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Risk-targeted safety distance of reinforced concrete buildings from natural-gas transmission pipelines

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ABSTRACT

Natural-gas pipeline accidents mostly result in major damage even to buildings located far away. Therefore, proper safety distances should be observed in land use planning to ensure target safety levels for both existing and new buildings.

In this paper, a quantitative risk assessment procedure is presented for the estimation of the annual probability of direct structural damage to reinforced concrete buildings associated with high-pressure natural-gas pipeline explosions. The procedure is based on Monte Carlo simulation and takes into account physical features of blast generation and propagation, as well as damage to reinforced concrete columns. The natural-gas jet release process and the flammable cloud size are estimated through SLAB one-dimensional integral model incorporating a release rate model. The explosion effects are evaluated by a Multi-Energy Method. Damage to reinforced concrete columns is predicted by means of pressure–impulse diagrams. The conditional probability of damage was estimated at multiple pressure–impulse levels, allowing blast fragility surfaces to be derived at different performance limit states. Finally, blast risk was evaluated and allowed the estimation of minimum pipeline-to-building safety distances for risk-informed urban planning. The probabilistic procedure presented herein may be used for performance-based design/assessment of buildings and to define the path of new natural-gas pipeline networks.

1. Introduction

The failure of a high-pressure natural-gas pipeline can lead to various outcomes, some of which can pose a significant threat to people and property in the vicinity of the failure location. For a given pipeline, the type of hazard that develops and associated effects in terms of damage, injured and fatalities will depend on the mode of line failure (i.e. leak vs. rupture), the nature of gas discharge (i.e. vertical vs. inclined jet, obstructed vs. unobstructed jet) and the time to ignition (i.e. immediate vs. delayed).

In recent years, a significant number of gas explosions have occurred either inside or outside buildings, highlighting a urgent need of appropriate safety levels for people and properties against these hazards [1,2]. Gas explosions may be generated by failure of pipelines that carry natural gas through both rural and urban areas. Pipeline failure may be induced by several events (e.g. construction or operational errors, material defects, corrosion, man-made actions, and soil failure under earthquakes), causing gas leakage, cloud formation and ignition [3]. If a natural-gas explosion occurs, structures located close or within the ignited gas cloud are subjected to severe overpressures and may suffer loss of one or more components [4]. After that blast overpressures vanish, local damage to some structural members may propagate throughout the structure resulting in a progressive collapse [5]. Structural safety to this type of accidents needs to account for many uncertain parameters related to loads and structural system, hence requiring a quantitative risk approach.

In this paper, a probabilistic risk assessment procedure for the estimation of the failure probability of reinforced concrete columns threatened by natural-gas pipeline explosions is presented. Structural risk is estimated as convolution of blast hazard and fragility of single reinforced concrete columns. Hazard is estimated through the Multi-Energy Method [6], whereas fragility is estimated by means of Monte Carlo (MC) simulation. Blast capacity and demand are defined in the pressure–impulse space and a damage criterion is used to detect the occurrence of failure. Thousands of samples of reinforced concrete columns, pipelines and environmental conditions were randomly generated. Blast hazard was assessed by assuming a horizontal gas jet from the leakage point of the pipeline. Compared to a previous research [4], this study takes into account the influence of wind and atmospheric stability. Wind velocities of 10, 20 and 30 m/s at a height

