



## SITTING THE BARRIER AIMED AT PROTECTING ROADSIDE PROPERTY FROM ACCIDENTAL FIRES AND EXPLOSIONS ON ROAD: A PRE-OPTIMISATION STAGE

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**Abstract.** An early stage of the design of a safety barrier intended for protecting roadside property against fires and explosions on road is studied. Three main problems of this design stage are highlighted: determination of the road segment from which a roadside object to be protected can be damaged; specification of area for barrier construction; and positioning of the barrier within available construction area. A solution of these problems is considered to be a necessary step providing helpful information for a detailed design of the barrier by applying methods of structural optimisation. It is shown that the most challenging problem of the early stage of barrier design will be the determination of an unsafe road segment. This problem is formulated as a problem of quantitative risk assessment (QRA) and solved by combining rigorous methods of QRA and structural reliability theory. Apart from rigorous methods, engineering judgement may be required for the positioning of the barrier within available area. A case study is used to illustrate the main steps of the early, pre-optimisation stage of barrier design.

**Keywords:** barrier, fire, explosion, BLEVE, hazardous material, separation distance, safety distance, accident, road tank, risk, QRA.

### 1. Introduction

The transport of flammable and explosive materials by road and rail has an increasing trend. The quantities of hazardous materials shipped by rail are larger than ones routed by road. Therefore the railway transportation has a higher potential of fires and explosions (e.g., Pontiggia *et al.* 2011). However, the damage caused by fires and explosions on road can be larger, because roads often pass populated areas or run in dangerous vicinity of or even inside industrial facilities (Lozano *et al.* 2010; Ratkevičiūtė 2010). Fires are the most often accidents suffered during the transportation of hazardous materials, followed by explosions and gas releases (Darbra *et al.* 2010).

The risk posed by potential fires and explosions on road can be controlled by providing adequate separation distances between road and facility site or individual roadside objects (process units, say). An employment of separation distances is a part of wider safety strategies known as facility sitting and land use planning (Scheier 2005; Cahen 2006; Cozzani *et al.* 2006; Nagashima *et al.* 2011; Taveau 2010). However, the cost of land acquisition for a provision of future road-to-facility separation distances can be unacceptably high. An employment of adequate separation

distances is impossible where existing roads adjoin existing facilities or where the space available for constructing a future road (facility) nears an existing facility (road) is limited.

A compensation for less than desired separation distances includes options available on both transportation side and endangered facility side. Safeguards can be built into truck vehicles and safer routing applied (Förster, Günther 2009; Paltrinieri *et al.* 2009). However, the owner (designer) of the endangered facility may have little influence, if any, on the routing of flammable and explosive materials over an adjacent public road. The transportation of such materials over access and on-site roads is often vital to running the facility. The presence of congested vulnerable areas adjoined by on-site roads makes the on-site transportation more hazardous than the transportation over off-site, public roads (e.g., Bakke *et al.* 2010; Boudet *et al.* 2011; Johnson 2010).

Safety barriers built alongside on-site and off-site roads can in certain cases compensate for separation distances. If designed properly, the safety barriers will provide protection allowing not to modify roadside objects or to reduce the costs of their strengthening (shielding). Safety

barriers are similar to structures known as blast or barrier walls and used to protect against military weapons and improvised explosive devices (e.g., Smith 2010). A design of safety barriers and blast walls will have much in common; however, they will not be identical. Wilful military and terrorist explosions are generally less predictable than unintentional explosions of civilian vehicles carrying hazardous goods by road. Blast walls are normally not designed to resist effects of fireballs and large projectiles from road tank explosions or to influence, in a way, a spread of flammable gases and liquids accidentally released from tank vehicles. The disadvantage of blast walls in terms of assuring security is that they prohibit observation of activities occurring on other side (Krauthammer 2008). A reduction of visibility by safety barriers should not be a problem as long as it does not impair road safety or prohibit a warning to personnel about an imminent fire or explosion on road.

A design of safety barriers will be governed by the specific effects of an accidental fire and/or explosion on road. A comprehensive review of such accidents seems not to be available, although data on some specific accidents was examined (Ronza *et al.* 2007). It is reasonably safe to suggest that the largest potential of major fires and explosions on road has a transportation of flammable liquids, particularly, liquefied gases. Road accidents of tank vehicles carrying liquefied gases can escalate into boiling liquid expanding vapour explosions (BLEVEs) (Planas-Cuchi *et al.* 2004; Tauseef *et al.* 2010).

The design of a safety barrier aimed at protecting against such explosions as BLEVE will include estimation of thermal and mechanical effects to be resisted or attenuated as well as determination of an optimal barrier structure. The barrier can be optimised by means of conventional deterministic or reliability-based methods as well as methods of multi-criteria decision making (MCDM) (Vaidogas 2007b; Vaidogas, Šakėnaitė 2010, 2011; Bražiūnas, Sivilevičius 2010, Zavadskas, Vaidogas 2009). However, the optimal design of the barrier should be preceded by making several decisions concerning sitting the barrier: determination of the area available for its construction; positioning the barrier between road and roadside object(s); and configuring the barrier in plan. Making such decisions may be seen as a pre-optimisation stage of the barrier design. The present study seeks to highlight several problems which may arise in this design stage. The further text refers mainly to explosions on road, whereas fires are mentioned where necessary.

## 2. Determination of an unsafe road segment

### 2.1. Geometry of an unsafe area

There are two obvious geometric factors which influence the degree of damage to a roadside object from an accidental explosion on road, namely, distance from road to target object and relief of the terrain where the explosion occurs. The role of a large distance in minimising effects of a violent release of energy during an explosion is obvious. However, these effects can be enhanced or reduced if

the explosion will take place on a road built on embankment or in cutting, respectively (e.g., Elvik *et al.* 2009; Sivilevičius 2011).

Road segments located at large distances from the target object are naturally safe. When the road comes closer to the object, the distance alone may be insufficient to ensure safety and a safety barrier may be required to protect the target object. The configuration of the barrier in the roadside terrain will directly depend on the layout of the road segment where the explosion occurs and a safety distance around the target object.

