Loss-of-Life Modelling in Risk Acceptance Criteria

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Abstract

When questioning whether the risk a structure poses to society is acceptable, socio-economic, demographic and hazard-related aspects have to be considered. The hazard aspect comprises two phenomena, one of which is the probability of a failure, well described by reliability theory. The second one is the expected loss of human life on occasion of such a failure. The current paper seeks to point out the common traits in existing loss-of-life estimation models dealing with – as it seems – entirely differently structured event types, such as dam failure, fire and earthquake-induced building collapse. A general conceptual and methodological basis is developed.

1 Societal Risk Acceptability

After decades of research into structural reliability by means of probabilistic methods, the probability of failure has become a well-defined quantity in various technical applications. Given this achievement, the obvious question to follow was "How safe is safe enough?", with respect to involuntary risks to an anonymous member of society. In 1994, Lind defined a composite social indicator, which eventually was developed into the Life Quality Index (LQI) by Nathwani/Lind/Pandey [10]:

$$L = \frac{g^q}{q} e \tag{1}$$

In this formulation g denotes the share of the GDP per capita that is available for risk reduction, which approximately is taken as an average individual's personal consumption (roughly 0.6·GDP). $e = e(0)$ is the life expectancy at birth, while q is equal to $w / (1 - w)$, w being the average fraction of life expectancy spent at work (around 20 %). Outside the engineering domain, health related socio-economics have been dealing with the same kind of issue already somewhat earlier, arriving at fairly similar results in spite of a quite different point of departure. The corresponding criterion, which is owed to economists like Arthur, Shepard & Zeckhauser, Rosen and others, is referred to as the Value of a Statistical Life (VSL) approach (see [12]). At a later point, Pandey/Nathwani added some aspects originally introduced with the VSL, thus refining the LQI approach (see [12]). These refinements included replacing the life expectancy at birth $e(0)$ with the age-dependent life expectancy $e(a)$, calculating the age-averaged life expectancy by weighting with the age-dependent population distribution $h(a, n)$ and "discounting" life years. Actually it is not the life expectancy, which is discounted, but the utility an individual assigns to life years in the distant future.

$$L_{\bar{E}} = \frac{g^q}{q} \int_0^{a_u} \int_a^{a_u} \exp\left[-\int_0^t \left(\mu(\tau) + \eta \right) d\tau \right] dt \cdot h(a,n) da = \frac{g^q}{q} \bar{E}(\eta) \quad (2)$$

Here, $\mu(a)$ is age-dependent mortality, a_u is some maximum possible life time and n denotes the population growth rate. The different aspects of discounting are summarized by η (see Rackwitz [12] for details).   is called the "discounted age-averaged life expectancy", while (2) is referred to as the Societal Life Quality Index (SLQI).

It is demanded of a technical project, that the value of L it brings along be at least equal to the previous value, i.e. dL ≥ 0, when dL is a small change in L . In other words, reduced income should be compensated by longer life and vice versa. This is the point at which technical risk enters the considerations: Any technical measure changing the reliability of a structure has a two-fold influence on the SLQI: First, the costs of the measure will directly influence the fraction of GDP available for private consumption. Second, the change in reliability will cause a change in an anonymous person's chance of getting killed on the condition of being within reach of an event, which, together with the number of people present during the event has an impact on crude mortality in a population. Mortality directly determines life expectancy. This dependence is rather complex, but considering a small change dm in crude mortality m, linearization is an appropriate simplification:

$$\frac{d\bar{E}}{\bar{E}} \approx \frac{\frac{d}{d\Delta} \bar{E}(\eta + \Delta)\big|_{\Delta=0}}{\bar{E}(\eta)} \cdot \Delta = -C_{\Delta\bar{E}}(\eta, n) \cdot \Delta \quad (3)$$

Here, Δ is equal to dm. When the additional safety costs dK in a project are interpreted as $-dg$, inserting (2) and (3) into criterion dL ≥ 0 yields

$$\begin{aligned} -dg + \frac{g}{q} C_{\Delta\bar{E}}(\eta, n) dm &= dK + \frac{g}{q} C_{\Delta\bar{E}}(\eta, n) dm \\ &= dK + G_{\Delta\bar{E}}(\eta, n) dm \geq 0 \end{aligned} \quad (4)$$

where G_{Δ} (η, n) is introduced not just because it merges all project-independent societal parameters into one quantity, but mainly due to its purely monetary dimension, which makes comparison between different countries and different socio-economic studies possible. Typical values range between 3 and 5 million PPP US$ for industrialized countries, depending on the country and the chosen discounting concept (compare [12]). Yet, it is important to realize that the idea is not to assign a monetary value to human life, but to determine, how the limited resources of a society can be invested into safety in an appropriate way. Rather, the value of dK for which (4) is fulfilled, is the affordable investment into risk reduction.

