Reliability Engineering and System Safety 132 (2014) 125–145

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Release of hazardous substances in flood events: Damage model for horizontal cylindrical vessels

Gabriele Landucci [a], Amos Necci [b], Giacomo Antonioni [b], Alessandro Tugnoli [b], Valerio Cozzani [b,*]

[a] Dipartimento di Ingegneria Civile e Industriale – Università di Pisa, largo Lucio Lazzarino, 56126 Pisa, Italy

[b] Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum – Università di Bologna, via Terracini n.28, 40131 Bologna, Italy

ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form
14 June 2014
Accepted 17 July 2014
Available online 1 August 2014

Keywords:
NaTech
Flood
Major accident hazard
Hazardous materials release
Storage tanks
Pressure vessels

ABSTRACT

Severe accidents may be triggered by the impact of floods on process and storage equipment containing hazardous substances. The present study analyses the possible damage of horizontal cylindrical equipment, either operating at atmospheric or at higher pressures. A mechanical damage model was developed and validated by available literature data on past accidents. Simplified correlations were then obtained to calculate the critical flooding conditions leading to vessel failure. A fragility model was proposed for the straightforward assessment of equipment damage probability in the framework of the quantitative risk assessment of NaTech scenarios triggered by floods. A case-study was discussed to test the potentialities of the method.

1. Introduction

Global climate changes may significantly influence temperatures and precipitation patterns, increasing the frequency of severe meteorological events which may lead to flooding [1–5]. Flooding may dramatically impact on population among urban areas but it can also affect industrial facilities. In the latter case, damages to equipment and structures may lead to the release of hazardous materials with potential escalation leading to domino effects [6–12]. This type of accident scenario is indicated as a "Natural-Technological" (NaTech) event. Specific studies [13–19] and recent publications concerning the analysis of industrial accidents reported in available databases [11,20] highlighted that NaTech accidents often generate severe consequences. Besides, the severe events that affected several industrial sites and the Fukushima power station after the Tōhoku earthquake and consequent tsunami in Japan (April 2011) [13,21] showed the potential dramatic consequences of NaTech events.

Therefore, NaTech events may significantly impact on the risk profile of an industrial facility. However, the implementation of NaTech scenarios in conventional Quantitative Risk Assessment (QRA) studies is a critical task [16,22–24]. In particular, the frequency assessment needs to take into account both parameters related to the likelihood of the natural event and to the credibility of equipment failures following the impact of the natural event. In the case of NaTech scenarios caused by flooding, the first type of input data can be usually retrieved from national or local competent Authorities. Specific equipment fragility models must be available in order to generate the data concerning the credibility of equipment damage. Such models are aimed at the estimation of equipment damage probability on the basis of the severity of the natural event. Due to the features of a QRA study that usually requires the assessment of a high number of scenarios, the use of simplified models able to yield a conservative estimation of equipment failure conditions is required to effectively support the assessment of equipment vulnerability [22–27].

Fragility curves and equipment vulnerability models are available for several equipment items in the case of earthquake [17,21]. In a previous study equipment vulnerability models were obtained for atmospheric vertical cylindrical storage tanks in the case of flood scenarios [8]. Specific fragility models for equipment vulnerability in the case of flood are thus not available for horizontal cylindrical storage tanks. Past accident data analysis [7] evidenced that these equipment items were often damaged in NaTech events triggered by floods. However, since these vessels are usually positioned on saddles or, more in general, are welded to supports anchored to the ground, flooding damage occurs by different mechanisms with respect to vertical cylindrical tanks. Actually,

* Corresponding auth. Tel.: +39 051 2090240; fax: +39 051 2090247.
E-mail address: valerio.cozzani@unibo.it (V. Cozzani).

http://dx.doi.org/10.1016/j.ress.2014.07.016
0951-8320/

horizontal cylindrical vessels are mostly damaged due to displacement caused by water drag and/or to floating [7,28].

The present study was devoted to the development of a model for the vulnerability assessment of horizontal cylindrical process and storage vessels involved in flood events. In order to evaluate the resistance of the equipment items considered, a mechanical model was developed. The model, validated with respect to the available data obtained from past accident records, was applied to derive simplified vulnerability functions to calculate vessel failure probability in flood events. In order to explore the model features and potentialities some case studies based on actual industrial lay-outs were analyzed.

2. Model

The approach proposed to assess the vulnerability of equipment items involved in flood events is schematized in Fig. 1. The key features of the methodology were derived from a previous study [8] and are briefly summarized in the following, evidencing the specific elements related to horizontal vessels.

