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RISK ORIENTED DESIGN OF PROTECTIVE HIGHWAY STRUCTURES

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Abstract. The problem of risk-based design of protective highway structures is considered. It is stated that the accidents involving damage to components of road infrastructure are a natural subject of a quantitative risk analysis. The paper discusses how to apply a risk oriented approach to the design of protective components of road infrastructure. A simulation-based procedure developed for a design of a protective highway structure by means of a multi-attribute selection is suggested. Attention is focused on uncertainties related to both accidental actions, which must be sustained by the protective structure, and behaviour of the structure under these actions. The proposed procedure serves for a comparison of alternative designs of the protective structure. The comparison takes into account epistemic uncertainties in failure-to-protect probabilities related to the alternative designs. It is shown that the multi-attribute selection can be carried out as a simulation-based propagation of the epistemic uncertainties. A loop of such simulation must involve deterministic algorithm of the multi-attribute selection. Repeating this loop a number of times yields relative frequencies of selecting individual alternative designs as the best ones. The optimal alternative design can be chosen as a design with the largest frequency of selection.

Keywords: road accident, collision, protective structure, risk analysis, Eschede disaster, Shelby crash.

1. Introduction

The road infrastructure is steadily subjected to the hazard of major accidents [1–3]. They can be initiated by conventional traffic, dangerous goods conveyed by road and failures in hazardous facilities built along the roads. An increased proneness to the accidents is characteristic of those parts of the road infrastructure where the road meets, crosses, bridges, or runs close to the railway or where it tunnels natural obstacles. The major accidents in Eschede (Germany, 1998) and Shelby (UK, 2001) as well as numerous catastrophic fires in road tunnels are sad examples of such proneness [4–6].

The "role" of structures in the accidents on the road is ambiguous. Structural components of roads, bridges, and tunnels are targets of abnormal effects induced during an accident, first of all, impacts by vehicles and impingement of fires. In the field of the structural engineering an abnormal effect is called the accidental action (AA). An improperly designed highway structure can initiate (contribute to) an escalation of the adverse events leading to a major accident. The insufficiently considered configurations of the bridges crossing the railway contributed to heavy consequences of Eschede and Shelby accidents [4, 5].

The protection of a highway structure against AA may have several options. The structure may be built sufficiently robust, where the robustness can be understood intuitively or quantified formally in probability terms [7]. A less expensive option can be sheltering the main structure by a protective structure (PS). For instance, a safety fence can be provided to absorb in part energy of a truck which could deviate from the lane on the course of collision with a bridge structure. Finally, a protective structure, say, a fire wall or a massive collision barrier can be built to prevent completely a propagation of a hazardous phenomenon (eg thermal radiation or vehicle which has left its normal track) outside the road. Sometimes a protective structure can be an inexpensive solution used for preventing a major accident. A simple albeit impressive example was the absence of fencing alongside the bridge embankment and/or the railway which was involved in the Shelby accident [5].

This paper follows the idea that AAs and potential damage, which can be caused by AAs, are natural subjects of quantitative risk assessment (QRA) [8, 9]. It is stated that the design of PS for the specific AA, which can occur in the road infrastructure, must be preceded by investigating this AA by means of QRA, first of all, quantifying un-

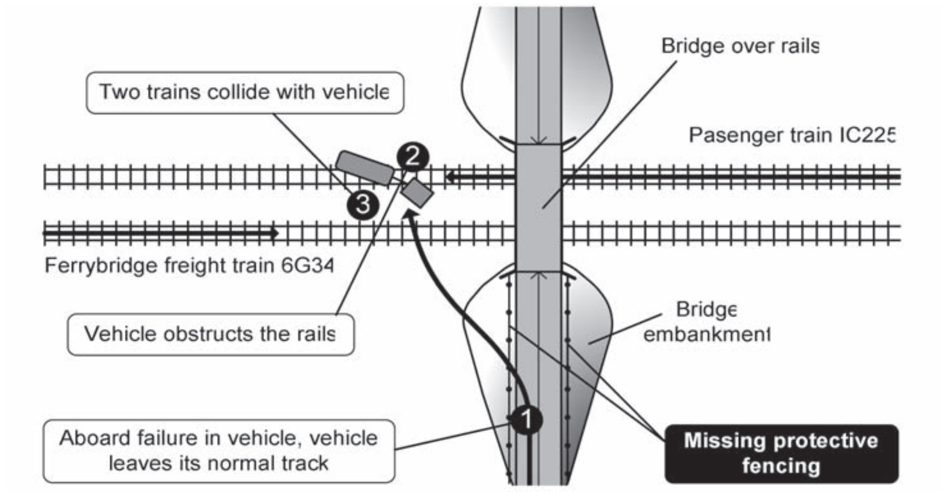

Fig 1. Railway accident escalated by the absence of protective fencing along the embankment (this scheme has been constructed according to the HSE report [5])

