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A method of quantitative risk assessment for transmission pipeline carrying natural gas

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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 paper focuses on the development of a simplified method for 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 by using the information of pipeline geometry and population density of a Geographic Information Systems (GIS). To demonstrate the proposed method, individual and societal risks for a sample pipeline have been estimated from the historical data of European Gas Pipeline Incident Data Group and BG Transco. With currently acceptable criteria taken into account for individual risk, the minimum proximity of the pipeline to occupied buildings is approximately proportional to the square root of the operating pressure of the pipeline. The proposed method of quantitative risk assessment may be useful for risk management during the planning and building stages of a new pipeline, and modification of a buried pipeline.

Keywords: Individual risk; Societal risk; Natural gas pipeline; Risk assessment; Safety management

1. Introduction

Transmission pipelines carrying natural gas are not on secure industrial site as a potentially hazardous plant, but are routed across the land, i.e., busy city or a network of superhighways. Consequently, there is the ever-present potential for third parties to interfere with the integrity of these pipelines. In addition, the combination of third-party interference and pipeline route might suggest that people around the pipelines are subject to significant risk from pipeline failure. The hazard distance associated with the pipeline ranges from under 20 m for a smaller pipeline at lower pressure, up to over 300 m for a larger one at higher pressure [1]. Therefore, regulatory authorities and pipeline managers have endeavored to improve the level of safety of the pipeline.

Recently, safety regulations associated with the pipeline are moving away from prescriptive approaches. As its alternative way, risk management based on the quantitative risk assessment has been under consideration in many countries. Risk is generally defined as a measure of human death in terms of two quantities: the probability of a pipeline failure occurring and the magnitude of death that arise as a result.

Until now, the failure rate of gas pipeline was estimated with high uncertainty from historical data or hierarchical analysis. Some of the failures are time independent, such as those resulting from external mechanical interference by third parties, earthquake or overpressure, while others are time dependent as in cases as corrosion or fatigue failures. The failure rate varies significantly with design factors, construction conditions, maintenance techniques and environmental situation. Thomas [2] proposed an empirical model to correlate the failure rate of the pipe. This approach relies on estimating the failure frequency for leakage and then predicting the

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Nomenclature

A	area bound by hazard range (m^2)
A_p	cross-section area of pipeline (m)
a	constant
a_k	variable of correction function
b	constant
C	decay factor for the effective rate of gas release
D	thermal dose for given exposure time ($s\,(J/m^2\,s)^{4/3}$)
d	pipe diameter (m)
F	cumulative frequency of the accident with N or more fatalities (1/year)
f_F	Fanning friction factor
H	distance from gas pipeline to populated area (m)
$\bar{H}$	distance from pipeline to populated area scaled by effective rate of gas release ($m/(kg\,s)^{1/2}$)
H_c	heat of combustion (J/kg)
h	distance from pipeline to a specified point (m)
$\bar{h}$	distance from pipeline to a specified point scaled by square root of effective rate of gas release ($m/(kg\,s)^{1/2}$)
I	radiational heat flux at the location of interest ($J/m^2\,s$)
K_j	correction function associated with failure causes
L	pipe length from gas supply station to leak point (m)
L_{CFL}	cumulative fatal length of pipeline (m)
L_{FL}	fatal length of pipeline (m)
$\bar{L}_{FL}$	fatal length scaled by square root of effective rate of gas release($m/(kg\,s)^{1/2}$)
$l_{\pm}$	ends of interacting section (m)
l_{50-1}	length of pipeline within from 50 to 1% fatality (m)
l_{99-50}	length of pipeline within from 99 to 50% fatality (m)
l_{100-99}	length of pipeline within from 100 to 99% fatality (m)
N	expected number of fatalities (person)
$\bar{N}$	number of fatalities scaled by release rate and again by population density ($m^2\,s/kg$)
$N_{i,a-b}$	number of people within the range from a to b% fatality (person)
P	probability of death
Pr	Probability unit
p_0	stagnation pressure at operating condition (N/m^2)
Q	rate of gas release from a hole (kg/s)
Q_{eff}	effective rate of gas release from a hole (kg/s)
Q_{peak}	peak initial rate of gas release from a hole (kg/s)
$Q_{steady-state}$	rate of gas release from a hole at steady-state (kg/s)
Re	operator of complex number
r	radial distance from fire (m)
$\bar{r}$	distance from fire scaled by square root of effective release rate ($m/(kg/s)^{1/2}$)
r_1	radius of fatality 1% (m)
r_{50}	radius of fatality 50% (m)
r_{99}	radius of fatality 99% (m)
r_h	hazard distance (m)
t	expose time (s)
u	unit function
Greek letters	
α	dimensionless hole size
φ	expected failure rate per unit pipe length (1/year km)
γ	specific heat ratio of gas
η	ratio of total heat radiated to total heat released from fire
ρ_0	stagnation density at operation condition (kg/m^3)
ρ_p	population density ($person/m^2$)
τ_a	atmospheric transmissivity
subscript	
i	denotes the accident scenarios such as small, medium and great hole on the pipeline
j	denotes the cause of failure such as external interference, construction defects, corrosion, ground movement and others

rupture frequency. The failure rate for leakage is estimated from global statistics by using an observed correlation of geometric and weld material factor. This estimate is scaled by other factors such as plant age. The failure rate of ruptures is evaluated with a given failure rate of leakage, partly by using a fracture mechanics model. The Thomas model may be suitable for estimating failure rate of pipes or vessels in a chemical plant. However, it is inappropriate to use it for transmission pipelines carrying natural gas because some of the most serious pipeline accidents resulting in ruptures have been caused by third-party activities which are not included in the Thomas model. In this work, the failure frequencies are estimated simply from the historical data of the European Gas Pipeline Incident Data Group (EGIG) and BG Transco [3,4].

The consequences of accident depend on its scenarios of the elements, such as hole size on the pipeline, time to ignition, meteorological condition and environmental condition at the failure point. In risk assessment, therefore, different results may be obtained depending on the assumptions of accident scenarios. Tedious calculations are sometimes unavoidable because of many accident scenarios and the distribution of hazard sources along the pipeline. However, investigation of real accidents associated with natural gas pipelines shows that the consequences are dominated by a few accident scenarios. For handy implementation of risk management, there are things to consider about accident scenarios and calculation methods of the consequences. This paper focuses on a simple method to calculate the consequences for the quantitative risk assessment of transmission pipelines carrying natural gas using reasonable accident scenarios.

