Journal of Loss Prevention in the Process Industries 43 (2016) 315–331

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Underground parallel pipelines domino effect: An analysis based on pipeline crater models and historical accidents

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ARTICLE INFO

Article history:
Received 3 September 2015
Received in revised form
20 February 2016
Accepted 30 May 2016
Available online 2 June 2016

Keywords:
Underground pipelines
Domino effect
Risk assessment
Past accidents

ABSTRACT

This paper focuses on the analysis of the possibility of domino effect in underground parallel pipelines relying on historical accident data and pipeline crater models. An underground pipeline can be considered as safe following an accident with an adjacent gas or liquefied pipeline when it remains outside the ground crater generated. In order to prevent the domino effect in these cases, the design of parallel pipelines has to consider adequate pipeline separations based on the crater width, which is one of the widely used methods in engineering applications. The objective of this work is the analysis of underground petroleum product pipelines ruptures with the formation of a ground crater as well as the evaluation of possible domino effects in these cases. A detailed literature survey has been carried out to review existing crater models along with a historical analysis of past accidents. A FORTRAN code has been implemented to assess the performance of the Gasunie, the Batelle and the Advantica crater models. In addition to this, a novel Accident-Based crater model has been presented, which allows the prediction of the crater width as a function of the relevant design pipeline parameters as well as the soil density. Modifications have also been made to the Batelle and Accident-Based models in order to overcome the underestimation of the crater width. The calculated crater widths have been compared with real accident data and the performance evaluation showed that the proposed Accident-Based model has a better performance compared to other models studied in this work. The analysis of forty-eight past accidents indicated a major potential of underground parallel pipelines domino effect which is proven by two real cases taken from the literature. Relying on the investigated accidents, the crater width was smaller than or equal to 20 m in most cases indicating that the definition of underground pipeline separations at around 10 m would be sufficient to ensure a small probability of the domino effect.

1. Introduction

The evolving demand for oil and natural gas supply along with the efficiency of distributing them by using pipelines over long distances generates need for construction of a number of pipelines. On the other hand, the need of easements or servitudes to provide the passage of pipelines launches a challenge to pipeline operators to design pipelines to minimize land conflicts and environmental impacts. At the same time, it is necessary to assure the safety of population. The solution to these issues often involves the construction of parallel pipelines along new or existing right-of-ways (rows).

The underground parallel pipelines escalation or domino effect could occur when two or more pipelines run adjacent to a gas or liquefied pipeline. When it happens, the consequences of the final event are notably greater than the consequences associated with the primary event (Cozzani et al., 2005). Therefore, neglecting the evaluation of the domino effect in the risk assessment of underground parallel pipelines can give rise to a risk underestimation (CCPS, 2000; Uijt de Haag and Ale, 2005).

The rupture of an underground gas or liquefied product pipeline occurs with the formation of a ground crater by the source jet (Kinsman and Lewis, 2000; Acton et al., 2010; Bartenev et al., 1996).

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http://dx.doi.org/10.1016/j.jlp.2016.05.031

Nomenclature

Abbreviations

CONCAWE	Conservation of Clean Air and Water in Europe
DOT	United States Department of Transportation
EGIG	European Gas Pipeline Incident Data Group
HSE	Health and Safety Executive
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
NA	Not available
NTSB	United States National Transportation Safety Board
PHMSA	Pipeline Hazardous Material Safety Administration
TSB	Transportation Safety Board of Canada
UKOPA	United Kingdom Onshore Pipeline Operator's Association
USDA	United States Department of Agriculture
WSS	Web Soil Survey

Greek symbols

α_{C1}	crater angle wall at ground level (deg)
α_{C2}	crater angle wall at half of the crater depth (deg)
γ	specific heat ratio of the gas (−)
ρ	density of the gas (kg/m^3)
ρ_{soil}	density of the soil (kg/m^3)

Roman symbols

a	length of the semi-minor axis of the elliptically shaped crater (m)
A_{dyn}	work required to disturb a unit of mass of soil (J)
b	length of the semi-major axis of the elliptically shaped crater (m)
c	speed of sound (m/s)
CW	crater width (m)
D	crater depth (m)
D_c	depth of cover (m)
D_p	pipeline diameter (m)
m_i	correlation constant (m)
n_i	correlation constant (m/inch)
NPS	nominal pipe size (in)
P	pipeline operating pressure (bar)
Q_w	energy per unit mass of the explosion (J/kg)
$R(w)$	function of the soil parameter
u_x	outburst speed of the explosive gases (m/s)
u_{kr}	critical velocity (m/s)
w	soil parameter (−)

