Seismic fragility assessment of equipment and support structure in a unit of a petrochemical plant

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Abstract

Petrochemical plants and industrial facilities have shown high vulnerability during the past earthquakes like Kobe (Japan, 1995), Izmit (Turkey, 1999), Gujarat (India, 2001), Tokachi-Oki (Japan, 2003) and other earthquakes. As more than 50% of the petrochemical and refineries in Iran are located on hazardous areas, it is absolutely essential to allocate a great deal of attention to such places. Apart from economic impacts, damage to such facilities may have considerable effects on peoples' lives. Therefore, it is extremely vital to try to prevent natural disasters from damaging these highly regarded sites. For this reason, this research aims to investigate the seismic fragility of equipment and support structure in a unit that is located in Shiraz-Iran. In so doing, their impact on the overall vulnerability of petrochemical plant will be evaluated. As one of the common methods for this aim seismic risk assessment should be done, and IDA (incremental dynamic analysis) method_a probability method_is utilized. Seismic risk assessment in petrochemical plants plays a key role in making decisions for risk management strategies such as retrofit, etc. For this purpose, seismic risk assessment of equipment and support structure as a section of a petrochemical plant are evaluated. To fulfil the main goal of the research, in this project fragility curves are used to explain the seismic vulnerability of structure. In this method, failure modes are selected based on damages caused by past earthquakes. Shear failure of bolts have been considered as a failure mode of equipment and inter story drift ratio have been considered as failure mode of support structure. Peak ground acceleration is chosen as an earthquake intensity measure. In order to develop seismic fragility curves, created models are subjected to 40 ground motion records, each scaled to multiple levels of intensity to perform incremental dynamic analysis using Seismostruct software. Numerical results represent the significant influence of essential and hazardous equipment on the seismic fragility of the under-study unit of petrochemical plant. Final results show that the equipment that is located on fifth story is the most vulnerable component of the unit.

Keywords Seismic fragility · Support structure · Equipment · Incremental dynamic analysis

1 Introduction

Direct damages, due to seismic shaking and indirect damage which are caused by secondary effects (e.g. liquefaction, soil densification and landslides), make the seismic risk one of the most common causes of structural failures among natural disasters [1]. The earthquakes of Kobe (Japan, 1995), Izmit (Turkey, 1999), Gujarat (India, 2001),

Tokachi-Oki (Japan, 2003) and the Katrina tornado in the East Coast of the United States (2005) are natural disasters that happened during last years. The mentioned events made it clear that natural disasters can cause a considerable loss to petrochemical and industrial plants, as they usually release dangerous substances and create emergency situations which can be really hard to control. These facts justify the need to adjust the risk analysis procedures

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to natural events, and to recast the actual planning rules, which often do not take into account natural actions to industrial plants. The following features can be considered for petrochemical plants: airtight environments, high temperature and pressure, and natural substances and products which are highly flammable, toxic, and corrosive. Catching fire in daily outputs due to a number of factors can happen in this process. After a powerful earthquake, fires are likely to happen in petrochemical refineries with the leakage of flammable materials which can lead to a blow-up. Friction sparks or open blazes will damage workshops, equipment, containers, and other structures [2]. Therefore, it would be really crucial to evaluate the seismic vulnerability of these structure which was carried out in this study. The main purpose of the study is based on assessing the seismic fragility curves of a unit of a petrochemical plant which is located in Shiraz, Iran.

Deterministic method, assessing seismic risk, is based on the maximum credible intensity of earthquake. The interplay of the earthquake vibration with equipment could make a conservative estimate of the following accidental scenario, which can lead to a loss of material or energy. In the above form, the deterministic method often leads to considerable overestimation of the risk, so that such a risk grade becomes economically unsustainable.

Since uncertainties are clearly taken into account and described by probability distribution, and the uncertainties which are related to the initial conditions, seismic scenarios are usually too large, leading analysts to use a probabilistic approach [3].

In order to clarify this aim, important points and results of some studies and research in this field will be reviewed.