2. Quantitative risk assessment

Risk can be described in different ways: individual risk, societal risk, maximum individual risk, average individual risk of exposed population, average individual risk of total population and average rate of death. Two popular measures are individual risk (IR) and societal risk (SR) [5]. The former is usually shown on a risk contour plot, while the latter is presented with a frequency–number (*F*–*N*) curve. The individual risk is defined as the probability of death at any particular location due to all undesired events. It can be expressed as the probability of a person at a specific location becoming a casualty within a year. With the risk of multiple fatalities being concerned, the societal risk is defined as the relationship between the frequency of an incident and the number of resulting casualties. It is usually expressed in the form of a graph of cumulative frequency (*F*) of *N* or more casualties plotted against *N* (an "*F*–*N* curve") [6]. The individual and societal risks of pipelines carrying natural gas will be discussed in more detail in the following sections.

2.1. Individual risk

Estimating the individual risk at a specified location from a pipeline is complicated because the failure position is unknown and the failure rate may vary along the pipeline. It can be estimated by integrating along the pipeline the likelihood of an accident multiplied by the fatality at the location from all accident scenarios, and can be written as the following equation:

$$\mathrm{IR} = \sum_i \int_{l_-}^{l_+} \varphi_i P_i \, \mathrm{d}L \tag{1}$$

where the subscript i denotes the accident scenarios, φ_i the failure rate per unit length of the pipeline associated with the accident scenario i, L the pipeline length, P_i the lethality associated with the accident scenario i and $l_\pm$ represents the ends of the interacting section of the pipeline in which an accident pose hazard to the specified location.

The accident scenarios in natural gas pipelines are generally explosion and jet fire sustained with the released gas from a small, medium, or great hole on the pipeline. The ends of the interacting section, which affects a person at a specified location, are related to the hazard distance associated with the pipeline. The hazard distance is related directly in turn to the release rate of natural gas, and this relationship has been proposed as the following equation [1]:

$$r_\mathrm{h} = 10.285\sqrt{Q_\mathrm{eff}} \tag{2}$$

where Q_eff is the effective release rate from a hole on a pipeline carrying natural gas.

The above equation is derived by setting the hazard distance as the distance within which there is more than one percent chance of fatality due to the radiational heat of jet fire from pipeline rupture. The interacting section of a straight pipeline, which is separated by h from a specified location, is estimated then by the Pythagorean Theorem.

$$l_\pm = \pm\sqrt{106 Q_\mathrm{eff} - h^2} \tag{3}$$

Shown in Fig. 1 are the geometric relations among the variables in this work. The interacting section calculated with Eq. (3) would be a rather conservative estimate, being long enough in other words, due to the assumption of the worst case scenario, such as horizontal jet fire, complete combustion and disregard of reduction in transmissivity resulting from carbon dioxide, water and shoot in the air.

The failure rate of pipelines varies according to different conditions along the route of the pipeline, such as soil conditions, coating conditions, design conditions or age of pipeline. Thus, the pipeline has to be divided into sections whenever those conditions are changed significantly. By assuming a constant failure rate, the individual risk can be estimated as

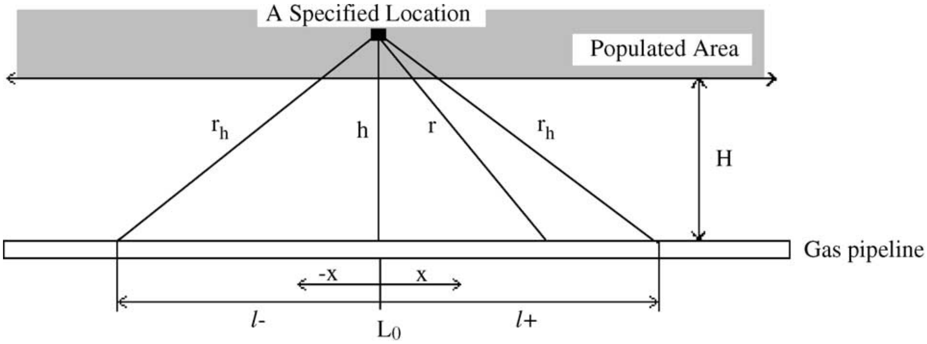

Fig. 1. The relation of variables.

the following equation:

$$\mathrm{IR} = \sum\nolimits_i \varphi_i \int_{l_-}^{l_+} P_i \,\mathrm{d}L \tag{4}$$

The integration of the lethality depends on operating pressure, pipe diameter, distance from a specified point of interest to the pipeline and the length of the pipeline from the gas supply or compressing station to the failure point. By defining fatal length as the integrated value in Eq. (4), the equation can be expressed simply as following.

$$\mathrm{IR} = \sum\nolimits_i L_{\mathrm{FL},i} \varphi_i \tag{5}$$

where $L_{\mathrm{FL},i}$ is the fatal length associated with accident scenario i.

The fatal length means a weighted length of pipeline within which an accident has a fatal effect on a person at a specified location. A simpler method for estimating the fatal length will be discussed later.

2.2. 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.

$$N_i = \int_{A_i} \rho_{\mathrm{P}} P_i \,\mathrm{d}A_i \tag{6}$$

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.

$$F = \sum\nolimits_i \int_0^L \varphi_i u(N_i \geq N) \,\mathrm{d}L \tag{7}$$

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.

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

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

2.3. Failure rate

The failure rate of a pipeline has the unit of the number of failures per year and per unit length of the pipeline, 1/(year km), with the uniform conditions assumed along the pipeline section of interest. It is somewhat different from the case of a point source of an accident in which the rate is defined as the number of failures per year. Failure rate of the pipeline in each accident scenario may be written as the following equation:

$$\varphi_i = \sum\nolimits_j \varphi_{i,j,0} K_j(a_1, a_2, a_{3,} \cdots) \tag{9}$$

where φ_i is the expected failure rate per unit pipeline length (1/(year km)), $\varphi_{i,j,0}$ is the basic failure rate per unit length of pipeline(1/(year km)), K_j is the correction function associated with failure causes, a_k is variable of the correction function, the subscript i denotes an accident scenario, such as that of small, medium and great hole pierced on the pipeline and the subscript j denotes the causes of failure such as external interference, construction defects, corrosion, ground movement and others.