In the safety engineering, the terms “safety distance” and “separation distance” are used to denote a distance at which a hazard source is placed and after an accident causes no destruction or risk of any kind to living beings and their facilities (Argent, Morainville 2007; Bangash 2009; Cozzani *et al.* 2009; Marangon *et al.* 2007). In what follows the term “safety distance” will be applied to a minimum separation between an explosion on road (near the road) and a roadside object which will mitigate explosion effects and prevent damage to the object. Such effects include air blast, fireball, primary and secondary projectiles (e.g., Casal 2008). The above definition of the safety distance expresses only a general idea. A mathematical definition of this term will require characterising it in a more precise way (Sec. 2.2).

Safety distances plotted in all directions around the target object will form a perimeter of an unsafe zone (zone  $\Omega$ , say) (Fig. 1). A layout of  $\Omega$  will be fairly complex when the safety distances are significantly directional. Relief around the target object and incursions of the road into environment (embankments and cuttings) may contribute to this complexity.

In a somewhat idealised case of one or several structures having relatively simple geometry in plan, it is possible to express the safety distance by a single variable  $\Delta$ . In such a case the unsafe zone  $\Omega$  will be either a land strip along a linear structure (e.g., pipeline or power transmission line, Fig. 1a) or a circle around a cylindrical structure (e.g., a storage tank, Fig. 1b) or an area with a relatively simple shape along several similar structures built in a row (Fig. 1c).

An intersection of the unsafe zone  $\Omega$  by road network will form a road segment from which an accidental explosion will endanger the target object. This segment will be denoted by the symbol  $\omega$  and called the unsafe road segment (Fig. 1). The area  $\omega$  can be interpreted as a set of explosion centre positions  $\mathbf{x} = (x_1, x_2)$  defined in a coordinate system  $\{0; x_1, x_2\}$  which is fixed, for instance, to the target object. Clearly, an explosion can occur also outside the road surface denoted by  $\omega$ . For example, a road tank BLEVE may happen after a tank vehicle is involved in a traffic accident, departs from the road surface and encroaches on the roadside territory inside the zone  $\Omega$ . Generally the position of a potential accidental explosion on road,  $\mathbf{x}$ , is uncertain. A bivariate probability density function  $f(\mathbf{x})$  is a natural means for quantifying this uncertainty (Vaidogas *et al.* 2012a, 2012b). It is evident that the density

$f(\mathbf{x})$  must be defined on the zone  $\Omega$  and not only on the segment  $\omega$ .

With the coordinate system introduced above, the direction of incidence of explosion effects can be expressed through the position of explosion centre  $\mathbf{x}$  (Fig. 1b). This allows to formulate the safety distance as a function of an incidence angle  $\varphi$ , in brief,  $\Delta_\varphi$ . The angle  $\varphi$  is determined by the explosion position  $\mathbf{x}$  and can be related to the coordinate system  $\{0; x_1, x_2\}$  or principal axes of an individual target structure (Figs 1b, 1c). The safety distance is usually a directional quantity even in the case of the cylindrical tank structures shown in Fig. 1b. Piping and other system components are attached to the tanks only in one or several points and so cylindrical structures are in some directions more vulnerable than in others.

An individual structure or a set of structures built close together can be very irregular in plan. Safety distances  $\Delta_\varphi$  estimated for such structures will be highly directional and a corresponding unsafe area  $\Omega$  indicate an irregular layout. However, a road segment  $\omega$  within such an area will in many cases have a regular layout (Fig. 2a).

### 2.2. Dealing with uncertainties in specifying the unsafe road segment

Factors determining safety distances around hazardous stationary equipment are more or less obvious and well-documented (e.g., Argent, Morainville 2007; Marangon *et al.* 2007). A determination of safety distances in the case where the hazard source (vehicle with an explosion potential) is moving in a relative vicinity of a target object involves several aggravating factors:

- I. the possibility of several explosions of different nature within the same road segment  $\omega$  (e.g., road tank BLEVE and detonation of the load of explosive material);

- II. uncertainty related to characteristics of specific explosion (e.g., orientation and tonnage) of a liquefied gas tank at the instant of BLEVE);
- III. uncertain position of explosion centre  $\mathbf{x}$  within or near  $\omega$  and variability in features of the territory between the position  $\mathbf{x}$  and target object;
- IV. the possibility of different degree of damage to the target object which can be caused by explosion of a specific type.

An estimation of the safety distance for all possible combinations of the aforementioned factors is a challenging task. It will become simpler by estimating the distance for a discrete set of values of the incidence angle  $\varphi$ . The task can also be simplified by taking into account the fact that variety of accidental explosions on road is not wide. It is possible to estimate the safety distance for each type of probable explosion and to assume the most conservative value as  $\Delta_\varphi$ .

Generally, an explosion related to the direction  $\varphi$  and represented by the random event  $E_\varphi$  will lead to some outcome  $O_{\varphi r}$  with the outcome likelihood  $P(O_{\varphi r} | E_\varphi) \times L(E_\varphi)$ , where  $P(O_{\varphi r} | E_\varphi)$  is the conditional probability of  $O_{\varphi r}$  given  $E_\varphi$  and  $L(E_\varphi)$  is the likelihood of  $E_\varphi$ . Alternative accident scenarios leading to different outcomes  $O_{\varphi r}$  are related to different degrees of damage to the target object. Outcome severity can be expressed by the vector  $\mathbf{s}_{\varphi r} = (s_{1\varphi r}, s_{2\varphi r}, \dots, s_{s\varphi r}, \dots)$  including lost money, lost time, number of fatalities, etc. and related to specific direction  $\varphi$  and accident scenario  $r$  (Kumamoto 2007; Zavadskas, Vaidogas 2009). With the above accident characteristics, the direction  $\varphi$  can be associated with the risk profile

$$\text{Risk}_\varphi \equiv \{(P(O_{\varphi r} | E_\varphi)L(E_\varphi), \mathbf{s}_{\varphi r}) \mid r = 1, 2, \dots, n_\varphi\}, \quad (1)$$

where  $n_\varphi$  – the number of accident scenarios associated with  $\varphi$ . The above expression of risk posed a potential