When the released gas ignites, the fire will develop inside the crater (Giovanni Ramírez-Camacho et al., 2015). If an adjacent pipeline is present in the row and outside the crater formed, it will remain safe as it is protected by the surrounding soil. However, if the adjacent pipeline is inside the crater, it will be subject to the pressure exerted by the gas released on the soil and the thermal load generated by the fire. In this instance, there is the possibility of the domino effect (Duckworth and Eiber, 2004). According to (Acton et al., 2010), among twelve incidents involving a rupture of underground pipelines, one incident was reported in which domino effect was believed to have occurred.

In this paper, among 17 accidents involving underground parallel pipelines, two cases of domino effect have been identified. To prevent underground parallel pipelines domino effect, it is necessary to define minimum separations between two or more pipelines adjacent to gas pipelines, or to implement mitigating measures ensuring that they may be arranged and operated safely (Acton et al., 2010; Leis et al., 2002; Jia and Feng, 2011).

A schematic drawing of an arrangement of three parallel pipelines is shown in Fig. 1 as can be designed in a row, and Fig. 2 illustrates an example where the failure of pipeline 2 generates a crater.

In Fig. 2, pipeline 1 can be considered as safe, because it is outside the crater. However, pipeline 3 would be subject to a ground pressure load during the crater formation and a thermal load caused by the jet fire in case of ignition. Therefore, the safety of pipeline 3 will depend on whether it can withstand these loads without losing its integrity (Acton et al., 2010; Giovanni Ramírez-Camacho et al., 2015).

An example of an accident involving underground parallel pipelines without domino effect is shown in Fig. 3. This accident occurred in Ghislenghien, Belgium, in 2004. The ruptured pipeline transported natural gas at a pressure of 80 bar with the diameter of 39 inch. At the accident site, a parallel pipeline with the diameter of 35 inch was operating at a distance of 7 m (SSC Safety Solutions Consultants BV, 2010) (see the crater dimensions in Fig. 3). It can

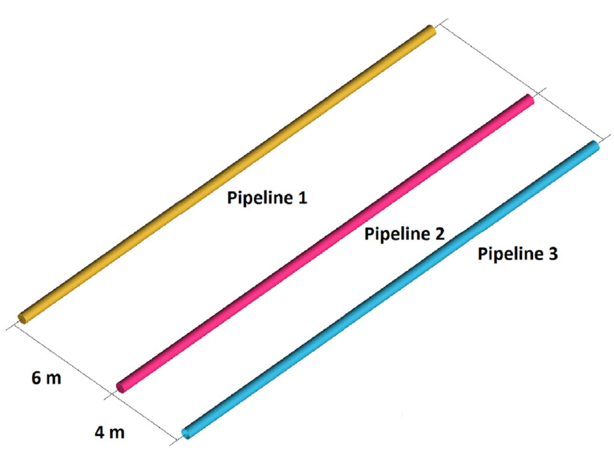

Fig. 1. Schematic drawing of the pipeline arrangement in a row.

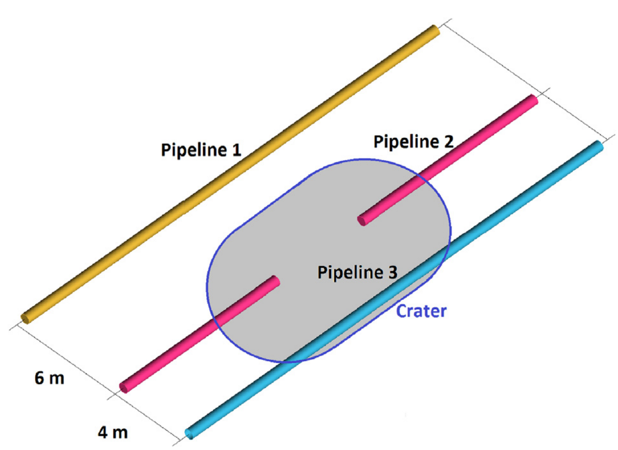

Fig. 2. Crater schematic drawing with parallel pipelines.