It should be recognized that a pipeline does not have usually the constant probability of failure over its entire length. As conditions vary along the route of the pipeline, so does the probability. Therefore, the pipeline has to be divided into sections according to conditions such as soil, coating, design, cathodic protection or age of pipeline. The failure rate in a particular section of pipeline depends on many variables,

Table 1
Failure frequencies based on failure causes and hole size (EGIG, 1993) [3]

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

The hole sizes are defined as follows: small hole, hole size is lower than 2 cm; medium hole, hole size ranges from 2 cm up to the pipe diameter; great hole, full bore rupture or hole size is greater than the pipe diameter.

such as the above conditions, 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 a pipeline is estimated simply with some variables from historical data. The failure rate of onshore natural gas-pipelines in Western Europe is reported by the European Gas Pipeline Incident Data Group [3]. It is based on the experience of 1.5 million kilometer-years in eight countries of Western Europe. As shown in Table 1, the external interference by third party activity is the leading cause of major accidents related to medium or great holes. Thus, it is necessary to analyze the external interference in more detail. It is known that the extent of damage caused by third party activity depends on several factors, such as pipe diameter, depth of cover, wall thickness, population density and prevention method. But the EGIG report has not identified the prevention methods employed by pipeline operators to mitigate the damage caused by third party activity. Nor has the report provided the effect of population density in the vicinity of the pipeline. It is not practical to determine the factors by which the failure rates could be adjusted for those variables. The BG Transco data contain, however, information about those variables for the BG Transco's gas transmission network in the United Kingdom (UK). Moreover, the HSE in UK published recently a method for predicting the failure frequency caused by third party activity, and it is applied in PIPIN (pipeline integrity model) software [4]. The failure rate caused by third party activity is given by:

$$\varphi_{i,\mathrm{EI}} = \varphi_{i,\mathrm{EI},d} K_{\mathrm{DC}} K_{\mathrm{WT}} K_{\mathrm{PD}} K_{\mathrm{PM}} \tag{10}$$

where $\varphi_{i,\mathrm{EI},d}$ is the failure rate varying with pipe diameter due to external interference and K_{DC}, K_{WT}, K_{PD} and K_{PM} are the correction factors of depth of cover, wall thickness, population density and prevention method, respectively. Values of the factors in Eq. (10) are summarized in Tables 3 and 4, as recommended in HSE report [4]. The failure rates varying with pipeline diameter are given by using the least square method of data in Table 2 as following:

$$\varphi_{\mathrm{small},\mathrm{EI},d} = 0.001\mathrm{e}^{-4.18d-2.18562} \tag{11}$$

$$\varphi_{\mathrm{medium},\mathrm{EI},d} = 0.001\mathrm{e}^{-4.12d-2.02841} \tag{12}$$

$$\varphi_{\mathrm{great},\mathrm{EI},d} = 0.001\mathrm{e}^{-4.05d-2.13441} \tag{13}$$

The failure rates from the other causes, such as construction defect, corrosion, ground movement and unknown causes contribute less to the risk, which will be discussed in the later section, and can be estimated simply by using EGIG data. The total failure rate can be estimated then by adding all the failure rates of various causes for each hole size. The likelihood of an accident can be assumed conservatively as the failure rate of the pipeline, considering abundant ignition sources at the populated region.

2.4. Consequences

Investigations of real accidents of natural gas pipelines show that the consequences are dominated by a few accident scenarios such as explosion and jet fire [7]. The possibility of a significant flash fire resulting from the delayed remote ignition is extremely low due to the buoyant nature of the vapor, which generally precludes the formation of a persistent vapor cloud at ground level. Unconfined vapor cloud explosion of methane produces negligible overpressure with the flame travelling through a gas and air mixture [8]. If the rupture point for the pipeline is close to a building, the leaked gas would migrate into the building and make a significant confined explosion by ignition [9]. Therefore, the dominant hazards of natural gas pipelines are the confined explosion and the thermal radiation of a sustained jet fire, on the other hand, the effects of unconfined vapor cloud explosion and flash fire are ignorable to analyze the risk. When a person is exposed the two events at the same time, the death probability should be considered for the intersection of both events in order to avoid the overestimation. The hazard distance from confined explosion and jet fire can be estimated by analyzing jet dispersion, jet fire and thermal radiation. The hazard distance from the confined explosion is shorter than that from the jet fire which may follow the explosion, if the accident point is not very close to a gas supply station [1]. It implies that the death probability by the explosion should be included in that of the jet fire following it. The death probability at a specified location from an accident of a natural gas pipeline

Table 2
Failure frequencies caused by third party activity (BG Transco data) [4]

Diameter range (mm)	Representing diameter (mm)	Total failure rate (1/1000 km year)	Failure rate (1/1000 km year)		
			Small	Medium	Great
0–100	100	0.218	0.044	0.087	0.087
125–250	187	0.180	0.072	0.060	0.048
300–400	350	0.095	0.024	0.071	–
450–550	500	0.043	0.029	–	0.014
600–700	650	–	–	–	–
750–850	800	0.041	–	–	0.041
900–1000	950	–	–	–	–
1000+	1050	–	–	–	–

can be estimated then simply by considering only the thermal effect of jet fire.

2.4.1. Thermal effect

The probability of death from an accident can be estimated as the following equation [10,11]:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mathrm{Pr}-5} \mathrm{e}^{-s^2/2}\,\mathrm{d}s \tag{14}$$

The argument of the function is the probability unit, Pr, characterizing the dose–effect relationship between the doses of such concrete harmful load as pressure, heat or toxicity and such recipient categories as death or injuries.

$$\mathrm{Pr} = a + b\ln(D) \tag{15}$$

where a and b are empirical constants that reflect the hazard specifics of a harmful load studied and the susceptibility of recipients to the load, while D is a dose of the load for a given exposure time.

For the fatality of a person from heat effect, it can be expressed as the following equation [11]:

$$\mathrm{Pr} = -14.9 + 2.56\ln\left(\frac{tI^{4/3}}{10^4}\right) \tag{16}$$

where t is the exposure time and I is the radiational heat flux at a specified location of interest.