In a body of research, carried out by Lei Su et al., the effects of soil-pile interaction (SPI) on seismic fragility curves of a wharf structure have been studied. Pushover analysis has been used for classification of damage states, and as a result of this project, they realized that when SPI was considered the wharf deck, it had less vulnerability comparing to other elements [4]. In the field of retrofitted structures with bracing devices, for investigation of the behavior and effects of various kinds of braces on fragility and self-centering performance, Xiang and Alam considered three types of braces for their research project including: BRBs,¹ VDBs² and PBSCs.³ Results showed that PBSCs decreased the vulnerability in structure comparing to other braces. In addition, it was observed that residual drift in PBSCs was much less than other ones. Therefore, it can be concluded that this kind of brace has a better behavior

than other common braces in structures [5]. Another research about fragility assessment has been done by Kabir et al. In this study they analyzed a 3-span highway bridge by using 48 ground motion records including: 16 near field, 16 far field and 16 long duration earthquakes. After generating fragility curves, results showed that isolation bearings in this bridge have higher probability of failure than other components like piers in this specific structure. Moreover, as another result of this study it has been observed that, long duration earthquake records have affected bridge more than short duration ones [6].

In terms of industrial structures, researches and studies, related to failure and fragility analysis of them, recently a study has been done by Miladi and Razzaghi which is about failure analysis of an un-anchored steel oil tank that has been damaged due to Silakhor earthquake in Iran. Two numerical methods as the methodology for analyzing this tank have been considered:

1. The response history analysis
2. IDA.⁴

Shell uplift and buckling were the main damages that occurred during this earthquake in the tank. Results of this analysis process showed that critical PGA for dynamic buckling was 0.285 g and it was 0.23 g for uplift. Also, it was observed that the numerical model showed the performance like actual tank precisely [7]. Moreover, a research, which has been done in Sicily (Italy) by Phan et al., was conducted on fragility curves of cylindrical steel storage tanks for oil and gas industries which showed the importance of buckling in these tanks like the previous research.

120 earthquake records were functioned to obtain fragility curves and the structures were closely analyzed.

In these tanks, among the main damage states that have been observed, failure of the joint and the buckling of the bottom shell course were more frequent than others specially when the uplift occurs [8].

Data from previous earthquakes delineated that even though accidental events, which have a natural beginning such as earthquakes, have a relatively modest frequency, they often caused serious consequences. Scientists and competent authorities agree on improving the knowledge about some strong natural phenomena which can have serious effects on industrial activities [9].

There are some main parameters which play a key role in evaluating the probability of failure which in analysis process of seismic reliability is connected to the earthquake intensity and also nature. Materials and dynamic

¹ Buckling-restrained braces.

² Viscous damper braces.

³ Piston-based self-centering braces.

⁴ Incremental dynamic analysis.

behaviour are two types of uncertainties taken into account by fragility. Each process to get fragility needs a dynamic model optimisation and a dependable formulation of failure modes to achieve the research goals. As a very powerful and important tool in the process of risk assessment, fragility curves consider typical structural arrangements and represent probability of failure and system performance [10].

Since most of the studies in this field have been mainly developed for residential buildings, seismic analysis of industrial structures has not been evaluated enough, particularly their equipment. So, it can be considered as the main difference between this paper and others. Hence, either because of geometry or distribution of masses, the resultant structures fall into the category of irregular or perhaps special structures.

Since this research is going to draw and evaluate fragility curves for considered structure, in the next section, generation procedure of this function will be explained and after that this procedure will be carried out for the modelled structure and corresponding results will be discussed.

2 Fragility function

One of the significant keys to assess the seismic performance of a structure is the ability to quantify the potential for damage as a function of earthquake intensity. A probabilistic seismic performance analysis, based on fragility curves, can estimate the seismic performance and reliability of the structures [11]. Fragility functions can be defined as probability distributions, used to show the probability that an element or system will be damaged to a given or more severe damage state as a function of a single predictive demand parameter. Generally, fragility functions take the form of lognormal cumulative distribution functions and they have a median value θ and logarithmic standard deviation. The mathematical form for such a fragility function is as follows:

$$F_i(D) = \Phi \left[\frac{\ln x - \ln \theta_i}{\beta_i} \right] \quad (1)$$

where " $F_i(D)$ " is the probability that the component will be damaged to a damage state " i " or a more severe damage state as a function of demand parameter, D . " Φ " denotes the standard normal cumulative distribution function. " θ_i " denotes the median value of the probability distribution, and " β_i " depicts the logarithmic standard deviation. Both θ and β are established for each component type and damage state using dynamic time history analysis' results performed on support structure and equipment [12].

