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A comprehensive risk evaluation method for natural gas pipelines by combining a risk matrix with a bow-tie model

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ABSTRACT

Leakage from natural gas pipelines causes severe economic loss and significantly affects social security considering the gas' combustibility and the difficulties in detecting leakage. This study proposes a comprehensive risk evaluation method by combining a risk matrix with a bow-tie model. First, a bow-tie model is built, considering the risk factors that may lead to an accident using a fault tree; the consequences of unwanted events are then described in an event tree. Second, a fuzzy method is used to calculate the failure probabilities. Third, the severity of an accident is evaluated through an index system that includes personal casualties, economic losses and environmental disruptions. Finally, a risk matrix consisting of a probability ranking criterion and a consequence ranking criterion is proposed to reach an integrated quantitative conclusion of a bow-tie model. A case study of an underwater pipeline carrying natural gas has been investigated to validate the utility of the proposed method.

1. Introduction

Leakage from natural gas pipelines can cause devastating accidents due to the flammability of the gas, which is transported at high pressures. In recent years, accidents in natural gas pipelines have occurred too often and have drawn significant public attention. Thus, the implementation of safety measures followed by a comprehensive risk evaluation is critical to maintain a level of risk below the acceptable criteria. The risk evaluation of pipelines currently includes a quantitative risk analysis (QRA) and an accident consequence analysis (ACA).

In a QRA, Muhlbauer (2004) proposed an integrated and continuously improving risk evaluation framework for pipelines that has become the guideline for pipeline risk assessment. The purpose of this framework is to evaluate a pipeline's risk exposure to the public and to identify ways to effectively manage that risk. Ma et al. (2013a) used geographical information systems (GIS) to calculate the quantitative risk of urban natural gas pipeline networks. The proposed QRA process incorporated an assessment of the failure rates of integrated pipeline networks, a quantitative analysis model of accident consequences, and assessments of individual and societal risks. Jo and Ahn (2005) also used GIS to assess the quantitative risk of natural gas pipelines. Han and Weng (2010) proposed a quantitative assessment index system that included a causation index, an inherent index, a consequence index and their corresponding weights for urban natural gas pipelines. The failure probability calculation is an important part of a QRA. Yuhua and Datao (2005) used a fuzzy fault tree to investigate the risk factors and calculate the failure probabilities of natural gas pipelines. Shahriar et al. (2012) applied a fuzzy approach to calculate the fuzzy probabilities (i.e., likelihood) of a basic event in a fault tree for oil and gas pipelines. There are also other relevant works in the literature, such as that of Ma et al. (2013b) and Jamshidi et al. (2013), that investigate the QRAs of pipelines.

In an ACA, an event tree has been shown to be an efficient tool. As the first step in the multidimensional risk analysis of a hydrogen pipeline, Lins and de Almeida (2012) built an event tree that included all possible accident scenarios including punctures and ruptures of the pipeline. To calculate the safety distances around a pipeline transporting liquefied gas and pressurized natural gas, Sklavounos and Rigas (2006) used an event tree analysis as a formal technique to determine the possible outcomes of an accidental fuel gas release. Event tree analysis is also widely used to identify dangerous scenarios with regard to hydrogen pipelines (Lins and de Almeida, 2012), dynamic analyses for transient systems (Zamalieva et al., 2013) and accident analyses of different hazardous materials (Vílchez et al., 2011).

QRA and ACA are related and dependent on each other because risk identification is the first step of consequence analysis. The

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bow-tie model is an innovative approach and a good combination of QRA and ACA and is thus widely used in safety analysis (Ferdous et al., 2013) and risk management (Chevreau et al., 2006). However, one of the limitations in the existing implementation of the bow-tie model is a lack of quantitative conclusions; many researchers have investigated the construction of bow-tie models but not their quantification.

To achieve a quantitative conclusion from a bow-tie model, a quantitative risk matrix that includes ranking probability criteria and consequence severity criteria is proposed in this study to quantify the probability and consequence of a given accident. The purpose of this study is to develop a comprehensive approach to identify the risk factors and evaluate the severity of the consequences of an unexpected event. The procedure of the proposed approach is presented in Section 2. This procedure includes four steps: the construction of the bow-tie model, the fuzzy probability calculation, the consequence analysis of an accident and a risk matrix analysis. In Section 3, an application of the proposed approach is presented for the risk analysis and consequence assessment of an underwater pipeline. Section 4 then presents the conclusions of the study.