The heat flux at a certain distance from a jet fire depends on the shape of flame. A jet flame can be idealized as a series of point source heat emitters spread along the length of the flame. The total heat flux reaching a given point is obtained by summing the radiation received from each point source emitter. By collapsing the set of heat emitters into a single point source emitter located at ground level, the total heat flux received by ground level damage receptor is estimated conservatively. This assumption has advantage to avoid tedious calculation and it gives very simple equation for risk assessment, even though the result has some error. Therefore, heat flux at a certain distance from the fire source, which is defined by the receiver per unit area, can be calculated as suggested in API RP 521 [12].

$$I = \frac{\eta\tau_{\mathrm{a}} Q H_{\mathrm{c}}}{4\pi r^2} \tag{17}$$

where η is the ratio of the radiated heat to total heat released from the fire, τ_{a} the atmospheric transmissivity, Q the gas release rate, H_{c} the heat of combustion and r is the radial distance from the fire to the location of interest.

Radiation fraction (η) cannot be estimated theoretically, and is normally estimated from the data measured with radiometer. Laboratory data suggest that it is 0.2 for methane [11].

The duration of exposure depends on so many circumstances that it would not be possible in fact to establish any specific rule to evaluate the degree of harm. Rausch recommends a value of 30 s as exposure time for people in an urban area [13]. Therefore, the Probit equation for death at a specified location from a jet flame of natural gas can be written conservatively as the following equation, with the heat of combustion of the natural gas at room temperature, $H_{\mathrm{c}} = 5.002 \times 10^7$ J/kg and the atmospheric transmissivity assumed as the unity, $\tau_{\mathrm{a}} = 1$.

$$\mathrm{Pr} = 16.61 + 3.4\ln\left(\frac{Q}{r^2}\right) \tag{18}$$

where r is the distance from a specified location to the fire.

The probability of death at a specified location from an accident of natural gas pipeline can be estimated now simply with the gas release rate.

2.4.2. Gas release rate

The gas release rate from a hole of the pipeline varies with time. Within seconds of failure, the release rate will have dropped to a fraction of the peak initial value. It will decay even further over time until steady-state. The peak initial release can be estimated by assuming the sonic flow through an orifice as the following equation [11]:

$$Q_{\mathrm{peak}} = \frac{\pi d^2 \alpha}{4}\sqrt{\gamma \rho_0 p_0 \left[\frac{2}{\gamma+1}\right]^{\gamma+1/\gamma-1}} \tag{19}$$

where α is the dimensionless hole size which is the ratio of effective hole area to the pipe cross-sectional area, d the pipe diameter, ρ_0 the stagnation density of gas at operating conditions, p_0 the stagnation pressure at operating conditions and γ is the specific heat ratio of gas.

The release rate at steady-state can be estimated approximately by assuming choke flow at the release point [14].

$$Q_{\text{steady-state}} = \frac{Q_{\mathrm{peak}}}{\sqrt{1 + (4\alpha^2 f_{\mathrm{F}} L/d)(2/\gamma+1)^{2/\gamma-1}}} \tag{20}$$

where f_{F} is Fanning friction factor and L is the pipe length from the gas supply station to the release point.

The numerator in the above equation is the release rate without friction loss through pipeline, while the denominator acts as a decay factor due to the wall friction loss at steady-state. The effective release rate associated with the death probability of a person from fire would depend on the exact time of ignition. The death probability can be estimated by approximating the transient jet fire as a steady-state fire that is fed by the gas released at the effective rate. The effective release rate, CQ_{peak}, is a fractional multiple of the peak initial release rate. It can be used to obtain the heat flux comparable to that from the real transient fire ignited with a slight delay. In general, the most appropriate value for the decay factor would depend on the pipe size, the pressure at the time of failure, the assumed time to ignition and the time period required to cause harm to people. In one-dimensional transient flow through the arrested crack tip of a tube with constant cross-section, the decay factor is expressed as the following equation [15]:

$$C = \left[1 - \frac{\gamma - 1}{\gamma + 1}\right]^{2\gamma/\gamma - 1} \tag{21}$$

In a study of risks of hazardous pipelines in the UK conducted by A.D. Little Ltd. [16], the authors quoted 0.25 as the decay factor. A more conservative value of 0.3 is adopted here for the factor. It is not to underestimate the intensity of the sustained fire associated with the nearly immediate ignition of leaked gas from large diameter pipelines. However, sometimes the decay factor appears greater than 0.3 at steady-state from the denominator of Eq. (20). Therefore, the decay factor can be assumed as the following equation:

$$C = \max\left[0.3, \frac{1}{\sqrt{1 + 4\alpha^2 f_{\mathrm{F}} L/d(2/\gamma + 1)^{2/\gamma - 1}}}\right] \tag{22}$$

The effective release rate can be estimated for the risk analysis by using Eqs. (19) and (22) as following:

$$Q_{\mathrm{eff}} = C Q_{\mathrm{peak}} \tag{23}$$

By assuming the specific heat ratio $\gamma = 1.42$, gas density at atmosphere $\rho = 0.68\,\mathrm{kg/m^3}$ and Fanning friction factor $f_{\mathrm{F}} = 0.0026$ conservatively for steel pipeline, the effective rate of gas release from a hole on the pipeline is given as below:

$$Q_{\mathrm{eff},i} = 1.783 \times 10^{-3} A_{\mathrm{P}} \alpha_i p_0 \times \max\left[0.3, \frac{1}{\sqrt{1 + 4.196 \times 10^{-3} \alpha_i{}^2 (L_0 + x)/d}}\right] \tag{24}$$

where α_i dimensionless size of small, medium and great hole resulted from the failure of the pipeline and x is the distance from L_0 as shown in Fig. 1.

If a specified location is not very close to a gas supply station, $L_0 \gg x$, or the decay factor is not greater than 0.3, the effective rate of gas release from a hole appears approximately constant.

2.5. Fatal length

The fatal length is defined here as the pipeline length weighted by the death probability at a specified location. It is evaluated by integrating the death probability associated with hypothetical accidents over the entire pipeline. The probability of death from a jet fire, which is the dominant accident in the natural gas pipeline as discussed above, depends on the effective rate of gas release and the distance from the fire to the specified location. Solved by Eqs. (14) and (18), it decreases suddenly from unity (1) to zero, as shown in Fig. 2, at a certain scaled distance from the pipeline to the specified location, $\bar{r} = r/\sqrt{Q_{\mathrm{eff}}}$. The integration of the fatality along the pipeline can be approximated then by adding the pipe lengths multiplied with corresponding average values of lethality in the zones, i.e., 1–50, 50–99 and 99–100% lethal. The radii of fatality 99, 50 and 1% associated with the effective rate of gas release are calculated simply from Eq. (18) by using the probability unit, 7.33, 5 and 2.67, respectively.

