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Derivation of Risk Areas Associated with High-Pressure Natural-Gas Pipelines Explosions Including Effects on Structural Components

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A number of high-profile incidents involving transmission pipelines in urban and environmentally sensitive areas have recently focused public attention on pipeline safety. The consequences of incidents that involve large diameter, high-pressure transmission pipelines can pose a significant threat of damage to people and properties in the vicinity of the failure location. This study attempts to develop a risk assessment procedure for the estimation of the annual probability of direct structural damage to reinforced concrete (RC) buildings associated with high-pressure natural-gas pipeline explosions. First, blast hazard is estimated using the Multi-Energy method and then blast fragility of single RC columns through pressure-impulse equations. The results are combined to assess the annual risk of structural collapse and the extent of ground area where the failure of a high-pressure pipeline carrying natural gas can lead to the collapse of RC buildings.

1. Introduction

Transmission pipelines carrying natural gas are not typically within safe industrial sites and may cross through both rural and heavily populated areas. Statistical data have shown an overall mean annual failure rate of 0.351 per 1,000 km over the period 1970-2010 and a mean annual failure rate over the past 5 years equal to 0.162 per 1,000 km (EGIG, 2011). Failure of the pipeline can have several effects, some of which can pose a significant threat of damage to people and properties in the immediate vicinity of the failure location, as observed in the recent major pipeline incidents occurred in Ghislenghien, Belgium (30 July 2004), San Bruno, California (9 September 2010), Lunigiana, Italy (18 January, 2012), Sissonville, West Virginia (11December 2012). These events have highlighted the need to assess carefully and rationally the actual risks associated with living and working in proximity to transmission pipelines and to consider land use controls near pipelines that will allow people and pipelines to coexist in a manner that does not pose undue risk to each other.
There are many causes and contributors to pipeline failures including construction errors, material defects, internal and external corrosion, operational errors, malfunctions of control systems or relief equipment, outside force damage (e.g., by third parties during excavation) and earthquake (Cunha, 2012).
The accident scenarios for high-pressure natural gas pipelines can be selected from a few scenarios based on actual accidents. In the event of rupture, a gas cloud would form and its size depends on the geometrical and operation parameters of the pipeline and of the rupture. An unconfined vapour cloud explosion produces negligible overpressure with the flame travelling through the gas and air mixture. When objects, such as buildings, are near or within an ignited gas cloud, they restrict the free expansion of combustion products and cause a significant overpressure. Therefore, the buildings could be destroyed by semi confined explosion of gas either outside the building or migrated into the building. The probability of occurrence of a significant flash fire conditioned on delayed remote ignition is extremely low due to the

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buoyant nature of the vapour, which generally precludes the formation of a persistent vapour cloud at ground level. The major hazards are, therefore, the collapse of buildings under the explosion, and the heat effect of thermal radiation from a sustained jet fire, which may be preceded by a short-lived fireball.

This study presents a risk assessment procedure which allows one to estimate the annual probability of direct structural damage to reinforced concrete (RC) buildings associated with high-pressure natural-gas pipeline explosions. Blast hazard is estimated using the Multi-Energy (TNO) Method and is expressed as overpressure and positive phase duration generated by the explosion occurring outside the building. To this end, different conditions are considered in terms of geometrical and operating conditions of the pipeline. Then, blast fragility of single RC columns is estimated through pressure-impulse equations and is convolved with blast hazard to provide annual risk of structural collapse. It is emphasised that the collapse of single columns can be a critical condition for the remaining part of the structure, because it can induce progressive collapse (Parisi and Augenti, 2012) resulting in huge economic and human life losses. Therefore, a probability-based approach is proposed to evaluate the ground area where the failure of a high-pressure pipeline carrying natural gas can lead to the collapse of RC buildings, which are common structures worldwide.