certainty related to a potential AA. In line with QRA this uncertainty will have aleatory and epistemic components which will result mainly from scarcity or even absence of direct data on AA characteristics [10, 11]. They can be transformed in the uncertainty related to the behaviour of PS subjected to AA. The latter uncertainties can be expressed by the uncertain probability that PS subjected to AA will not perform its protective function(s) (failure-to-protect probability or f.p.p., in brief). In line with QRA, f.p.p. can be uncertain in the epistemic sense and this uncertainty is quantified within the classical Bayesian approach (CBA) to QRA [10].

The present paper considers the problem of design of PS for AA. This problem is formulated as comparison of several configurations of PS. The methodology of the multiattribute selection (MAS) is suggested for such a comparison [12, 13]. It is shown how to introduce into MAS such f.p.p.s which are uncertain in the epistemic sense. This uncertainty is quantified within CBA and then applied within the MAS.

2. Protective structures in the view of risk analysis

Generally the term "protective structure" is associated with hardened structures that are designed to protect assets for war fighting capabilities [14]. PSs are designed to resists actions of weapons. One, if not the largest, challenge of such a design are large uncertainties related to weapon-induced actions and non-linear dynamic response behaviour of PSs under these actions.

The situation of exposure to extreme and uncertain dynamic actions of short duration and the need to protect assets for such actions is characteristic not only of a military field. Such situation is well known in structural engineering as "accidental situation" (AS) [15]. In essence, every structure deliberately designed and built to block up (reduce) actions induced during an AS may be considered to be PS. This clearly applies to the structures used for the road infrastructure.

The problem of quantifying uncertainties related to AA imposed during AS and response of a highway structure to this action may be no less complicated than in case of a military structure. AA induced during a rare and unexpected AS can be as uncertain and destructive as actions of weapons.

An AS on the road often occurs as a sequence of adverse events which are random by their nature. A presence or absence as well as failure or survival of PS can substantially influence this sequence and contribute to the escalation or de-escalation of the sequence. An example of such a sequence is the series of the events that led to the Shelby rail crash (Fig 1). One simple lesson learned from this accident is obvious: a PS in the form of a properly designed and not necessarily expensive safety barrier built along the bridge embankment could prevent the train crash.

A formalised QRA can help in preventing the accidents like the Shelby rail crash [5]. As applied to the design of PS, QRA should be used for making decisions concerning the following questions:

- Are there any events/processes in the road infrastructure which can initiate an accident (e g conveyance of flammable or explosive goods)?
- What are potential escalations of the aforementioned events/processes into accidents inducing AAs?
- Is the estimated likelihood (annual probability, say) of the accidents large enough to take protective measures?
- How to express quantitatively the uncertainty related to characteristics of the AA back by sparse

historical data, say, velocity and mass of a colliding truck?

PSs by their very nature are direct and usually affordable measures which can be applied to mitigation of accident consequences or reducing the likelihood of accident. However, each PS is not a fail-safe structure which generally has to be designed for a highly uncertain AA, say, an accidental impact by a motor vehicle. A successful design of PS for a specific AA must assure a sufficiently high reliability (probability of performing the protective function) or, conversely, a tolerably low f.p.p. The nature of accidents involving imposition of AA's implies that the failure-to-protect can be a fairly uncertain event.

3. Reliability of protective highway structures

3.1. Performance-based classification of design tasks

In many cases the general scenario of potential AS and type of AA induced during this AS can be roughly predicted with relative ease. At the same time, the design of PS for this AS can be a highly case-specific task. It depends on the accuracy with which AA can be predicted and a particular protective function which PS is expected to perform by suffering an anticipated degree of damage. In terms of protective function and anticipated damage, one can distinguish at least six types of PSs (Table 1).

In line with QRA, the design of each type of PS should involve selecting a probabilistic model of AA and predicting behaviour of PS subjected to this AA. With the model of AA, the design of Type I structures is close to a conventional design of sufficiently reliable structures by means of a structural reliability analysis (SRA). The design of Type II structure is dominated by modelling the physical process of damping AA by PS. The "structural" part of this design should assure that PS will be intact after an occurrence of AA.

Type III and IV structures are more realistic than structures of previous two types. The design of Type III and IV structures requires mathematical models which define the "reparable damage". This design should allow sufficiently large probabilities of suffering reparable damage. Type IV structures may be disintegrated by AA. For instance, PS may contain drop-off panels which are likely to be blown-off by an accidental explosion from a sufficiently strong main structure, say, a skyway bridge. The repair of this PS will consist in replacing the panels.

