Risk assessment for a high-pressure natural gas pipeline in an urban area

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Abstract

Regulatory authorities in many countries are moving away from prescriptive approaches for keeping natural gas pipelines safe. As an alternative, risk management based on a quantitative assessment is being considered to improve the level of safety. This work focuses on the quantitative risk assessment for natural gas pipelines and introduces parameters of fatal length and cumulative fatal length. The fatal length is defined as the integrated fatality along the pipeline associated with hypothetical accidents. The cumulative fatal length is defined as the section of pipeline in which an accident leads to N or more fatalities. These parameters can be estimated easily within a geographic information systems (GIS). With currently acceptable criteria taken into account for individual risk, the minimum proximity of the pipeline to occupied buildings is proportional to the square root of the operating pressure of the pipeline. This quantitative risk assessment may be useful for risk management during the planning and building stages of a new pipeline, modification of the pipeline, and to lower the risk of a buried pipeline.

Keywords: public safety, natural gas pipeline, quantitative risk, individual risk, societal risk, fatal length, cumulative fatal length, minimum proximity.

1 Introduction

Unlike other hazardous plant, the transmission pipelines carrying natural gas are not within secure industrial site, but are routed across land out of owned by the pipeline company. If the natural gas is accidentally released and ignited, the

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hazard distance associated with these pipelines to people and property is known to range from under 20 m for a smaller pipeline at lower pressure, up to over 300m for a larger one at higher pressure [1]. Therefore, pipeline operators and regulators must address the associated public safety issues.

This paper focuses on a method to calculate the consequences for the quantitative risk assessment of transmission pipelines carrying natural gas using reasonable accident scenarios.

2 Individual risk

The individual risk at a location near a natural gas pipeline can be estimated by integrating along the pipeline the likelihood of accident multiplied by the fatality at the location from all accident scenarios and can be written as the following equation.

$$IR = \sum_{i} \int_{0}^{L} \varphi_i P_i dL \tag{1}$$

where the subscript i denotes the accident scenarios, φ_i failure rate per unit length of the pipeline associated with the accident scenario i, L pipeline length, and P_i lethality associated with the accident scenario i.

By assuming constant failure rate, the individual risk is:

$$IR = \sum_{i} \varphi_i \int_{l_-}^{l_+} P_i dL \tag{2}$$

The integration of the lethality depends on operating pressure, pipe diameter, and distance from a specified point of interest to the pipeline. By defining the integration part as fatal length, the individual risk is expressed in terms of the fatal length and the failure rate. The fatal length means a weighted length of pipeline within which an accident has the fatal effect on the person at a specified location.

2.1 Failure rate

The failure rate in a particular section of pipeline depends on many variables, such as soil, coating, design, cathodic protection, age of pipeline, depth of cover, hydrostatic test, survey, patrol, training, and so on. It is very difficult to include the effects of those variables on the failure rate because data may not be sufficient for statistical analysis. Generally for the risk analysis, the failure rate of pipeline is estimated simply using some variables from historical data. The failure rate of major gas pipelines in Western Europe is reported by the European Gas Pipeline Incident Data Group (EGIG). It is currently based on the experience of 1.5 million kilometre-years in eight countries of Western Europe. As shown in table 1, the external interference by third party activity is the leading cause to major accidents with the medium or great hole generated. The total failure rates for small, medium and great hole are 2.76 x 10^{-4}, 2.243 x 10^{-4} and

7.475 x 10^{-5} 1/yr.km, respectively [2]. These values are an order of magnitude higher than the values estimated from DOT data or British Gas Transco data. In this work, we adapt the EGIG data conservatively.

Table 1: Failure frequencies based on failure causes and hole size (EGIG, 1993 [27]).

Failure causes	Failure frequency [1/yr.km]	Percentage of total failure rate	Percentage of different hole size[%]		
			Small	Medium	Great
External interference	3.0 x 10^{-4}	51 %	25	56	19
Construction defects	1.1 x 10^{-4}	19 %	69	25	6
Corrosion	8.1 x 10^{-5}	14 %	97	3	<1
Ground movement	3.6 x 10^{-5}	6 %	29	31	40
Others/unknown	5.4 x 10^{-5}	10 %	74	25	<1
Total failure rate	5.75 x 10^{-4}	100 %	48	39	13

The hole sizes are defined as follows: Small hole: hole size is lower than 2cm; Medium hole: hole size ranges from 2cm up to the pipe diameter; Great hole: Full bore rupture or hole size is greater than the pipe diameter.

