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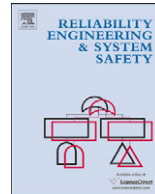
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A general approach for the estimation of loss of life due to natural and technological disasters

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ABSTRACT

In assessing the safety of engineering systems in the context of quantitative risk analysis one of the most important consequence types concerns the loss of life due to accidents and disasters. In this paper, a general approach for loss of life estimation is proposed which includes three elements: (1) the assessment of physical effects associated with the event; (2) determination of the number of exposed persons (taking into account warning and evacuation); and (3) determination of mortality amongst the population exposed. The typical characteristics of and modelling approaches for these three elements are discussed. This paper focuses on “small probability–large consequences” events within the engineering domain. It is demonstrated how the proposed approach can be applied to various case studies, such as tunnel fires, earthquakes and flood events.

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1. Introduction

Quantitative risk analysis is generally used to quantify the risks associated with accidents in a technical system. The resulting risk estimates, expressing the combination of probabilities and consequences of a set of possible accident scenarios, provide the input for risk evaluation and decision-making. One of the most important types of consequences of accidents concerns the loss of human life and this type of impact also plays an important role in the public perception of the severity of accidents. The risk to life will generally be very important for risk evaluation and decision-making and various risk metrics have been developed that include the risk to life [1,2].

In general, there is limited insight in the magnitude of the potential loss of life caused by accident scenarios, and no general methodology that can be used to estimate loss of life for different event types is available. Within the field of risk assessment methods for the estimation of accident probabilities are relatively well established and they are used throughout different application fields. General methods for consequence and loss of life estimation have been standardized to a much lesser extent. There is some literature dealing with the quantification of loss of life consequences from technical failure for individual event types (see Section 2 for an overview). However, parallels existing

between different cases have been mostly neglected, and relatively little attention has been paid to the general principles of loss of life estimation.

The objective of this paper is to propose a general framework for the estimation of loss of life. Such an approach is not yet available in literature. When trying to predict the number of lives lost due to accidents, it is helpful to rely on a general methodology. Within the general framework it is explicitly shown what kind of information is necessary to estimate the loss of life for an activity. New applications and event types can be dealt with more efficiently, because a generalised approach points out the traits common to all kinds of event types and the kinds of information required to estimate loss of life in an activity. The general approach is also useful to measure the effect of a risk reduction strategy in a systematic and consistent way.

The method focuses on the estimation of loss of life due to “small probability–large consequence” accidents in the engineering domain, such as floods, tunnel fires and chemical accidents. In these events most fatalities occur directly due to the exposure to the effects of a single accident. Events with chronic exposure (e.g. air pollution), substantial delayed mortality (e.g. due to nuclear radiation) and other non-lethal health effects are not considered.

This paper is structured as follows. Section 2 discussed existing approaches for loss of life estimation. The proposed general approach is introduced in Section 3. Subsequently, specific characteristics of the analysis of the number of people exposed and evacuation (Section 4) and the estimation of mortality (Section 5) are discussed. Section 6 presents a number of case studies and examples and concluding remarks are given in Section 7.

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2. Existing approaches for loss of life estimation

A selection of loss of life models used in various sectors has been studied in order to derive a set of general principles for loss of life estimation. An overview of models that have been developed in the context of quantitative risk assessment is given in Table 1.

For some types of event, event mortality will be predictable without further extensive modelling: for example for airplane crashes the mortality amongst people present in the exposed or crash area appears to be relatively constant [14]. For other types of event, mortality shows a larger variation between different single events, due to their dependence on various event-specific variables. As an illustration, the number of fatalities is plotted against the number of people exposed for some historical tunnel fires in Fig. 1. Combinations with constant mortality are plotted with dashed lines in this figure.

Similar figures are available in literature for floods [20] and earthquakes [10]. These analyses indicate large variations in mortality between events within one domain. For these types of event, case-specific mortality can obviously only be predicted with sufficient accuracy when the event modelling itself moves

into a sufficient level of detail and tries to include the relevant event-specific variables.

Depending on these issues, loss of life modelling can be performed at different levels of detail:

1. *Individual level*: By accounting for individual circumstances and behaviour it is attempted to estimate the individual probability of death. For example, Johnstone et al. [21] propose a model for the assessment of the consequences of dam failure, which simulates individual escape behaviour.
2. *Group or zone level*: Groups of people, locations or zones with comparable circumstances are distinguished and mortality is estimated for these groups/zones. For example, Takahashi and Kubota [11] estimate earthquake mortality for groups of people in different states (in home, car or in open air). Jonkman et al. [6] distinguish different zones within a flooded area, applying a specific mortality function for each location.
3. *Overall event level*: One mortality fraction is applied to the exposed population as a whole. For the assessment of third party fatalities due to airplane crashes Piers [14] use one constant mortality fraction within the area affected by the crash.

It is important to note that for a proper calibration and validation of a loss of life model, the amount of available data has to be sufficient relative to the number of parameters included in the model. In practice, accident processes are often complex and involve many factors, whilst the availability of accident data is limited. The eventually chosen level of detail of analysis depends on the available data for calibration of the model and the required ability to take into account the effects of risk reducing measures.

3. A general approach for loss of life estimation

3.1. Context and terminology

This paper investigates the estimation of loss of human life within the context of quantitative risk analysis (QRA). Fig. 2 shows the accident sequence as typically considered in a quantitative risk analysis. Certain causes can result in the occurrence of a *critical event* in an originally normally operating system. This event can lead to the dispersion of *physical effects*

Table 1
Overview of models for estimation of loss of life for different fields of application.

Field/ disaster type	Model description and applications	References
Various natural disasters	Broad (conceptual) methods that could be applied to different hazards	[3,4] (both quoted in [5])
Floods	Overview of methods for loss of life estimation for river, coastal and dam break floods	[5–7]
Tsunamis	Loss of life due to tsunamis	[8,9]
Earthquakes	Earthquake protection	[10,11]
Volcanic eruption	Estimation of physical impacts and fatalities	[12]
Tunnel accidents	Assessment of consequences for fires and explosion in road tunnels	[13]
Airport safety	Method for determination of fatalities on the ground due to airplane crashes near Schiphol airport (NL)	[14]
Chemical accidents	Dutch guidelines for estimation of consequences for chemical accidents	[15–18]