2. Methodology of structural risk assessment

Natural gas explosions and bomb detonations under terrorist attack can induce local damage to individual structural components (e.g. columns at the ground floor of a building) and its propagation throughout the structure, resulting in a progressive collapse of the whole structural system or a part of it. Therefore, progressive collapse is conditioned upon local damage.

The annual probability of structural collapse under an extreme event can be estimated according to the risk analysis framework proposed by Ellingwood (2006) for progressive collapse, as follows:

$$P\left[C\right] = P\left[C \mid D\right] P\left[D \mid H\right] \lambda_H \tag{1}$$

where C is the progressive collapse that a structure can experience, D is the local structural damage, H is the extreme event under consideration, and λ_H is the mean annual rate of occurrence of H. A reliability-based design/assessment criterion should be $P\ [C] \leq p_{th}$, where p_{th} is the de minimis risk defining the acceptable risk level below which society normally does not impose any regulatory guidance. Pate-Cornell (1994) highlighted that p_{th} is in the order of 10^{-7}/y.

In this paper the annual risk is assessed at local structural level, so the following part of Eq. (1) is of interest:

$$P\left[D\right] = P\left[D \mid H\right] \lambda_H \tag{2}$$

and it can be convolved with conditional probability of global structural collapse as follows:

$$P\left[C\right] = P\left[C \mid D\right] P\left[D\right] \tag{3}$$

The annual probability of local structural damage can be further specialised to:

$$P\left[D\right] = P\left[D \mid E\right] P\left[E \mid R\right] \lambda_R \tag{4}$$

where E is the natural gas explosion and R is the pipeline rupture which is assumed to be the hazard source; this means that λ_R stands for λ_H. The conditional probability $P\ [D|E]$ is the blast fragility of the structural components under study, $P\ [E|R]$ is the blast hazard function, and λ_R is the mean annual rate of occurrence of rupture phenomena in natural gas transmission pipelines.

In this study the blast hazard is evaluated by means of the multi-energy method. The explosion generated by the natural gas release is assumed to induce a vector-valued engineering demand measure on RC columns, which includes both peak overpressure and impulse over the positive phase of the pressure time history. Then, the blast fragility is computed through the standard Monte Carlo simulation, assuming a capacity model of individual RC columns based on pressure–impulse equations.

3. Blast hazard analysis

Various models have been developed for assessing the explosive hazard of a flammable cloud ranging from simplified (empirical) models, phenomenological models or sophisticated computational fluid dynamics (CFD) models (AutoReaGas, Flacs). To obtain an initial estimate, it may be used methods that rely on expressing the explosive power of a cloud as an equivalent explosive charge (TNT or fuel-air), for which the blast characteristics are known. The TNT equivalency method and the Multi-Energy method fall into this category.

The TNT equivalency method is considered to be too conservative due to its application for detonation.

The Multi-Energy Method is a relatively simple model to determine the blast from vapour cloud explosions as a function of explosion characteristics and distance to the explosion source. It can be applied to obtain a conservative quantification of the explosive potential of a flammable vapour cloud. The concept of this method is based on flame acceleration due to turbulence, which can be created by a source term (i.e. high-velocity intensely turbulent jet) and by obstructed area. A vapour cloud is then defined as a number of sub-explosions corresponding to the various sources of blast in the cloud (TNO, 2005).

This method was chosen for the calculation of blast parameters. The first step in the procedure is to identify the individual potential centres of strong blast (i.e. in the case of natural gas transmission pipeline it consists of high-velocity jet by which fuel is released at high pressure from a leak in the tube). The next step is to determine the explosive power of the cloud. It is assumed that the full volume of fuel-air mixture present in a particular blast source contributes to the blast. The combustion energy contributing in the fuel-air charge is then found by assuming a stoichiometric composition and by multiplying the charge volume with specific heat of combustion. The corresponding radius R_o of the equivalent hemispherical fuel-air charge can be easily calculated from this volume.