Type I and III structures should not loose their integrity in consequence of resisting AA. The behaviour of these structures under AA should have little influence on load-structure interaction. They should behave like structures known in the structural design for accidental explosions as "decoupled" ones [16].

Type V and VI structures should perform the "blocking up" and "reducing" functions and are allowed to undergo foreseeable mechanical failures. These failures may influence the load-structure interaction process in a planned way. The structures known in the design for accidental explosions as "coupled" ones behave as Type V and VI structures [16]. The design of the latter two types of PS may be the most complicated as a disintegration of PS and related instantaneous changing of loading process can be difficult to model. On the other hand, Type V and VI structures may be of relatively cheap, "disposable" products. They may be preferred to other types of PS.

3.2. The random event of failure-to-protect

In line with QRA, a failure of PS under AA must be considered a part of accident escalation. The probability that PS will fail in one of possible modes should be kept at necessary level related to specific type of PS.

Let the m alternative designs (alternatives) of PS be $a_1, a_2, \dots, a_i, \dots, a_m$. Then the random events of failure associated with the design a_i will be F_{k_i} $(k_i = 1, 2, \dots)$.

Table 1. Classification of protective structures according to their function and potential damage cause by AA(1)

Anticipated degree of damage to PS due to AA	Protective function of PS(2)	
	Stopping progression of the physical phenomenon of AA	Reducing energy of the physical phenomenon occurring as AA
No damage	TYPE I: is to block up AA without any damage (eg fire/explosion shelter in tunnel)	TYPE II: is to reduce intensity of AA without suffering any damage (eg shelter wall alongside the road)
Reparable damage	TYPE III: is to block up AA and suffer a predictable damage (eg end wall for specific type of trucks/trains)	TYPE IV: may suffer a predictable damage due to minimising energy of AA (eg drop-off panels directly used for reducing pollution of noise emitted by an elevated road)
Irreparable damage	TYPE V: may be destroyed in consequence of blocking up AA (eg steel barrier protecting bridge pier against frontal vehicular impact)	TYPE VI: may be destroyed due to absorbing energy of AA (eg safety fence along the bridge carriageway)
(1) AA = accidental action; (2) PS = protective structure		

Given a probabilistic model of AA, the probability of specific F_{k_i} can be estimated by standard means of SRA as long as F_{k_i} is backed by a more or less accurate mechanical model (limit state function) $g_{k_i}(\cdot)$.

The failure-to-protect may be a more complex event Ψ_κ represented by a union $\Psi_\kappa = \bigcup_{k_i \in K_{\kappa_i}} F_{k_i}$, where K_{K_i} is the subset of F_{k_i}s, an occurrence of which leads to the th failure-to-protect related to the alternative design a_i. For instance, a failure of a wall built to protect against a vehicular impact can happen as a local penetration though the wall (event F_1), its overturning (event F_2), or attainment of the maximum resistance capacity of wall sections (event F_3). With these three failures, the failure-to-protect events are $\Psi_1 = F_1$ and $\Psi_2 = F_2 \cup F_3$. An occurrence of Ψ_1 can cause local damage behind the wall and so is less dangerous than Ψ_2. Clearly, the events Ψ_1 and Ψ_2 are dependent.

The probabilities of the failure-to-protect events Ψ_κ are important characteristics of PS. An application of these probabilities to a comparison of the alternative designs a_i depends on the way, how these probabilities are estimated, and, first of all, on information about the AA which can cause the events Ψ_κ.

3.3. Epistemic uncertainty in the failure-to-protect probability

Occurrences of a specific AS are described by stochastic models which have been proposed in the literature on safety assessment for predicting hazardous phenomena [9, 17]. A simple model which calculates the probability $P(r|t, \lambda)$ of r occurrences of AS in a period of time t is the Poisson distribution $e^{-\lambda t}(\lambda t)^r / r!$. Its only parameter λ is the constant rate of occurrence of AS. The probabilities $P(r|t, \lambda)$ are measures of aleatory uncertainty. Due to the fact that an AS is generally rare and difficult-to-predict event and so data on AS is usually sparse, the parameter λ can be uncertain. In line with CBA, the uncertainty in λ is expressed by an epistemic probability density function (p.d.f.) $(\pi\lambda)$.