2.2 Fatal length

Dominant hazards from natural gas pipeline are the effect of semi-confined explosion and the effect of thermal radiation from a sustained jet fire, which may be preceded by a short-lived fireball. When a person is afflicted from the two events at the same time, the death probability should be considered for the intersection of both events to avoid overestimation. The hazard distance from the explosion is shorter than that from the jet fire which may follow the explosion. It implies that death probability by the explosion should be included in that of jet fire following it. Therefore, the death probability at a specified location from an accident of natural gas pipeline can be estimated then simply by considering only the thermal effect of jet fire.

To calculate simply the thermal radiation from a jet fire, the flame jet may be treated as a point source located at the centre of flame. Heat flux at a certain distance from a point fire source, which is defined by the receiver per unit area, can be calculated by using the following equation [3].

$$I = 8.11\times10^{5}\, Q_{eff}\, r^{-2.09} \tag{3}$$

Probit equation for death from the heat flux can be written as following equation.

$$\Pr = 16.67 + 3.4\ln(Q_{eff} / r^{2.09}) \tag{4}$$

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where r is the distance from a specified location to the fire. The gas release rate[Q_{eff}] from a hole of pipeline can be estimated by using the following equation [4].

$$Q_{eff,i} \;=\; 5.349 \times 10^{-4} A_P \, \alpha_i \, p_0 \tag{5}$$

where A_p is cross-section area of pipeline, p_0 operating pressure, and α_i effective hole area divided by A_p. Therefore, the fatal length scaled with the effective release rate depends only on the scaled distance of a specified point as shown in Fig. 1.

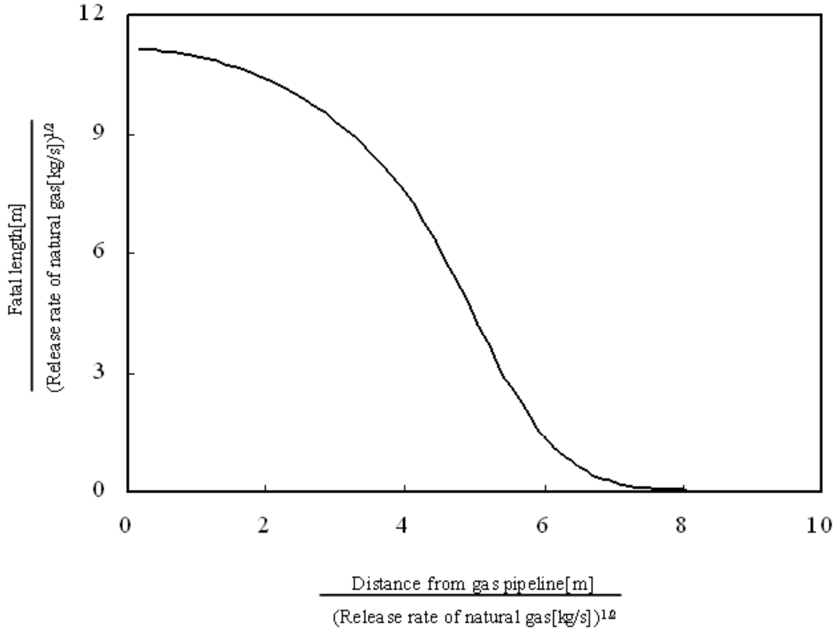

Figure 1: Fatal length at a specified location.

The fatal length is estimated by using Eq. (5) and Fig. 1. It is proportional to the square root of the operating pressure of the pipeline. If the minimum proximity of pipeline to normally occupied buildings is set up according to the acceptable criteria of individual risk, it will be also proportional to the square root of the operating pressure of the pipeline.

3 Societal risk

For hazardous pipelines, which have the potential to cause multiple fatalities, the societal risk is considered usually more important than the individual risk. The societal risk is defined from the societal point of view. It is expressed with the cumulative frequency and the expected number of death caused by an accident.

The expected number of death from a hypothetical accident could be calculated by integrating the multiplication of fatality and population density within a hazard area.

$$N_i = \int_{A_i} \rho_P P_i dA_i \tag{6}$$

where A_i is area bound by the hazard range associated with incident scenario i and ρ_P is population density.

