Seismic Risk Assessment of the 3rd Azerbaijan Gas Pipeline in Iran

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Abstract

A comprehensive seismic risk assessment has been performed for the existing route of the 3rd Azerbaijan natural gas buried pipeline in Iran. The major active seismic sources along the pipeline were identified and the geometrical parameters as well as the seismicity rates were determined. The seismic hazard assessment of the ground vibrations along the pipeline was performed in the framework of the Probabilistic Seismic Hazard Analysis using the CRISIS 2007 software. All of the components of the gas pipeline along the route were identified and the corresponding fragility functions are established through the methodology described in the HAZUS guideline. A detailed cost analyses was taken into consideration based on the expert opinions in the National Iranian Gas Company, in order to provide more practical loss model for the pipeline route. Also, a simple method is suggested in order to account for the vent gas in the total loss estimation. The spatial analysis of the hazard function layer in combination with the loss model layer, in Geographical Information System platform, reveal the financial consequences of different earthquake scenarios.

Keywords: *Seismic Hazard; Crisis 2007; HAZUS; Insurance, Fragility; GIS.*

1. Introduction

Natural gas pipeline is one of the most important lifeline networks that supplies the environmentally friendly hydrocarbon energy resource for industrial and domestic users. These buried or above-ground pipelines usually constitute wide-area energy delivery networks. The performance of such network during an earthquake has direct impact on economy and comfort of customers; hence, any significant disruption during energy providing process may cause a great disaster.

Buried pipelines behaviour assessment is generally relied upon past earthquake data to predict future performance and reliability. The pipeline damage is typically expressed in term of numbers of repairs occurring per unit length of pipeline (repair rate) in the common available seismic vulnerability assessment approaches. The available methods for seismic behaviour of pipelines are generally based on observations from earthquake characteristics and the corresponding pipeline seismic response. For the purpose of clarity, a brief review on some previous case studies is provided here.

In the case study, performed by Chang et al. (2008), the natural gas network of the Shelby county of Tennessee, owned by Memphis Light, Gas and Water (MLGW), was studied using the HAZUS methodology to assess the possible seismic damages to the network. The matrix-based system reliability analysis was also used to reduce the size and complexity of the large scale urban infrastructure system. Another practical methodology was conducted by Portante et al. (2009), in order to simulate the local and downstream impacts of the New Madrid and Wabash Valley seismic scenarios on natural gas transmission pipelines. Another case study was performed by Toprak et al. (2007) to estimate earthquake damage to buried pipelines caused by ground shaking. In that study, only ground shaking scenario for the city of Denizli in Turkey was taken into account by using the HAZUS methodology on the basis of the Geographical Information System (GIS). During a comprehensive seismic loss assessment project, for the state of south Carolina, which was conducted by Wong et al. (2005), the HAZUS methodology was applied to measure the expected losses corresponding to the gas pipeline in the conjunction with other lifelines. One of the major objectives in their study was to provide a reliable basis for strategic planning issue. In another research project, by Xie et al. (2000), a case study was performed for earthquake loss assessment in an oil transmission system located at Daqing oil field, China. The main objective was to provide an intelligent decision making system to be employed in the management of emergency situations. The GIS was used to analyse different data layers. Another case study, related to the gas pipeline, was performed for the Chi-Chi earthquake in Taiwan, by Hwang et al. (2004). Different ground motion intensity measures were studied, as independent variables in the vulnerability functions. To assess the seismic loss in gas pipelines, a study was conducted by Yamin et al. (2004) in Columbia. Their GIS based study integrated seismic vibration hazard with other seismic hazards including landslide, volcanic and liquefaction. A gas transmission pipeline was analysed, by Mori et al. (2012), for the great east Japan earthquake. Based on a field survey, for different damages, they developed a seismic safety assessment method for pipelines. O'Rourke et al. (2014) studied the key aspects of underground pipeline network response to the

Canterbury earthquake sequence in Christchurch, NZ, including the response of the gas distribution system to the 7.1 Mw in the case of 4th September 2010 earthquake, as well as the 22th February and 13th June events. They concluded that the excellent performance of the gas distribution network is the result of highly ductile polyethylene pipelines. For the seismic vulnerability assessment of the 500-km-long natural gas pipeline system in British Columbia, Wijewickreme et al. (2005) developed unique approaches in order to quantitatively estimate the regional seismic vulnerability. As the main aspect of this work, the liquefaction-induced lateral spreading has been characterized in a probabilistic manner and generic pipeline configurations have been modelled using finite elements. Koike et al. (2004) tried to quantify the seismic risk for the Great Tehran gas distribution system. The fault crossing, the wave effects, the liquefaction and the land-slide effects were simultaneously taken into account in that study. The current study, which is derived from a practical industrial project, aims to perform a comprehensive seismic risk assessment for the existing route of the 3rd Azerbaijan natural gas buried pipeline in Iran. The main skeleton of the implemented method is derived from the HAZUS methodology developed by the U.S. Federal Emergency Management Agency (FEMA). This methodology is one of the validated methods for seismic hazard analysis, risk assessment and producing loss estimation model. HAZUS is a general method which was developed by collecting different databases, combining researches and verification of the results with empirical data. Therefore, it can be used in any case when specific fragility curves are not available. The risk assessment in this study is discussed in these sections:

- Case study definition: The 3rd Azerbaijan gas pipeline.
- Seismic hazard model creation by using CRISIS2007 software.
- Definition of HAZUS methodology for the gas network risk assessment.
- Seismic losses, including damages to pipeline, compressor stations and monetary losses to the gas network sub-components.

The major novelty of this work is on the side of the monetary loss calculation methodology which is entirely different from that of the HAZUS proposal. According to the HAZUS technical manual, only one constant cost is proposed for repairing pipeline (break or leak). This rough estimation has significant deviation with the Iranian practical experiences and barely covers the realistic monetary loss. Based on the expert opinions in the National Iranian Gas Company (NIGC), the detailed cost analyses were provided for the both cases of the Leak and Break, separately. Another unique aspect of the proposed methodology in this paper is the vent gas calculation which is not considered in the HAZUS methodology. It is worth mentioning that, based on the results of this study, sometimes, the gas content in high pressure pipelines costs even more than the repairing cost of the damaged section.

2. The 3rd Azerbaijan Gas pipeline

Iran is one of the countries that produces and consumes natural gas for the domestic and industrial demands. The natural gas is the first energy resource in Iran since it has less environmental disadvantages compared with most of the other available energy resources. On the other hand, the seismic performance assessment of gas pipelines is an important issue in Iran as a consequence of high potential seismic activity.

For the current case study, the 3rd Azerbaijan Gas Pipeline has been studied which is located in the North-West region in Iran. The studied area includes the east-Azerbaijan and west-Azerbaijan provinces, which are located in the cold climate mountainous regions with high level of energy demand especially in the case of natural gas. The 48 inch 3rd Azerbaijan gas pipeline has been built in 2007 in order to supply the increasing demands of the natural gas for all industrial and domestic users. This 48 inches diameter pipeline has approximately 618 kilometres length. It passes throughout four provinces and supplies major part of energy demand for these provinces as seen in Fig. 1. This pipeline was designed and constructed by the NIGC. The seismic vulnerability of the compressor stations is also taken into account since four compressor stations were designed to maintain the required gas pressure and flow rate in this route.