2 Single Events and Crude Mortality

For technical facilities exposed to adverse events, crude mortality is increased by

$$dm = \frac{N_{LOL}}{N_{POP}} = \frac{N_{LOL|F}}{N_{POP}} \cdot dP_F \tag{5}$$

with N_{LOL} quantifying the expected (yearly) number of fatalities due to a single structure or facility (LOL for "loss of life") and N_{POP} being the total population referred to. Typically, N_{POP} would include all inhabitants of a city, province or country. This number may include a vast proportion of people who never actually get into reach of the event. $N_{LOL/F}$ is the expected number of lives lost on the occasion of a single event of failure F, P_F denoting the (yearly) probability of failure.

3 Predictive Loss-of-Life Estimation

Given that P_F is well described e.g. by reliability theory, the focus shall be on $N_{LOL|F}$. There is plenty of literature dealing with the quantification of loss-of-life consequences from technical failure. However, most of these approaches limit themselves to just to one event type, thus neglecting the parallels existing between different cases: Even though the conditional probability of death k is strongly case-specific, two other basic quantities determining the expected number of fatalities are universal: One is the expected number of people at risk N_{PAR}, i.e. the population actually present within reach of the event *prior* to any sort of warning. The second one, the probability of successful escape $P(Q)$ (Q for "quit"), follows from the human tendency to flee from an imminent threat, once it is perceived as such. In consequence, the expected number of fatalities given failure is written as

$$N_{LOL|F} = N_{PAR} \cdot \left(1 - P(Q)\right) \cdot k \tag{6}$$

Three of the most prominent types of failure event from the civil engineering domain have been selected for closer analysis and comparison: Dam failure causing flooding, building collapse during earthquakes and tunnel fires[1].

The following sections of this chapter aim at giving a brief impression of how to model the three quantities on the right side of (6). Special weight is given to the development of general concepts and formulations valid for all event types, taking advantage of existing analogies.

[1] In the case of tunnel fires, it is not the structural system itself which fails; rather, its layout *fails to protect* human beings from harm during a fire.

3.1 The Number of People at Risk

Above all, N_{PAR} is a function of time. The effect of time on the expected number of people present at given location has to be seen on three levels – time of day (i.e. working, sleeping, leisure times), day of the week (working/weekend day) and season. The seasonal aspect concerns not only touristic regions, since most people will automatically spend more time indoors in times of colder weather.

In order to estimate N_{PAR}, three basic approaches can be identified:

The idea behind the *distribution-based approach* is to ask how the registered population N_{POP} of a given area is distributed over different buildings and locations as a function of time. This approach is preferable, when an event concerning a large area is considered (e.g. [13]).

The *object-based approach* consists in counting all persons entering and leaving a building or structure in a survey. This procedure is preferable for buildings with a special purpose, like hospitals, hotels or traffic infrastructure. Besides, the necessary data are often available from ticket sales, registration desks etc. in these cases.

The *conditional distribution-based approach* is a means of applying the distribution-based approach to single objects or groups of similar objects in an effective way without requiring additional data collection (as opposed to the object-based approach). Every individual belongs to several different occupational groups simultaneously (residential, working, commuting, student etc.), but generally realizes only one of these assignments at a given time. When, for instance, an office building is considered, it is not relevant how the total population behaves, but rather what the building-specific occupational group does, i.e. office workers in this case. Apart from office buildings, this approach is also useful for residential, industrial and educational facilities (see chapter 13 of the HAZUS technical manual [2]).

Data can be found in [1], [2], [5], [9], [11] and [13], with a brief overview in [7].