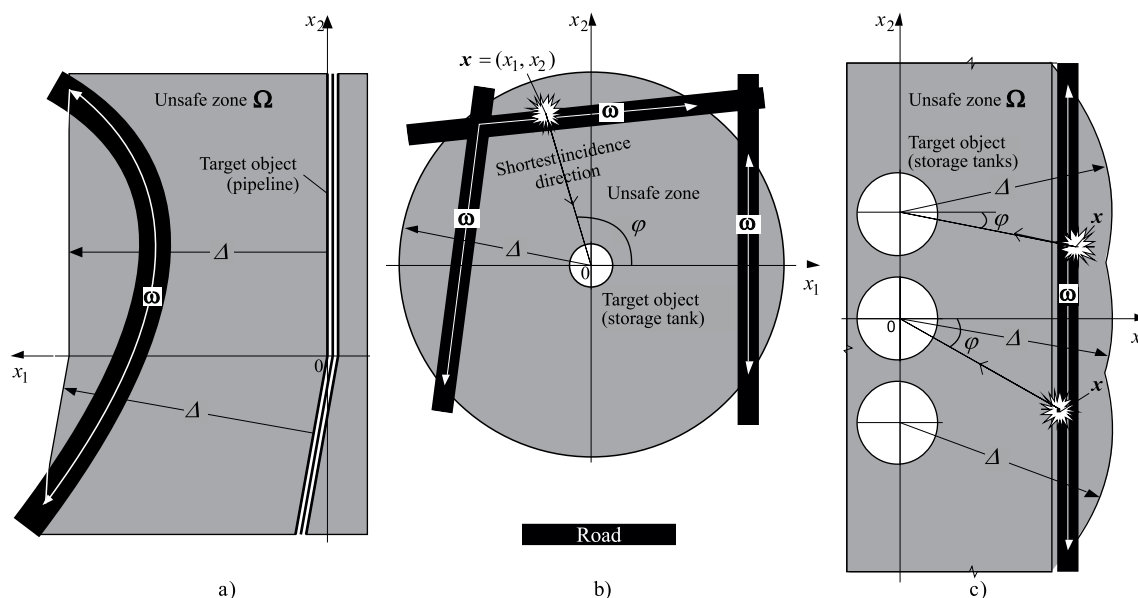


Fig. 1. Safety distance  $\Delta$ , unsafe zone  $\Omega$  and unsafe road segment  $\omega$  at different configurations of the target object: a – above-ground pipeline or other energy supply line; b – circular storage tank; c – storage tanks arranged in a row

explosion is well-known in the field of QRA applied to technologies involving fire and explosion hazards (e.g., Aven, Vinnem 2007; Vinnem 2007). The risk expressed by Eq (1) presents diverse and comprehensive information, especially if the vector  $s_{\varphi r}$  has more than one component. It is difficult to specify the safety distance  $\Delta_{\varphi}$  on the basis of such information. In the case where the list of components  $n_s$  of  $s_{\varphi r}$  is identical for all  $r$ , the risk is expressed in a more concise form, namely, through the vector of expected severities:

$$(\bar{s}_{s\varphi}, s = 1, 2, \dots, n_s) = \left( L(E_{\varphi r}) \sum_{r=1}^{n_s} P(O_{\varphi r} | E_{\varphi}) s_{s\varphi r}, s = 1, 2, \dots, n_s \right). \quad (2)$$

Decisions concerning  $\Delta_{\varphi}$  can be made on the basis of this vector. The simple decision rule is to choose such  $\Delta_{\varphi}$  which corresponds to expected severities  $\bar{s}_{s\varphi}$  satisfying the inequalities  $\bar{s}_{s\varphi} \leq s_{s,tol}$  for all  $s$ , where  $s_{s,tol}$  is a tolerable value of  $\bar{s}_{s\varphi}$ . In brief, one can write

$$\Delta_{\varphi} = \min\{\Delta | \bar{s}_{s\varphi}(\Delta) \leq s_{s,tol}, \forall s\}, \quad (3)$$

where  $\Delta$  – used as an optimisation (design) variable. Estimation of the expected severities  $\bar{s}_{s\varphi}$  and specification of the corresponding tolerable values  $s_{s,tol}$  for a given incidence direction  $\varphi$  may be a non-trivial task. In addition, this estimation must be carried out repeatedly until a satisfactory value of  $\Delta_{\varphi}$  is found.

The task of estimating the expected severities can be sidestepped in the case where all accident scenarios include the same random damage event  $D$  which can escalate into the outcomes  $O_{\varphi r}$ . Examples of  $D$  are relatively simple events:

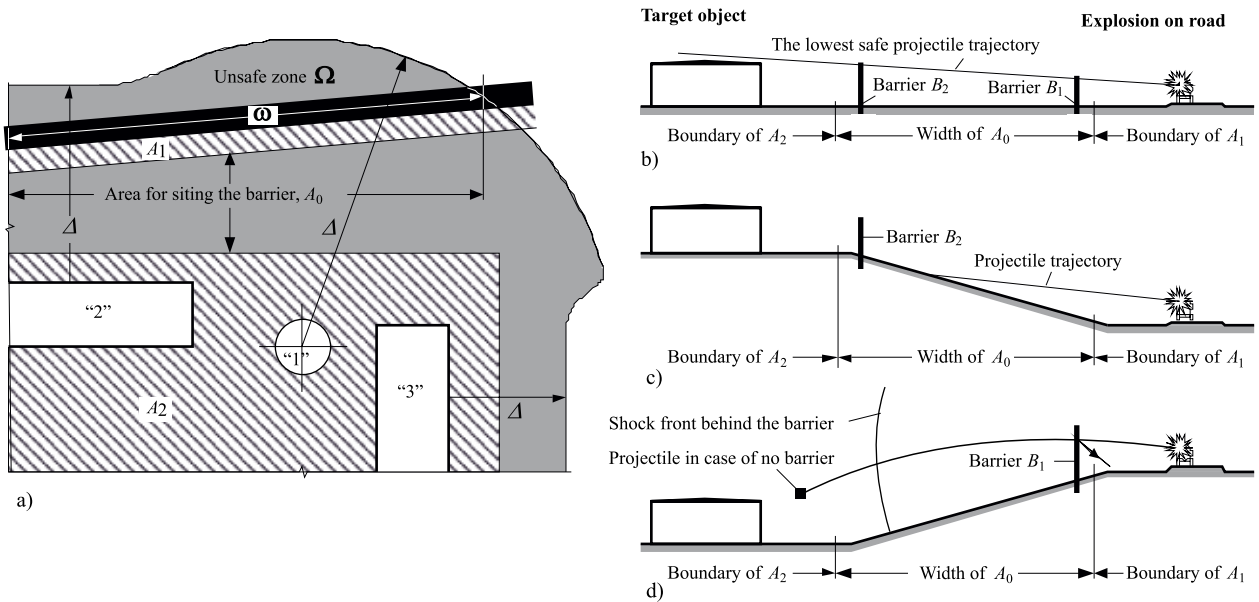
- toxic release due loss of containment by a storage tank or rupture of a pipeline in consequence of an explosion;
- ignition of flammable material released due to mechanical and thermal effects of an explosion;
- interruption to service of a critical infrastructure (e.g., energy transportation system) due to explosive damage.

After  $D$  is specified for a given target object, the conditional probability  $P(D | E_{\varphi})$  can be estimated and  $\Delta_{\varphi}$  chosen as a distance for which  $P(D | E_{\varphi})$  does not exceed some tolerable value  $P_{tol}$ :

$$\Delta_{\varphi} = \min\{\Delta | P(D | E_{\varphi}, \Delta) \leq P_{tol}\}, \quad (4)$$

where  $P(D | E_{\varphi}, \Delta)$  denotes the damage probability expressed as a function of the optimisation variable  $\Delta$ .

The decision rules given by Eqs (3) and (4) are analogous to the problem of a reliability-based structural optimisation, in which a tolerable failure probability must be specified or, in other words, the problem “how safe is safe enough” solved (e.g., Lemaire 2009). Eqs (3) and (4) yield a fixed value of  $\Delta_{\varphi}$  although this value is obtained by carrying out a probabilistic analysis, that is, an estimation of the damage probability  $P(D | E_{\varphi}, \Delta)$  (Fig. 3a).



**Fig. 2.** The area  $A_0$  available for siting the barrier between road and target object(s): a –  $A_0$  formed by the unsafe zone with irregular shape around the target objects “1” to “3” and the areas  $A_1$  and  $A_2$  in which a barrier construction is prohibited; b – the choice between two barriers in a flat horizontal area  $A_0$ ; c and d – siting the barrier by taking into account the influence of the relief on attenuation or strengthening of explosion effects

An estimation of  $P(D|E_\varphi, \Delta)$  is a problem of a reliability-based structural analysis (RBSA). There is vast literature on a deterministic analysis and design of structures for explosive actions, to say nothing of the literature devoted to the design for fire actions (e.g., Van Geel 2005; Bangash, Bangash 2006; Bangash 2009). However, RBSA applications to assessing specific explosive damage to large, real-world structures (not individual structural elements) are limited and not systematized in widely known documents. The estimation of  $P(D|E_\varphi, \Delta)$  is possible in theory by applying sophisticated methodology of RBSA. In practice, such estimation will require highly specific statistical data used to feed models developed for predicting explosion effects and describing interaction of complex structures with these effects. It is probable that this data will be inaccessible to the designer (land use planner). Our impression is that in some highly specific cases the aforementioned data and models may not be available at all.

In the case where the damage event  $D$  is caused by air blast only and  $D$  is expressed by broad categories of explosive damage to buildings or industrial installations (minor damage, major damage, collapse), the probability  $P(D|E_\varphi, \Delta)$  can be approximately estimated with relative ease using simple empirical models (probit functions) given in such documents as the Green book published by a Dutch organisation TNO (Roos 1992; Van Geel 2005). The event  $D$  can be associated with damage levels represented by either overpressure levels of incident shock wave,  $\hat{p}_0$ , or iso-damage diagrams (incident pressure-impulse diagrams or, in brief,  $p_0$ - $i_0$  diagrams). Overpressure levels  $\hat{p}_0$

were chosen empirically and  $p_0$ - $i_0$  iso-curves were developed both empirically and analytically for typical structural elements. The safety distance  $\Delta_\varphi$  corresponding to given values of  $\hat{p}_0$  and regions of  $p_0$ - $i_0$  plots can be traced back from the models which relate values  $\hat{p}_0$  and pairs  $(p_0, i_0)$  to explosion characteristics (e.g., Krauthammer 2008). Schematically these models can be represented by the functions