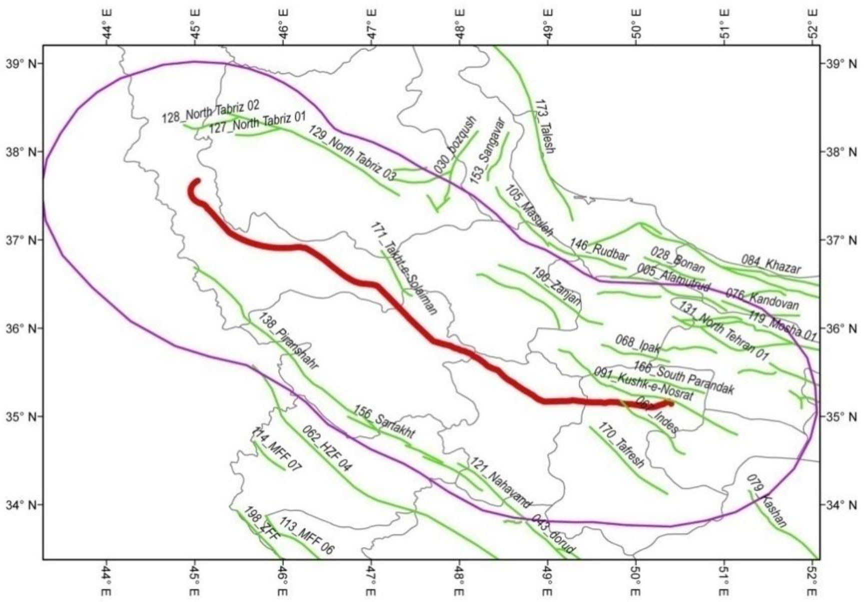

Fig. 1: The geometry input data and overall view of the pipeline route under investigation.

3. Seismic Hazard Model

Loss estimation for a gas network is fully dependent on the seismic hazard parameters i.e. Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Permanent Ground Deformation (PGD). Therefore, these parameters should be calculated in order to obtain the damage functions for all components. In order to determine PGA, PGV and PGD, the Probabilistic Seismic Hazard Analysis (PSHA) was performed by employing the CRISIS 2007 platform. The main required data for PSHA consist of three categories including (i) Source geometry, (ii) Source seismicity and (iii) Attenuation relationship.

i. The geometry of each major source was defined based on the available fault maps (Berberian 1976 & 1994) as shown in Fig.2. Each fault is modelled by assuming it as a linear source.

ii. The source seismicity data is based on the previous studies conducted by seismic researchers, after modelling all recorded seismic events by means of the historical and instrumental records (e.g. Tavakoli and Ghafory-Ashtiany, 1999). Several seismically clustering models have been established for Iran as indicated in Table 1. It is worth noting that the seismicity parameters for the considered sources on each seismic province are assumed to be the same.

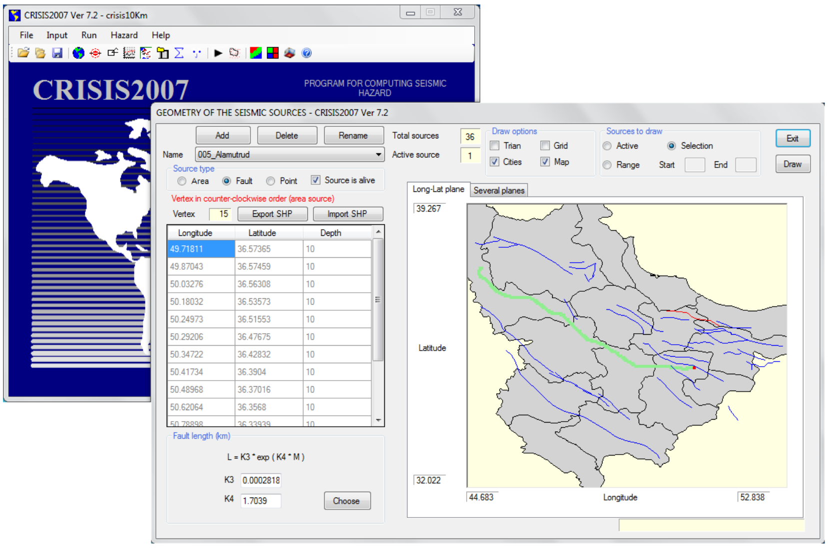

Fig.2: The source geometry menu of faults in the CRISIS 2007 software.

Table 1: Different models for seismically clustering of Iran.

Clustering Model	Year	Number of seismic Provinces
Stocklin	1968	9
Takin	1972	4
Berberian	1976	4
Nowroozi	1976	23
Tavakoli	1999	20

In this study, Tavakoli et al. 1999 model was chosen for the seismicity parameters. Two types of seismicity parameters are acceptable within the CRISIS 2007 platform, which are the Poisson model and Characteristic earthquake model. As the seismicity parameters for each seismic province are available, the Poisson model and Guttenberg-Richter parameters were selected. An area with 150 km radius around the pipeline was taken into account as the considered active region. All of the line sources inside or on the boundary were assumed as active sources. Totally, 36 main line sources contribute to the final seismic hazard. Table 2 indicates the seismicity parameters for the selected seismic provinces which comprise the mentioned line sources.

Table 2: Seismicity parameters for the selected seismic provinces by Tavakoli et al. 1999.

Province number	Time window	β	M_{max}	M(observed)	λ	Number of events	Number of faults
8	1924-1995	1.34	7.4	7.2	0.16	54	2
9	1922-1995	1.4	7.3	6.8	0.27	53	10
11	1944-1995	1.59	7.6	7.4	0.48	130	6
12	1920-1995	1.98	7.2	7	1.7	622	1

15	1927-1995	1.19	7.9	7.7	0.37	71	11
16	1900-1992	1.83	7.6	7.4	0.14	42	5
17	1907-1992	1.68	7.5	7.3	0.53	99	1

In Table 2, λ and β indicate the Guttenberg-Richter parameters and M(observed) is the maximum observed magnitude in the considered seismic province. Fig. 3 shows the chosen seismic provinces as well as the 150 km band pipeline.

