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Accident occurrence model for the risk analysis of industrial facilities

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A B S T R A C T

This paper describes an accident occurrence model for the risk analysis of industrial facilities. To better understand the characteristics of industrial accident data, the proposed accident occurrence model is based on a chemical reaction. The model introduces a defensive barrier, which corresponds to the activation energy in a chemical reaction, to prevent an accident. Furthermore, the uncertainty factor in the defensive barrier is mathematically derived as a gamma distribution. The analytical results for the proposed accident occurrence model indicate a Pareto type II distribution, which is the same result found by using a risk curve. Therefore, the analytical model validates the effectiveness of analyzing industrial risk with a risk curve.

1. Introduction

Risk analysis is a very important technique [1] to prevent large-scale accidents and is used in various fields, such as government safety [2], social risk [3], tunnel safety [4], offshore activities [5], and infrastructures [6–8]. Researchers have used Renn and Klinke's approach [9] for risk analysis. Øien presented a methodology for the establishment of risk indicators [10]. Pan exhibited a methodological risk estimation framework for accident data in the aluminum extrusion industry [11].

For risk analysis, many stochastic approaches of the zero-inflated Poisson model have been proposed: prediction of accident frequencies for roadways [12], combined stochastic and quantitative risk assessment [13] and a stochastic and deterministic model [14] for electric power, and a competing risk model for bus failure data [15]. Markov switching models have been used to estimate severity outcomes [16] and frequencies [17] occurring on roadways. Moreover, a risk analysis tool combined with a Bayesian belief network [18] has been proposed.

The authors of the current paper previously proposed a statistical risk analysis method for accidents at industrial facilities by using a risk curve to show the relationship between the cumulative frequencies and the damage magnitude of the accidents on a log–log scale [19]. In these studies, risk curves with the accident data of various industrial facilities were plotted. The risk curve generally indicates linearity by introducing the γ parameter, and the curve is a Pareto type II distribution [20]. The risk level of industrial facilities can be estimated from the slope of the straight part of the risk curve, and a prediction method of the maximum damage of industrial facilities by using the risk curve was also proposed [21,22]. However, the authors did not understand why the industrial accident data shows the Pareto type II distribution for various industrial facilities, even though a large region in the risk curve shows linearity, which is a Pareto type II distribution.

Therefore, this paper proposes an accident occurrence model based on a chemical reaction as a theoretical risk analysis model. In the proposed accident occurrence model, a defensive barrier to prevent an accident is introduced and expressed with an exponential function. The defensive barrier corresponds to the activation energy. In addition, the distribution of λ as the uncertainty of the defensive barrier is introduced and mathematically derived. By using the proposed model, the reason for the Pareto type II distribution of industrial accident data is clarified. Furthermore, its effectiveness in analyzing industrial risk with a risk curve is reinforced.

2. Mathematical expression of normalized risk curve and expected value of industrial accident data

The data were provided by the Hazardous Materials Safety Techniques Association in Japan. The data, arranged in ascending order, were plotted on a log–log graph. Fig. 1(a) shows the risk curve for fire accidents at hazardous materials facilities in Japan. The risk curve indicates the relationship between the cumulative frequency (or probability) and the magnitude of the accident. The curve has generally a convex shape. The risk curve has a linear relationship in the large scale damage region. The large

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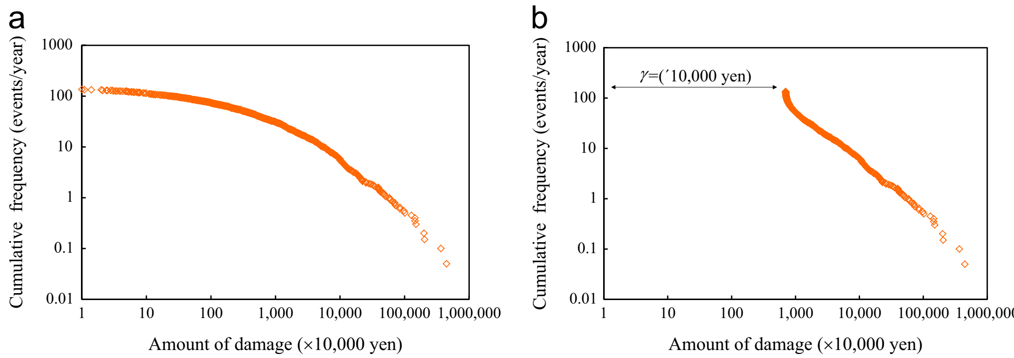

Fig. 1. Risk curve for fire accidents at hazardous material facilities (Observation period: 1986–2005). (a) Original risk curve and (b) Generalized risk curve.

scale damage region of the risk curve is expressed by

$$F(h) \propto h^{-D} \quad (1)$$

where h is the magnitude of damage, $F(h)$ is the cumulative frequency of the accident, and D is a shape parameter, which the authors call the safety index. Eq. (1) shows the Pareto distribution.[20] When h becomes larger, the frequency exponentially decreases by the Dth power. Safety index D shows the change ratio of the frequency of a large scale accident. If safety index D obtained from the dataset of some system A is large, a large scale accident does not easily occur in system A. Conversely, if safety index D obtained from the dataset in some system B is small, a large accident easily occurs in system B. Therefore, safety index D shows the risk and safety condition of the dataset.