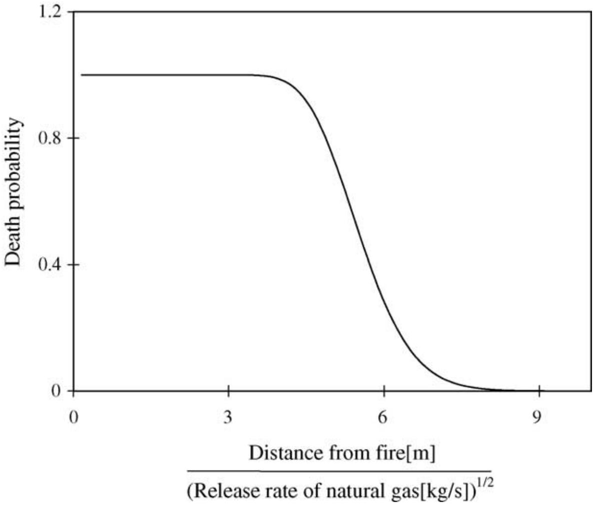

Fig. 2. Death probability from the fire of natural gas.

$$r_{i,99} = \sqrt{15.3 Q_{\mathrm{eff},i}} \tag{25}$$

$$r_{i,50} = \sqrt{30.4 Q_{\mathrm{eff},i}} \tag{26}$$

$$r_{i,1} = \sqrt{60.3 Q_{\mathrm{eff},i}} \tag{27}$$

For a straight gas pipeline, the length in each zone can be estimated by using the operator, Re, which represents the value of real part in the complex number.

$$l_{i,100-99} = 2\sqrt{Q_{\mathrm{eff},i}}\,\mathrm{Re}\left[\sqrt{15.3 - \bar{h}_i^2}\right] \tag{28}$$

$$l_{i,} = 2\sqrt{Q_{eff,i}}\,\mathrm{Re}\left[\sqrt{30.4 - \bar{h}_i^2} - \sqrt{15.3 - \bar{h}_i^2}\right] \tag{29}$$

$$l_{i,50-1} = 2\sqrt{Q_{eff,i}}\,\mathrm{Re}\left[\sqrt{60.3 - \bar{h}_i^2} - \sqrt{30.4 - \bar{h}_i^2}\right] \tag{30}$$

where $\bar{h}_i$ is the distance scaled by the square root of the effective rate of gas release, $\bar{h}_i = h/\sqrt{Q_{\mathrm{eff},i}}$, h the distance from the pipeline to a specified location of interest and $l_{i,a\text{–}b}$ is the length of pipeline within the range from a to b% fatality.

The average fatalities of those three zones are given from Fig. 2.

$$\frac{\int_0^{\sqrt{15.3}} P\,\mathrm{d}\bar{r}}{\int_0^{\sqrt{15.3}} \mathrm{d}\bar{r}} \approx 1 \tag{31}$$

$$\frac{\int_{\sqrt{15.3}}^{\sqrt{30.4}} P\,\mathrm{d}\bar{r}}{\int_{\sqrt{15.3}}^{\sqrt{30.4}} \mathrm{d}\bar{r}} \approx 0.816 \tag{32}$$

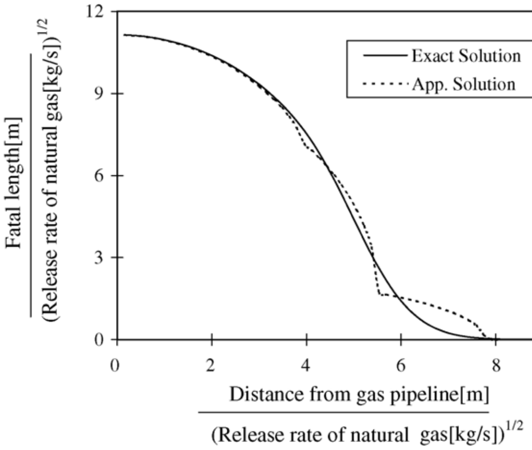

Fig. 3. Fatal length at a specified location.

$$\frac{\int_{\sqrt{30.4}}^{\sqrt{60.3}} P\,\mathrm{d}\bar{r}}{\int_{\sqrt{30.4}}^{\sqrt{60.3}} \mathrm{d}\bar{r}} \approx 0.156 \tag{33}$$

Therefore, the fatal length can be estimated from the length of pipeline within each zone as the following equation:

$$L_{\mathrm{FL},i} = \int_0^L P_i\,\mathrm{d}L \approx l_{i,100-99} + 0.86 l_{i,99-50} + 0.156 l_{i,50-1} \tag{34}$$

As shown in Fig. 3, the fatal length scaled by the square root of the effective release rate, $\bar{L}_{\mathrm{FL}} = L_{\mathrm{FL}}/\sqrt{Q_{\mathrm{eff}}}$, depends only on the scaled distance of a specified point. Even though the approximate solution deviates slightly from the exact one, it has a big advantage of being extended easily to the curved gas pipeline as well as being used directly within a Geographic Information Systems. One such system now is in use widely in the pipeline industry for the purpose of safety and data management.

2.6. 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. As discussed in the previous section, the area can also 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 from Eqs. (14), (18) and (24)–(27).

$$\frac{\int_0^{r_{99}} rP\,\mathrm{d}r}{\int_0^{r_{99}} r\,\mathrm{d}r} \approx 1 \tag{35}$$

$$\frac{\int_{r_{99}}^{r_{50}} rP\,\mathrm{d}r}{\int_{r_{99}}^{r_{50}} r\,\mathrm{d}r} \approx 0.802 \tag{36}$$

$$\frac{\int_{r_{50}}^{r_{1}} rP\,\mathrm{d}r}{\int_{r_{50}}^{r_{1}} r\,\mathrm{d}r} \approx 0.145 \tag{37}$$

Therefore, the number of fatalities from an accident can be estimated approximately as the following equation:

$$N_i = N_{i,100-99} + 0.802 N_{i,99-50} + 0.142 N_{i,50-1} \tag{38}$$

where $N_{i,a\text{–}b}$ 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.