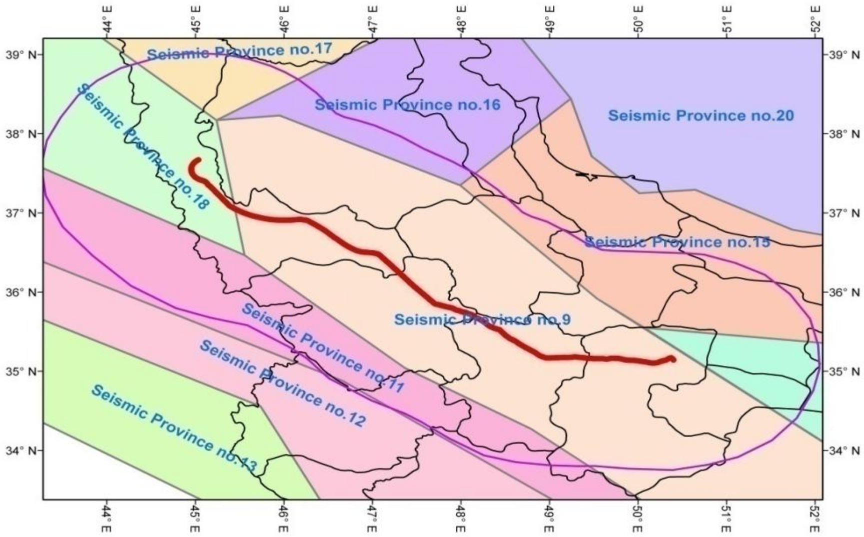

Fig. 3: The study region and contributing seismic provinces.

iii. As the third major input for CRISIS 2007, an appropriate attenuation model should be defined. CRISIS 2007 has the ability to use more than one attenuation relationship in one PSHA analysis. Despite it can employ logic tree for performing PSHA analysis, the user can specify more than one CRISIS input data files that are interpreted as branches of a logic tree. Each branch has a user-defined weight. Based on previous researches, by Mousavi et al. (2012), eight attenuation relations, which best fit to the Iranian database for the Zagros Region with the respective weightings in Table 3, have been used in this study.

Table 3: The applied attenuation models and assigned weights.

Model name	Assigned Weight
Zafarani et al. (2011)	0.182
Ghasemi et al. (2009)	0.174
Sharma et al. (2009)	0.174
Akkar and Bommer (2010)	0.098
Abrahamson and Silva (2008)	0.096
Boore and Atkinson (2008)	0.087
Chiou and Youngs (2008)	0.097
Kalkan and Gulkan (2004)	0.092

Zafarani's model is based on a finite source stochastic approach to be used in the Zagros region, Iran (Zafarani et al 2011). Ghasemi's model is developed based on Iranian recoded ground motions and some selected West-Eurasian records (Ghasemi et al 2009). Sharma's model was derived to be applied for the Indian Himalaya (Sharma et al. 2009). However, due to the lack of data from India, additional strong-motion data were included from the Zagros region of Iran which has comparable seismo-tectonics to the Himalaya. For the Akkar and Bommer 2010, (AB10) a wide range of ground motion data from the Europe and Middle East has been applied to develop the AB10 model. Abrahamson and Silva 2008 (AS08) model is applicable to magnitudes 5-8.5, distances 0-200 km, and spectral periods of 0-10 sec. Boor and Atkinson introduced a model in 2008 (BA08) which the main predictor variables are moment magnitude M, closest horizontal distance to the surface projection of the fault plane (R_{JB}), and the time-averaged shear-wave velocity from the surface to 30 meters. Chiou and Youngs (CY08) limit the data to recordings within 70 km of the earthquake rupture in order to remove the effects of bias in the strong motion data sample.

Now all of essential inputs are prepared to perform PSHA. The expected PGA contour corresponding to the 475 years return period is seen in Fig. 4. Also, Fig. 5 shows the expected spectral acceleration corresponding to 475 years return period for the given site.

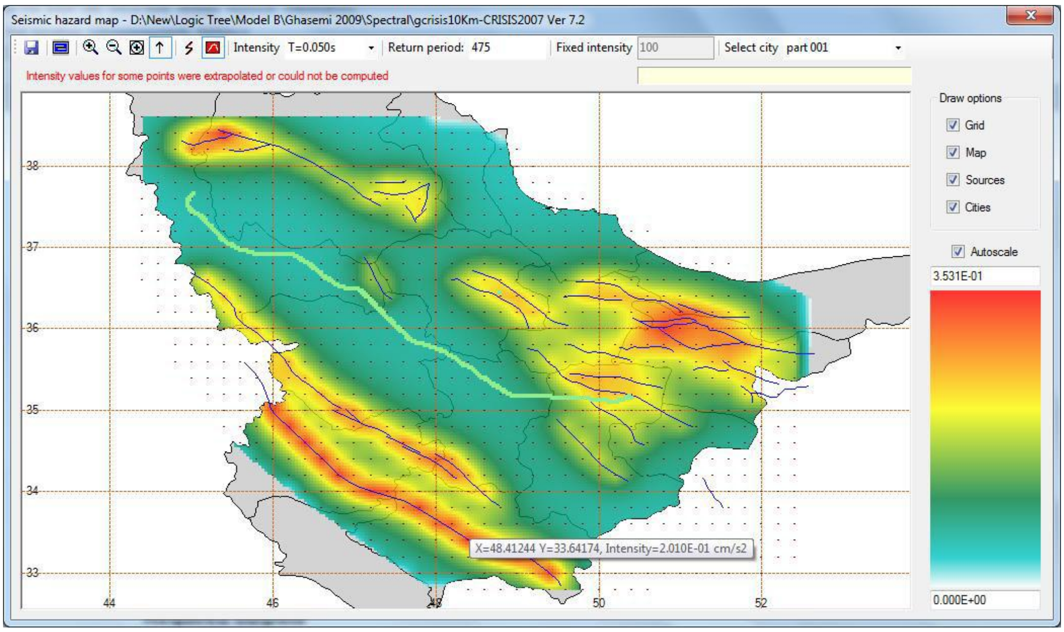

Fig. 4: The expected PGA contour corresponding to the 475 years return period.

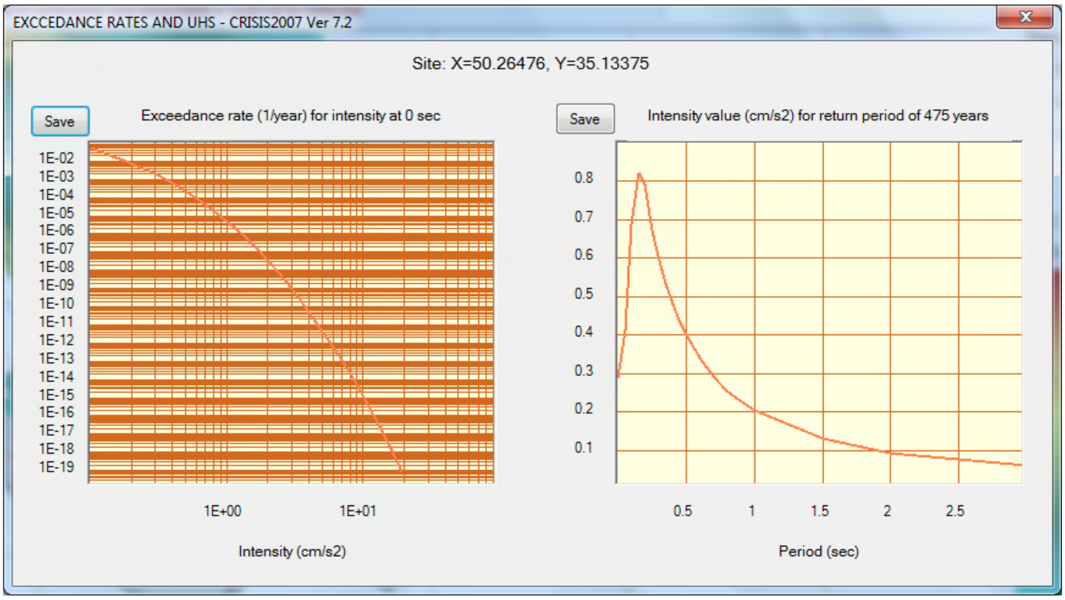

Fig. 5: The expected spectral acceleration and hazard curve corresponding to the 475 years return period.