$$\hat{p}_0 = \psi(\Delta(\varphi) | e, \pi) \tag{5a}$$

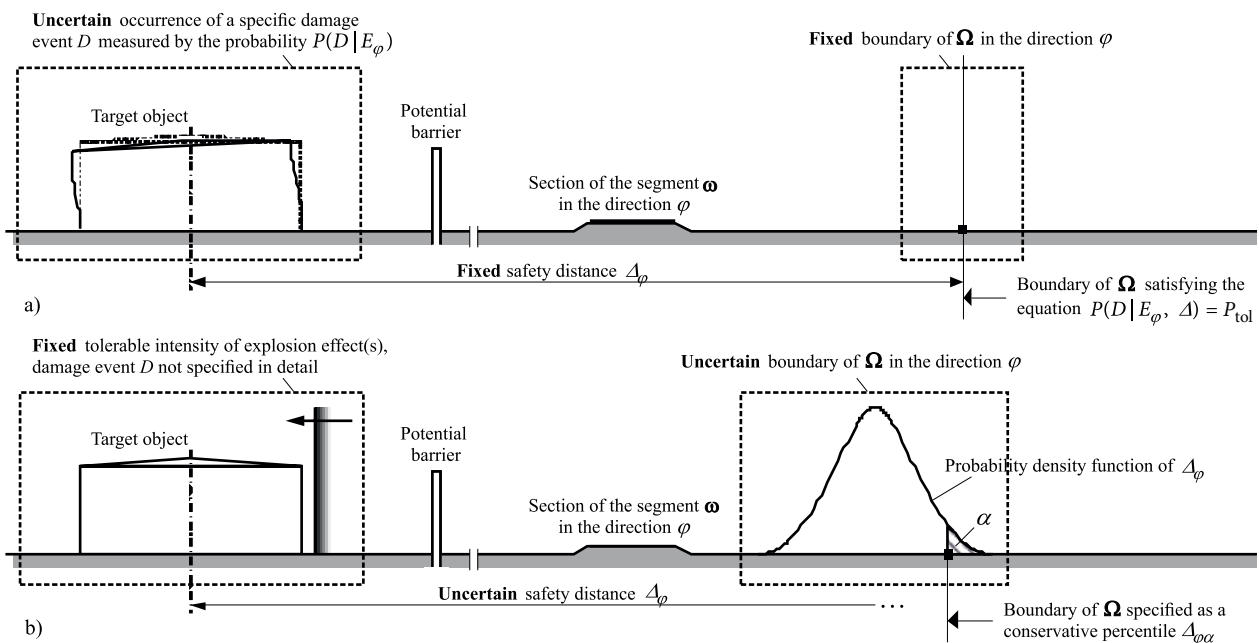
and

$$\begin{pmatrix} p_0 \\ i_0 \end{pmatrix} = \Psi(\Delta_\varphi | e, \pi) = \begin{pmatrix} \psi_p(\Delta_\varphi | e, \pi) \\ \psi_i(\Delta_\varphi | e, \pi) \end{pmatrix}, \tag{5b}$$

where  $e$  – the explosion energy (mass of explosives);  $\pi$  and  $\boldsymbol{\pi}$  – the scalar variable and vector used to express uncertainty in (inaccuracy of) the models  $\psi(\cdot)$  and  $\Psi(\cdot)$ , respectively.

A solution of Eqs (5) for given values of  $\hat{p}_0$ ,  $(p_0, i_0)$ ,  $\pi$  and  $\boldsymbol{\pi}$  will yield a fixed value of the safety distance  $\Delta_\varphi$ . However, the deterministic application of  $\psi(\cdot)$  and  $\Psi(\cdot)$  is questionable due to at least two reasons:

- (i) The energy (mass)  $e$  and inaccuracy measures  $\pi$  and  $\boldsymbol{\pi}$  will be uncertain in many practical applications; the uncertainty in  $e$ ,  $\pi$  and  $\boldsymbol{\pi}$  is quantified by means of random variables, say, random variables  $\tilde{e}$  and  $\tilde{\boldsymbol{\pi}}$  and vector of random variables,  $\tilde{\boldsymbol{\pi}}$  (e.g., Aven, Zio 2011);



**Fig. 3.** Two approaches to a specification of the safety distance  $\Delta_\varphi$ : a – specification of a fixed value of  $\Delta_\varphi$  based on a tolerable value  $P_{tot}$  of the damage probability  $P(D|E_\varphi)$ ; b – specification of  $\Delta_\varphi$  based on a fixed tolerable value of explosion effect and yielding a boundary of the unsafe zone  $\varphi$  defined by a percentile  $\Delta_{\varphi\alpha}$  of  $\Delta_\varphi$

- (ii) the damage levels  $D$  are represented by intervals of  $\hat{p}_0$  and areas of pairs  $(p_0, i_0)$  in the incident pressure-impulse diagrams; the distance  $\Delta_\varphi$  can be determined with most conservative values of  $\hat{p}_0$  and  $(p_0, i_0)$  related to specific damage level; however, this conservative approach is not automatically justified and so  $\hat{p}_0$  and  $(p_0, i_0)$  related to specific damage level should be considered uncertain.

Even though the quantities on the left-hand side of Eq (5) are fixed, the safety distance  $\Delta_\varphi$  will be a function of random variables and so a random variable itself:

$$\Delta_\varphi = \psi^{-1}(\hat{p}_0 | \tilde{\epsilon}, \tilde{\pi}), \quad (6a)$$

$$\Delta_\varphi = \Psi^{-1}(p_0, i_0 | \tilde{\epsilon}, \tilde{\pi}), \quad (6b)$$

where  $\psi^{-1}(\cdot)$  and  $\Psi^{-1}(\cdot)$  denote the inverse functions of  $\psi(\cdot)$  and  $\Psi(\cdot)$ , respectively. A probability density function of  $\Delta_\varphi$  can be estimated by means of Monte Carlo simulation. With the random safety distances  $\Delta_\varphi$ , the unsafe zone  $\Omega$  will be fuzzy (uncertain) and its boundary can be specified by means of conservative percentiles  $\Delta_{\varphi\alpha}$  of  $\Delta_\varphi$  as shown in Fig. 3b.

The two approaches to the specification of the safety distances  $\Delta_\varphi$  illustrated in Fig. 3 present two alternative ways of defining the unsafe zone  $\Omega$ . The specification of  $\Delta_\varphi$  by estimating the damage probabilities  $P(D | E_\varphi, \Delta)$  is applicable to all types of explosion accidents and consistent in terms of uncertainty quantification and propagation. However, such specification is usually difficult to implement. The specification of  $\Delta_\varphi$  on the basis of the overpressure levels  $\hat{p}_0$  and iso-damage  $(p_0-i_0)$  diagrams is significantly simpler; however, it is applicable only to specific accidents and broad damage categories caused by these accidents.