However, the boundary between large and small scale damage regions is obscure, as shown in Fig. 1(a). Therefore, location parameter γ was introduced into the risk curve, as shown in Fig. 1(b). The authors refer to Fig. 1(b) as a generalized risk curve. The γ parameter is calculated so that safety index D' after introducing the γ parameter is approximately the same safety index D of the original risk curve. In Fig. 1(b), by introducing γ=700 (10,000 yen), the generalized risk curve indicates complete linearity. Therefore, the risk is easily evaluated by the slope of the generalized risk curve. Large D' means low risk of the dataset, whereas small D' means high risk, because D' shows the change ratio of the frequency with respect to the magnitude of the accident. The relationship in the generalized risk curve is described as follows:

$$F(h) \propto (h+\gamma)^{-D'} \quad (2)$$

To compare the various risks even if the unit of damage magnitude is different, the magnitude of damage is normalized with the γ parameter, as follows: (3).

$$F(h) \propto \left(\frac{h}{\gamma}+1\right)^{-D'} \quad (3)$$

the complementary cumulative distribution function $R(h)$ is expressed by dividing $F(h)$ by N_0, which is the number of accidents occurring during the observation period. Therefore, complementary cumulative distribution function $R(h)$ is obtained in the following equation.

$$R(h) = \left(\frac{h}{\gamma}+1\right)^{-D'} \quad (4)$$

In Eq. (4), h/γ, which is the normalized value, is replaced by random variable X'. $R(x)$ is then written as

$$R(x) = \Pr(X' \geq x) = (x+1)^{-D'} \quad (5)$$

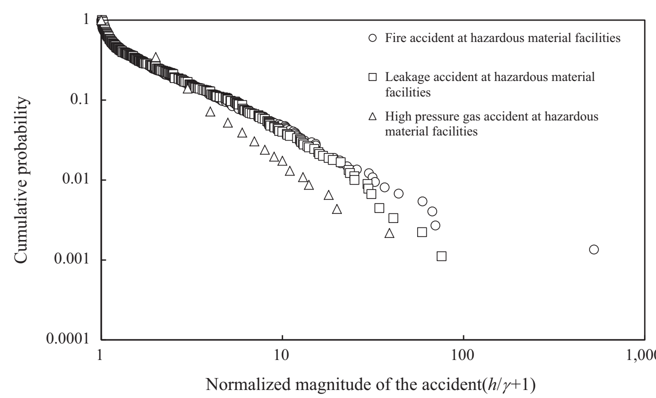

Fig. 2. Normalized risk curves for various types of accidents at hazardous material facilities.

Eq. (5) shows a Pareto type II distribution. The authors call the relationship expressed by Eq. (5) the normalized risk curve. In Fig. 2, the accident data of hazardous material facilities are arranged as a normalized risk curve. The data for high pressure gas accident were provided by the High Pressure Gas safety Institute of Japan. Fig. 2 indicates a Pareto type II distribution for the accident data of various industrial facilities. The risks of the various industrial facilities on the risk curve using safety index D' can be compared because the damage magnitude is normalized by the γ parameter [20]. The expected value of the normalized risk curve is then expressed by

$$E(x) = \int_0^{\infty} \frac{D'x}{(1+x)^{D'+1}} dx = D'Be(2, D'-1) \quad (6)$$

where Be(α, β) is the beta function. Eq. (6) is transformed into

$$E(x) = \frac{1}{D'-1} \quad (D' > 1) \quad (7)$$

By using $x=h/\gamma$, Eq. (7) is expressed by

$$E(h) = \frac{\gamma}{D'-1}, \quad (D' > 1) \quad (8)$$

from Eq. (8), it is verified that safety index D' shows the risk or safety level because the expected value is small when the safety index is large.

As shown in Eqs. (1)–(5), the data with the random variable are distributed according to a Pareto type II distribution with a complementary cumulative distribution function. Moreover, the statistical notion of risk is often modeled as the expected value, such as risk = probability of an accident occurring × expected loss from the accident. Therefore, D' is the risk of the dataset because D' is related to the expected value, as shown in Eq. (8).