2. Procedures

The procedure of the proposed risk evaluation method is shown in Fig. 1 and consists of a risk analysis and a consequence assessment in terms of a building fault tree and an event tree, respectively. In the risk analysis, a fuzzy method is applied to convert a natural linguistic expression into a failure probability. In the consequence assessment, an index system is introduced to further assess the consequence in terms of environmental cost, personal injury and economic loss. In the end, to reach a comprehensive conclusion, the risk matrix method is applied to combine the results of the risk analysis and the consequence assessment.

2.1. Construction of a bow-tie model

A bow-tie model is widely applied in risk analyses, including probability calculations (Khakzad et al., 2013), human error risk analysis (Deacon et al., 2010, 2013), dynamic risk analysis (Khakzad et al., 2012), etc. A bow-tie model is comprised of a fault tree, which represents the risk factors of a failure, and an event tree, which represents the consequences of a failure. Both the fault tree and the event tree are effective graphical methods and are widely used in safety analyses of complex systems; this makes a bow-tie model to have significant potential in this field. Fig. 2 shows the basic structure of a bow-tie model. X, E and T are the primary, intermediate and top events of the fault tree, respectively, and I and C stand for the ignition (or safety barrier) and the accident consequence in an event tree, respectively.

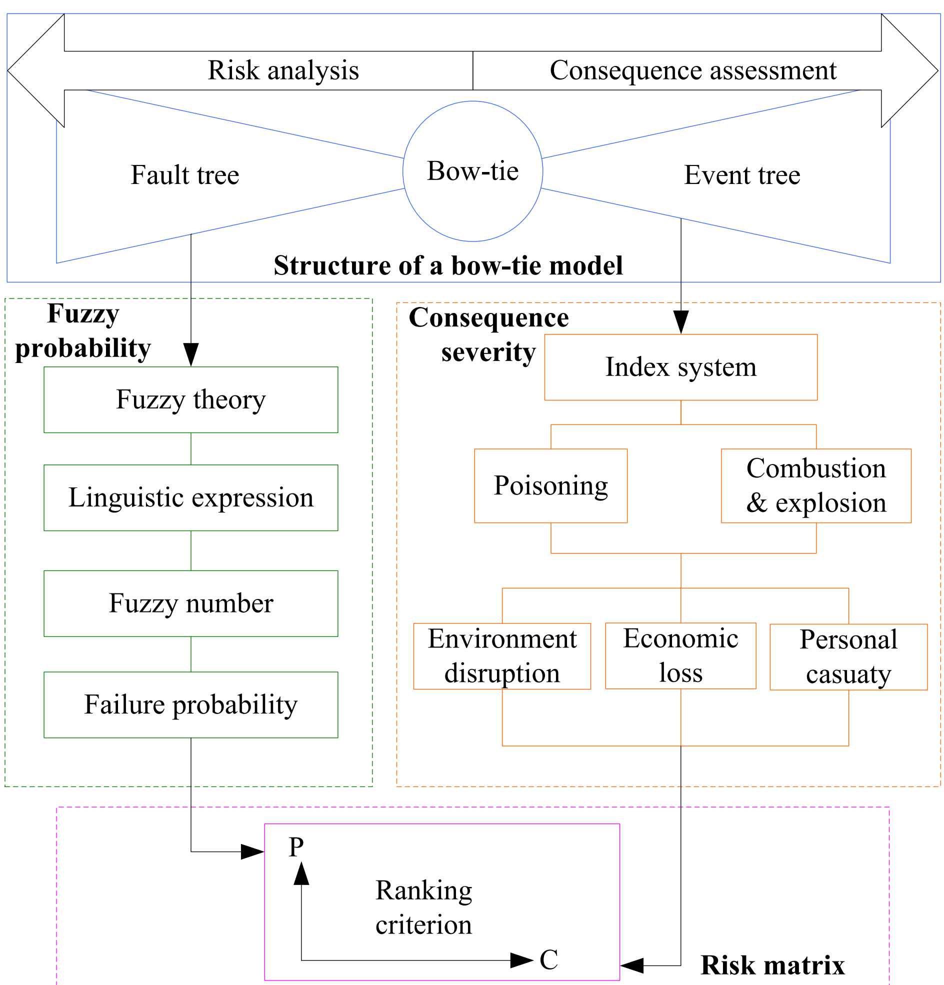

Fig. 1. Schematic diagram of building a bow-tie model.