International Journal of Greenhouse Gas Control 77 (2018) 1–13

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

# Quantitative risk assessment of offshore carbon dioxide injection system considering seismic effects

Younggeun Lee[a], Gunhak Lee[a], Jinjoo An[b], Kyeongsu Kim[a], Usama Ahmed[c], Chul-Jin Lee[d,*], Chonghun Han[a,*]

[a] School of Chemical and Biological Engineering, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, 08826, Republic of Korea
[b] Carbon Resources Institute, Korea Research Institute of Chemical Technology (KRICT), 141 Gajeong-ro, Yuseong-gu, Deajeon, 34114, Republic of Korea
[c] Chemical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia
[d] School of Chemical Engineering and Materials Science, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul, 06980, Republic of Korea

ARTICLE INFO

*Keywords:*
Quantitative risk analysis
$CO_2$ storage
Seismic effect
Domino effect
Safety management

ABSTRACT

Quantitative risk analysis (QRA) is one of the most generally used safety analysis measures for risk management in process industries. Currently, earthquakes occur worldwide, resulting in significant damage. Despite the importance of considering the danger of earthquakes, however, seismic effects are often not included in risk analysis owing to difficulties in considering the multi-hazard nature and domino effects of earthquakes.

In this study, an improved methodology for QRA was proposed to consider the seismic effects including domino effects, and multi-hazard impacts of an earthquake by using a Bayesian network (BN). This analysis was applied to a topside $CO_2$ injection system for underground storage, which is susceptible to seismic effects. Because frequency analysis is based on a causal relationship, the BN can be used to simultaneously consider domino effects and multi-hazard risks. As a result, the societal risk integral, one of the factors in risk analysis, was $9.667 \times 10^{-4}$/year in modified QRA; this value shows an increase of 3.9% compared with the societal risk integral in conventional QRA. Furthermore, the value can be increased to 35% in the sensitivity analysis depending on annual exceedance probability (AEP). This result shows the importance of considering seismic effects, including both the domino effect and multi-hazard impacts, in QRA. A risk reduction method was additionally applied to mitigate the process risk.

## 1. Introduction

Risk in industrial fields is the probability or threat of negative effects including damage, injury, or loss caused by accidental events. Risk assessment and management is an important concept because failure to assess and manage risk can lead to dangerous accidents. If assessing and managing risk is neglected, accidents resulting in loss of life or property damage can occur. Among the techniques used to assess the risk, quantitative risk analysis (QRA), derived from probabilistic safety assessment (PSA) used in the nuclear industry, is used for risk assessment in chemical processes. QRA allows investigation of the existing risks on a process to decide whether the risks are acceptable (Center for Chemical Process Safety, 2010). In the QRA method, consequence analysis and frequency analysis are used. Consequence analysis considers the effect of an expected chemical accident, whereas the latter used historical accident data to consider the occurrence probability of an expected chemical accident.

QRA has been widely applied to processes or systems in many studies owing to its reliability. Lee et al. (2015) studied risk assessment and management by QRA methodology on gas treating units in gas–oil separation plants. Risks in a topside LNG-liquefaction process of Liquefied Natural Gas Floating Production Storage and Offloading (LNG–FPSO) was analyzed by Jafari et al. (2012), including a hydrogen generator that uses natural gas in the reforming process. Domenico et al. (2014) analyzed risk in methanol production plants by using QRA methodology. Cunha (2016) studied several risk assessment research results including frequency and consequence analysis on onshore pipelines. Similarly, risk in $CO_2$ transportation pipelines, including uncertainties and effects, was assessed by Koornneef et al. (2010a), and quantitative risk in $CO_2$ capture facilities was analyzed by Engebø et al. (2013). However, although earthquakes are currently considered as risk factor in all industrial plants, previous research is limited in considering such risk.

From the 2011 Tohoku earthquake (Japan) accident to the Perugia

* Corresponding authors.
*E-mail addresses:* cjlee@cau.ac.kr (C.-J. Lee), chhan@snu.ac.kr (C. Han).

https://doi.org/10.1016/j.ijggc.2018.07.010
Received 10 October 2017; Received in revised form 16 June 2018; Accepted 6 July 2018

**Nomenclature**

*Acronyms*

| | |
|---|---|
| ALARP | As low as reasonably practicable |
| AEP | Annual exceedance probability |
| BN | Bayesian network |
| DAG | Directed acyclic graph |
| FTA | Fault tree analysis |
| PGA | Peak ground acceleration |
| ETA | Event tree analysis |
| HAZID | Hazard identification |
| IDLH | Immediately dangerous to life or health concentrations |
| PSA | Probabilistic safety assessment |
| QRA | Quantitative risk analysis |

*Variables*

| | |
|---|---|
| $f$ | Frequency rate considering seismic effect |
| $f_0$ | Frequency rate from historical data |
| $f_\alpha$ | Frequency rate from seismic effect including multi-hazard and domino-effects |
| $f_{h,i,j}$ | Frequency rate of leak event from historical data |
| $f_{s,i,j}$ | Frequency rate from direct seismic effect |
| $f_{d,i,j}$ | Frequency rate from effect by domino-effects and by multi-hazard effects |
| $F_i$ | Frequency of event I |
| $F_N$ | Frequency of all events |
| $IR_i$ | Individual risk by event I |
| $N_i$ | The number of fatalities resulting from event I |
| $N_p$ | The number of people |
| $P_{fi}$ | Probability of fatality by event I |
| $P_{PGA}$ | Leak probability of the tank according to PGA value |