The blast wave parameters such as peak overpressure, peak dynamic pressure and positive phase duration of the blast wave are represented dependent on the distance to the blast centre for a hemi-spherical fuel-air charge of radius R_o on the earth surface. The data are reported on blast charts parametric of the initial blast strengths or class number. The explosive potential is primarily determined by the environment in which the vapour disperses (obstructed or not, confined or not) and then explosion occurs. For the choice of the class number, two projects, GAME [1] and GAME [2] (Mercx et al., 1998), provide guidance, based on the experimental literature, to calculate maximum positive overpressure resulting from an explosion taking into account the volume blockage ratio, the length travelled by the flame, the obstacle diameter and the laminar combustion speed of the mixture. An estimate of the initial strengths of the blast may be obtained by consulting of experimental data. For methane British gas assumes a maximum overpressure of $4 \cdot 10^5$ Pa (Harris and Wickens, 1989). This value complies with an explosion class of almost nine.

3.1 Gas release rate

The process of leakage is a isentropic adiabatic expansion process and the release rate can be calculated by leakage model for different failure style, including small hole model, pipe model and approximate fitting algorithm, etc. The gas release rate from a hole of pipeline varies with time: within seconds of failure, the release rate decreases from the peak initial value to a fraction of it, until it reaches a steady-state value.

In order to engineering calculation the effective gas release rate can be estimated by using decay factor, which is referred to as the ratio of the effective gas release rate and peak gas release rate. The decay factor k varies from 0.2 to 0.5 and a conservative value of 0.3 is adopted here for calculation. Jo e Crowl (2008) reported the following equations for effective gas release rate through a hole on the pipeline obtained by assuming gas density at atmosphere ρ = 0.68 kg/m^3 and Fanning friction factor equal to 0.0026 conservatively for steel pipeline.

For an accident near the gas supply station, the effective gas release rate Q_{eff} (kg/s) is given by:

$$Q_{eff} = \frac{1.783 \cdot 10^{-3} A_p \alpha p_0}{\sqrt{1 + 4.196 \cdot 10^{-3} \alpha^2 \frac{L}{d}}}, \alpha^2 \frac{L}{d} \le 2410 \qquad (5)$$

For an accident far away from the gas supply station:

$$Q_{eff} = 5.349 \cdot 10^{-4} A_p \alpha p_0, \alpha^2 \frac{L}{d} > 2410 \qquad (6)$$

where A_p (m^2) is the cross-section of the pipeline, d (m) is the pipeline diameter, α is the ratio of effective hole area to the pipe cross-sectional area, p_0 (Pa) is stagnation pressure at operating conditions, L (m) is the pipeline length from the gas supply station to the release point.

3.2 Leakage mass

The released gas jet may be conical and apparently diverges from a virtual point source somewhere upstream of the hole. Released gas is diluted by turbulent mixing, and time-averaged velocity and concentration profiles across the width of the gas jet are approximately gaussian (Jo and Ahn, 2002)

The explosive contents of jets is obtained by integrating over the volume between upper and lower flammability isocontours. The mass of gas within the flammability limits ($Q_{FL,}$ kg) is calculated as follows:

$$Q_{FL} = \frac{\pi \rho_G r_s^3 (C_c^{'})^3 c_G}{6 C_{yc}} \left[\left(\frac{c_G}{c_{LFL}} \right)^2 - \left(\frac{c_G}{c_{UFL}} \right)^2 \right] \tag{7}$$

where $c_{G,}$ c_{LFL} and c_{UFL} are the concentrations (in parts per unit volume) of the initial gas, of the lower and upper flammability limits; ρ□ is density of gas, C'_c and C_{yc} are empirical constants for the jet model; r_s is the radius of the virtual source (m) (TNO, 2005). The radius of the virtual source is calculated according to the Birch model reported in Yellow Book (TNO, 2005)