The number of fatalities can be calculated by using Eqs. (6), (14) and (18), when the populated area is separated by H from a pipeline carrying natural gas and is extended along the pipeline with a constant population density as shown in Fig. 1. The number of fatalities scaled by the population density and again by the effective rate of gas release, $\bar{N} = N/(\rho_{\mathrm{p}} Q_{\mathrm{eff}})$, is related only to the distance of populated area scaled by the square root of the effective release rate, $\bar{H} = H/\sqrt{Q_{\mathrm{eff}}}$, as shown in Fig. 4. The approximate solution of the three-zone method deviates slightly from the exact curve and the error can be ignored in the societal risk analysis. Therefore, the three-zone approximation may be employed to calculate the cumulative fatal length as well as the fatal length of transmission pipeline carrying natural gas.

A profile can be drawn up graphically with thus 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. It generally takes the shape of a ball as shown in Fig. 9. The cumulative fatal length is determined

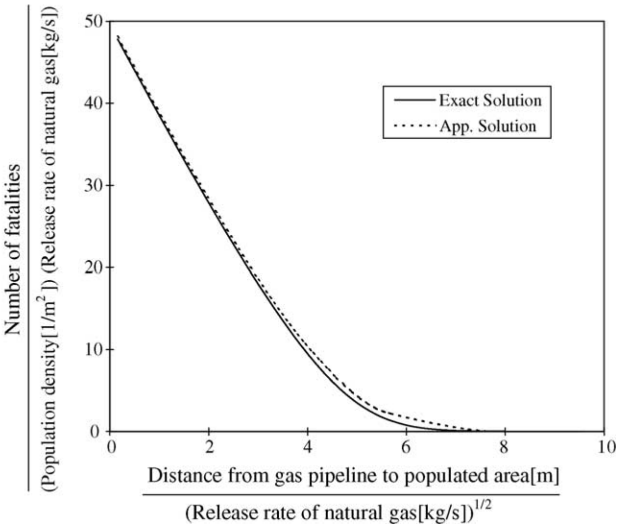

Fig. 4. Number of fatalities from an accident of natural gas pipeline with constant population density.

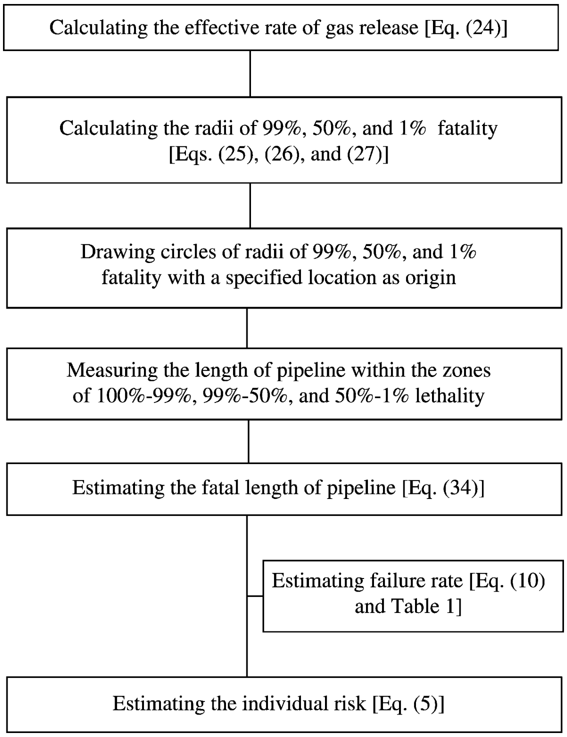

Fig. 5. Procedure to calculate the individual risk of natural gas pipeline.

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

$$L_{\mathrm{CFL},i}(N_i \geq N) = \int_0^L u(N_i \geq N)\,\mathrm{d}L \qquad (39)$$

The procedures to determine the individual risk at a specified location of interest from natural gas transmission pipelines and to construct the societal risk curve are summarized in Figs. 5 and 6. The individual risk is estimated by multiplying the fatal length with the failure rate of the pipeline. The fatal length can be obtained by adding together three pipe lengths multiplied with corresponding average lethality within the zones divided by radii of 99, 50 and 1% lethality. And the radius of each zone can be calculated in turn by putting the effective rate of gas release into Eqs. (25)–(27). The failure rate of a pipeline section may be estimated by adding the failure rates caused by external interference, construction defect, corrosion, ground movement and unknown causes. The failure rate caused by external interference can be estimated by using BG Transco data and that by other causes can be estimated by using EGIG data. The societal risk curve can be constructed 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.

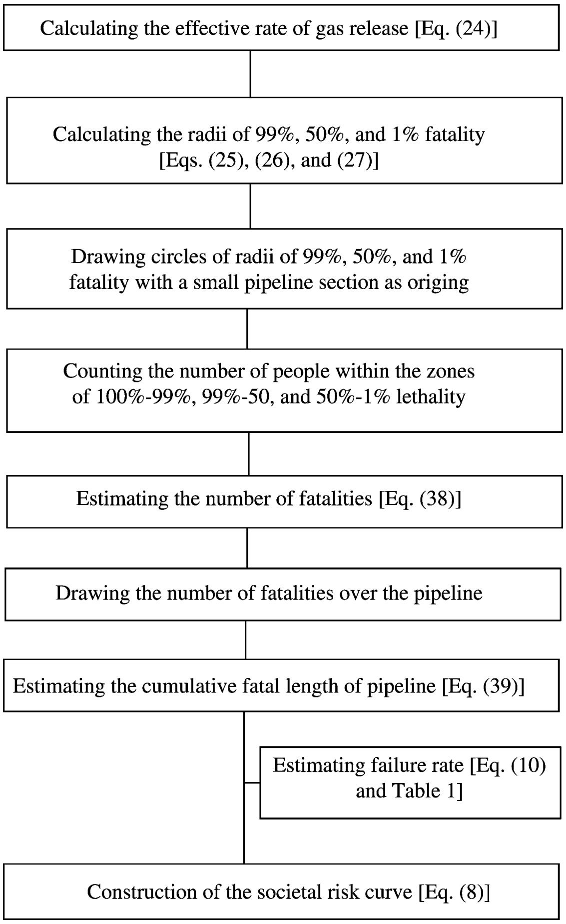

Fig. 6. Procedure to construct the societal risk curve of natural gas pipeline.