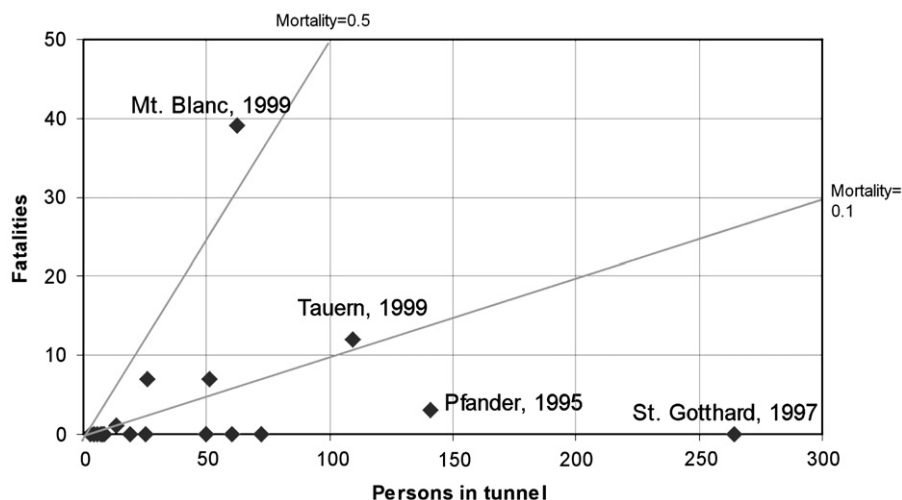


Fig. 1. Fatalities and estimated number of people exposed in historical tunnel fires ([19] analysis by O. Kübler) For some characteristic events the year and tunnel name are indicated.

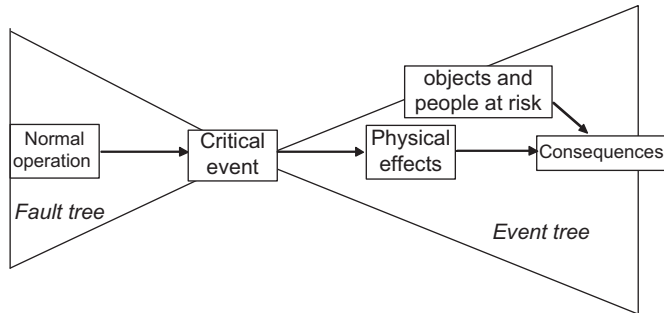


Fig. 2. Evolvement of a critical event and the accident sequence.

(e.g. heat and smoke from fire) within an exposed area. When people and/or objects at risk are exposed to them, this can result in *consequences*, including economic damage and loss of life. In general the probability of occurrence of a critical event is estimated by means of a fault tree. The different possible scenarios for occurrence of physical effects and consequences are often elaborated by means of an event tree. By combining the probabilities and consequences of different event scenarios the probability density function (and the corresponding cumulative distribution function) of the consequences and the risk can be estimated.

A certain area will be exposed to the physical effects that are associated with the critical event. This *exposed area* represents the spatial footprint of the event, and for some types of events (e.g. airplane crashes) it is referred to as the crash area. It is noted that safe locations may exist that are surrounded by exposed area, for example high grounds in a flooded area.

All the individuals that are present in the exposed area before any signs or warnings can be perceived are referred to as the *population affected*, *population at risk* or *people at risk*: N_{PAR} . For larger exposed areas it can often be approximated by the registered population in the area. However, in some cases it might be necessary to take into account population dynamics. The number of people at risk might be smaller than the original population. For example, when a part of the reference population will be working elsewhere most of the time. In other cases N_{PAR} might be larger than the population, for example when many people visit the exposed area. More specific approaches for determining N_{PAR} are discussed by Lentz [2,22].

The actually exposed population involves all people exposed to the physical effects of the disaster. The number of people exposed can be deduced from the population affected by taking into account the effects of evacuation, shelter, rescue and escape. A first description of these elements is given below, further explanation is provided in Section 4. *Evacuation* is defined here as: “the movement of people from a (potentially) exposed area to a safe location outside that area before they come into contact with physical effects”. Within the area people may find protection within *shelters*. These are constructed facilities in the exposed area, which offer protection. Examples of shelters are high-rise buildings during floods, or emergency niches in a tunnel that are safe during a fire. In addition (natural) *safe areas* may exist that offer protection, e.g. high grounds in a flooded area.

After initial exposure of people to the event, the population exposed could be reduced due to escape and rescue. *Escape* refers to the movement of people by themselves through the exposed area, for example people running through a toxic cloud or moving through a flooded area. *Rescue* concerns the removal of people by others from an exposed area. Rescue and escape only prevent loss of life if people are rescued or escape before they will lose their life due to exposure.

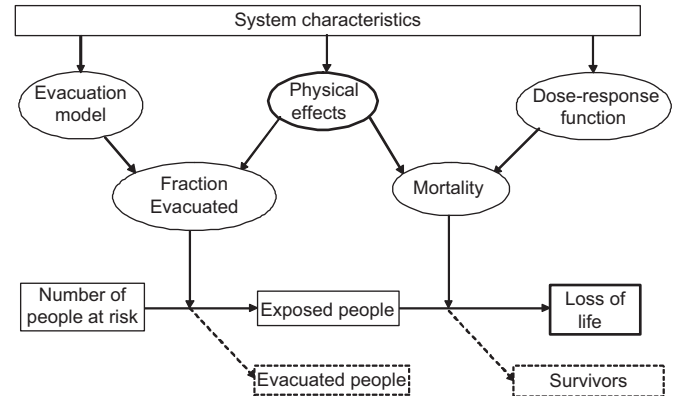


Fig. 3. Framework for loss of life estimation. (Note: For clarity of the figure shelter, rescue and escape are not included in this figure, i.e. it is assumed that $F_5(c)=0$.)

Finally, the exposure of people to the physical effects of a disaster can result in *loss of life*. To provide an estimate, a mortality fraction is usually determined. *Mortality* is defined throughout this paper³ as the fraction of fatalities amongst the exposed population. It can be determined for one event (‘event mortality’) or on a more detailed level for different groups of the population (‘subpopulations’), or zones or locations affected by the event. In literature the following synonyms are used:

- Loss of life: fatalities, (number of) killed, (number of) deaths;
- Mortality: lethality, death rate, fatality rate, proportion of lives lost.

3.2. General approach

It has been observed that the existing approaches of life estimation in different fields include the following three general elements:

1. The assessment of *physical effects* associated with the critical event, including the dispersion of the effects and the extent of the exposed area.
2. Determination of the *number of people exposed* in the exposed area, taking into account the initial population at risk and the possibilities for evacuation, shelter, escape and rescue.
3. Estimation of the *mortality* and *loss of life* amongst the exposed population, taking into account the extent of physical effects and the number of people exposed. This step is often indicated as vulnerability assessment [3,23].

By combining these three main elements loss of life can be estimated as is shown in the general framework in Fig. 3. A critical event with physical effects (c) is assumed to occur. The variable c is a general vector signifying the event’s intensity of physical effects, and it represents dimensions, such as arrival time of effects, concentration, spatial extent, etc. The number of people at risk depends on the extent of the exposed area, which is a function of the physical effects, leading to $N_{PAR}=N_{PAR}(c)$. The exposed population (N_{EXP}) is found by correcting the population at risk for the fractions of the population that are able to evacuate

³ Other studies might define mortality as a fraction of the population affected. The disadvantage of such a definition is that it does not take into account the actual number of exposed persons and effects of evacuation. In other contexts mortality is defined alternatively, for example as the number of killed per capita per year.

