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An individual risk assessment framework for high-pressure natural gas wells with hydrogen sulphide, applied to a case study in China

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ABSTRACT

Accidents of high-pressure sour gas wells at the well drilling and completion stages may cause serious consequences when poisonous H_2S gas diffuses with the diversity of terrain and wind etc., especially in China, where most of sour gas wells are located in mountainous areas with complicated geological conditions. This paper focuses on an assessment framework to explicitly calculate the individual risk of high-pressure sour gas wells at the well drilling and completion stages. The method is based on accident probability analysis by fault tree simulation as well as accident consequence analysis through building reasonable accident scenarios for H_2S gas diffusion related to death probability within a given distance. The death probability curves of different wind directions and corresponding minimum proximity distances to the surrounding buildings could be provided by probabilistic risk analysis. Finally the individual risk contours could be mapped by concentration interpolation, and be compared with acceptable risk level. The case study in Chinese Sichuan–Chongqing region shows that the minimum proximity distances of different directions range from 600 to 1200 m locating between individual risk values of 10^{-4} and 10^{-6}. The zones within 1.2-km radius and northwest area deserve more attentions in the design and deployment of the protective measures.

1. Introduction

In recent years, with the sustained growth of China's economy and increasing worldwide pressure on China to reduce its air pollution to acceptable levels, the demand for natural gas is increasingly growing in China since it is the most important source of clean energy in China. Currently, many high-sulphur gas fields have stepped into the large-scale development phase in China, while China is confronting with the severe security situation for the exploration of high-pressure sour gas fields. Due to the lack of risk control and safety measures to the points, many accidental cases such as out-of-control blowout and hydrogen sulphide poisoning have occurred in succession at the well drilling and completion stages, leading to enormous economic losses, personal injury and environment pollution. The serious consequences of such kind of accidents spur the oil–gas operators and regulators to must address the associated public safety issues.

Generally, the vast majority of high-pressure sour gas wells are located in mountainous and hilly terrain, especially in China, where the altitudes of gas wells generally rise from 300 to 600 m. The features of high-pressure, high-sulphur and complex geological conditions easily lead to accidents, such as the "12.23" catastrophic blowout accident in Kaixian County of Chongqing City in 2003, resulting in the deaths of 243 people by H_2S poisoning, the hospitalisation of 2142 people and a direct economic loss of 64.3 million RMB (about 10.5 million dollars). The exploration and development of high-pressure sour gas wells is a complex problem with high operating risks and serious potential hazards. Therefore, it is necessary to measure the individual risk level around the gas wells for public safety and to deploy the relevant safety measures at the well drilling and completion stages.

Currently, the quantitative risk assessment (QRA) for major hazards has attracted a great deal of attentions, and the objective is to limit the underlying risk to the given range (Franks and Maddison, 2006). Since the early 1980s, risk-based assessment tools involving quantitative criteria for the tolerability of risk were extensively developed in the Netherlands, and the relevant study formed the basis for the Dutch external safety policy (Bottelberghs, 2000). The risk-based safety assessment asserts the necessity to keep safe distances between hazardous activities and vulnerable objects. The safety distances are based on iso-risk contours from QRA and on tolerability criteria. Franks and Maddison (2006) presented a simplified method for estimating individual risk by defining different population group and event outcomes. The studies showed that

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the risk-based quantitative assessment was the most effect instrument for handling the hazardous activities, and could be used to design effective policies to prevent and control major hazards with these activities (Ale, 1991; Jo and Crowl, 2008; Pikaar and Seaman, 1995).

In China, the related study started relatively late, but still, much progress has been made in the accident probability and consequence analysis, The QRA techniques regarding high-pressure sour gas wells were promoted by means of risk assessment for deep water well control (Gao et al., 2008), individual risk assessment of poison leaks in public (Li et al., 2007) and H_2S gas diffusion process simulation in blowout accidents (Wu et al., 2009a). In order to conduct the risk assessment for sour gas wells, it is a scientific and effective solution to evaluate the security level combining the accident probability analysis as well as the accident consequence analysis considering the possible scarcity of historical statistical data, uncertainty associated with the accident probability and the dynamics of H_2S gas diffusion.