3. Calculations and discussions

To illustrate and discuss the method presented in the above sections, a sample risk assessment is presented with a straight natural gas pipeline of 1000 mm diameter, operating at 50 bar, covered 130 cm depth and located in a town area. The individual risk is estimated at the location of 50 m apart from the pipeline. Meanwhile the societal risk has been analyzed assuming that the pipeline passes the central area of town.

3.1. Individual risk

Summarized in Table 5 are the failure rates of pipelines from BG Transco data for the external interference and from EGIG data for the other causes. Obtained from the Tables 3 and 4, the correction factors of the external interference are 0.54 for the depth of cover, 1 for wall thickness, 18.77 for population density and 1.03 for prevention method. At the location of 50 m away from the pipeline, the fatal length is estimated with the diameters of small, medium and great hole being assumed as 2 cm, the half of the pipe diameter and the pipe diameter, respectively. The method of calculating the fatal length approximately is successful as shown in Fig. 7 which compares with the exact solution. The approximate

Table 3
Correction values of failure frequencies caused by third party activity

Factors	Correction value	Conditions
Depth of cover	2.54	dc < 0.91 m
	0.78	0.91 m $\leq$ dc $\leq$ 1.22 m
	0.54	dc > 1.22 m
Wall thickness	1	$t = t_{\mathrm{min}}$ or $d > 0.9$ m
	0.4	6.4 mm < $t \leq$ 7.9 mm and 0.15 m < $d \leq$ 0.45 m
	0.2	$t > t_{\mathrm{min}}$
Population density	18.77	Town
	3.16	Suburban
	0.81	Rural
Prevention methods	1.03	Marker posts only
	0.91	All other methods

Table 4
Minimum wall thickness with pipeline diameter

d (mm)	–150	150–450	450–600	600–900	900–1050	1050
t_{min} (mm)	4.8	6.4	7.9	9.5	11.9	12.7

dc: depth of cover; t: wall thickness of pipeline; d: diameter of pipeline; rural: a population density not exceeding 2.5 persons/ha; town: central areas of towns or cities; suburban: area intermediate in character between rural and town; t_{min}: minimum wall thickness.

fatal length is obtained by using three-zones method of Eqs. from (24)–(34) with the effective release rate at L_0 on the pipeline, while the exact one is solved by line integration of fatality associated with hypothetical incidents along pipeline by using Eqs. (14), (18) and (24). The fatal length due to a small hole is nearly zero because of much less release rate than in others. For the great hole on the pipeline, the fatal length remains constant at about 500 m as the pipeline gets longer than 3000 m because of the decay factor in Eq. (22) assumed to be 0.3.

The individual risk is estimated by quoting Table 5, Fig. 7 and Eq. (5), and it decreases with the length of pipeline as shown in Fig. 8 because the effective release rate gets smaller. The external interference contributes about 75%, the construction defects 10%, the ground movement 10% and the unknown causes 5%, to the total individual risk. The most serious risk in pipelines carrying natural gas is caused by

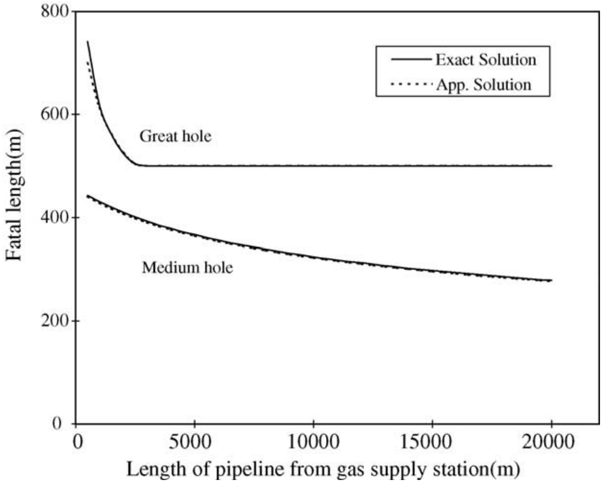

Fig. 7. Change of fatal length with pipeline length ($d_{\mathrm{small}} = 20$ mm, $d_{\mathrm{medium}} = 500$ mm, $d_{\mathrm{great}} = 1000$ mm, $d = 1000$ mm, $p_0 = 50$ atm and $h = 50$ m).

Table 5
Failure frequencies of pipeline estimated with EGIG and BG Transco data

Failure causes	Failure frequency of different hole size (1/year km)		
	Small	Medium	Great
External interference	1.7×10^{-5}	2.2×10^{-5}	2.1×10^{-5}
Construction defects	7.6×10^{-5}	2.8×10^{-5}	0.7×10^{-5}
Corrosion	7.9×10^{-5}	2.4×10^{-6}	8.1×10^{-7}
Ground movement	1.0×10^{-6}	1.1×10^{-6}	1.4×10^{-6}
Others/unknown	4.0×10^{-5}	1.4×10^{-5}	5.4×10^{-7}
Total failure rate	2.1×10^{-4}	6.8×10^{-5}	3.10×10^{-5}

Pipeline: 1000 mm diameter, 50 bar operating pressure, 130 cm the depth of cover and located in a town area. $\varphi_{\mathrm{small,EI}} = 0.001\mathrm{e}^{-4.18-2.18562} \times 0.54 \times 1 \times 18.77 \times 1.03 = 1.7 \times 10^{-5}$; $\varphi_{\mathrm{medium,EI}} = 0.001\mathrm{e}^{-4.12-2.02841} \times 0.54 \times 1 \times 18.77 \times 1.03 = 2.2 \times 10^{-5}$; $\varphi_{\mathrm{great,EI}} = 0.001\mathrm{e}^{-4.05-2.13441} \times 0.54 \times 1 \times 18.77 \times 1.03 = 2.1 \times 10^{-5}$.

