x^2 + 4.75x - 35.0\) | 1 | \(y = 0.0002 \times 3 - 0.05 \times 2 + 2.9x - 16.93\) | 1 |
|              | 7–7.5                     | \(y = 0.0002x^3 - 0.046x^2 + 2.97x - 20.57\) | 1 | \(y = 4E-05 \times 3 - 0.017 \times 2 + 1.75x - 12.31\) | 1 |
| Moderate     | 4–5                       | \(y = -0.0022x^3 + 0.034x^2 - 1.98x + 38\) | 1 | \(y = -0.0003 \times 3 + 0.06 \times 2 - 3.7x + 76.37\) | 1 |
|              | 5–6                       | \(y = 7E-05x^3 - 0.008x^2 - 0.06x + 19.9\) | 1 | \(y = -5E-05 \times 3 + 0.02 \times 2 - 1.78x + 68\) | 1 |
|              | 6–7                       | \(y = 0.0003x^3 - 0.055x^2 + 2.26x - 6.01\) | 1 | \(y = 0.0003 \times 3 - 0.05 \times 2 + 1.80x + 31.54\) | 1 |
|              | 7–7.5                     | \(y = 0.0004x^3 - 0.065x^2 + 3.01x - 16.92\) | 1 | \(y = 0.0005 \times 3 - 0.08 \times 2 + 3.76x + 4.1\) | 1 |
| Extensive    | 4–5                       | \(y = -0.0004x^3 + 0.07x^2 - 3.84x + 58.4\) | 1 | \(y = -0.0001 \times 3 + 0.02 \times 2 - 1.16x + 17.8\) | 1 |
|              | 5–6                       | \(y = -0.0005x^3 + 0.096x^2 - 5.14x + 84.25\) | 1 | \(y = -0.0002 \times 3 + 0.04 \times 2 - 1.99x + 32.3\) | 1 |
|              | 6–7                       | \(y = -0.0003x^3 + 0.059x^2 - 3.67x + 77.88\) | 1 | \(y = -0.0002 \times 3 + 0.036 \times 2 - 2.13x + 41.6\) | 1 |
|              | 7–7.5                     | \(y = 0.0074x^3 - 1.28x + 55.48\) | 0.99 | \(y = 0.0055 \times 2 - 0.89x + 33.3\) | 0.992 |
| Complete     | 4–5                       | \(y = -8E-05x^3 + 0.15x^2 - 0.74x + 10.68\) | 1 | \(y = -5E-05 \times 3 + 0.008 \times 2 - 0.43x + 6.54\) | 1 |
|              | 5–6                       | \(y = -0.0002x^3 + 0.04x^2 - 1.97x + 28.95\) | 1 | \(y = -0.0001 \times 3 + 0.03 \times 2 - 1.29x + 20.16\) | 1 |
|              | 6–7                       | \(y = -0.0005x^3 + 0.085x^2 - 4.35x + 65\) | 1 | \(y = -0.0003 \times 3 + 0.05 \times 2 - 2.86x + 46.9\) | 1 |
|              | 7–7.5                     | \(y = -0.0003x^3 + 0.18x^2 - 6.15x + 94\) | 1 | \(y = -0.0004 \times 3 + 0.076 \times 2 - 4.15x + 71.2\) | 1 |

Note: \(y\): Probability of each state of damage and \(x\): distance between the earthquake epicentre to each feature (km).
4.4. Simultaneous change in magnitude and focal distance

As changes in the non-damage probability for the input parameters of magnitude and distance are more effective than changes in the focal depth, the effects of changing both factors (magnitude and distance) to each component are considered, and the results are shown in Figure 12(a,b). Based on the results, the gradient of changes in the non-damage probability of both types of infrastructure is not equal and it changes from 4 to 5 on the Richter scale, while, the gradient is almost constant in the ranges, 5–6, 6–7 and 7–7.5. Table 3 also shows the damage probability equations for all damage states for both types of infrastructure, CGS and gas station, in each damage state.

5. Conclusion

Lifelines play an important role in urban areas in which the quality and quantity of their operations and their ability to provide such services is dependent on the efficiency of how they are planned, designed, implemented and maintained. Recently, the vulnerability of lifelines to disasters has been the subject of many studies. The vulnerability of the infrastructures would have a negative impact not only on the environment and health but also result significantly increases costs and extend the recovery period. Hence, the reduction and control of the seismic hazard, especially in urban areas, is an immediate need. However, seismic hazard analysis is a complex problem that needs a combination of all reliable information in a systematic risk model to determine the exposed risk to all the components of a city.