Even if the Poisson is valid for a specific AS, the designer of a highway structure will most probably have interest not in the probabilities $P(r|t, l)$ but in the failure rates $\lambda \times p_{f_i}$ and primarily in the conditional failure probabilities of Ψ_κ, namely,

$$p_{f_i} = P(\Psi_K AA), \quad (1)$$

where AA – the random event of imposition of AA induced during the AS and having any characteristics (any intensity, say). For simplicity, the symbol "K" is not used, where possible, as one of the subscripts of the conditional probabilities p_{f_i}. In context of CBA, the probabilities p_{f_i} serve as measures of aleatory uncertainty.

In principle, the designer can control both λ and p_{f_i}. However, it is more likely that $a_i s$ will be designed for a given, unavoidable environment characterized, among other things, by λ. For a practical design, the expression (1) should be detailed to introduce mathematical model(s) of PS subjected to the potential AA. The standard definition of p_{f_i} used to SRA has the form:

$$p_{f_i} \equiv p_f(x_i) = \int_{\text{all } y} p(y \mid x_i) dF_y(y \mid \theta), \quad (2)$$

where x_i – the vector describing a_i (components of x_i can be either nominal parameters of a_i or characteristics of a joint probability distribution (p.d.) characterising a_i); y – the vector of physical characteristics of AA; $F_Y(y)$ – the distribution function (d.f.) of y with the parameters θ; $P(y|x_i)$ is the fragility function quantifying the failure probability given an AA with the fixed characteristics y.

In SRA, the function $P(y|x_i)$ is usually expressed as:

$$P(y|x_i) = \int_{\{z | \bigcup_{k_i \in K_{\kappa_i}} (g_{k_i}(z|y) \le 0)\}} dF_{Z_i}(z|x_i), \quad (3)$$

where z – the value of the vector Z_i with d.f. $F_{Z_i}(\cdot)$ used to model random characteristics of a_i; $g_{k_i}(\cdot)$ – the mathematical model of a_i determining an occurrence or non-occurrence of F_{k_i}.

Generally the vectors x_i and Z_i as well as the set of failure events F_{k_i} related to different $a_i s$ will be of different structure. However, the expressions (2) and (3) allow transforming x_i, Z_i, and $F_{k_i} s$ into the single values $p_f(x_i)$ which are well suited for comparison ais.

Estimates of $p_f(x_i)$ yielded by CBA will have the form of epistemic uncertainty distributions [9, 18]. The epistemic uncertainty in $p_f(x_i)$ may stem primarily from sparse information on AA. Clearly, another source of potential epistemic uncertainty in $p_f(x_i)$ is uncertainty related to the accuracy of the models $g_{k_i}(\cdot)$. Quantitatively the uncertainty related to AA can be expressed through the probabilistic model of AA, namely, the aleatory d.f. $F_Y(y)$. Measures of epistemic uncertainty can be introduced in $F_Y(y)$ and propagated through (2) to a d.f. of the epistemic uncertainty related to $p_f(x_i)$.

In the standard way, the uncertainty in $p_f(x_i)$ can be expressed through uncertainty in parameters θ of d.f. $F_Y(y|\theta)$. In context of CBA, the uncertainty in θ is modelled by means a random vector Θ with a prior (posterior) p.d.f. $\pi(\theta)$. Given Θ, the epistemic uncertainty in $p_f(x_i)$ is expressed by the random variable (r.v.):

$$\tilde{p}_f(x_i) = \int_{\text{all } y} P(y \mid x_i) dF_Y(y \mid \Theta). \quad (4)$$

The d.f. $F_Y(\cdot)$ can be specified and the p.d.f. $\pi(\theta)$ updated using standard means of Bayesian statistics. The distribution of $\tilde{p}_f(x_i)$ can be expressed in the form of a posterior density obtained by combining prior information on AA with a small-size sample of AA characteristics, $\{y_1, y_2, \ldots\}$. The posterior density can be obtained by updating a prior density using a fictitious sample of fragility function values, $\{P(y_1|x_i), P(y_2|x_i), \ldots\}$. A technique of Bayesian bootstrap can be applied for such updating [19, 20].

4. Design of a protective structure by comparing its alternative configurations

4.1. Possible design formats

The uncertain f.p.p.s $\tilde{p}_f(x_i)$ should be incorporated into the design of PS which typically has the form of an optimisation. This can be carried out intuitively (without applying any mathematical techniques); however, the probabilities $\tilde{p}_f(x_i)$ can be used most effectively if the optimisation is carried out by formal means.

With the uncertain f.p.p.s $\tilde{p}_f(x_i)$, the optimisation of PS will have to take into account both aleatory and epistemic uncertainties. Aleatory uncertainty ("certain" or "crisp" f.p.p.s $\tilde{p}_f(x_i)$) can be introduced into problems of mathematical programming with relative ease. A highly relevant example of such problems are classical single- and multi-objective problems of a reliability-based structural optimisation (RBO) [21, 22].