3.3 Overpressure and impulse

For blast wave parameters calculation Multi-energy method makes use of blast charts (TNO, 2005) where the scaled peak overpressure ($\Delta P'_S = \Delta P_S/p_a$) and the scaled positive phase duration ($t'_p = t_p/[(E/p_a)^{1/3}/c_o]$) are reported for 10 different explosion classes as function of the scaled distance R' given by:

$$R' = \frac{R}{\left(E/p_a \right)^{1/3}} \tag{8}$$

where R (m) is the distance from the blast centre, p_a (Pa) is the atmospheric pressure, c_o (m/s) is the sound velocity and E (J) is the combustion energy contributing in the fuel-air charge obtained by assuming a stoichiometric composition and by multiplying the charge volume with the heat of combustion.

For methane British gas assumes a maximum overpressure of 400 kPa (Harris and Wickens, 1989). This value complies with an explosion class of almost 9. The explosion parameters (ΔP_S *and* t_p) at a given distance R from an explosion source were then calculated from the scaled values relevant to class 9.

Finally, the positive impulse I (Pa s) was evaluated by integrating the overpressure variation over the positive phase duration which can be approximated by the following formula:

$$I = \frac{1}{2} \Delta P_s t_p \tag{9}$$

4. Blast fragility analysis of RC columns

Blast fragility of RC columns was estimated by assuming the pressure–impulse capacity model proposed by Shi et al. (2008). Three limit states corresponding to increasing levels of damage to columns were considered for risk assessment and the following pressure–impulse equation was used:

$$\left(\Delta P_s - P_0 \right) \left(I - I_0 \right) = 6 \left(P_0 + I_0 \right)^{1.5} \tag{10}$$

where P_0 and I_0 are the overpressure and impulse asymptotes corresponding to the limit state of interest. A limit state is reached when peak overpressure and impulse generate a threshold reduction in the axial load-carrying capacity of the column. Hence, the demand reduction factor D (D = 1 - N_{uR}/N_{uD} where N_{uR} and N_{uD} are the residual and design load-carrying capacity of the RC column) reaches a limit state damage factor D_{LS}. For the limit states of interest, the authors assumed D_{LS} to be 0.2 (slight damage), 0.5 (moderate damage) and 0.8 (collapse). Pressure and impulse asymptotes depend on D_{LS} as well as geometric and mechanical properties of RC columns, such as transverse and longitudinal reinforcement ratios, concrete strength, and column dimensions. The following class of RC columns typically detected in existing European buildings was investigated: cross-section 300×300 mm^2 and height equal to 3.00 m; concrete strength class $R_{ck}25$ (equivalent to the current C20/25 class); reinforcing steel class FeB44K (equivalent to the current B450C class). A vector of uncertain variables Θ was defined to account for uncertainties associated with the capacity model, column and reinforcement geometry, and material properties. Based on probability density functions assigned to uncertain variables, a standard Monte Carlo simulation was used to generate N_S samples of uncertain variables θ_j, so blast fragility was estimated by:

$$P\left[D \mid E \right] = \frac{1}{N_S} \sum_{j=1}^{N_S} I_{C|E} \left(\Theta_j \right) \tag{11}$$

where N_S was 10^4 and $I_{C|E}(\Theta_j)$ is an index limit state function which is equal to unity if the *j*-th realization Θ_j of the vector Θ leads to the collapse of the RC column. Strain rate effects, namely the dynamic increase in strength of concrete and reinforcing steel, were taken into account. Both the concrete cover of columns and ultimate strain of concrete were assumed to be deterministically known, so nominal values were assigned to them.

5. Results

Blast wave parameters at different distances (*R*) from the explosion source (pipeline) were calculated by assuming explosion class 9 and considering the following influencing parameters: pipeline diameter (*d*), operating pressure (p_0), pipeline length from the gas supply station to the release point (*L*), hole diameter (d_{hole}). The values of these parameters and the relevant frequency were obtained by data of European Gas pipeline Incident data Group, a cooperation of fifteen major gas transmission system operators in Europe (EGIG, 2011). In particular, the influencing parameters were varied in the range of: d = 0.127–1.321 m; p_0 = 2,000–10,000 kPa; L = 50–20000 m; d_{hole} = 0.01m–d; R = 50–10,000 m.