3.2 The Probability of Successful Escape

Escape Q is only possible, when some sort of warning W has taken place beforehand:

$$P(Q) = P(W) \cdot P(Q|W) \tag{7}$$

The probability of warning, including the decision to attempt escape, is written as

$$\begin{aligned} P(W) &= P(W_0) \cdot P(W_{PRC}|W_0) \cdot P(W_{DC}|W_0 \cap W_{PRC}) \\ &= P(W_0) \cdot P(W_{prc}) \cdot P(W_{dc}) \end{aligned} \tag{8}$$

where W_0 is the bare fact of a warning, W_{prc} stands for the correct perception of the warning and W_{dc} is the decision to attempt escape. If a person decides to flee, then the successfulness of his attempt depends on whether the time T_Q he needs for escaping (including apperception and reaction time) is smaller than the time span T_W between the issuing of the warning and the occurrence of life-threatening conditions:

$$P(Q|W) = P\{T_W - T_Q < 0\} \tag{9}$$

If T_W and T_Q are deterministic quantities, $P(Q/W)$ will only take on the values 0 and 1. For randomly distributed parameters, (9) becomes a limit state problem as described by reliability theory, where $P(Q/W)$ can take on any value in between. T_Q is the quotient of a person's moving speed and the distance to be covered into safety; for spatially progressing threats (floods, fires) T_W is determined in a similar way [7].

In some cases it is necessary to differentiate between two kinds of warning: Indirect warning *W'* is spread by eye witnesses or automatic systems among the threatened population, whereas *W"* denotes the direct warning through visual and audible signs from the threatening phenomenon. Since *W'* principally precedes *W"*, people get a second chance of successful escape *Q"*, given *Q'* fails:

$$P(Q) = P(Q') + P(Q'') \cdot \left(1 - P(Q')\right) \tag{10}$$

This differentiation is especially relevant for flood waves: Frequently, their sometimes considerable travelling time or the short-term predictability of dam failure make indirect warning possible. For most other event types, there is $Q' = 0$.

Data for the different parameters in (8) and (9), including the quantities T_Q and T_W themselves depend on, are given in [1], [3], [4], [8], [11] and are compiled in [7].

3.3 The Conditional Probability of Death

Due to its dependency on the event type and the corresponding death causes it is hardly possible to make any general statements about the factor *k*, except for the fact that it is usually a function of the intensity of an event (see [7] for overview).

Earthquake-caused building collapse includes so many side constraints that it is impossible to express *k* other than in tables listing typical values for different building types, failure mechanisms, heights etc. (see [1] and [9] for data).

The intensity of floods can be expressed by a relatively limited number of parameters, such as water depth and velocity. Therefore it is possible to use continuous relations in order to specify *k*. People inside houses have to be treated differently than those outside. Jonkman [6] gives a broad overview of quantitative approaches, including the models from [4], [5], [8], [13] and many more.

Critical values for toxic gases and heat in fires are given e.g. in [11].

3.4 Discussion and Example

Up to here it has been implicitly assumed that persons at risk will either have escaped before the arrival of the event or will be captured by it. According to (6), a proportion *k* of those captured is expected to die. This assumption is appropriate for phenomena propagating faster than a person's pace or not propagating at all (flood waves, earthquakes). However, there are events, where potentially lethal conditions spread approximately at the same speed as a person can move, so that it can not be said from the beginning, whether a fleeing individual will make it into safety. Thus, the LOL calculation has to be iterated periodically. Typical examples are slowly rising floods [5] and tunnel fires [11].

As a brief example, a small valley with $N_{POP} = 300$ is considered. People have their work outside the valley, so the number those present during working hours will be $N_{PAR} = 0.2 \cdot N_{POP}$ [5]. Following a dam break 10 km upstream, a flood wave propagates with random log-normally distributed velocity $v \sim \mathsf{LN}(5\text{ms}^{-1}, 2\text{ms}^{-1})$. With a delay $T_{ini}' \sim \mathsf{LN}(5\text{min}, 1\text{min})$, a warning will be issued. Thus, $T_W' = (v / 10\text{km}) - T_{ini}'$. After [8], T_W'' is assumed as uniformly distributed $\mathsf{U}(1\text{min}, 4\text{min})$ and $T_Q' = T_Q'' \sim \mathsf{U}(1\text{min}, 2\text{min})$. Further, we estimate $P(W_0') = 0.9$, $P(W_0'') = 1$, $P(W_{prc}') = 0.8$, $P(W_{prc}'') = 0.95$, $P(W_{dc}') = 0.9$ and $P(W_{dc}'') = 1$. $k(v) = \Phi((v - 1.8\text{ms}^{-1}) / 0.486\text{ms}^{-1})$ is a simple relation from [6] for people indoors and outdoors. As a result, the estimate following (6) to (10) is $N_{LOL|F} = 4.71$ persons.

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