(F_E) or shelter (F_S). Both fractions depend on the development of physical effects c :

$$N_{EXP}(c) = (1 - F_E(c))(1 - F_S(c))N_{PAR}(c) \quad (1)$$

After initial exposure the exposed population could be further reduced by rescue and escape. These phenomena could be accounted for in quantitative modelling in the same way as evacuation and shelter, so formulas are omitted below for reasons of brevity.

Event-specific mortality is generally determined by means of so-called dose–response functions, which determine mortality (F_D) as a function of the (intensity of) physical effects: $F_D(c)$. We assume that the dose–response function returns one certain (expected) number of fatalities. The number of fatalities (N) for an event with intensity c is now found by estimating the number of evacuated and sheltered people, in combination with the mortality amongst the exposed population (see also [22]):

$$N(c) = F_D(c)N_{EXP}(c) = F_D(c)(1 - F_E(c))(1 - F_S(c))N_{PAR} \quad (2)$$

F_D , F_S and F_E can be formulated as typical distribution functions, with values: $0 \leq F \leq 1$. Their forms and characteristics are discussed in later sections. Based on the above elements the general framework for loss of life estimation is shown in Fig. 3.

3.2.1. Combination of evacuation and mortality analyses

The assessments of physical effects, evacuation and mortality can be combined in different ways (see also [22]). For some applications it is possible to analyse evacuation and mortality independently and as separated steps. This approach is *static*; people are either exposed or evacuated/safe. In this case, the framework proposed in Fig. 3 is elaborated linearly. The static approach is especially appropriate for instantaneous events with little possibilities for evacuation, and for larger-scale events where evacuation predominantly takes place before arrival of physical effects. As an implication the presence of population during event becomes static and independent of time. In some situations it is often difficult to treat the analysis of effects, evacuation and consequence completely independently. Then, a *dynamic* approach could be used, in which the spatial and temporal developments of physical effects, evacuation and the sustained injury have to be considered. For cases such as slowly rising floods or tunnel fires, people can escape/survive the danger in a certain zone at a given moment, and have to undertake another escape/survival in the next moment due to the spatial propagation of the danger zone. An individual can only survive the whole event, if he/she survives each single time step. The combination of time dependent modelling of involvement of physical effects and a person's evacuation path will be further discussed in Section 4.2. In practice a choice between the static and dynamic approaches has to be made, depending on characteristics of the event and the situation and the preferred level of detail of analysis.

3.2.2. Remarks regarding the general approach

In loss of life estimation the influence of system characteristics on evacuation, development of physical effects, and mortality has to be considered, as is shown in the upper part of Fig. 3. Relationships between system characteristics and evacuation or dose–response functions can be quantified. For example, evacuation progress will depend on the capacity of roads and exits; development of physical effects will depend on the topography and configuration of the area (e.g. tunnel or polder dimensions) and meteorological conditions.

3.5. Risk estimation and uncertainties in loss of life estimates

By means of the above approach the loss of life can be quantified for one accident scenario with a given intensity of effects c . In the context of risk assessment the loss of life is generally estimated for a set of discrete event scenarios. If the probabilities of occurrence of all possible accidents are known, the probability density function and cumulative distribution function of the number of fatalities can be presented. This can be displayed as a so-called FN curve or be used to calculate the expected number of fatalities [1]. It represents the inherent uncertainties associated with the various event scenarios that can occur.

However, this type of elaboration does not account for epistemic uncertainties in the methods that are used to assess physical effects, evacuation and mortality. For example uncertainty could be associated with the dose–response function that is used. If these epistemic uncertainties in the underlying models that are needed for the loss of life estimate are quantitatively known, these can be combined to obtain a distribution of the resulting number of fatalities for a single event scenario.

The difference between the two approaches can be demonstrated by means of an example. Suppose that we have a flood event that affects an area with 10,000 inhabitants. In this case 60% of the population can evacuate and the mortality equals 1%.

In the deterministic scenario based approach the calculated number of fatalities according to formula 1 would be 40 fatalities.

However, epistemic uncertainty is associated with all the three variables, representing the uncertainty in the presence of the population or uncertainties in the models that are used to analyse evacuation and mortality. It is assumed that all these variations can be described by means of a normal distribution and a variation coefficient of 0.1. In that case the result for this scenario is a normal distribution of the number of fatalities with an average of $\mu = 40$ fatalities and a standard deviation of $\sigma = 11.5$ fatalities.

4. Estimation of the number of people exposed

4.1. General

In order to estimate the extent of exposed population the number of people at risk and the effects of evacuation, escape, shelter and rescue have to be considered. Approaches for determining the initial number of people at risk (N_{PAR}) have been discussed in Section 3.1 and [22].

In general the possibilities for successful evacuation will depend on the time available until occurrence and arrival of the physical effects (T_A) and the time required for evacuation (T_R). The *time available* (T_A) is the time between the first signs and the occurrence of physical effects (at a location). It depends on the extent of spatial and temporal development of physical effects, i.e. $T_A = T_A(c)$. The time available depends on the type of hazard. Obviously, an event with a fast development (e.g. an explosion) leads to potentially lethal conditions faster than a slower developing event.

A general timeline for elements in the analysis evacuation is shown in Fig. 4. It shows the different phases of evacuation and the situations that mark the boundaries between the phases. Lindell et al. [24] and Oppen [25] suggest similar evacuation timelines. A general classification of the phases of the evacuation process is supported by the literature, as the relevant evacuation phases are very similar for different disasters. For example, Mileti and Peek [26] state that the principles of how humans respond to warnings remain constant across hazard agents as diverse as floods, earthquakes, tornadoes, explosions, and toxic chemicals. The classification proposed below is expected to be useful for the

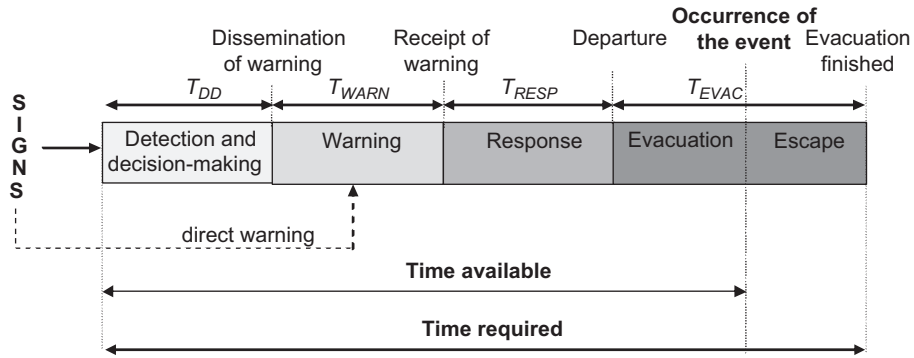


Fig. 4. General evacuation timeline (after Frieser [27]).

analysis of evacuation for different types of event and at different levels of detail (for individuals and for a whole population, see next section).