To take the discrete hazardous sources into consideration, a pipeline should be divided into small sections. It should be short enough not to influence the calculated results. For all accident scenarios, the cumulative frequency of the accident with N or more fatalities is determined by adding the multiplied values of the next two: the failure rate for the accident scenario, and the length of a small section, within which an accident results in N or more fatalities.

$$F = \sum_i \int_0^L \varphi_i \, u(N_i \geq N) dL \tag{7}$$

where $u(N_i \geq N)$ is the unit function which is unity(1) if the argument is true or zero otherwise.

By assuming constant failure rate within a section of the pipeline, the societal risk can be expressed with the cumulative fatal length.

$$F = \sum_i \varphi_i \, L_{CFL,i}(N_i \geq N) \tag{8}$$

The cumulative fatal length, L_{CFL}, means a length within which an accident leads to N or more fatalities.

3.1 Cumulative fatal length

The cumulative fatal length is defined here as the length of pipeline in which an accident results in N or more fatalities. The number of fatalities from an accident is calculated by considering the number of persons and by taking an average probability of death within the area encountered. The area can be divided into three zones of 1%-50%, 50%-99%, and 99%-100% lethality. The number of people within each zone can be estimated simply by drawing the circles with radii r_{99}, r_{50}, and r_1, which are centered at the point of an accident, and then by counting the number of people in the zone. It can be estimated otherwise by multiplying the average population density with the area of each zone. The average lethality of each zone is given as 1, 0.802, and 0.145, respectively [5]. Therefore, the number of fatalities from an accident can be estimated approximately as the following equation.

$$N_i = N_{i,100-99} + 0.802 N_{i,99-50} + 0.142 N_{i,50-1} \tag{9}$$

where $N_{i,a-b}$ is the number of people within the range from a% to b% fatality and the subscript i denotes the small, medium and great hole on the pipeline.

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A profile can be drawn up graphically with calculated fatalities from an accident at each pipe segment which should be short enough not to influence the results. The curve could be constructed in a manner of segment by segment over the entire pipeline passing through urban area as shown in Fig. 2. It generally takes the shape of a ball.

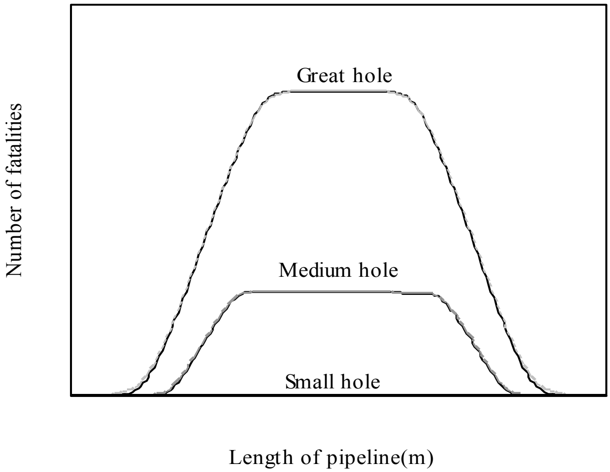

Figure 2: A typical curve of fatalities from accidents of natural gas pipeline passing through urban area.

The cumulative fatal length is determined simply from the profile of fatalities. It is just the length of the horizontal line of fatalities N intersected by the fatality curve.

$$L_{CFL,i}(N_i \geq N) = \int_0^L u(N_i \geq N)dL \tag{10}$$

The cumulative frequency for constructing societal risk curve can be estimated by using cumulative fatal length and the failure rate of the pipeline. The cumulative fatal length is obtained by drawing up the profile of the number of fatalities over the length of pipeline and then measuring the length of pipeline which has N or more fatalities on the profile curve.

4 Conclusions

Quantitative risk assessment recently has become important in controlling the risk level effectively in gas pipeline management. This work proposes a simple method of quantitative risk assessment for natural gas pipeline and introduces the parameters of fatal length and cumulative fatal length. These parameters can be estimated directly within a Geographic Information Systems (GIS) and are sensitive to pipeline length, pipeline diameter, and operating conditions.

With currently acceptable criteria taken into account for individual risk, the minimum proximity of the pipeline to occupied buildings is proportional to the square root of the operating pressure of the pipeline. And it decreases with the pipeline length due to resistance of gas flow through the pipeline. The proposed method for risk assessment may be useful for risk management during the planning and building stages of a new pipeline, modification of the pipeline, and to lower the risk of a buried pipeline.

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