As shown in Fig. 1, in the first step of model development a simplified representation of the vessel geometry and of its supports was introduced. In step 2, on the basis of this schematization, a mechanical model was developed, able to evaluate the effects of floodwater impact on the vessel. In particular, in the case of horizontal vessels, damages are caused by the displacement of vessels due to water drag and/or to floating, leading to the rupture of the connected pipelines and to a potential impact on the other equipment items or structures. Hence, on the basis of available data on past flooding events [29,30], the flood water impact was schematized considering a credible range of values for flood water depth and velocity (step 3). Reference data from past events were then used for model validation (step 4). In step 5, a vessel database was developed, including an extended set of representative geometries of horizontal separators and vessel storage tanks, obtained from actual data available from industrial facilities and from current design standards. In particular, pressurized vessels (defined as vessels operating at pressures higher than 103.4 kPa [31]) and atmospheric vessels were both included in the database. The vessel database was used to obtain a dataset of failure conditions with respect to flood intensity parameters (step 5). In step 6, the dataset of failure conditions and vessel properties obtained in step 5 was used to extrapolate simplified damage correlations for the calculation of vessel failure probability (step 7).

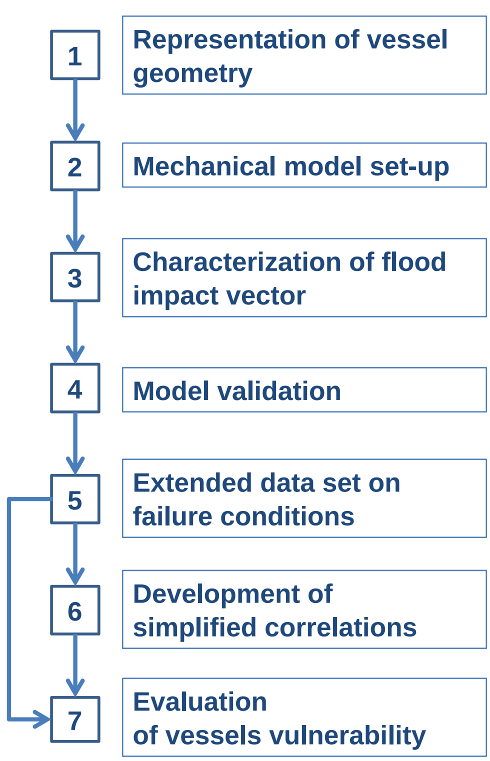

Fig. 1. Schematization of the methodological approach adopted for the development of a vulnerability model for horizontal vessels involved in flood events.

2.1. Representation of vessel geometry (step 1)

In the present study, storage tanks and process vessels consisting of a horizontal cylindrical body with spherical edges were considered. The vessels, operating at atmospheric pressure or higher, were assumed as disposed on saddle-type supports, fixed to the ground. The references for the design and features of the tanks considered in the present study are the API Standard 620 [32] and the ASME Pressure Vessel Code (Sec. VIII of the ASME Boiler and Pressure Vessel Code [31]).

The schematic representation of these vessels is reported in Fig. 2a, while the relevant mechanical features considered are summarized in Table 1. As shown in Fig. 2a, one of the vessel saddles is assumed to be fixed to the ground with a bolt connection, while the other assumed to be only laid on the ground. This configuration is frequently adopted in the process industry in order to limit the stress due to steelwork thermal expansion [33].

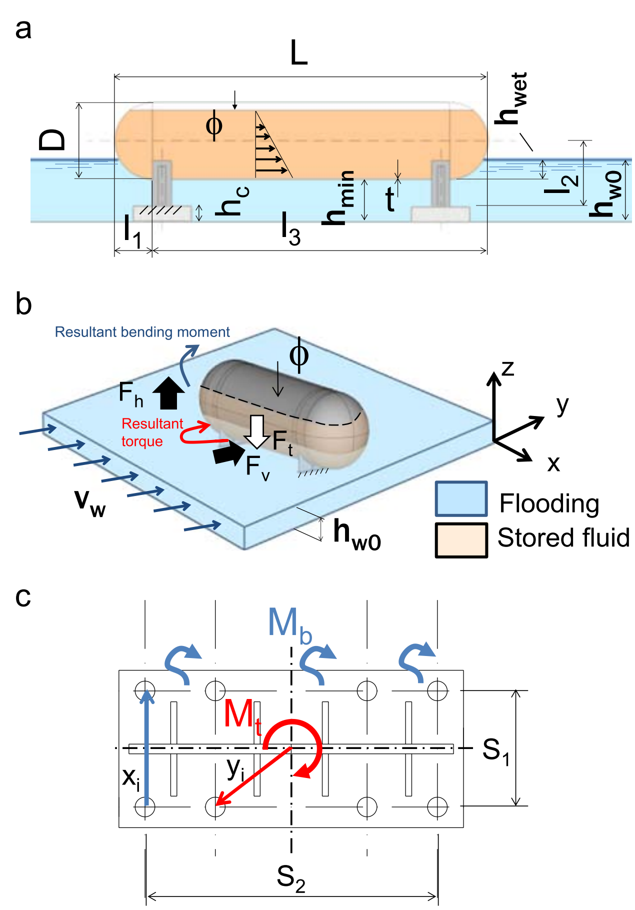

Fig. 2. Schematization adopted to describe the impact of floodwater on horizontal vessels: (a) definition of geometrical parameters and sketch of the vessel; (b) force balance on the vessel and schematization of the wave impact; (c) schematization of the base plate bolt connection to the ground.