The time required (T_R) for evacuation equals the time needed to complete the following four phases (abbreviations for the phases are indicated in the figure):

1. *Detection and decision-making*: A critical event is often preceded by signs, which can lead to its prediction, detection and consequent decision-making on an evacuation;
2. *Warning*: Following the above decision or direct warning by signs the threatened population is warned;
3. *Response*: This phase includes perception, interpretation and reaction to warning and/or the threat of the hazard;
4. *Actual evacuation*: This phase concerns the movement of people from an initial location to a safe area.

In addition to evacuation before the exposure to harmful physical effects, there sometimes is a possibility of escape. It refers to the movement of people through an exposed area, for example people running through a toxic cloud or moving through a flooded area. Movement can be impeded by physical effects, e.g. due to limited visibility, reduction of walking speed or sustained injury. The exposure can lead to the death of a person trying to escape.

4.2. Modelling of evacuation and escape

Depending on the event characteristics, evacuation can be analysed at different levels of detail. The two main levels concern the population and the individual level.

4.2.1. Analysis of the evacuation of a population

For larger affected populations the different phases of time required can be described by distribution functions, which can be combined in one overall distribution for evacuation $F_E(t)$. It describes the fraction of the population that can be evacuated as a function of time t . Fig. 5 schematically shows the distribution curve of the time required for the evacuation process. The different phases are distinguished. The partial "failure" of different phases of evacuation has to be accounted for by including the failure of warning (fraction not warned) and the fact that people do not respond to warnings (fraction of non-compliance). In case of a successful evacuation, the time required is smaller than the time available. Thus, the probability of successful evacuation is found as follows:

$$P(T_R \leq T_A) = F_E(T_A), \quad 0 \leq F_E(t) \leq 1 \quad (3)$$

If the time available is deterministically known, $F_E(T_A)$ describes the fraction of the population at risk (N_{PAR}) that is able

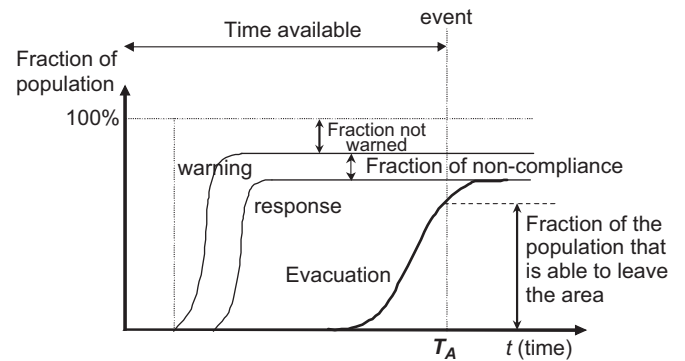


Fig. 5. Distribution function of time required for evacuation ($F_E(t)$), based on different phases of evacuation.

to leave the exposed area before conditions become potentially harmful.

4.2.2. Analysis of the evacuation of an individual

For certain events, such as fires in tunnels or buildings, a more detailed analysis of evacuation at an individual level is preferable. In this case, the progress of an escaping individual can be schematically shown in an x, t diagram and it can be combined with development of physical effects (see Fig. 6). Assume that the event occurs at a certain location or origin $x=0$ and that the safe exit location lies at distance x_E (m). The time available until exposure to physical effects depends on a persons' location relative to this origin. The required evacuation time is found as follows: $T_{EVAC} = x_E/v$ (i.e. distance to the exit divided by the movement speed of the evacuating person v [m/s]). The distance to the exit depends on the size of the area exposed. The figure shows that evacuation will become particularly hazardous when the dispersion velocity of physical effects is larger than the movement speed of people. Instantaneous events, such as (sudden) explosions, airplane crashes and earthquakes, will allow neither escape time before the event, nor sufficient time for escape after the event.⁴ For such events it can thus be assumed that $F_E=0$, thus the whole population at risk will be exposed. Other events will be better predictable in advance and physical effects will develop relatively slower. For example, floods will often allow the evacuation of large fractions of the population.

There are also situations, in which a person escapes through physical effects and still manages to reach a safe area. In that case, it is often difficult to treat the analysis of effects, evacuation and

⁴ In these cases the development of physical effects can be approximated with an (almost) horizontal line as dx/dt is very large.

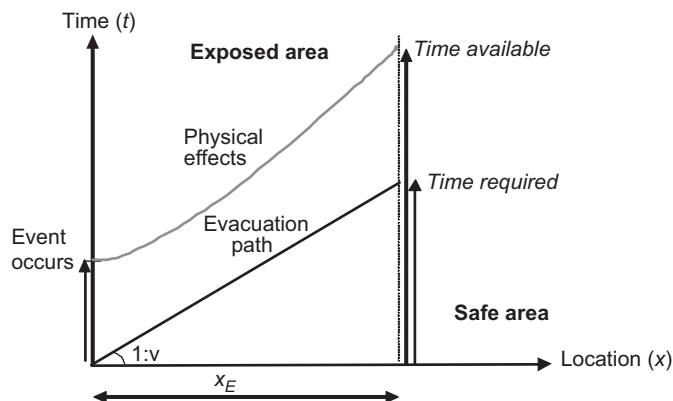


Fig. 6. x, t diagram indicating development of physical effects and escape progress for a person who starts to evacuate before the occurrence of the event.

injury/mortality completely independently. In this case the experienced dose of effects has to be integrated over the escape path and over time to assess if a person has sustained some type of injury (see appendix 2.IV in [7] for further background).

The above analysis treats evacuation and escape of an individual in one spatial dimension. In practical situations the problem has to be analysed in two dimensions or even three dimensions when both horizontal and vertical movement are possible. The possibilities for evacuation will be determined by the location of escape routes and exits relative to the development direction of physical effects. For example for dam break in a narrow canyon, it is only safe to move out of the canyon up the hill. In a tunnel fire or toxic release safe escape might be possible in directions opposite or perpendicular to development of effects.

In practice a choice between the two modelling approaches (individual vs. population analysis) has to be made. This will depend on the characteristics of the situation and the preferred level of detail of output. For example, for flood evacuation one can choose to model the spatial and temporal development of evacuation at the individual level with a detailed traffic model or to use the general population evacuation curves for the whole area (see e.g. [28]).