A single- or multi-objective RBO, which includes measures of epistemic uncertainty, can be useful mainly for improving the current, specific design a_i of PS. However, the designer may face the need to choose between several alternative and sufficiently different designs represented by the vector $(a_1, a_2, \ldots, a_i, \ldots, a_m)$T. For instance, a protective barrier can be built of structural steel or reinforced concrete, or, alternatively, have the form of a soil embankment (ie $m = 3$). The alternative designs a_i may be too different to be considered several solutions of different distance to an "optimum" of RBO problem. In other words, a method of mathematical programming used to RBO cannot allow a transition from one a_i to the other.

The need to compare alternative designs will almost inevitably require taking into account conflicting attributes of these designs. In many cases these attributes can be similar or identical to objective functions of a multi-objective RBO [21, 22]. For PS exposed to potential AS such attributes should include f.p.p.s.

Alternative designs of PSs can be compared by applying methods of MAS. This methodology seeks to determine the best alternative a^* or a subset of leading alternatives among the discrete set of alternatives denoted by a_is. The quality of a_i is evaluated by means of a row-vector $c = (c_1, c_2, \ldots, c_j, \ldots, c_n)$, the components of which, c_j, are attributes (characteristics) of a_is. The structure of c depends on the objectives of a particular MAS problem and, of course, influences results of this MAS.

4.2. Design procedure accounting for uncertain failure-to-protect probabilities

Data for solving an MAS problem is formulated as a $m \times n$ decision matrix:

$$\boldsymbol{C} = [c_1, \ldots, c_i, \ldots, c_m]^T, \quad (5)$$

where $c_i = (c_{i_1}, c_{i_2}, \ldots, c_{i_j}, \ldots, c_{i_n})$ ($i = 1, 2, \ldots, m$) is the value of c associated with the corresponding a_i. In terms of MAS, the element c_{i_j} expresses impact of the i^{th} alternative on the j^{th} attribute [12].

Formally MAS is capable to consider very different attributes of a^is, among them the reliability [13]. In case that "crisp" f.p.p.s $p_f(x_i)$ serve as characteristic of a_is, they can be easily introduced into MAS as one of c_js:

$$c_i = \left(p_f(x_i), c_{i_2}, c_{i_3}, \ldots, c_{i_n}\right), \quad (6)$$

where $c_{i_2}, c_{i_3}, \ldots, c_{i_n}$ – values of MAS attributes which are not necessarily probabilistic. In this way $p_f(x_i)$ becomes a part of an MAS problem.

If the uncertain f.p.p.s $p_{f_K}(x_i)$ related to the failure-to-protect events Ψ_κ ($K = 1, 2, \ldots, n_\kappa$) are applied as MAS attributes c_j, MAS problem will involve stochastic c_js. The vectors c_i will contain at least one random component. They can be replaced by the stochastic attribute vectors:

$$\tilde{c}_i = (\tilde{p}_{f_1}(x_i), \ldots, \tilde{p}_{f_{n_K}}(x_i), \; c_{i,n_K+1}, \ldots, \; c_{i_n}). \quad (7)$$

As the events Ψ_κ may occur due to the same AA, the epistemic r.v.s $\tilde{p}_{f_K}(x_i)$ in (7) can be highly dependent. This dependence makes difficult representing the r.v.s $\tilde{p}_{f_K}(x_i)$ by one or two characteristic values (conservative percentiles, say).

Replacing $\tilde{c}_i$s in the initial deterministic decision matrix C by $\tilde{c}_i$s defined by (7) yields a stochastic decision matrix:

$$\tilde{\boldsymbol{C}} = [\tilde{c}_1, \ldots, \tilde{c}_i, \ldots, \tilde{c}_m]^T. \quad (8)$$

Clearly, the uncertainties expressed by elements of $\tilde{\boldsymbol{C}}$ may be not necessarily epistemic ones. Apart from the epistemic r.v.s $\tilde{p}_{f_K}(x_i)$, the matrix $\tilde{\boldsymbol{C}}$ may contain elements that are uncertain in the aleatory sense. In terms of MAS, the former ones and the latter ones are stochastic attributes. Given such attributes, the MAS problem formulated in the form of $\tilde{\boldsymbol{C}}$ can be solved by means of the uncertainty propagation which is widely used in the field of QRA [23].