The results of analysis were in terms of probability to achieve given values of overpressure and impulse during the explosion. The maximum values of overpressure and impulse were 507 kPa and 60,000 Pa s, respectively. The highest probability (94.2 %) was found for values of overpressure equal to 19 kPa and impulse of 5,000 Pa s; it decreased to 0% at ΔP_s = 19 kPa and I = 12,500 Pa s and at 0.1% at ΔP_s = 374 kPa and I = 5,000 Pa s .

The convolution of blast fragility and hazard according to Eq. (4) allowed to estimate the annual probability of damage P [D] for the three damage levels under consideration and 1000 km of pipeline length. That probability was found to be $1.78\cdot10^{-3}$/1,000 km/y at D_{SL} = 0.2, $1.64\cdot10^{-3}$/1,000 km/y at D_{SL} = 0.5, and $6.04\cdot10^{-4}$/1,000 km/y at D_{SL} = 0.8. For the sake of brevity, Table 1 outlines the annual risk of structural collapse (i.e. D_{SL} = 0.8) per 1,000 km of pipeline length.

The impact radius of blast wave was then calculated as the maximum distance from the blast center at which the values of overpressure and impulse are achieved (Table 2). The values for which the risk is different from zero are indicated in bold in the case of D_{LS} = 0.2 and D_{LS} = 0.5, and underscored in the case of D_{LS} = 0.8.

The combination of results allows the derivation of iso-risk diagrams for each damage state of interest, namely the pipeline-to-column distance below which the de minimis risk of a given damage level is reached. This distance is a key parameter for performance-based design/assessment of RC structures subjected to natural gas pipeline explosion hazard.

Table 1: Annual risk of damage (D_{LS} = 0.8) at different values of peak overpressure and impulse.

		Impulse (Pa s)				
		5,000	***12,500***	***17,500***	***30,000***	***60,000***
Peak overpressure (kPa)	***19***	0	0	0	0	0
	54	0	0	0	0	0
	84	0	0	0	0	0
	119	0	0	0	0	0
	169	0	$1.4\cdot10^{-8}$	$1.0\cdot10^{-6}$	0	0
	249	0	$1.9\cdot10^{-6}$	$2.3\cdot10^{-6}$	$5.7\cdot10^{-6}$	0
	374	0	$1.0\cdot10^{-5}$	$2.7\cdot10^{-5}$	$6.1\cdot10^{-5}$	$1.8\cdot10^{-6}$
	478	0	0	$3.5\cdot10^{-6}$	$3.8\cdot10^{-6}$	0
	507	0	0	$5.2\cdot10^{-7}$	$1.2\cdot10^{-3}$	$5.2\cdot10^{-4}$

Table 2: Impact radius (m) at different values of peak overpressure and impulse.

	Impulse (Pa s)				
Peak overpressure (kPa)	*5,000*	*12,500*	*17,500*	*30,000*	*60,000*
19	10,000	-	-	-	-
54	**700**	-	-	-	-
84	**200**	-	**-**	-	-
119	**200**	**200**	-	-	-
169	**100**	**200**	**200**	-	-
249	**50**	**100**	**100**	**200**	-
374	**50**	**50**	**100**	**200**	**200**
478	-	-	**50**	**100**	-
507	-	-	**50**	**100**	**200**

6. Conclusion

This paper discusses a newly proposed procedure to estimate the annual probability of direct structural damage to reinforced concrete buildings associated with high-pressure natural-gas pipeline explosions. This reliability-based risk assessment procedure has been presented for the following purposes: (1) to design new pipeline networks close to urban habitats, accounting for the change in the structural safety level of existing buildings; (2) to design new buildings with a given safety level against potential gas explosions.

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