4.3. Shelter, emergency actions and rescue

4.3.1. Shelter

Different types of shelter can be distinguished [29]. Single-use shelters are constructed with the sole purpose to provide shelter during disasters. Examples are special cyclone shelters constructed in Bangladesh and emergency niches in a tunnel. In many cases it is more efficient to develop facilities that have a certain regular function during normal conditions, but serve as shelter during a disastrous event. These are indicated as multi-use shelters. An example is the use of a sports stadium as a hurricane shelter. These types of shelter facilities should be designed to withstand the loads in disaster conditions safely. For some types of event constructions that were originally not designed as shelters could provide shelter, for example high-rise buildings during floods.

For an adequate utilisation of shelters it is important that people are warned before the disaster and that they have information regarding the presence of shelters and the accessibility of shelters before the onset of the event. During the disaster shelters should preferably still be accessible and recognisable. Another issue is that shelters may only offer partial protection, as people in the shelter may still be exposed to a certain level of physical effects. For example during nuclear or chemical

accidents, radiation or concentration levels may be only partially reduced by the shelter. Finally, it is noted that adverse health conditions may develop in shelters when many people have to stay there for a long period. Sheltering is generally an attractive risk reduction strategy when evacuation of the whole population is not feasible.

4.3.2. Rescue and emergency actions

The emergency services include the police, fire brigade, medical services and professional rescuers. Their actions can influence loss of life in several ways. These can (a) reduce physical effects or prevent their further development; (b) reduce the number of people exposed (N_{EXP}) by rescue; and (c) influence mortality (F_D) and loss of life, by means of treatment of injured people that would not have survived otherwise and/or due to the occurrence of additional fatalities amongst the rescuers.

Rescue (often indicated as search and rescue) concerns the removal of people by others from (potentially dangerous locations inside) an exposed area. For example, removing people from houses or trees in a flooded area can reduce the number of people exposed. Rescue can only prevent loss of life if people are rescued before they become a (potential) fatality. Thus, the effects of rescue on loss of life have to be considered relative to survival of people as a function of time after the disaster. For example, Kuwata and Takada [30] analyse the effectiveness of rescue after earthquakes based on the probability of survival under debris as a function time. This implies that there will be a certain critical period in which rescue is still possible. For example for earthquakes search and rescue are reported to be critical within the first 48 h [31]. For other types of events, such as tunnel and building fires, less time is available to save people from the exposed area. In this respect the delay in the initiation of rescue actions will be very important. Depending on the event type and region, the delays in the actions of emergency services can range from about 15 min (e.g. for tunnel and building fires) to hours or even days (e.g. for floods and earthquakes). In addition, the capacity of emergency services has to be taken into account relative to the number of people that have to be rescued. In the analysis of search and rescue actions the environment in the exposed area is important. The physical effects in the area could hamper rescue operations (e.g. limited visibility) or require the use of special equipment. Whether mortality can be prevented by medical treatment of injured people will also depend on the type of injury.

Additional fatalities may occur amongst those that perform rescue actions. Experiences with some large accidents (Twin Towers 9-11-2001, Mont Blanc tunnel fire in 1999) have shown that additional deaths may occur amongst rescuers. Depending on the type of event and the level of detail of analysis, the actions of emergency services could be considered in loss of life estimation.

5. Estimation of mortality

5.1. Approaches to mortality estimation

In the reporting and analysis of fatalities due to disasters a distinction is often made between fatalities caused by either the direct or indirect exposure to the event [32]. Directly related deaths are those (directly) caused by the physical effects of the event. Indirectly related deaths are those caused by unsafe or unhealthy conditions that occur because of the anticipation to, or actual occurrence of the disaster. Indirect fatalities might also be associated with psychological effects (e.g. stress leading to heart attacks) and diseases and illnesses caused by the event. The relevance of indirect effects on should be explicitly considered in

loss of life estimation, as the number of fatalities due to indirect causes could be larger than the number of direct fatalities in some cases. Based on the above general approach it is possible to define more specific categorizations of death causes for event types (see for example, [33] for floods and [34] for earthquakes).

The extent of mortality can be predicted by means of dose–response functions. These give a relationship between the (intensity of the) physical effects and the mortality in the exposed population.⁵ The function expresses how the occurrence of mortality in the population is associated with the degree of exposure to physical effects. The term *mortality function* is used as synonym. A dose–response function is conceptually similar to so-called fragility or vulnerability curves. These are used to model the probability of structural failure of buildings as a function of loads, e.g. for earthquakes. Related concepts that are not discussed in detail here are the determination of deterministic threshold exposure limits, such as the acute exposure guideline level (AEGL) and the fractional effective dose (FED) concept [35].

A dose–response function forms the distribution function of resistances in a population. Its shape reflects the variability of resistances in a population. A general formulation for the dose–response function can be given based on the load–resistance approach that is commonly used in reliability engineering. We assume exposure of a population to a certain intensity of physical effects c . This represents the load. The lethal resistance intensity for a human is c_R . Now the dose–response function can be formulated as follows and it gives the probability that the lethal intensity c_R is smaller than the exposure intensity c :

$$F_D(c) = P(c_R < c), \quad 0 \leq F_D(c) \leq 1 \quad (4)$$

Two main types of such dose–response relations can be distinguished. In the first approach mortality will be some kind of function (f) of the level of physical effects, usually an occurred maximum value (c_{max}). Mortality can then be conceptually written as

$$F_D = f(c_{max}) \quad (5)$$

Examples of this approach are the proposed mortality functions for floods [6], where mortality is determined as a function of (maximum) water depth. For explosions mortality is determined as a function of the peak pressure [16]. Similar types of criteria are proposed for earthquakes, where mortality is a function of earthquake intensity, representing the degree of damage to buildings (e.g. [10]).

The second approach relates mortality to the sustained dose of physical effects (i.e. effects integrated over time, e.g. a sustained dose of toxic substances over time) and it can be used if the variation of physical effects over time is relevant ($c(t)$). It is generally used in the estimation of mortality due to toxic substances for chemical accidents, with so-called probit functions (see Section 5.2):

$$F_D = f\left(\int c(t) dt\right) \quad (6)$$

For many applications the probability of getting killed due to exposure will also depend on the state or situation in which a person is present. Dose–response functions can be developed for various relevant situations. For example, Takahashi and Kubota [11] estimate earthquake mortality for groups of persons in

different states (in a home, a car or in the open air). At a detailed level the eventual estimation of consequences to humans, might necessitate an assessment of the impacts of physical effects on structures or objects in which the humans are present. However, in many applications it is chosen to develop one general dose–response function, which is applicable over the exposed population as a whole, regardless of the exact states of individuals.