With the stochastic decision matrix $\tilde{\boldsymbol{C}}$, the selection of a specific alternative a_i as the best one a^* becomes a random event. Therefore one can introduce a conditional probability that a_i will be selected as a^*, namely,

$$p_i = P\left(\text{selecting } a_i \text{ as } a^* \mid NM, K\right), \quad (9)$$

where *NM* denotes the choice of the normalisation method used to calculate the normalised decision matrix $\overline{\boldsymbol{C}}$, and *K* indicates the MAS criterion used to select a^* (see e g [12] for details). Uncertainty quantified by p_is will generally reduce when epistemic, and possibly aleatory, uncertainties expressed by elements of $\overline{\boldsymbol{C}}$, reduce.

The best alternative a^* can be chosen as the alternative with the largest probability p_i, ie $a^* = a_i$, where

$$i = \text{argmax}\{pi, i = 1, 2,\ldots, m\}. \quad (10)$$

The probabilities p_i can be estimated by propagating uncertainties expressed by elements of $\tilde{\boldsymbol{C}}$ through the expressions behind *NM* and *K*.

Although QRA applies several different techniques to uncertainty propagation, the Monte Carlo simulation seems to be the best one for estimating p_is. This may consist in carrying out some number N_l of repetitions of the simulation loop which includes solving the MAS problem. The lth repetition ($l = 1, 2,\ldots, N_l$) will start from sampling values from p.d.s of elements of $\tilde{\boldsymbol{C}}$. This will result in an lth sampled value $\tilde{\boldsymbol{C}}_l$ of $\tilde{\boldsymbol{C}}$. Then the best alternative a^* corresponding to $\tilde{\boldsymbol{C}}_l$ must be selected using *NM* and *K*.

A repetition of this procedure a sufficiently large number of times, N_l, will yield the relative frequencies fr_i of selecting individual a_is as a^*. These frequencies can serve as estimates of the corresponding probabilities p_i. The alternative with the largest frequency among fr_i ($i = 1, 2,\ldots, m$) can be taken as a^*, namely, $a^* = a_i$, where i follows from (10).

5. Illustrative example

5.1. Exposure to potential accident on the road

A barrier with a two-way protective function is to be designed to shelter a tank with flammable liquid against a shock front generated be a distant accidental explosion on the road/rail (event *AA*) (Fig 2, see also [3, 24, 25]). It is known that the barrier height of 7 m is sufficient to provide such a protection. The tank is located behind the barrier, in the "downwind" direction of the potential shock front. The barrier must be a Type II structure in terms of the classification in Table 1. A mechanical failure (collapse) of the barrier will allow the shock front to pass this barrier in a dampened form and cause the loss of containment of the tank with the possibility of subsequent fire. This, in turn, can escalate into a major accident.

5.2. Design alternatives and decision matrix

Three alternative designs of the barrier, namely, a_1, a_2, and a_3 are to be compared by means of MAS (Fig 3). The designs a_i were prepared to MAS by keeping construction costs of each a_i comparable in size.

The failure-to-protect event Ψ_1 for all three a_is is a fall of the wall or a part of the wall in the "downwind" direction. It can happen due to attainment of the maximum resistance capacity of wall sections or overturning the wall segments in case of a_2. A further failure event, Ψ_2, consists in excessive deformations of a_is. An occurrence of Ψ_2 does not lead to the failure-to-protect; however, excessive deformations will require repairs of the wall.

The probabilities of Ψ_1 and Ψ_2 are assumed to be uncertain in the epistemic sense. This uncertainty is modelled by two epistemic r.v.s $\tilde{p}_{f_1}(x_i)$ and $\tilde{p}_{f_2}(x_i)$, where x_i is the vector describing the ith design of the wall. As both Ψ_1 and Ψ_2 occur in consequence of the same event *AA*, $\tilde{p}_{f_1}(x_i)$ and $\tilde{p}_{f_2}(x_i)$ are modelled as a pair of dependent r.v.s. each obeying a beta distribution. The specific distributions of $\tilde{p}_{f_1}(x_i)$ and $\tilde{p}_{f_2}(x_i)$ were obtained by a propa-

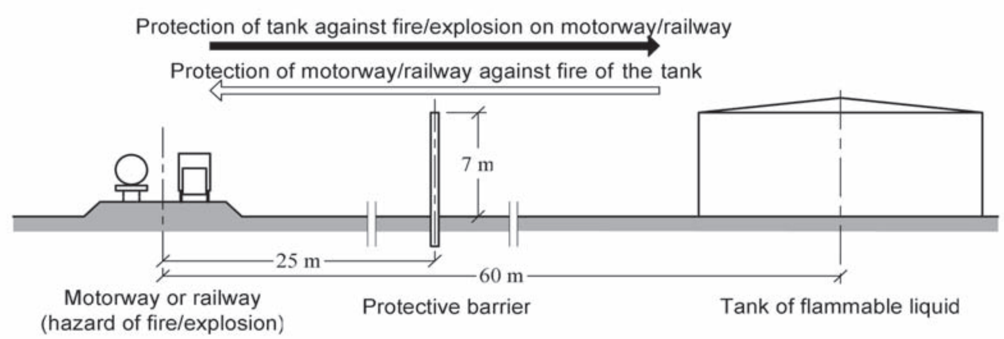

Fig 2. Situation of the design of a protective barrier between the motorway/railway and the steel tank to be built in the vicinity of the way

