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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.

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.

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]

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*

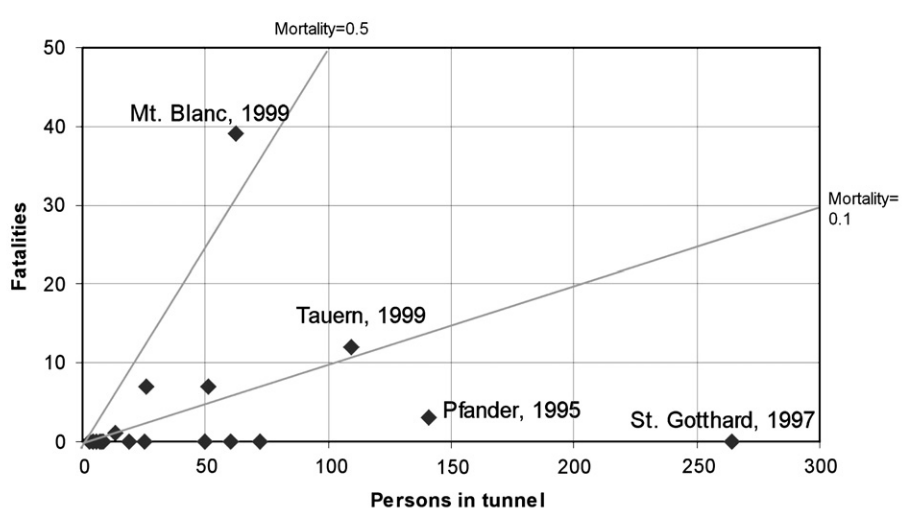

Fig. 1. Fatalities and estimated number of people exposed in historical tunnel fires ([19] analysis by O. Kübler) For some characteristic events the year and tunnel name are indicated.