(Italy) earthquake, earthquakes occur worldwide and cause considerable damages. With the increasing occurrence and power of earthquakes, damages from seismic effects have also risen. Thus, earthquakes have gained attention as important safety issues in industrial fields, including chemical plants. As a result, industries are considering seismic effects because resultant accidents increase the possibility of lethal events. In several studies, seismic effect has been considered in risk assessment. Fabbrocino et al. (2005) evaluated the effect of seismic action in a loss of containment accident, and Antonioni et al. (2007) considered seismic effect simply by using equipment-dependent failure probability models. A methodology to analyze life loss risk caused by airborne chemicals triggered by seismic effects was proposed by Meng et al. (2015). A QRA method considering multi-vessel failure scenarios triggered by seismic effect was proposed by Kim et al. (2016). Some researchers offered various proposals to consider seismic effect in risk assessment. However, there are still limitations in the previous studies. Few papers have considered multi-hazard impacts triggered by seismic effect, which affects the entire industrial process simultaneously rather than independently, such as that occurring in other natural hazards (Gallina et al., 2016). In addition, the domino effect was considered on a only limited basis owing to its complexity (Kim et al., 2016). Moreover, it is difficult to consider this method in other applications because most research proposes a method for specific cases.

Multi-hazard impacts define several hazards that occur simultaneously. In a process containing multiple equipment types, hazard scenarios generally occur separately on specific equipment. However, in the case of hazards by earthquake, several hazardous scenarios can occur simultaneously as results of simultaneous leakage or rupture of several pieces of equipment. Moreover, the domino effect from such failure can trigger other hazards through the transfer of accidental effects (Landucci et al., 2012). In this study, a Bayesian network (BN) is used for considering multi-hazard effects and domino effects, which are important factors to be considered in hazard assessment. A BN is a directed acyclic graph (DAG), which is a graphical model, and contains probability theory. BN can represent causal relationships, such as cause–effect relationships, and represents uncertain knowledge in probabilistic systems. Because frequency analysis is based on a causal relationship including event tree analysis (ETA), BN is used as tool for risk analysis in some research. Martins et al. (2014) studied application of a regasification system with methodology based on hybrid BNs of iterative six-step risk analyses. Liang et al. (2017) conducted risk analysis on level crossing using BN. Some papers studied risk assessment with BN of oil and gas pipelines (Kabir et al., 2016; Li et al., 2016). Thus, BN is a proper method for analyzing multi-hazard and domino effects, because these effects are also based on cause–effect relationships.

For application, an offshore topside $CO_2$ injection system for underground injection was used in South Korea owing to the necessity of risk assessment on the process itself, which has not been well studied previously. Previous studies of safety in $CO_2$ injection systems analyze whether the $CO_2$ injected underground is stable. Because use of this technology depends on stable storage of $CO_2$, many studies have been published about risk and stability associated with this storage. This research include studies on diverse risk assessment of $CO_2$ storage in a Salah $CO_2$ storage project (Dodds et al., 2011; Metcalfe et al., 2013; Oldenburg et al., 2011), studies on the stored $CO_2$ containment risk or leakage risk from storage site and its impacts (Blackford et al., 2014; Damen et al., 2006; Little and Jackson, 2010; Tucker et al., 2013), $CO_2$ release risk from failure of caprock trapping the $CO_2$ (Rohmer and Seyedi, 2010; Smith et al., 2011), $CO_2$ storage risk caused by earthquakes (Nicol et al., 2011; Vilarrasa and Carrera, 2015; Zoback and Gorelick, 2012), monitoring strategies and their demonstration for management of $CO_2$ storage risk (Blackford et al., 2015; Hvidevold et al., 2015; Zhang et al., 2014), and studies for assessment and management of four types of risk in geologic $CO_2$ storage: performance, long-term containment, public perception, and market (Pawar et al., 2015).

However, $CO_2$ offshore storage has other risks to be considered in addition to storage stability. In particular, some risks are caused by process characteristics. The injection system has some characteristics relating to process safety because the system is installed on topside processes in storage sites near oceans, First, the space required for these process facilities is smaller than that for onshore sites. Because of the cost issue, even in the same process, it should be placed in a smaller space. If accidental events occur in a topside system, more substantial damage can occur owing to its highly compact nature. Second, weather issues are more critical in offshore storage. Because the system is built in the sea, weather changes are diverse and rapid; therefore, this aspect of weather is also related to process safety. Despite these factors, safety or risk research of an offshore $CO_2$ storage system has not been conducted. Therefore, QRA on an offshore $CO_2$ storage system offers useful information. Moreover, earthquakes increasing in intensity have occurred near South Korea in recent times; thus, risk study of an offshore system near South Korea is meaningful for considering earthquakes in a process. Fig. 1 represents the ranking of the power of an earthquake near the Korean Peninsula. The most powerful earthquake, and the most recent, occurred in Gyeongju in September 2016. Because this region is near a storage site (red point in Fig. 1), risk assessment must be renewed by considering the seismic effect, which is an important