gation of epistemic uncertainties through the mechanical models of the barrier [18, 26]. The dependence between the pairs $\tilde{p}_{f_1}(x_i)$ and $\tilde{p}_{f_2}(x_i)$ is expressed by means of a correlation coefficient (Table 2).

The MAS problem was solved for the attribute vectors:

$$\tilde{c}_i = (\tilde{p}_{f_1}(x_i),\ \tilde{p}_{f_2}(x_i),\ c_{i_3}, c_{i_4}, c_{i_5}, c_{i_6}),$$

where c_{i_3} – the construction cost of a_i ($ per meter of length); c_{i_4} – the cost of maintenance of a_i ($ per meter of length and year of service); c_{i_5} – the cost of potential repairs of a_i after an occurrence of Ψ_2 ($ per one occurrence of Ψ_2); c_{i_6} – the degree of architectural appearance of a_i (number of points on the scale of maximum 10 points).

It is obvious that the attributes c_{i_3} to c_{i_5} may be uncertain in the stochastic sense; however, this uncertainty was not regarded for simplicity.

The stochastic decision matrix considered in this example has the form

$$\tilde{\boldsymbol{C}} = \begin{bmatrix} \tilde{c}_1 \\ \tilde{c}_2 \\ \tilde{c}_3 \end{bmatrix} = \begin{bmatrix} \tilde{p}_{f_1}(x_1) & \tilde{p}_{f_2}(x_1) & 2500 & 5 & 500 & 8 \\ \tilde{p}_{f_1}(x_2) & \tilde{p}_{f_2}(x_2) & 2630 & 15 & 200 & 7 \\ \tilde{p}_{f_1}(x_3) & \tilde{p}_{f_2}(x_3) & 2700 & 48 & 700 & 6 \end{bmatrix}. \quad (11)$$

Sampling the values $\tilde{\boldsymbol{C}}_l$ of $\tilde{\boldsymbol{C}}$ means sampling values of the correlated random variables having the beta distributions defined in Table 2. These values are then put into the first two columns of (11).

5.3. Computation and results

The classical Hodges-Lehman criterion was used as K for selecting a^* from a_1, a_2, and a_3 (see Eq (9)). It has the following form: choose a_i as a^* with i following from:

Table 2. Beta distributions expressing the epistemic uncertainty related to the failure-to-protect probabilities

Alternative a_i	Distribution of $\tilde{p}_{f_1}(x_i)$	Distribution of $\tilde{p}_{f_2}(x_i)$	Coeff. of correl. betw. $\tilde{p}_{f_1}(x_i)$ and $\tilde{p}_{f_2}(x_i)$
a_1	Be(2, 50)	Be(4, 48)	0,78
a_2	Be(2, 30)	Be(7, 55)	0,56
a_3	Be(2, 20)	Be(5, 25)	0,41

$$i = \text{argmax}\{(\delta \sum_{j=1}^{n} w_j \bar{c}_{i_j} + (1-\delta) \min_{j=1}^{n}\{\bar{c}_{i_j}\}),\ i = 1, 2, ..., m\}$$

with $\delta = 0{,}5$,

where δ – the confidence index ($\delta \in [0, 1]$).

The above criterion was chosen for the purposes of illustration only. The methodology of MAS developed a relatively large number of criteria having the same function as K; however, the choice of the "best" criterion still remains an unsolved problem [12, 27].

An application of the criterion K requires a normalisation of components of $\tilde{\boldsymbol{C}}_l$ in each simulation loop l. The method of linear scale transformation, *NM*, was applied to calculate the normalised decision matrices $\bar{\boldsymbol{C}}_l$, from the sampled values $\tilde{\boldsymbol{C}}_l$ [12, 28].

Elements of $\bar{\boldsymbol{C}}_l$ were calculated using the vector of weights, $w = (0{,}35;\ 0{,}25;\ 0{,}20;\ 0{,}05;\ 0{,}1;\ 0{,}05)^T$, the components of which correspond to the respective components of the attribute vectors $\tilde{c}_i$. The vector w implies that the greatest significance is assigned to the failure probabilities $P(\Psi_1|AA)$ and $P(\Psi_2|AA)$. The components of w have been chosen only as an illustration.