There are various data sources for the derivation of dose–response functions for mortality. Obviously, due to ethical concerns, it is impossible to undertake controlled and repeated lethal experiments with humans in practice. Therefore, two types of sources are generally used to derive dose–response functions: empirical data from observations regarding human mortality during past disasters or the results of animal tests. *Observations regarding mortality during past disasters* have the advantage that they are realistic. In this respect Dominici et al. [36] mention: “High exposures associated with disasters can provide a natural experiment” and “Ultimately, as perverse as it may sound, epidemiologists must view disasters as important opportunities to learn.” However, data are often difficult to obtain during crisis situations and will be collected under uncontrolled circumstances. In this approach biases might be included because only data from specific events are selected or because the measurements are representative for populations with specific vulnerabilities.

As few toxicity data for man are available, especially in the higher response fractions, human dose–response functions can be derived by extrapolating data from *animal tests*. These tests have the advantage that they can be performed in controlled settings. Scaling factors have been established to account for differences in breathing volume, lung area and body weight. However, large uncertainties exist with respect to scaling the results to humans (mechanisms, routes of transportation). A more extensive discussion of strengths and limitations of animal tests and epidemiological studies is provided by Covello and Merkhoffer [37].

5.2. Characteristic forms of dose–response functions

This section discusses a number of characteristic forms of dose–response functions that are found in literature. In the simplest form of a dose–response function a constant mortality fraction F_D is assumed amongst the exposed persons, irrespective of the magnitude of physical effects. Examples of such functions are the values applied to ground fatalities for airplane crashes ($F_D=0.28$ within the area exposed to effects of the crash [14]).

The dependency of F_D can also be displayed in discrete form (i.e. As a constant mortality fraction). For example, if a certain critical threshold value of physical effects (x_{cr}) is exceeded mortality will equal a certain (constant) value q (see Fig. 7 left):

$$\begin{aligned} F_D &= 0, & c < c_{cr} \\ F_D &= q, & c \geq c_{cr}, \quad 0 \leq q \leq 1 \end{aligned} \quad (7)$$

For example, for human stability in flowing water a critical product number of water depth and flow velocity has been derived by Abt et al. [38] to indicate the limit for instability.

In general mortality will depend on the intensity of the event. If discrete mortality values are given for different situations and levels of physical effects, these can be displayed in a table. Graham [39] gives an example of this approach for dam break floods. Earthquake-caused building collapse includes so many side constraints that it is impossible to express F_D other than in tables listing typical values for different building types, failure mechanisms, heights, etc. (see e.g. [10,40]).

In more advanced approaches functional relations have been developed which express mortality as a (continuous) function of

⁵ In other contexts dose–response functions are also used to model other non-lethal health effects, such as injury and hindrance due to noise. A more general definition, not restricted to mortality, is given in Covello and Merkhoffer [37]: “A dose–response model is a functional relationship between the dose and an adverse health response.”

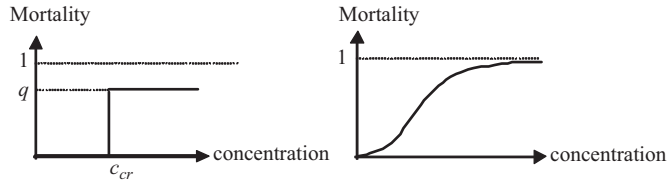


Fig. 7. Example of typical dose–response functions: a discrete function (left) and the probit function (right).

the level of physical effects. These dose–response functions are in fact distribution functions with values $0 \leq F_D \leq 1$, representing the resistance of those exposed. Some typical shapes found in literature are discussed below.

In some cases, data are insufficient for establishing an absolute dose–response function over the whole range of response values between 0 and 1. Then, one can alternatively relate a change in dose to a change in response over a limited exposure range with a linear relationship, i.e. $\Delta F_D / \Delta c = \text{constant}$. This approach encompasses the determination of the derivative of the dose–response function over a small range of exposures. Such an approach is generally used, when an epidemiological study is concerned with a phenomenon associated with chronic exposure and small response fractions. An example is a study on the effects of air pollution on mortality [41].

Lind et al. [42] use a normal distribution function to account for uncertainties in occurrence of instability of persons in flowing water.

Empirical analysis of historical data shows that the correlation between flood mortality and water depth can be described with a rising exponential distribution [8]. Covello and Merkhoffer [37] describe some additional shapes of dose–response function that are not discussed in detail here. These functions include the logit and Weibull distributions.

The most commonly used dose–response function is the probit function [43]. This is the inverse cumulative distribution function associated with the standard normal distribution. This model assumes that the relationship between the logarithmic value of the dose and mortality can be described with a cumulative normal distribution. The result is an S-shaped relationship between dose and mortality (see Fig. 7 (right)). Probits are used to model both lethal and non-lethal health effects for different substances. In [16] probit functions are given for the response of humans to explosions, toxic substances and heat radiation. The following expression for the probit value is used:

$$Pr = a + b \ln(c^n t) \quad (8)$$

where a , b , n are the probit constants that are used to influence shape and position of the distribution function (see below); c is the concentration (e.g. mg/m^3) for the concentration of a toxic substance or $[\text{kN}/\text{m}^2]$ for explosion pressure) and t is the exposure duration (often expressed in $[\text{min}]$).

The mortality fraction (F_D) is found as follows:

$$F_D(Pr) = \Phi_N \left(\frac{Pr - \mu_D}{\sigma_D} \right) \quad (9)$$

where: Φ_N is the cumulative normal distribution, Pr is the probit value, $\mu_D = 5$, and $\sigma_D = 1$.

When combining Eqs. (8) and (9) it is easily shown that the probit function can also be described by a lognormal distribution, in which the (scaled) dose $c^n t$ is taken as the dependent variable:

$$F_D(Pr) = \Phi_N \left(\frac{a + b \ln(c^n t) - \mu_D}{\sigma_D} \right) = \Phi_N \left(\frac{\ln(c^n t) - 1/b(\mu_D - a)}{\sigma_D/b} \right) \quad (10)$$

The average of the normal distribution equals $1/b(\mu_D - a)$ and the standard deviation σ_D/b . The value of a influences the horizontal position of the dose–response function. The values of b influence the shape of the dose–response function. In practical applications values of b and n are held constant, e.g. $bn = 2$ [18].

6. Case studies

To demonstrate the application of the proposed general approach for loss of life estimation three case studies are presented. As indicated below, these cover different types of accidents and different levels of detail and scale:

- Tunnel accident: shows how the approach can be applied at the individual level;
- Large-scale flood event: demonstrating how the approach can be applied to larger affected populations;
- Earthquake: shows how the approach can be integrated in risk assessments.

6.1. Tunnel accident: the Mt. Blanc tunnel fire (1999)

In order to test the proposed approach an analysis has been made of the fire in Mt. Blanc tunnel of 24 March 1999. A fire occurred in a heavy goods vehicle, which stopped near the middle of the tunnel near lay by 21. Due to natural ventilation the smoke mainly developed towards the French side. Here, the fire spread over 34 vehicles and eventually caused 39 fatalities, which all occurred within 500 m from the accident on the French side (Fig. 8).