An estimation of the safety distance  $\Delta_\varphi$  for fires will be somewhat simpler than for explosions. The distance  $\Delta_\varphi$  can be determined by using criteria of thermal damage given in such documents as guidelines of a chemical process QRA (Ormsby 2000). Methods developed for modelling thermal radiation of pool fires and BLEVE fireballs can be applied to relate  $\Delta_\varphi$  to a radiation intensity which is tolerated by a roadside object subjected to a fire on road (e.g., Casal 2008).

### 3. Barrier configuration within an available area

The terrain physically available for barrier construction can be restricted by factors of very different nature:

- land ownership;
- legal requirements and regulations (e.g., prohibition of construction in the immediate vicinity of the road, say, in the area  $A_1$  shown in Fig. 2a);
- configuration of facility involving the target object;
- irregular relief of the terrain and problematic geological conditions;
- architectural and aesthetical considerations.

In some cases restrictions posed by land ownership or construction regulations may force the owner of the facility at risk to build a barrier along the perimeter of the facility or even inside its territory. In such cases little space may be left for a barrier configuration in plan. In other cases, some area for barrier sitting, say,  $A_0$ , will be available. The area  $A_0$  will form a part of the unsafe zone  $\Omega$  and lie between two areas  $A_1$  and  $A_2$  in which the construction is either prohibited or impossible (Fig. 2a). The area along the road,  $A_1$ , can be required or recommended by regulations of road construction. For instance, a Lithuanian road regulation recommends 3–15 m wide clear strips alongside the roads with 70–130 km/h speed limits. The opposite restricting area  $A_2$  can be formed by installations surrounding the target object, for instance, diked area around storage tanks.

If the area  $A_0$  is sufficiently wide to attenuate explosion effects (air blast, projectiles, thermal radiation), positioning the barrier may face at least three different situations:

- If  $A_0$  is flat and horizontal, the barrier can be constructed in any position within available space (Fig. 2b). The barrier built in the vicinity of the road (barrier  $B_1$ ) will have to be strong enough to resist the so-called local explosion (e.g., Bulson 1997). The barrier sited in front of the area  $A_2$  (barrier  $B_2$ ) will have to sustain a generally weaker distant “free field” explosion. The barrier  $B_1$  can be lower than  $B_2$  to provide protection against an impact by projectiles generated, for instance, by a road tank BLEVE.
- If  $A_0$  is a sufficiently steep slope or even a banquette going upwards in relation to the road, the inclined

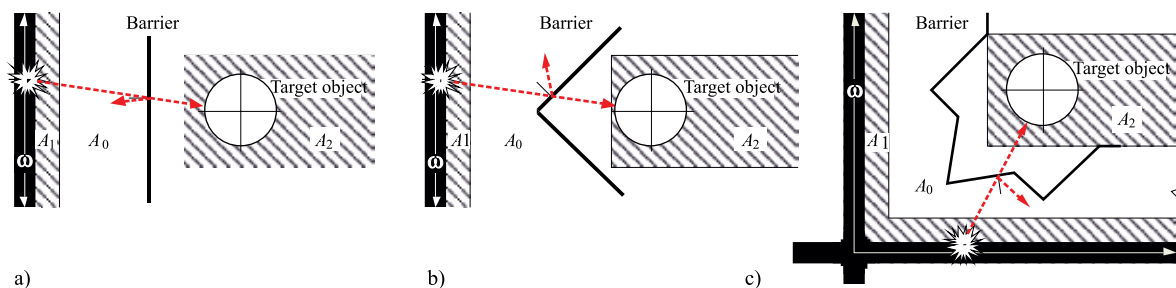


Fig. 4. Possibilities of a horizontal configuration of a barrier in the available area  $A_0$ : a – straight single-segment barrier (“blast wall”); b – two-segment (“arrow headed”) barrier; c – multi-segment barrier (“arrow headed bastion”)

$A_0$  will attenuate air-blast and catch some of projectiles as shown in Fig. 2c (Gebbeken, Döge 2010). In such a case it makes sense to build the barrier in front of the area  $A_2$  (i.e., barrier  $B_2$  in Fig. 2c).

- In case where  $A_0$  is a relatively steep downward slope, explosion effects will have favourable conditions to propagate towards the target object (Fig. 2d). Such surface will create the conditions for an explosion which can be considered intermediate between near-surface and open air explosion (e.g., Bulson 1997). In this case a sound decision is to build the barrier in front of the area  $A_1$  (i.e., barrier  $B_1$  in Fig. 2d).

A sufficiently wide space between the areas  $A_1$  and  $A_2$  opens up a possibility to give the barrier different forms in plan. The simplest and probably cheapest to build will be a straight barrier often called the blast wall (Fig. 4a). If the barrier will have to resist very intensive explosion effects, it can be shaped as “an arrow headed bastion” (Figs 4b, 4c). Such a shape allows increasing the potential angle at which air-blast and projectiles will be reflected by the barrier.

The type of structural material, vertical section and protective capacity of a barrier do not need to be constant along its length. Individual barrier segments may differ substantially according to the demand for protective capacity. In the case where characteristics of explosion or fire do not depend on the position of vehicle within the unsafe road segment  $\omega$ , this demand will be governed mainly by the distance between the target object and  $\omega$  as well as the position of barrier within the area  $A_0$ .

Effectiveness of a safety barrier will be very limited when it comes to protecting against a BLEVE fireball. The height and diameter of a fireball generated during a road tank BLEVE may exceed 100 m (Casal 2008). In the case where the horizontal distance between BLEVE and target object is small, a barrier protecting against blast and projectiles will not be able to stop thermal radiation. Consequently, shielding from thermal radiation should be provided in addition to the barrier. Such a case will be illustrated by an example presented in the next section.