Fig. 1 Support structure

The lognormal is used here because it fits a variety of structural component failure data and building collapse by incremental dynamic analysis. [13].

3 Introducing considered structure

The considered structure is located in a unit of petrochemical plant in Iran. The location of this unit is in Shiraz-Iran. Methanation process in this unit is a physical–chemical process to generate methane from a mixture of various gases out of biomass fermentation or thermo-chemical gasification. The main components are carbon monoxide and hydrogen. The main catalysts used for this reaction are ruthenium, cobalt, nickel and iron. This process is used for the generation of biogenous natural gas substitute, which can be fed into the gas grid. Methanation is the reverse reaction of steam methane reforming.

In this respect, the more common machination catalysts require that the gas flowing into the catalytic reactor be heated to a high temperature. Three massive heat exchangers are located on support structure to fulfil the goal of this unit.

In Fig. 1 the support structure is shown. This is a five-story support structure and three heat exchangers are located on the second story, forth story and fifth story. The heat exchangers, which are located on these stories, are demonstrated in Figs. 2,3 and 4.

These three heat exchangers are known as the most important equipment of the investigated unit, and

Fig. 2 Fifth story heat exchanger

Fig. 3 Second story heat exchanger

performance of the unit depends on performance of heat exchangers.

4 Dynamic analysis of support structure and equipment

In order to evaluate the dynamic behaviour of the support structure and equipment, which are located on support structure, this structure has been simulated in ETABS to design beams, columns and braces. Since the time history analysis in ETABS is time-consuming and based on that, for performing Incremental Dynamic Analysis (IDA),

Fig. 4 Forth story heat exchanger

Fig. 5 Created model in ETABS

forty ground motions have been selected and incremental dynamic analysis for those ground motions is performed in Seismostruct.

Created models in ETABS is shown in Fig. 5 and created model in Seismostruct is shown in Fig. 6.

In order to perform incremental dynamic analysis, forty ground motions have been selected. These ground motions are selected from different stations of Imperial Valley, Superstition Hills, Landers, Kobe, Duzce_ Turkey, Tottori_ Japan, El Mayor-Cucapah_ Mexico and Darfield_ New Zealand. Earthquake's soil type of selected ground motions is similar to the site of investigated oil complex and Moment magnitude (M_w) and ground motions are selected from 6.5 to 10 in PEER Ground Motion Database.

Fig. 6 Created model in Seismostruct

Fig. 8 Incremental dynamic analysis of second story equipment

Fig. 7 Incremental dynamic analysis of support structure

Fig. 9 Incremental dynamic analysis of fourth story equipment

Selected ground motions have been scaled to ten levels of intensities from 0.1 to 1 g. Ten levels of intensity and forty records lead to more than 400 times of the analyses of the structure. Since acceleration was considered as damage index in bolts in past studies, in this study to evaluate failure of structure and equipment, inter story drift ratio (IDR) and peak floor acceleration have been calculated from incremental dynamic analysis.

Figure 7 shows the results of incremental dynamic analysis of support structure. Based on this figure, the inter story drift ratio for different ground motions and different levels of intensity have been both calculated and observed.

Figures 8, 9 and 10 all show the results of incremental dynamic analysis of heat exchangers. Peak floor acceleration for different ground motions and different levels of

Fig. 10 Incremental dynamic analysis of fifth story equipment

Fig. 11 Fragility curve for support structure in moderate and extensive damage state

Fig. 13 Fragility curve for fourth story equipment

Fig. 12 Fragility curve for fifth story equipment

intensity have been calculated for second floor, fourth floor and fifth floor, which can be observed.

5 Generating fragility curves

To develop the fragility curve for each of the considered frames, the numerical results obtained from incremental dynamic analysis have been used. Figure 11 shows the fragility curve of support structure in a moderate damage state and also shows the fragility curve of support structure in an extensive damage state.