The uncertainty treatment is regarded as an inseparable part of the PSHA procedure. The modern PSHA studies distinguish between two types of uncertainties, namely epistemic uncertainty and aleatory variability. The size, location and time of the next earthquake and details of ground motion are examples of quantities considered as aleatory variability. The treatment of this type of uncertainty is performed via integration process which finally leads to a given site specific hazard curve. The second category of uncertainty is epistemic which results from imperfect knowledge about the process of earthquake generation. The seismicity modelling and the selection of attenuation model are examples of epistemic uncertainties. The epistemic uncertainties are treated via incorporating multiple hypotheses, models or parameter values. The epistemic uncertainties are usually considered by means of logic trees. It has been demonstrated that the uncertainty corresponding to the selection of the attenuation model tends to exert the dominant influence on the hazard results comparing with the seismicity modeling uncertainties (Toro 2006). In this study, the uncertainty treatment is limited to the attenuation model selection via logic tree approach.

The typical PSHA procedure is used for site-specific analysis. However, for systems, such as oil and gas pipelines, transportation networks, and power systems, the site-specific hazard analysis does not suffice. Therefore, the spatial correlation between earthquake ground motion across several sites should be taken into account in determining the system functionality (Jayaram and Baker

2009). As reported by Park et al. (2007), ignoring these correlations reduces the accuracy of monetary loss calculations. Lee and Kiremidjian (2007), Chang et al. (2000), and Decò and Frangopol (2013) are mentionable studies which addressed this concern. As another limitation, this issue has been neglected in the current research for the purpose of simplicity.

4. HAZUS Methodology for Gas Networks

HAZUS is a widely used methodology in order to assess seismic risk and estimate probable future losses. The earthquake loss estimation methodology provides the necessary tools for decision makers to plan and stimulate efforts to reduce risk from earthquakes and to prepare for emergency response and recovery. The methodology also provides the basis for assessment of nationwide risks of earthquake loss. In this study, the theory documented in the HAZUS technical manual was implemented on the basis of the ArcGIS as a well-known GIS mapping platform.

According to HAZUS, the lifelines are divided into two major categories which are the transportation and utility systems. The natural gas network is one of the utility system subcomponents. A natural gas network consists of compressor stations and buried or above ground pipelines. All of these components are vulnerable under a severe earthquake. The corresponding losses are classified into two different categories including direct and indirect losses. The inventory data required, for natural gas systems analysis, include the geographical location and classification of system components, PGA, PGV and PGD. In the loss analysis side, also the replacement cost for facilities and the repair cost for pipelines are required.

Based on the HAZUS technical manual, damages to a natural gas system shall be divided into two subsystems, which are compressor stations and pipelines. Compressor stations are mostly vulnerable to PGA and also PGD if located in a liquefiable or landslide zones. On the other hand, pipelines are vulnerable to PGV and also PGD only in the case of liquefiable or landslide threats.

4.1. Required hazard parameters

As mentioned above, to assess seismic damages to a natural gas system, it is necessary to calculate PGA, PGV and PGD. In our study, PGA is applicable for the compressor stations. Compressor stations in this study are located in non liquefiable ground. Hence, there is no need to study PGD damage algorithm. The PSHA results make it possible to find out PGA for these points. The damage functions or fragility curves for compressor stations in HAZUS are modelled as log-normally-distributed functions that give the probability of exceeding different damage states for a given level of ground motion (quantified in terms of PGA) as shown in Table 4.

As an important limitation of the roughly proposed fragility curves in HAZUS, the active fault crossing effects on the gas pipeline are not included. Therefore, the accuracy of the resulted loss should be suspected in the specified situations. The step-like permanent ground deformation, induced by the active crossing faults to the pipeline, has been reported as a significant factor of rupture (i.e. Uzarski and Arnold 2001). Hence, numerous studies have been focused on the numerical and experimental analysis of this issue (i.e. Karamitros et al. 2007, Takada et al. 2001, Trifonov and Chemity 2010, Vazouras et al. 2012, Xie et al. 2013). Fortunately, as shows in Fig. 4, the 3rd Azerbaijan gas pipeline is not crossed by any fault and therefore, the HAZUS rough fragility curves seem to be satisfactory.

Table 4: Definition of fragility curves for the compressor stations (**HAZUS Technical Manual)**

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**Beta**
Plants with anchored components	Slight/minor	0.15	0.75
	Moderate	0.34	0.65
	Extensive	0.77	0.65
	Complete	1.50	0.80
Plants with unanchored components	Slight/minor	0.12	0.60
	Moderate	0.24	0.60
	Extensive	0.77	0.65
	Complete	1.50	0.80

4.1.1. PGV calculation

Some of the attenuation relationships have the ability to explicitly calculate PGV and do not need any additional modification. However, some of the attenuation models can only calculate spectral acceleration quantities. To deal with this problem, HAZUS technical manual recommends to use an empirical relationship to calculate PGV as a function of Spectral Acceleration at T=1 sec as written in Equation (1).

$$PGV = \left(\frac{386.4}{2\pi} * S_{a1}\right)/1.65 \qquad [1]$$

where S_{a1} is the spectral acceleration at one second period. It is obvious that the prediction of PGV from spectral acceleration may lead to higher degrees of uncertainty compared with the direct calculation procedure. Therefore, using the above formula makes it possible to calculate PGV for all pipe length. It is worth mentioning that the studied pipeline was divided into equally two kilometres length segments and PGV was calculated for each segment.

4.1.2. PGD calculation

The PGD represents three types of ground failure: surface rupture, land sliding and liquefaction. Since the co-seismic fault slip at depth does not usually propagate to the earth's surface in the Zagros region (Talebian and Jackson 2004), keeping in mind that surface rupture is very rare in the Zagros region earthquakes, therefore, this source of PGD was neglected in this study. The landslide hazard was also ignored due to the soil/geologic conditions of the studied region. The geological investigations showed that the soil is dry and also has slope angle is below five degrees in the majority sections of the route. Thus, the liquefaction was assumed as the only source of the probable PGD.

The liquefaction susceptibility map is provided by the International Institute of Earthquake Engineering and Seismology (IIEES) based on the previous studies by Komakpanah et al. (1995) as seen in Fig. 6. According to this Figure, none of the compressor stations are located in the liquefaction zones. Therefore, the loss associated by PGD is neglected for compressor stations. However, some parts of the route are placed in the moderately susceptible zone.