A total of 1 000 000 simulation steps were applied to propagate the epistemic uncertainty in the probabilities P($P(\Psi_1|AA)$ and $P(\Psi_2|AA)$ ($N_l = 1\times10^6$). In the l^{th} step, the

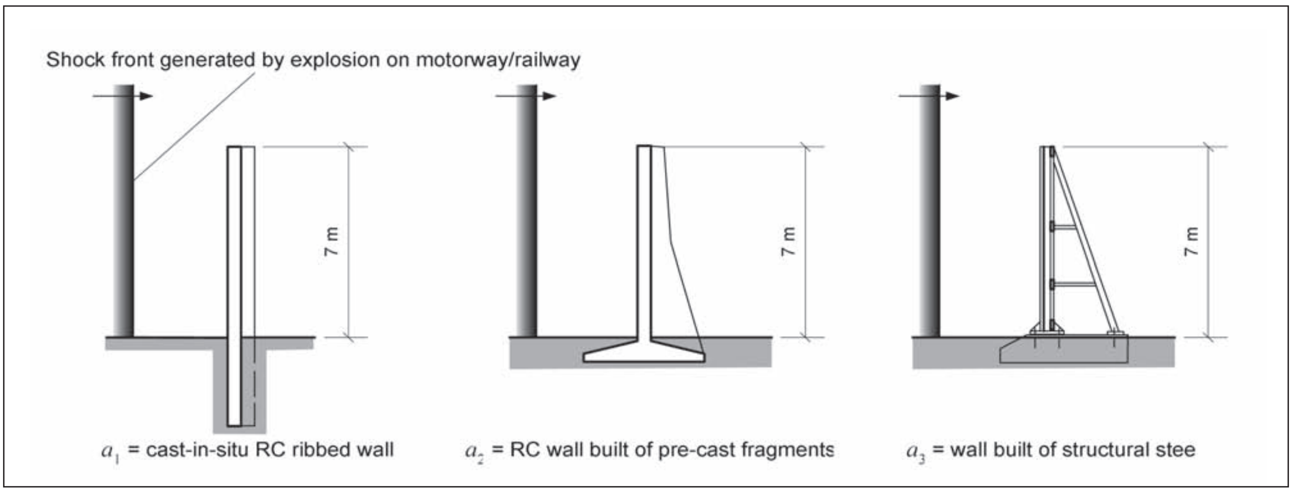

Fig 3. Three alternative designs of a protective barrier

criterion K was applied to find a^* using the sampled matrix $\tilde{\boldsymbol{C}}_l$. Results of the propagation of the epistemic uncertainty through the expressions of K and NM are the relative frequencies of selecting individual a_is as a^*, namely, $fr_1 = 0{,}3957$, $fr_2 = 0{,}5635$, and $fr_3 = 0{,}0408$. This means that the criterion K preferred a_2 as a^*.

6. Conclusions

An approach to the design of protective highway structures has been proposed in the paper. The main problem faced by this design is a considerable uncertainty related to both accidental actions, which must be sustained (reduced) by the protective structures, and response of the structures to these actions. The attention of the paper was focused on dealing with this uncertainty in the design process. It was stated that protective structures exposed to potential accidental actions are natural subject of a quantitative risk assessment (QRA). It was discussed how to introduce the methods of uncertainty quantification developed in QRA into the design of protective structures.

The approach considered in the paper was based on a multi-attribute selection (MAS) from alternative designs of a protective structure. Due to the uncertainty in behaviour of the structure subjected to an accidental action, a comparison of the alternative designs must take into account probabilities of failure-to-protect. These probabilities can be estimated by applying the classical Bayesian approach to QRA. It yields epistemic uncertainty distributions related to the failure-to-protect probabilities.

The epistemic uncertainty distributions of the failure-to-protect probabilities can be introduced into MAS. It can be done by carrying out the selection as a simulation-based propagation of epistemic uncertainties. The propagation can be carried out by a repeated solving an MAS problem for the failure-to-protect probabilities sampled from the epistemic uncertainty distributions. The simulation loop used for such propagation should involve the deterministic algorithm of MAS. A repetition of this loop a sufficiently large number of times will yield relative frequencies of selecting individual alternative designs as the best ones. The optimal alternative design can be chosen as the one with the largest frequency of selection.

The findings of the paper can be applied to the design of the road infrastructure components subjected to the hazard of potential accidents. One can argue that the proposed approach exceeds the deterministic design methodology in dealing with accidental actions. The latter prevails in the today's design practice; however, the deterministic design can hardly cope in a proper way with the uncertain phenomenon of road accidents which include potential damage to highway structures.

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