Since there is not important and heavy equipment on all the floors, in this research the fragility curves will be presented for stories with important equipment. Figure 12 shows the fragility curve of fifth story of heat exchanger in an extensive damage state and Fig. 13 shows the fragility curve of fourth story of heat exchanger in extensive damage state.

Fig. 14 Combined fragility curve using Bryant [14] method

It can be seen that when PGA is 0.6 g, the failure probability of fourth story equipment is fifteen percent and the failure probability of fifth story is fifty percent. The results depict that fifth story equipment is more vulnerable than fourth story equipment and support structure. Since in this study the main goal is to obtain a single curve for whole structure to take appropriate measures, common methods have been chosen to combine curves. Calculated fragility curves have been combined using two methods to have a fragility curve for the under-study unit.

First method to combine fragility curves is the method which Bryant [14] has suggested. Two formulas are presented to have median and standard deviation of combined fragility curve. Combined fragility curve using first method is shown in Fig. 14.

$$X_{m-ogg} = \exp \left[\left(\sum_{i=1}^N \frac{1}{\xi_i^2} \right)^{-1} \sum_{i=1}^N \frac{\ln X_{m-i}}{\xi_i^2} \right] \quad (2)$$

Fig. 15 Combined fragility curve using Choi (2004) method

$$\xi_{agg} = \sqrt{N \left[\sum_{i=1}^N \frac{1}{\xi_i^2} \right]^{-1}} \quad (3)$$

where " X_{m-agg} " and " ξ_{agg} " is the median and lognormal standard deviation of the aggregated distribution respectively.

Second method to combine fragility curves is the one which Choei et al. [15] has suggested. The mentioned method to combine fragility curves knows the most vulnerable component of system as the vulnerability of the system because the failure of each component can cause the whole system to fail. Combined fragility curve using second method is shown in Fig. 15. Since in this method the most critical curve is considered as the combined fragility curve, in Fig. 15, combined curve coincided with the curve for the fifth story equipment.

In order to obtain seismic fragility of support structure, inter story drift ratio has been selected as an engineering demand parameter (EDP). According to Iranian seismic codes and related articles in this field, 0.04 is chosen for Extensive damage state and 0.02 is chosen for moderate damage state. Shear failure of bolts has been considered as a failure mode of equipment. Peak floor acceleration of each ground motion has been calculated for equipment. Using fragility equation and calculating median and standard deviation of intensity measure for each ground motion, fragility curve of equipment has been plotted in Figs. 13 and 14. Peak floor acceleration is 11 m/s^2 which causes a shear failure of bolts of fifth and fourth story and also 18 m/s^2 are the peak floor acceleration which results in a shear failure of bolts of second floor. Equipment bolts designed for earthquakes lateral force which can be observed as following equation [16].

$$F_p = \frac{0.4a_p A(1+S)W_p I_p}{R_p} \left[1 + 2 \frac{Z}{h} \right] \quad (4)$$

Where: F_p : Earthquakes lateral force; A : Design base acceleration ratio; $1+S$: The parameter determined from the soil profile type and level of seismicity; a_p : Amplification factor; I_p : Importance factor; W_p : The weight of the element plus total live load; R_p : Component behavior factor; h : Average height of building from the base level; Z : Center of mass height

6 Conclusions

In this study, the probability of failure of equipment and support structure has been evaluated as the main goal of the study. Based on developed fragility curves for support structure and three equipment located on support structure, by implementing time history dynamic analyses and considering inter story drift ratio and shear failure of bolts as failure mode of support structure and equipment, as an important result, it can be concluded that fifth story equipment is the most vulnerable component of the unit. This means failure of this equipment will stop the process of unit and identification of the most vulnerable component is helpful for risk management strategies. Based on the importance of each equipment and support structure, risk management strategies have to be selected and fragility curves can be important factors in the risk management strategies. Furthermore, as the most vulnerable part of the structure, it is observed that the probability of failure (pf) for equipment on fifth story in $\text{PGA} = 0.6 \text{ g}$ is 50%. In comparison to other related researches, it can be seen that this paper showed the results of combination of fragility curves based on two methods and revealed that which one is more reliable in this specific structure.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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