Physical effects have been simulated with available analytical expressions for development of smoke, heat and toxicants [13]. Mortality has been estimated with available criteria for toxicants and heat [35]. To provide input values for the simulation of physical effects descriptions and reports of the accident have been used [44–46]. In this case the spatial and temporal progress of effects and escape are simulated using a space, time (x, t) diagram and the escape path of an individual is analysed.

It is estimated that the fire reaches a maximum heat release rate in first phase of 135 MW within 5 min. The development of radiant heat, temperature and carbon monoxide (CO) has been modelled. Only the effects in the French direction are considered, as the smoke mainly developed in that direction. Fig. 9 is an x, t diagram that shows the development of the smoke front, an escape path of an individual near the fire. By combining the physical effect calculations with dose–response functions the mortality value at a certain location can be estimated as a function of time. The graph shows for every location the time at which a 90% mortality value ($F_D = 0.9$) is reached for convective and radiant heat and CO.

It shows that radiant heat will be the dominating criterion very near the accident and convective heat for the other parts of the tunnel. Critical levels of CO will be reached after critical levels for convective heat. Given the rapid evolution of lethal

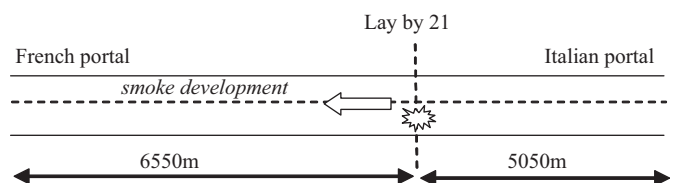


Fig. 8. Schematic view of the Mt. Blanc tunnel and the fire location.

circumstances it is considered likely that all 27 persons who stayed in their vehicles were killed in the fire within several minutes.

Eleven people left their motor vehicles and attempted to escape. Two of these persons went into a shelter and two persons entered another vehicle. To account for the possibility of escape a dynamic calculation has been undertaken for an individual near the fire. The person starts at 50 m from the accident ($x_0=50$) and is assumed to have a delay (a so-called wake up time) of 60 s ($t_w=60$). As the person is covered by smoke before the actual initiation of escape, a walking speed (v_E) of 0.5 m/s is assumed. For this case it is found that after 230 s and 135 m travelled lethal circumstances due to convective heat are reached. Further sensitivity analyses show that also for other values of escape variables and fire growth lethal circumstances will be reached within a few minutes without the possibility to escape.

Based on the above findings it is expected that all persons that tried to escape on foot and stayed in the car could not survive. In total the number of fatalities is estimated at 36, no analysis is given for the persons in the shelter. The actual number of fatalities amounted 39. Overall, the above findings correspond to the reported consequences of Mt. Blanc tunnel fire [44]: both persons who stayed in their cars and those who tried to escape could not survive this fire.

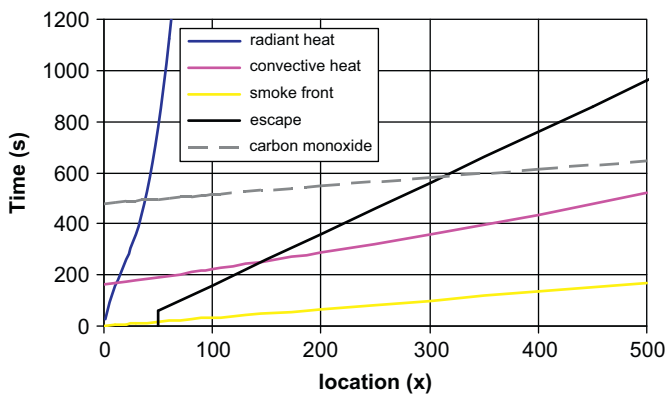


Fig. 9. x, t diagram with 0.9 mortality boundaries for the Mt. Blanc tunnel fire.

6.2. Flood event: Coastal flood event in the Netherlands

In this section a loss of life estimation is considered for a large-scale coastal flood event in the Netherlands (see [6,7,47] for further details). We consider a coastal flood scenario due to breaches in the coastal defences that could inundate large parts of South Holland. This is one of the largest flood prone areas in the Netherlands. The area has 3.6 million inhabitants and it is also the most densely populated area in the country. The extent of flooding (see Fig. 10) has been estimated by means of hydrodynamic models. In this case an area of approximately 230 km² could be flooded with more than 700,000 inhabitants. It is expected that the possibilities for evacuation of this area are limited because the time available for evacuation (approximately one day) is insufficient for a large-scale evacuation of this densely populated area. Based on evacuation and shelter models it is estimated that approximately 5% of the population evacuated out of the area and approximately 15% finds shelter within the area on higher grounds or in high buildings. Based on mortality functions for different flooding zones [6,7] it is estimated that this flood scenario could lead to more than 3000 fatalities. Fig. 10 shows the flooded area and the spatial distribution of the number of fatalities. These deterministic consequence estimates for single scenarios can be combined within information on scenario probabilities to estimate the overall level of flood risk [47].

6.3. Earthquake: Risk estimate for an earthquake in the Tokyo region

In order to show the application of the proposed approach in risk estimate a simplified and highly schematised example is given for earthquakes in the Tokyo area. For this area the yearly probability of exceedance of a certain peak ground velocity (PGV) has been estimated by Kanda and Nishijima [48] by Monte Carlo simulations. The generalised Pareto distribution of the PGV forms the best approximation of this data (Nishijima, personal communication, 2004) (see also Fig. 11)

$$F(x) = \exp \left[-\lambda \left(1 + k \frac{(x-u)}{\sigma} \right)^{-1/k} \right], \quad x > u \quad (11)$$

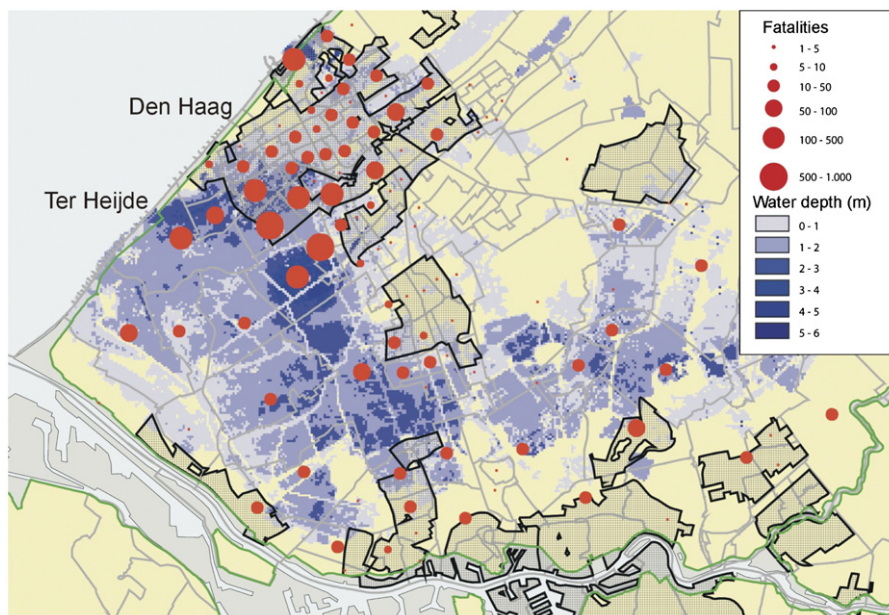


Fig. 10. Fatalities by neighbourhood and flooded area for the scenario with breaches at Den Haag and Ter Heijde [7].

where x is the peak ground velocity (cm/s) and u , k , λ , σ are the variables of the generalised Pareto distribution.