This paper, through the accident probability analysis and accident consequence analysis based on uncertainty analysis and reasonable accident scenario assumptions, focuses on an assessment framework to explicitly calculate the individual risk facing high-pressure sour gas wells at the well drilling and completion phases. And a case study in China is performed and analyzed. The main contributions are as follows: (1) An individual risk assessment framework, considering underlying uncertainties from accident probability and accident consequence, is built for risk assessment of high-pressure sour gas wells at the well drilling and completion phases. In particular, the fault tree is developed to identify the underlying accident mechanism, and the probability distribution of the well blowout accidents is estimated to reduce uncertainty through Monte Carlo simulation. (2) The Gaussian distribution curve is proposed to describe the decline process of H_2S concentration at the given location, and further the death probability curves of different wind directions are obtained. The individual risk contours are further mapped and compared with the acceptable risk level, which provide support for risk decision-making at early planning stage. (3) The individual risk of a typical high-pressure sour gas well in China is assessed as a case study and the minimum proximity distance between the gas well and buildings is suggested. The specific area deserving worthy of more attentions and corresponding safety measures are analyzed and suggested clearly.

2. Individual risk assessment

Individual risk is often defined as the death probability per year of exposure to an individual at a certain distance from the hazard source (Crowl, 1999). In the case of high-pressure sour gas wells, "the individual" refers to people who live at a certain distance from a natural gas well for a long time and meanwhile do not take any protective measures. This probability is usually expressed in the form of iso-risk contours around the gas well, which are composed of rings representing different risk levels, and are used in the process of risk decision making, by combining different functional areas (such as industrial areas, commercial areas and residential areas).

Within the field of high-pressure sour gas well development, the blowout accident is the most serious and harmful catastrophic accident. This paper focuses on the individual risk to the public due to the diffusion of a large amount of poisonous H_2S in the blowout. For the given hazard source, two aspects need to be considered in the QRA: the likelihood of accidents and the consequence caused by the accidents, as shown in Fig. 1, for the probability analysis, a fault tree is developed to characterize the process mechanism of the blowout accident based on process hazard identification. Bayesian method is used to update failure rates of basic events so that the limited historical statistics and expert judgements could be integrated to improve reliability. Based on Monte Carlo simulation, the probability distribution of blowout accident is obtained for more reliable results.

For the consequence analysis, the wind tunnel experiment method is recommended to simulate the accident consequence based on reasonable accident scenario assumptions in this paper. For the most part, high-pressure sour gas wells are located in mountainous areas. Because the density of H_2S is slightly higher than that of air, it is characterized by diffusion along low channels (valley) and the complicated dynamic of the diffusion process. In this case, the diffusion process could be well characterized by wind tunnel experiment method, which could reflect the interference of the terrain and weather conditions on the diffusion of H_2S gas in a more exact way, therefore has the advantages of repeatable and accurate measurement and more reliable results compared to other method, such as numerical simulation method in the high sour gas field development (Hu and Yao, 2000).[1] Afterwards, the death probability of different wind directions could be calculated based on the simulation results. Finally, the individual risk around the high-pressure sour gas wells could be analyzed by considering the uncertainty of a serial of relevant factors that may significantly influence the diffusion of H_2S gas, such as ignition probability, recipient exposure degree and wind and weather conditions.[2] Table 1 lists the variables involved in the individual risk assessment in this paper.

In a blowout accident, the individual risks caused by different accident scenarios differ greatly, therefore, the individual risk of a certain location could be estimated by integrating the likelihood of an accident scenario multiplied by the death probability at the location from all accident scenarios. The individual risk at geographical location (x, y) could be expressed using the following equation:

$$IR_{x,y} = \sum_{i=1}^{m} f_i \cdot P_{x,y,i} \tag{1}$$

where the subscript i denotes the accident scenarios, f_i is the probability associated with accident scenario i and is from probability analysis, while $P_{x,y,i}$ is the death probability at location (x, y) associated with accident scenario i and it is from accident consequence analysis.

2.1. Accident probability estimation

The probability associated with accident scenario i can be estimated by the following equation:

$$f_i = F \cdot P_{o,i} \tag{2}$$

where F is the probability of a blowout accident, and $P_{o,i}$ is the conditional probability associated with accident scenario i. The detailed definition of an accident scenario can be found in Section 2.2.1.

The estimation for blowout probability F is one of key and difficult points in accident risk assessment. Based on the former study in Xu et al. (2012), here, the estimation for probability of blowout accident is further investigated and discussed as basic component

[1] In this paper, the results of the wind tunnel experiment are provided and completed by National Laboratory for Environment Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University (http://english.pku.edu.cn/).

[2] The harm of a blowout accident also depends on the recipient vulnerability (for example, a healthy adult will be more resistant than children) and personnel activities. This paper assumes that the recipient is the non-vulnerable individual who is constantly in a location (Franks and Maddison, 2006).