The probability of liquefaction occurrence, at a given site, is primarily affected by the susceptibility of the soil and the amplitude of ground motions. Based on the statistical modelling of the empirical liquefaction catalogue, presented by Liao et al. 1988, Equation (2) has been proposed to roughly estimate the conditional liquefaction probability for the moderately susceptible zones at a specified level of PGA:

$$P\left[Liquifaction \middle| PGA = pga \right] = 6.67\, pga - 1 \qquad [2]$$

$$0 \le P\left[Liquifaction \middle| PGA = pga \right] \le 1.0$$

The above Equation has been developed for M=7.5 earthquake moment magnitude, and for five feet ground water depth. The chance of liquefaction is significantly affected by ground shaking duration as reflected by earthquake magnitude, M, as well as the ground water depth. Hence, as suggested by HAZUS, the probability of liquefaction can be determined as written in Equation (3):

$$P\left[Liquifaction \right] = \frac{P\left[Liquifaction \middle| PGA = pga \right]}{K_M . K_W} P_{ml} \qquad [3]$$

where, K_M is the moment magnitude correction factor:

$$K_M = 0.0027M^3 - 0.0267M^2 - 0.2055M + 2.9188 \qquad [4]$$

K_W is the correction factor for ground water depths other than 5 feets:

$$K_W = 0.022 d_w + 0.93 \qquad [5]$$

d_w denotes the depth to the ground water in feet; and P_{ml} is a correction factor equal by 0.10 for moderately susceptible soils, as proposed by HAZUS.

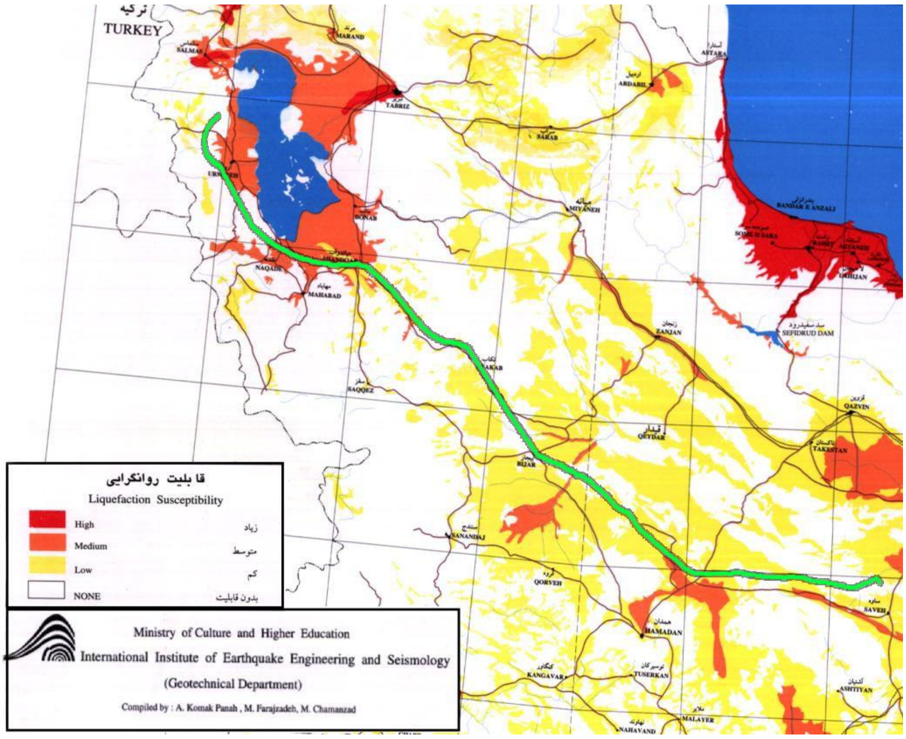

Fig. 6: Liquefaction susceptibility map provided by IIEES, Source: Komakpanah et al. (1995)

The expected value of PGD conditioned to the occurrence of liquefaction can be stated as a function of PGA (Sadigh et al 1986):

$$E[PGD|liquefaction] = \begin{cases} 12\dfrac{PGA}{PGA(t)} - 12 & 1 < \dfrac{PGA}{PGA(t)} < 2 \\ 18\dfrac{PGA}{PGA(t)} - 24 & 2 < \dfrac{PGA}{PGA(t)} < 3 \\ 70\dfrac{PGA}{PGA(t)} - 180 & 3 < \dfrac{PGA}{PGA(t)} < 4 \end{cases} \quad [6]$$

where PGA(t) is the threshold ground acceleration to induce liquefaction, roughly equal by 0.15g for moderately susceptible soils. The above relationship is based on M=7.5 earthquakes and can be extended to the other magnitudes if being multiplied by the correction factor K_Δ (Seed and Idriss 1982) ;

$$K_\Delta = 0.0086M^3 - 0.0914M^2 + 0.4698M - 0.9835 \quad [7]$$

Here in this study, the ground water depth conservatively assumed to be five feet in the susceptible regions and the moment magnitude was taken from Tavakoli and Ghafory Ashtiany model's (1999) [Table 2] maximum magnitude. By performing the aforementioned procedure in the GIS platform, the probability of liquefaction as well as the expected value of PGD conditioned to the liquefaction occurrence is in hand to calculate the repair rates of the pipeline in different hazard levels i.e. 475 or 2500 years return periods.

5. Seismic Loss

5.1. Pipeline damage

According to the HAZUS, it is assumed that the pipeline damages, subjected to earthquakes, are independent from the pipe size, pipe class, and mechanical specifications. The only available classification for the pipeline is either brittle or ductile. The brittle pipeline is commonly old ones with gas welded joints and the ductile type is steel pipeline with welded joints. The 3rd Azerbaijan gas pipeline is taken as the ductile pipeline type.

The required inputs to estimate the damage to the given Natural Gas pipeline are: Geographic location of the pipe links, PGV, PGD and pipeline classification (Brittle or Ductile). The considered pipeline may encounter two damage states which are leak and break. Generally when a pipe is damaged due to the ground failure, the type of damage is likely to be a break whereas the type of damage is likely to be a leak when the pipe is damaged due to seismic wave propagation. In the loss methodology, it is assumed that the damage due to seismic waves consists of 80% leaks and 20% breaks, while damage due to ground failure consists of 20% leaks and 80% breaks.

5.1.1. Pipeline Repair Rate due to wave propagation (PGV Algorithm)

Based on the post empirical studies by O'Rourke and Ayala (1993) on the pipelines in the four U.S. and two Mexican earthquakes, the damage functions for pipelines due to ground shaking were established. Equation (8) expresses the relationship which represents a reasonable fit to the mentioned empirical data.

$$Repair\ Rate[Repairs/Km] \cong 0.0001 * (PGV)^{2.25} \quad [8]$$

where PGV is the peak ground velocity (cm/sec). Equation (2) is assumed to be applied to brittle pipelines. Ductile pipelines experience 70% less damage than the brittle ones. Hence, the above relationship for the ductile pipelines should be multiplied by 0.3 to fit to the corresponding empirical data. This rough reduction has been also proposed in the HAZUS technical manual.

By applying Equation (2), the repair rates is calculated for the pipeline in two hazard levels i.e. 475 and 2500 years return periods. Table 5 shows some of the calculated numbers of Leaks and Breaks in each two kilometres segment, and summation of damages along the 618 km pipeline.

Based on the resulted repair rates, as seen in Table 5, the pipeline is classified into six vulnerable classes as described in Table 6. Extensive, very high, moderate high, high, moderate, and low are the defined classes of vulnerability. Fig. 7 shows the distribution of repair rate along the pipeline. The vulnerability of the pipeline increases in direction from the north-west to sought-east, as it is obvious in Fig.8. This result is compatible with the hazard distribution, as shown in Fig 4.