#### 4. Example case study

The roadside object to be protected by a future safety barrier consists of three cylindrical reservoirs built in an oil transshipment facility located on the shore in the main sea port of Lithuania (Fig. 5, Vaidogas *et al.* 2012b). The reservoirs can be damaged by fire or explosion of a tank vehicle on a two-lane public road going along the perimeter of the facility. The speed limit on this road is 70 km/h. The terrain schematically depicted in Fig. 5 is flat and horizontal.

No land acquisition is planned by facility owners and so the barrier is to be built inside the fenced perimeter of the facility. The area available for barrier construction,  $A_0$ , will be partially restricted by a 4 m clear strip alongside the road,  $A_1$ , recommended in a Lithuanian road regulation. On the opposite side,  $A_0$  will border the rectangular

area  $A_2$  where the barrier construction is prohibited due to technological reasons.

In order to keep the area occupied and obstructed by the barrier at a minimum, this structure should have the form of a wall which either is built along the facility perimeter (points  $B_1$  to  $B_6$ , Fig. 5) or corresponds with the contour of the area  $A_2$  (points  $C_1$  to  $C_3$ , Fig. 5). Barriers sited in these two alternative positions will be called barrier “B” and barrier “C” and, for brevity, the word “barrier” will be skipped in some cases.

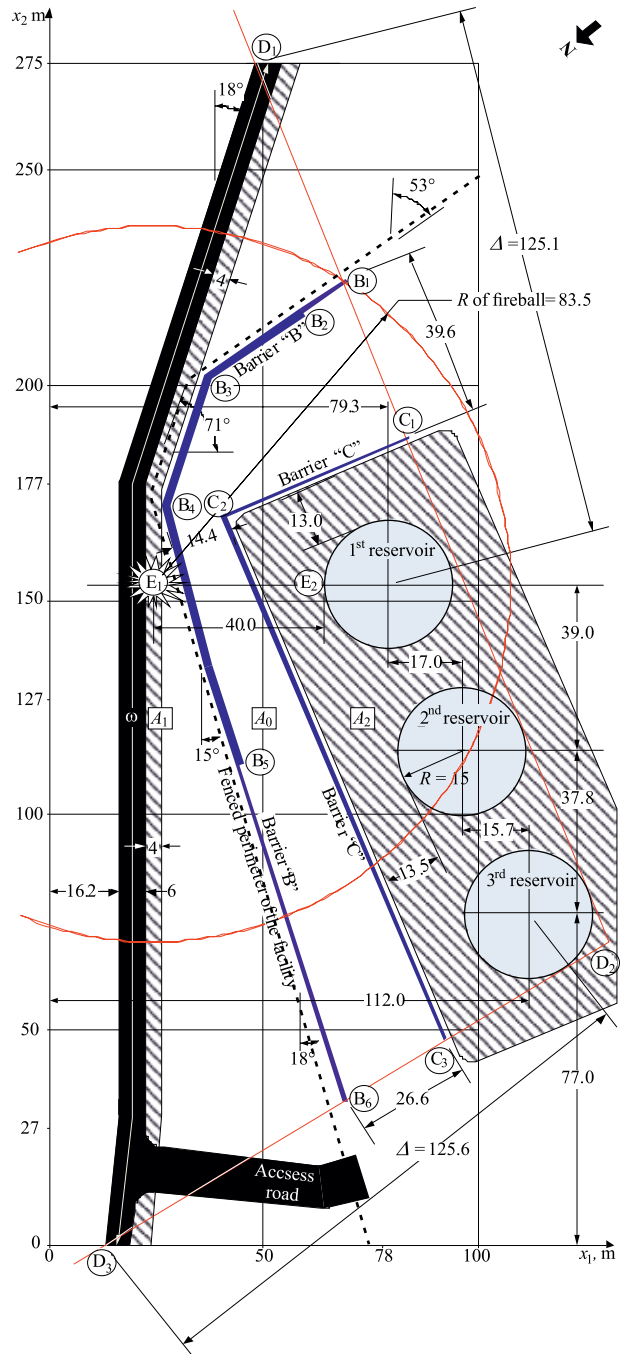


Fig. 5. The situation of a potential explosion on road and a roadside object to be protected by a safety barrier

Barrier “C” lies farther away from the road than barrier “B”. However, the distance between them is relatively small, especially between barrier segments protecting the

**Table 1.** List of advantages and disadvantages of the barriers “B” and “C”

Advantages
Barrier “B” (points $B_1$ to $B_6$ , Fig. 5)
Protects larger area of the facility than barrier “C”.
Can serve as vehicle barrier (anti-ram wall) if so designed (barrier segment $B_2$ to $B_5$ should be capable to resist vehicular impact) (Keršys <i>et al.</i> 2011).
Can prevent a vapour cloud accidentally released from a tank vehicle from encroaching on the facility area along the line $B_1$ – $B_6$ in order to avoid a Viareggio-type accident (Pontiggia <i>et al.</i> 2011).
Can prevent a pool of flammable liquid accidentally discharged from a tank vehicle in the vicinity of the segment $B_3$ – $B_4$ from encroaching on the facility area.
Can be lower than “C”, especially in the segment $B_3$ – $B_4$ due to reasons explained in Fig. 2b.
Can safely collapse onto the area $A_0$ and so can be designed as a sacrificial barrier (Krauthammer 2008).
The space behind “B” is available to provide counter forts, if necessary.
Does not restrict access to the technological area $A_2$ .
May serve as a part of perimeter fencing.
Construction of “B” should not hinder technological activities in the area $A_2$ .
Barrier “C” (points $C_1$ to $C_3$ , Fig. 5)
Can serve as an “arrow headed” barrier with a knee joint in point $C_2$ which is closest to the turn of the road.
If designed taller than “B”, provides larger area of shielding against thermal radiation.
Will not reduce visibility at the turn of the road.
Disadvantages
Barrier “B” (points $B_1$ to $B_6$ , Fig. 5)
Must have higher resistance than “C”, especially in the segment $B_3$ – $B_4$ .
Will hinder visibility on the road along the segment $B_3$ – $B_4$ .
Provides little of its surface for a reflection of blast and projectiles at large angles.
Barrier “C” (points $C_1$ to $C_3$ , Fig. 5)
Protects the technological area $A_2$ only.
Can not be designed as a “sacrificial barrier” if a collapse onto the technological area is not allowed.
The space behind “C” is limited to provide counter forts.
Will not prevent vapour cloud or pool of flammable liquid accidentally released from a tank vehicle from an encroaching on the facility territory.
Construction of “B” can hinder technological activities in the area $A_2$ .