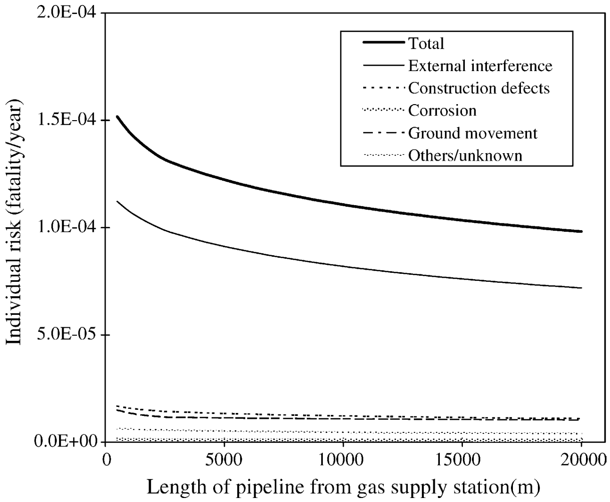

Fig. 8. Change of individual risk with pipeline length (conditions the same as in Fig. 4).

the external interference. The risk caused by the corrosion of the pipeline is much less serious compared to that caused by other causes, because the majority of failure caused by corrosion generally contributes only to the failure of small holes as shown in Table 1. Therefore, the corrosion problem is relatively less important in the risk assessment of transmission pipeline carrying natural gas, even though it is a research field of interest.

Published in Europe are the criteria of individual risk considered to be acceptable in regulating industrial risk [6]. The HSE quotes 1×10^{-6} per year as the risk of fatality that is regarded broadly as acceptable, and 1×10^{-4} per year as that representing the boundary between tolerable and unacceptable for the public. The distance from the pipeline, at which the individual risk is 1×10^{-4} per year, is directly proportional to the square root of the operating pressure. It is because the fatal length is approximately proportional to the square root of the effective release rate and so is the release rate in turn to the operating pressure, as given in Eqs. from (24)–(34). If the minimum proximity of pipeline to normally occupied buildings is thus 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.

3.2. Societal risk

The proposed procedure concerns a sample pipeline passing through a town area at 20 km from the gas supply station. The area is 1 km × 1 km wide and populated by 20 persons/ha. The profile of fatalities can be constructed by adopting three-zone method of Eq. (38) with the gas release rate obtained from Eq. (24). The approximate solution has little deviation from the exact one calculated by Eq. (6), and the error may be negligible as shown in Fig. 9. The integration of fatality with the three zones is sufficient for calculating the cumulative fatal length. The number of fatalities from a small hole of a pipeline may be ignorable and the *F–N* curve can be constructed directly by measuring the length of the horizontal line of fatalities *N* intersected by the fatality curves. The cumulative failure rate drops steeply near the maximum fatalities with given accident scenario as shown in Fig. 10.

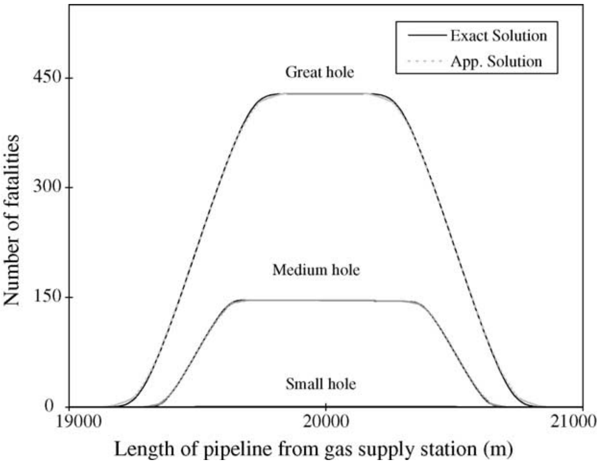

Fig. 9. The number of fatalities associated with accidents along the sample pipeline.

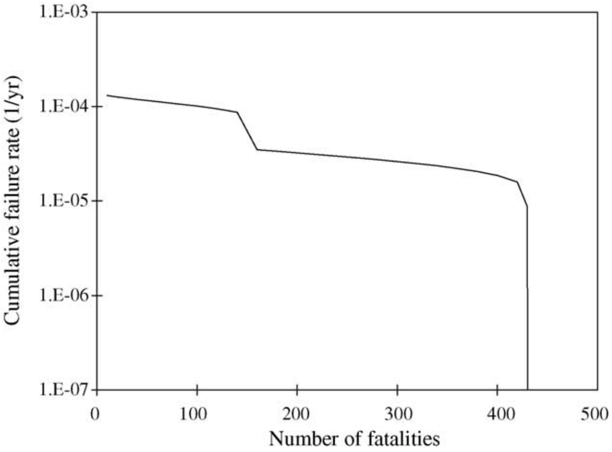

Fig. 10. Societal risk curve associated with Fig. 9.

The criterion for acceptable societal risk is not standardized among the EU countries. The limit of acceptable level of societal risk has been set down generally as the cumulative frequency multiplied by the square of the number of fatalities to be lower than a certain value. In industrial processes, the acceptable societal risk is $FN^2 \leq 10^{-5}$ persons^2/year and the boundary between tolerable and unacceptable is $FN^2 = 10^{-3}$ persons^2/year [17]. Because of the steep change of cumulative failure rate, it can be checked simply with the value of FN^2 near the maximum fatalities for each accident scenario in order to determine whether the pipeline could be accepted or not.

The procedure of quantitative risk analysis, individual and societal risks, can be simplified by using the fatal length and the cumulative fatal length for transmission pipelines carrying natural gas. Since the expected failure rates are highly uncertain in the pipeline system, the fatal length and cumulative fatal length with a hypothetical accident can be employed instead as one measure for safety management.

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 by using the information of pipeline geometry and population density of a Geographic Information Systems and are sensitive to pipeline length, pipeline diameter and operating conditions. The proposed simplified method turns out to be successful through being applied to a sample pipeline.

Individual risk can be estimated with the fatal length in addition to the failure rate of the pipeline. Societal risk can be estimated similarly with the cumulative fatal length and the failure rate. The fatal length is obtained by adding the pipe lengths multiplied with corresponding average values of lethality in the zone of 1–50, 50–99 and 99–100% lethality. The cumulative fatal length is obtained graphically on the fatalities curve by measuring the length of the horizontal line of fatalities *N* intersected by the profile of potential fatalities over the pipeline. The fatalities from an accident are calculated by adding the number of people multiplied with the average lethality within the three zones.

With currently acceptable criteria taken into account for individual risk, the minimum proximity of the pipeline to occupied buildings is approximately 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, and modification of a buried pipeline.

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