Table 5: The expected repair numbers, leaks and breaks along pipeline in 475 and 2500 years return periods.

	Return Period, 475 years				Return Period, 2500 years			
Length (m)	PGV	Repair no.	Leaks	Breaks	PGV	Repair no.	Leaks	Breaks
2000	18.45	0.042329	0.033864	0.008466	27.69	0.10553	0.084424	0.021106
2000	18.65	0.043369	0.034694	0.008674	28.05	0.108643	0.086914	0.021728
2000	18.52	0.042692	0.034154	0.008538	27.86	0.106994	0.085595	0.021399
2000	18.44	0.042278	0.033822	0.008456	27.74	0.10596	0.084768	0.021192
.	.	.	.	.	.	.	.	.
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SUM: 618Km		4.063306	3.250671	0.812652		10.088101	8.070484	2.017629

Table 6: The defined vulnerability classes.

Vulnerability level	Repair Rate Range
Extensive	0.040 - 0.059
Very High	0.026 - 0.039
Moderate High	0.018 - 0.025
High	0.013 - 0.017
Moderate	0.009 - 0.012
Low	0.004 - 0.008

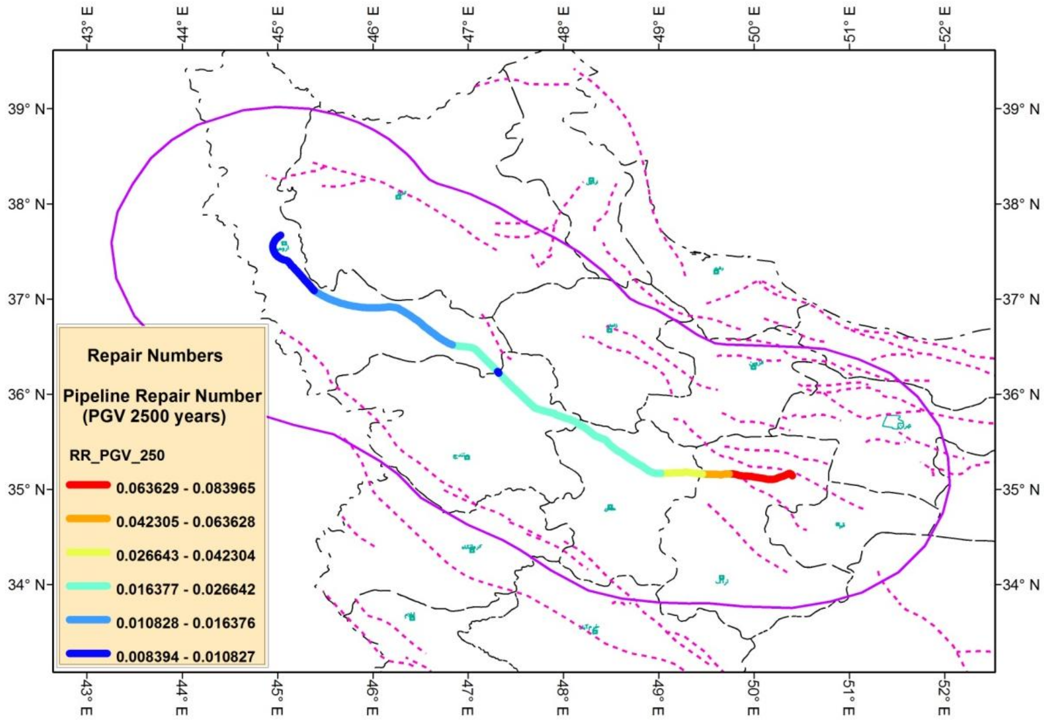

Fig. 7: The distribution of vulnerability along the pipeline.

5.1.2. Pipeline Repair Rate due to ground failure (PGD Algorithm)

The damage algorithm for buried pipelines due to ground failure is based on research conducted by Honegger and Eguchi (1992) for the San Diego County Water Authority (SDCWA). Equation (9) shows the best-fit function to the fragility curve for the pipeline subjected to PGD.

$$Repair\ Rate\left(\frac{Repair}{Km}\right) \cong Probability[Liquefaction] \times PGD^{(0.56)} \qquad [9]$$

where PGD expressed in inches. Both the probability of liquefaction and expected value of PGD were described in Section 4. This relationship is also applied for the brittle pipelines. For the ductile type, this rate should be multiplied by 0.3, as proposed by HAZUS.

The repair rate, due to ground failure, is calculated using Equation (3). To estimate probable damages to pipeline, PGD values along the pipeline segments are calculated. The total amount of these parameters is shown in Table 7. As seen in Table 7, PGD and repair numbers are calculated and presented. Based on the HAZUS methodology, damages caused by PGD consist of 80% breaks and 20% of leaks.

Table 7: Total amount of Ground Failure parameters.

Parameter Name	Total amount along whole pipeline
Expected PGD 475 years (inches)	63.280
Expected PGD 2500 years (inches)	713.294
Ground Settlement 475 years (inches)	0.6042
Ground Settlement 2500 years (inches)	4.3369
Repair Number 475 years	4.082
Break number 475 years	3.265
Leak number 475 years	0.817
Repair Number 2500 years	5.844
Break number 2500 years	4.675
Leak number 2500 years	1.169
Pipeline Length (Kilometres)	618

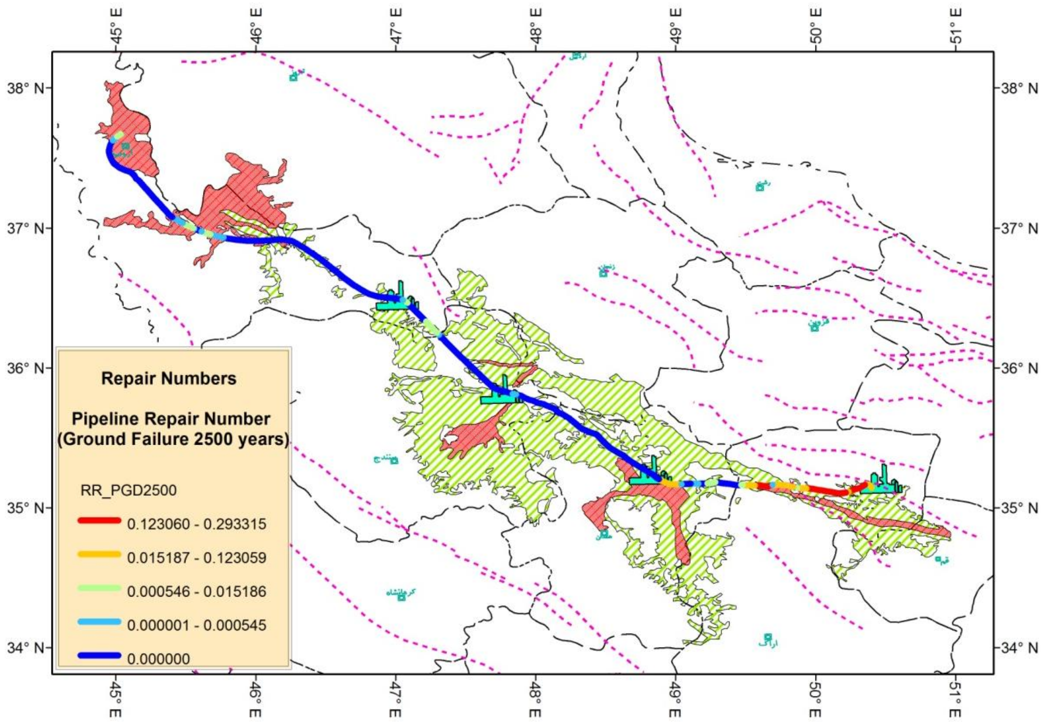

Fig. 8: Repair number caused by Ground Failure for 2475 years return period.