1<sup>st</sup> reservoir. Thus the position of “C” is not much better than the one of “B” in terms of a larger separation from a potential explosion or fire. Cross-sectional shape and distribution of protective capacity along the axes of “B” and “C” can be chosen by applying methods of structural optimisation. Different variants of “B” and “C” can be designed and the best one selected by means of formal methods of MCDM (Vaidogas 2007b; Zavadskas, Vaidogas 2009; Sivilevičius, Maskeliūnaitė 2010). However, it is possible to weight pros and cons of “B” and “C” before the optimisation. Table 1 lists advantages and disadvantages of “B” and “C” for the case where the barriers have to protect the facility not only against BLEVE but also against pool fire and formation of vapour cloud with subsequent flash fire or explosion. It is possible to conclude at this stage of barrier design that, at least arithmetically, barrier “B” “overweight’s” barrier “C”.

The position of endpoints of barriers “B” and “C” was chosen by introducing an unsafe road segment  $\omega$  in the manner shown in Fig. 1c. The outermost points of  $\omega$ ,  $D_1$  and  $D_3$ , correspond to a safety distance  $\Delta$  which is approximately equal to 125 m (Fig. 5). Two lines connecting  $D_1$  and  $D_3$  to the point  $D_2$  are tangents to the 3<sup>rd</sup> reservoir. These lines show two extreme trajectories of projectiles which can be ejected by an explosion on road and collide with the reservoirs. The barriers can be ended where they intersect the line segments  $D_1$ – $D_2$  and  $D_2$ – $D_3$ .

The safety distance  $\Delta$  used in this example is hypothetical and serves as an illustration. Generally,  $\Delta$  should be estimated by solving the optimisation problem given by Eq (4). The random damage event  $D$  in this problem is a loss of containment by at least one of the reservoirs. If the reservoirs are nominally identical, the distance  $\Delta$  can be estimated only for one of them and the unsafe zone  $\Omega$  plotted as shown in Fig. 1c.

An estimation of the damage probability  $P(D|E_\varphi, \Delta)$  in Eq (4) is a non-trivial task, especially for such a complex event as BLEVE. A solution of this task requires a great deal of space and is beyond the scope of this study. At present is one can only say that the estimation of  $P(D|E_\varphi, \Delta)$  may face two problems: (i) scarcity of data on effects of fires and/or explosions recorded during/after past accidents, and (ii) need to predict these effects and response of reservoirs to them by means of models which are not necessarily very accurate. The best way to deal with these problems is an application of methods based on the Bayesian statistical theory and widely used for QRA (Juocevičius, Vaidogas 2010; Vaidogas 2003, 2006, 2007a, 2009; Vaidogas, Juocevičius 2007, 2008, 2009).

If designed properly, barriers “B” and “C” will protect the reservoirs against effects of blast and projectiles. They will provide also protection against pool fire and flash fire, both preceded by accidental release of flammable liquid or gas from a road tank. However, such event as a road tank BLEVE will generate a fireball, the height of which may considerably exceed the height



of “B” and “C”. Characteristics of the fireball can be estimated by simple deterministic models (e.g., Casal 2008). For instance, if a typical LPG semi-trailer with a volume of 56 m<sup>3</sup>, 85% of which are filled with propane, is heated by a fire to 55 °C (approx 19 bar) and bursts, the mass of fuel involved in the fireball will be 23 800 kg. Estimates of fireball diameter and height of its centre are 167 m and 125 m, respectively. The duration of the fireball will be around 11 seconds. If the centre of BLEVE will be in the point  $E_1$ , which is placed only 40 m apart from the 1<sup>st</sup> reservoir, the fireball will fully cover the 1<sup>st</sup> reservoir and partially the 2<sup>nd</sup> reservoir (Fig. 5). An estimate of the thermal radiation of the fireball on the top edge of the 1<sup>st</sup> reservoir (point  $E_2$ ) is 38.5 kW/m<sup>2</sup>. Such a radiation is capable to damage the reservoirs (Ormsby 2000). Thermal shielding of these structures must be provided because barriers “B” and “C” will not adequately protect against thermal radiation coming from the altitude far above the ground surface.

## 5. Conclusions

An early stage of the design of barriers aimed at protecting built property from accidental explosions and fires on road has been studied. The main problems of this design stage include: (a) determination of a road segment from which roadside property can be damaged; (b) specification of an area for a barrier construction between the unsafe road segment and property to be protected; and (c) positioning the barrier in the available area. A solution of these three problems will yield input information for a detailed design of the barrier. The detailed design should normally be carried out by applying methods of structural optimisation.

The determination of the unsafe road segment will be a non-trivial problem. A comprehensive solution of this problem requires assessing a potential explosion and/or fire damage to an unprotected roadside object by applying methods of structural reliability theory and quantitative risk assessment. A layout of the unsafe road segment will determine the area where the barrier is required. This area should fully overlap the area available for barrier construction. A configuration of the latter area will be influenced by factors of very different nature. The size, layout and obliquity of the construction area will influence decisions concerning a configuration of the barrier in plan and positioning it between road and roadside objects subjected to the hazard of fire or explosion on road.

Methods applied to solving problems of the early, pre-optimisation stage of barrier design will range from rigorous mathematical techniques of probabilistic structural analysis to a judgemental choice of barrier configuration and position in plan. Results produced by these methods can positively contribute to improving the final design of the barrier and so increasing safety of hazardous goods transportation along the roadside area to be protected by the barrier.

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