The main aim of this study was to design an integrated loss estimation model to evaluate the earthquake damage for critical infrastructure. The desired model allows the development and implementation of an effective damage reduction program in hazardous seismic regions. In this regard, all the required data were collected and after running quality control check, they were compiled into an integrated GIS database for risk and uncertainty analysis.

Based on the seismic damage and seismic hazard analyses, six different outputs were calculated using Monte Carlo simulation with 10,000 iterations as: (1) peak ground velocity (PGA), (2) PGV, (3) PGD, (4) PGD due to vertical settlement, (5) PGD due to lateral spread and (6) PGD due to landslide. Each of these outputs was used in the earthquake loss estimation of the system. In the case of damage analysis, the probability of seismic damage for GS and GF hazards was independently determined. Then, these probabilities were combined with the probability rules of union and intersection of two events, and, finally, the seismic damage probability was determined for each component of the infrastructure for the five different damage states (none, slight, moderate, extensive and complete). It should be mentioned that for the seismic damage analysis, different parameters and relations, such as the descriptive and spatial data of each infrastructure, regional geological information, various attenuation relations, the median and beta parameters of the fragility curve for the GS hazard, vertical settlement, lateral spreading and landslides, and other different relations for seismic hazard and damage analysis were used.

Based on the achieved results, the following conclusions can be drawn:

- The PGA values are very similar in different areas of the desired case study, and their values are trended toward the north and near three faults of the city. As moderate liquefaction susceptibility and low landslide susceptibility exist in the study area, the PGD values are low in most areas due to liquefaction and landslide.
- The results of damage analysis for the CGS and gas station show that there is more moderate damage to the desired infrastructure, and so, generally, after combining the values for the five damage states based on five damage ratios, the final damage to the infrastructure is mostly moderate.
- In order to estimate the damage probability of two types of infrastructure – CGS and gas station – the best probability distribution function for all damage states is estimated and all damage possibilities for these types of infrastructure fit by lognormal distribution.
Based on the results of sensitivity analysis, it can be concluded that by increasing the median and beta parameters, the probability of damage to the infrastructure increases. Conversely, by decreasing the median up to 50%, the probability of non-damage to the infrastructure decreases by 50% of the main median value. By changing the beta parameter between different states, less change was observed in the results of the probability of non-damage. Therefore, it can be concluded that the model is not very sensitive to changes in the beta parameter.

Based on the results of sensitivity analysis for attention relationships, it can be concluded that the most pessimistic relation is Zare et al.’s relationship. The probability of the non-damage state is less than the two other relationships, while the Campbell and Bozorgnia’s method gives the highest probability of non-damage compared to the other relationships. Interestingly, the result of Zare et al.’s relationship is similar to the estimated results based on the maximum of the three relationships.

According to the sensitivity analysis for liquefaction and landslide susceptibility, changing the liquefaction and landslide susceptibility will result in large changes in the non-damage probability between the types of infrastructure. Conversely, by decreasing from non-susceptibility to moderate susceptibility, the probability of non-damage decreases up to 50%. Therefore, it can be concluded that the model is very sensitive to changes in geological susceptibility.

Based on the results of the sensitivity analysis of the grid size (cells), it can be concluded that the results of seismic hazard analysis can slightly affect the output results.

The effect of the magnitude on the output results was remarkable in which a reduction of 0.5 degrees on the Richter scale increased the probability of non-damage increases by up to 8%–10%. Interestingly, the focal depth does not affect the output results like the magnitude parameter. Hence, by increasing the focal depth up to 10 km, the probability of non-damage in the infrastructure increases in the range of 6%–8%. The impact of input parameters of focal distance is very impressive like the effect of magnitude on the results. If the location of earthquake reduces from a radius of 25 to 10 km, the probability of damage increases up to 25%, although the gradient of variation is high for low distances. Based on the high effect of magnitude and distance, both parameters are considered simultaneously for damage probability. The results of this analysis show that the damage associated with a magnitude of 1 degree and a focal distance of 25 km is almost the same as the damage for 1 degree more and a focal distance of 50 km. For instance, the probability of non-damage for a magnitude of 5 degrees on the Richter scale at a focal distance of 25 km is the same as the probability of non-damage for a magnitude of 6 degrees on the Richter scale and a focal distance of 50 km.

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