5.2. Compressor Station damage ratio

All of the compressor stations, along the pipeline, have anchored subcomponents and are classified as anchored facilities. Therefore, the required parameters, in order to calculate the probability of exceeding a certain damage state, are derived from Table 4 or fragility curves which are shown in Fig. 9. Five damage states are considered for the compressor stations: (1) None, (2) Minor/Slight, (3) Moderate, (4) Extensive and (5) Complete. PGA is the main important parameter for the compressor stations damage ratio. It was derived from the logic tree combination based on PSHA as described in "Seismic hazard model" section for the four compressor stations in the two considered hazard levels (i.e. 475 and 2500 years return period). The probability for each damage state is calculated using PGA and data in Fig. 9. The calculated parameters and probabilities are presented in Table 8.

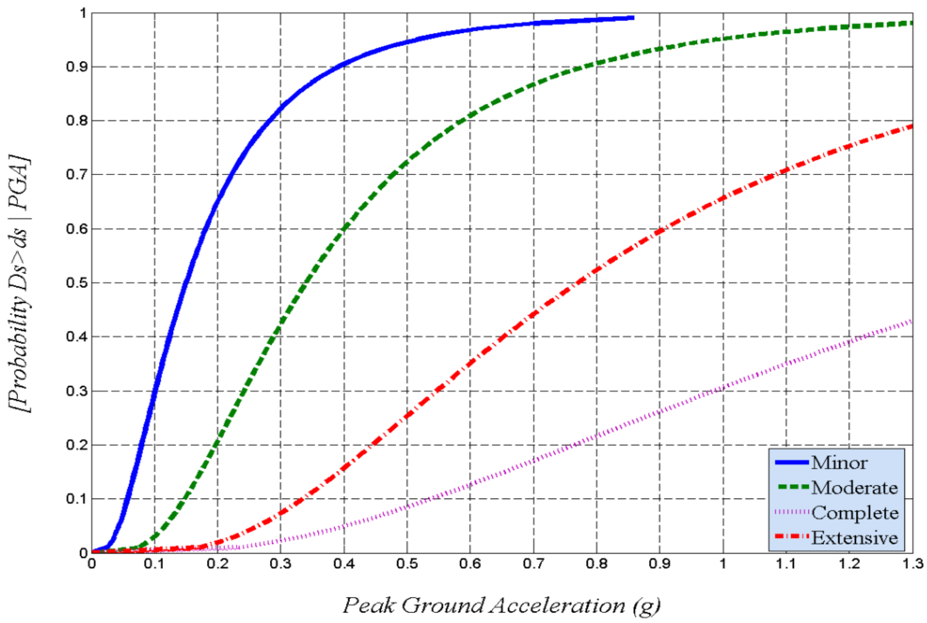

Fig. 9: Fragility curve for compressor stations with anchored subcomponents.

Table 8: Damages states probability for compressor stations for 475 and 2500 years return period.

Station Name	PGA 475 years (g)	No Damage	Minor	Moderate	Extensive	Complete
Saveh	0.24	27 %	47 %	22 %	3 %	1 %
Hamadan	0.11	77 %	21 %	2 %	0 %	0 %
Bijar	0.09	78 %	20 %	2 %	0 %	0 %
Takab	0.12	60 %	35 %	4 %	1 %	0 %

Table 8. (Continued).

Station Name	PGA 2500 years (g)	No Damage	Minor	Moderate	Extensive	Complete
Saveh	0.46	13 %	24 %	43 %	13 %	7 %
Hamadan	0.18	42 %	43 %	14 %	1 %	0 %
Bijar	0.15	45 %	34 %	21 %	0 %	0 %
Takab	0.25	22 %	55 %	19 %	3 %	1 %

5.3. Monetary loss for pipeline

The monetary losses are calculated based on the Iranian practice and local conditions. In this case, losses are calculated by means of expert opinions in NIGC. In this study, only the direct loss was taken into account. The direct loss for the gas pipeline consists of two major parts: (1) the vented gas cost, and (2) the repair cost.

5.3.1. The vented Gas Cost

Usually repairing the damaged gas pipeline includes welding procedure and grinding for polishing the surface. As the natural gas is explosive, it is necessary to completely vent the pipeline section gas before welding procedure. The isolation and then ventilation tasks are applicable by using Line Break Valve (LBV) among the pipeline in each 20 km. This type of valve has the ability to sense pipeline breaks at the upstream or downstream and shuts off the line immediately in the associated section. In the case of line break or line leak, the closest two LBVs to the damaged joint isolate the pipe section and only the containing gas of this section is vented for the purpose of repairing. Therefore, this amount of vented gas is the wasted gas. By assuming the average working pressure of pipeline equal to 55 bars, and the natural gas as an ideal gas, the wasted gas volume is calculated as written in Equation (10).

$$V = \frac{\pi D^2}{4} * L * P_{ave} \qquad [10]$$

where V indicates the volume of wasted gas with the standard pressure (1 bar), D indicates the pipe diameter, L is the pipeline segment length and P_{ave} is the average working pressure. In the case of current study, the wasted gas volume is 1,284,000 cubic meter. Each cubic meter is about 35.315 cubic feet and one thousand cubic feet of natural gas costs approximately 4.5 U.S. dollars. Therefore, the vented gas price per repair is approximately 204,000 U.S. dollars.

5.3.2. The Pipeline Repair Cost

The pipeline repair cost is approximately 5 to 7 times more than the construction procedure as a consequence of the mobilization costs, machinery transfer for each repair and lack of time for pressurizing the line after repair to make the line alive. 5000 U.S. dollars for repairing a meter of 48 inch gas pipeline has been considered in this study as a reasonable estimation. The pipeline repair procedure (and consequently the corresponding cost) differs for the leak and break cases as describes below.

In the case of leak, after the LBVs closure, the containing gas is vented. Then, the soil backfill and the corrosion protection cover are removed and the pipeline surface is completely cleaned. The repair procedure can be either based on pipe section replacement or using sleeves. The leaked section is repaired by covering the leaked section with another pipe segment named sleeve and fully welding its whole around. The normal sleeve width for 48 inch diameter pipeline is about 70 cm. In the case of extensive leaks, the pipe section needs to be replaced. *The repair cost for a common leak is approximately 3500 U.S. dollars*.