The probability of the total collapse of buildings as a function of PGV can be estimated with a so-called fragility curve, which has a lognormal distribution [48]:

$$F_B(x) = \Phi\left(\frac{\ln(x) - \ln 250}{0.4}\right) \quad (12)$$

where $F_B(x)$ is the fraction of buildings totally collapsed.

Due to the collapse of buildings a certain number of inhabitants is assumed to be killed. Based on empirical data for Japanese historical earthquakes Kanda and Shah [49] show that the ratio between fatalities and collapsed houses equals 0.1. Assuming 2.5 inhabitants per house a mortality fraction of 0.04 for every individual is obtained. Now the dose–response function for mortality can be written as follows:

$$F_D(x) = 0.04\Phi\left(\frac{\ln(x) - \ln 250}{0.4}\right) \quad (13)$$

where $F_D(x)$ is the Mortality amongst exposed persons as a function of PGV.

As an earthquake generally occurs unexpectedly no evacuation is possible and F_E is assumed to be equal to 0. The number of exposed persons in the Tokyo area is assumed to be equal to $N_{EXP} = 12 \times 10^6$. By combining this information the probability of exceedance of a certain number of fatalities is obtained, in a so-called FN curve (Fig. 12). A numerical approximation shows that the expected number of fatalities $E(N) = 154$ fatalities per year.

This example is mainly intended to show the application of the general approach. It has to be noted that several assumptions will have a major influence on the outcomes. Kanda and Nishijima [48] state that the hazard curve is considered as conservative. In loss estimation only total loss of building is considered while partial collapse may also contribute to mortality. One general fragility curve is used for building collapse, while collapse will actually depend on the type of building. Finally, one constant mortality fraction is assumed in the calculation, while in fact it will depend on the floor of the building where persons are present and the operations of rescue services.

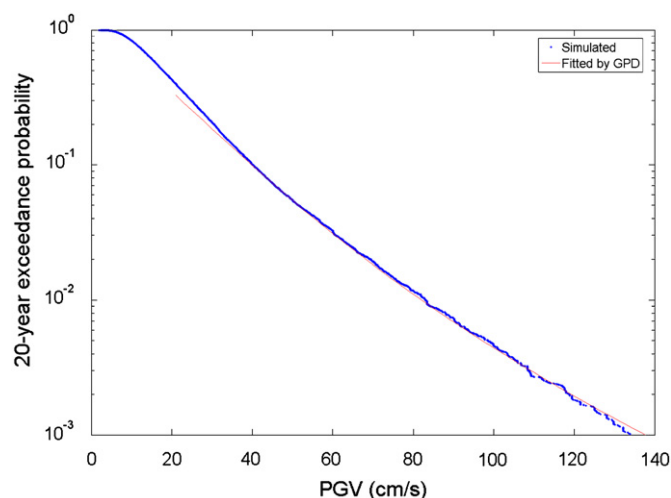


Fig. 11. Probability of exceedance of peak ground velocities (PGVs) simulated for Tokyo area [47] and fit obtained with the generalised Pareto distribution, variables: $u=20$, $k=0.126$, $\sigma=12.95$ and $\lambda=0.428$.

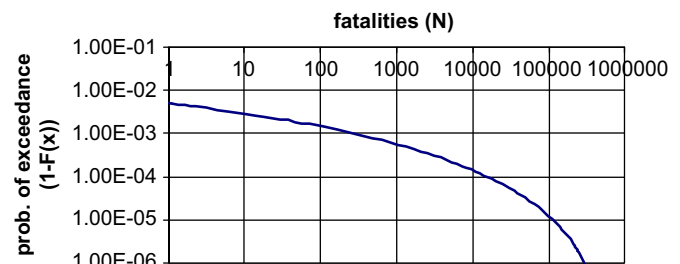


Fig. 12. FN curve showing the probability of exceedance of a certain number of fatalities for an earthquake in the Tokyo area.

7. Concluding remarks

Based on the observations that the existing approaches of life estimation in different fields include similar elements, a general approach for loss of life estimation is proposed which can be used over different domains. The methodology provides a basis for more efficient and standardised consequence estimation for different fields. In order to achieve more realistic consequence estimations a further empirical foundation of loss of life models based on past accidents is important. (Improved) Recording and storage of data on loss of life and the use of this information in validation of the existing methods is recommended. Whereas approaches for the treatment of uncertainty in probability estimation are well-established, it is recommended to further investigate how uncertainties in loss of life estimates can be assessed and treated in the context of risk evaluation and decision-making.

Estimation of loss of life often requires a multi-disciplinary approach, which expands outside the traditional engineering domain. For example, knowledge from toxicology is needed to establish dose–response functions. Study of evacuation requires insight in psychological issues regarding human reaction to disasters. For realistic loss of life estimates it is required to transfer knowledge and information from these disciplines to (quantitative) input for loss of life estimates and multidisciplinary cooperation is needed to achieve this.

It has been shown how the approach can be applied for consequence and risk estimation for different case studies. Further applications could involve other engineering related sectors, such as naval and offshore safety. This paper mainly focuses on the assessment of fatalities that occur due to direct exposure during a disastrous event. In addition, the relevance of non-instantaneous effects (e.g. disease, stress) should be explicitly considered in loss-of-life estimation as these effects can be significant. In addition to the loss of life it is relevant to assess the overall public health impacts, including the number of injuries. These effects can be combined by assessing the effects of disaster risks on the number of quality adjusted life years (QALYs) (see e.g. [2]).

Outcomes of consequence and risk calculations can be used in the decision process regarding the “acceptable” level of risk, for example by comparison with risk standards. Effectiveness of measures can be analysed by considering their reduction of loss of life. Comparison of the investments in risk reduction and the reduction of (expected) loss of life can be related to discussions on the (implicit) “value of human life”. More in general, it requires further research to determine if and how loss of life estimates can be included in economic valuation of projects and measures [50]. Furthermore it can be investigated how outcomes of consequence and loss of life estimates can provide valuable information for risk communication and emergency management.

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