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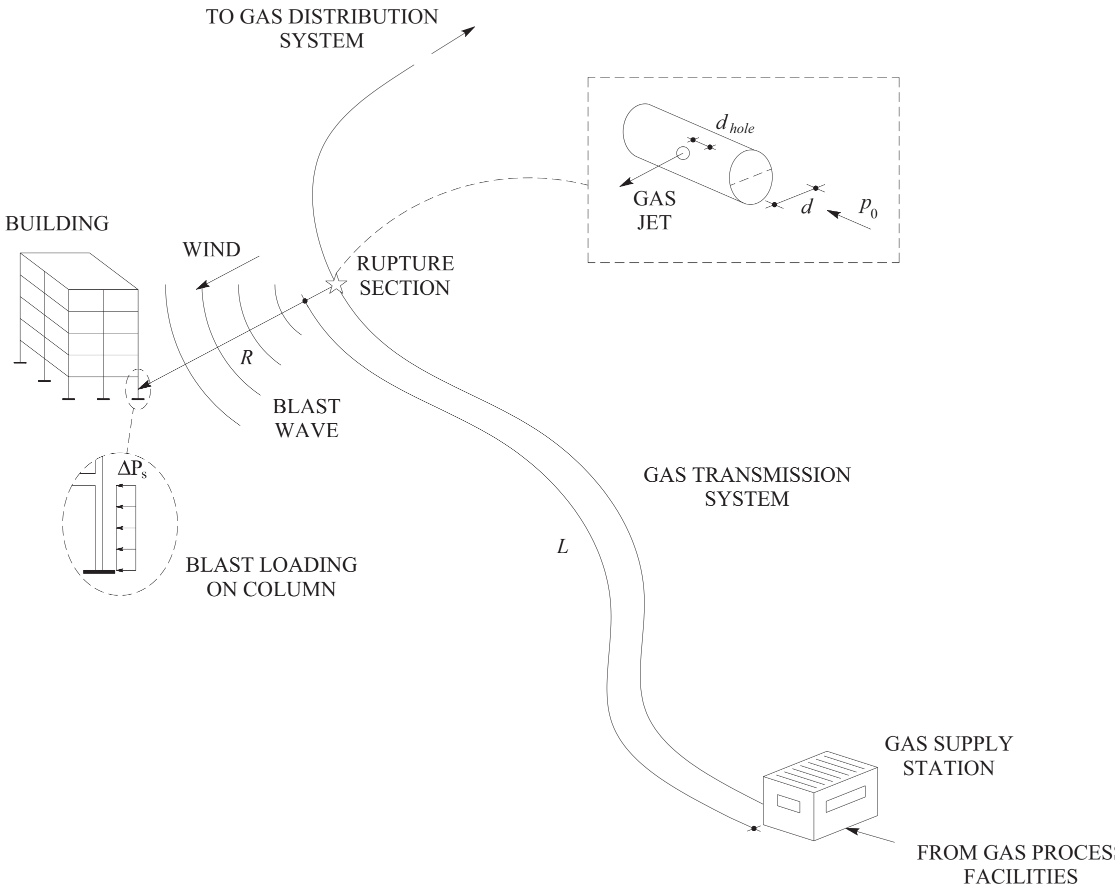

Fig. 1. Scheme of gas explosion from gas transmission system.

of 10 m above ground were randomly produced, assuming a wind direction parallel to the gas jet and vertical logarithmic increase of wind velocity from the terrain roughness height. From a structural standpoint, different probability distributions were used to consider uncertainty in material and geometrical properties, as well as capacity models. Assuming a threshold probability of structural collapse, a (minimum) risk-targeted safety distance between pipeline and building was derived. The threshold probability is the *de minimis* risk defining the acceptable risk level below which society normally does not impose any regulatory guidance. Safety distance is provided for (i) reinforced concrete columns of gravity-load designed residential buildings, (ii) high-pressure pipelines, (iii) blast strengths 6 and 9, and (iv) Pasquill atmospheric stability classes A and C. The influence of wind velocity is also considered. This safety distance may be used as a threshold below which existing buildings should be assessed against natural-gas pipeline explosions. The proposed methodology may be also applied to regulate the distance of new buildings from pipelines, namely for urban planning purposes.

2. Probabilistic risk assessment framework for blast threats

Natural gas explosions can induce local damage to individual structural components (e.g. columns at the ground floor of a building). The propagation of that damage throughout the structure can result in a progressive collapse of the whole structural system or a part of it, hence producing significant consequences to property and people. From a phenomenological viewpoint, progressive collapse is then an event conditioned upon local damage.

The annual probability of structural collapse under an extreme event H can be estimated according to the risk analysis framework proposed by Ellingwood [7], as follows:

$$\Pr[C] = \Pr[C \mid \mathrm{LD}]\Pr[\mathrm{LD}|H]\lambda_H \quad (1)$$

where LD is the event that local damage occurs as a result of H, C is the event of progressive collapse induced by LD, λ_H is the mean annual rate of occurrence of H that is numerically interchangeable with the annual probability of occurrence for randomly occurring events with rates less than 10^{-2}/year, $\Pr[LD|H]$ is the conditional probability of local damage given H, and $\Pr[C|LD]$ is the conditional probability of progressive collapse given LD. This formulation allows one to design/assess a structure so that $\Pr[C] \le p_{th}$ where p_{th} is the *de minimis* risk. This establishes a reliability-based criterion for design and assessment against one or multiple events. Amongst others, Pate-Cornell [8] highlighted that p_{th} is in the order of 10^{-7}/year.

In this study, the annual risk is assessed at local structural level, namely the scale of single reinforced concrete columns, which are the key components of reinforced concrete framed structures. Therefore, this research is focused on the following part of Eq. (1):

$$\Pr[LD] = Pr[LD|H]\lambda_H \quad (2)$$

If one is interested in assessing the probability of progressive collapse, the following equation can be used:

$$\Pr[C] = Pr[C|LD]Pr[LD] \quad (3)$$

Assuming the natural-gas transmission pipeline to be the hazard source, the annual probability of local structural damage is further specialised to:

$$\Pr[LD] = \Pr[LD|E]\Pr[E|R]\lambda_R \quad (4)$$

where E is the natural-gas explosion, R is the pipeline rupture, and λ_R is the annual mean rate of occurrence of the pipeline rupture.