In the case of break, the pipeline acts as a pressure vessel and immediately explodes because of its own internal pressure. The explosion implies an extremely high stress to the pipe body on the extended area. The explosion force can highly affect the pipeline, for example, it may cause local buckling or bend the pipe in a large deformation way. In some cases, neighbour welded joints were extremely affected and needed to be repaired. For the break damage state, usually one or more pipes are necessary to be replaced. It is assumed, in this study, that only one complete pipe with 12 meters length should be replaced for each break. Therefore, the *repair cost for each pipeline repair is approximately 60,000 U.S. dollars*.

Table 9: Damage to Pipeline and Loss for 475 Years Return Period.

Damage to Pipeline and Loss for 475 Years Return Period						
		Number of leak	Number of break	Vented gas cost	Pipe repair cost	**Total loss**
PGV Algorithm	Equation 2	*3.2*	*0.8*	*816,000*	*59,200*	***875,200***

PGD Algorithm	Equation 3	*0.8*	*3.2*	*816,000*	*194,800*	***1,010,800***

Table 10: Damage to Pipeline and Loss for 2500 Years Return Period.

Damage to Pipeline and Loss for 2500 Years Return Period						
		Number of leak	Number of break	Vented gas cost	Pipe repair cost	**Total loss**
PGV Algorithm	Equation 2	*8*	*2*	*2,040,000*	*148,000*	***2,188,000***
PGD Algorithm	Equation 3	*1.2*	*4.7*	*1,203,600*	*286,200*	***1,489,800***

5.4. Monetary Loss for the Compressor Stations

The HAZUS methodology divides a compressor station into four subcomponents: (1) Electric Backup power (Fig. 10), (2) Pump (Fig. **11**), (3) Building (Fig. 12) and (4) Electrical/Mechanical Equipment (Fig. 13) with their respective fraction of total compressor station value. A common compressor station for the 3rd Azerbaijan Gas Pipeline with all its subcomponents costs approximately 40 million U.S. dollars.

Fig. 10: Electric backup power.

Fig. 11: Pump.

Fig. 12: Building.

Fig. 13: Electrical/Mechanical equipments.

The damage ratio for the subcomponents of each compressor station was calculated by using the probability of being in a certain damage state as seen in Table 11 and Table 12. It is worth noting that the damage ratio, for each subcomponent, is calculated based on its own fragility function. Additionally, the total damage ratio, for each compressor station in the two intensity levels (i.e. 475 and 2500 years return period), was calculated as written in the last row of each table. Finally, the corresponding monetary loss, caused by PGA for 475 and 2500 years return period, was calculated.

Table 11: Calculation results for Compressor Stations Monetary Losses (475 Years Return Period).

Subcomponents	*Fraction of Total Component Value*	*Damage Ratio for 475 years return period*			
		Saveh	Hamadan	Bijar	Takab
Electric Backup Power	30%	0.1186	0.0069	0.0042	0.0214
Pump	20%	0.0006	0. 000112	0.000092	0.0001226
Building	20%	0.179	0.0538	0.036842	0.0626
Electrical/Mechanical Equipment	30%	0.0054	0.00042	0.000345	0.0004596
Total	***100%***	***7.312%***	***1.29784%***	***0.87503%***	***1.91024%***
Compressor Station Monetary Loss		***$2,924,800***	***$519,136***	***$350,012***	***$764,096***
Total Monetary Loss for Compressor Stations			***$4,558,044***		

Table 12: Calculation results for Compressor Stations Monetary Losses (2500 Years Return Period).

Subcomponents	*Fraction of Total Component Value*	*Damage Ratio for 2500 years return period*			
		Saveh	Hamadan	Bijar	Takab
Electric Backup Power	30%	0.0184	0.0011	0.00055	0.0013
Pump	20%	0.0096	0.0002	0.000152	0.000736
Building	20%	0.4637	0.12	0.0906	0.1892
Electrical/Mechanical Equipment	30%	0.0588	0.0012	0.0006	0.006264
Total	***100%***	***11.782%***	***2.473%***	***1.84954%***	***4.02564%***
Compressor Station Monetary Loss		***$4,712,800***	***$989,200***	***$739,816***	***$1,610,256***
Total Monetary Loss for Compressor Stations			***$8,052,072***		

5.5. Total monetary loss for Gas System

As previously discussed, the monetary losses for the two hazard levels of 475 and 2500 years were calculated as followings:

Total loss for 475 years return period: *Pipeline:* *1,886,000 $*

Compressor Station: *4,558,044 $*

Total loss for 2500 years return period: *Pipeline:* *3,677,800 $*

Compressor Station: *8,052,072 $*

The comparison of the monetary loss by the corresponding hazard distribution is interesting. Table 13 shows the monetary loss for the compressor stations and PGA values in two hazard levels (475 and 2500 years). The compatibility of PGA values with the associated monetary loss is completely obvious.

Table 133: Comparison of the monetary loss by the corresponding hazard in compressor stations

Compressor station	*PGA (475 years)*	*Monetary loss (475 years)*	*PGA (2500 years)*	*Monetary loss (2500 years)*
Saveh	0.2399	$2,924,800	0.461	$4,712,800
Hamadan	0.107	$519,136	0.183	$989,200
Bijar	0.0896	$350,012	0.1531	$739,816
Takab	0.1189	$764,096	0.2457	$1,610,256

The sensitivity analysis of the final monetary loss versus the attenuation models is studied here as the final issue. As stated in the aforementioned hazard section, the selection of attenuation models plays the dominant role in the PSHA uncertainty concern. Consequently, the assigned weights for different attenuation models shall be done with enough thoughtfulness. It is not so strange that the monetary loss is also influenced by the attenuation models. Table 14 compares the calculated monetary loss for the pipeline when different prior-introduced attenuation models were solely utilized.

Table 144: The sensitivity of pipeline monetary loss to different attenuation models

Attenuation model	*Pipeline Monetary Loss (475 years)*	*Pipeline Monetary Loss (2500 years)*
Zafarani et al. (2011)	*$3,572,440*	*$7,529,880*
Ghasemi et al. (2009)	*$1,738,600*	*$2,597,760*
Sharma et al. (2009)	*$993,920*	*$1,886,520*
Akkar and Bommer (2010)	*$1,412,360*	*$3,064,840*
Abrahamson and Silva (2008)	*$2,492,400*	*$5,631,200*
Boore and Atkinson (2008)	*$830,800*	*$3,157,040*
Chiou and Youngs (2008)	*$1,412,360*	*$6,895,640*
Kalkan and Gulkan (2004)	*$1,560,280*	*$3,739,600*
Logic Tree combination	***$1,886,000***	***$3,677,800***

6. CONCLUSIONS

The main aim in this study is to estimate the corresponding loss during and after a probable future earthquake in the region of the 3rd Azerbaijan gas pipeline in Iran. All of analyses were performed with spatial coordinates and on the GIS basis. In addition to the PSHA procedure along the pipeline, the HAZUS methodology was also implemented as the main skeleton for the loss estimation purpose. Due to incompatibility of the HAZUS approach with the domestic practices for the pipeline repairing cost analysis, a different methodology was proposed for more accurate monetary loss estimation. Including the vent gas cost in the total loss model can be accounted as one unique aspect of the proposed methodology. The final results reveal that the financial loss, corresponding to 475 and 2475 years return period earthquakes, respectively, exceeds 6.4 and 11.7 million dollars which highlight the necessity for a reasonable risk mitigation plan.

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