PROBABILISTIC MODELS FOR RISK ASSESSMENT OF DISASTERS

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ABSTRACT
This article considers risk models related to disasters of complex engineering systems. It is proposed to include parameters of system vulnerability, survivability and security into risk models. Types of risk function for different disaster mechanisms are discussed. It is shown that the risk functions may have both exponential and power mode peculiarity. The mechanism of transformation of the exponential distribution into power mode (Pareto) distribution is determined.
Keywords: Disaster, engineering systems, failure processes, probabilistic model, risk function.

1 INTRODUCTION

Numerous studies have been carried out in recent years on safety of engineering systems and technologies. Safety factors, criteria, models and methods of risk assessment are permanently discussed in literature [1, 2]. Based on the analysis of theory and practices on safety measures for technical systems, a number of problems in risk analysis methodology can be formulated [3].

The first problem is that technological progress provides the opportunity of making more and more complex and large systems. This in turn increases man-made hazards. Along with, the safety requirements are becoming stricter, while the securing resource base is limited. We think that we are now above the crisis point when the safety requirements exceed securing resources. In future, the gap will grow and the risks will increase. These new risks will be of critical and global type and must be investigated. The problem is that the main attention is paid for research of statistical events with small risks. At the present time, evolving critical systems are the main source of engineering hazards. These systems are deeply integrated in the life-supporting infrastructure. The disasters of the systems influence a great number of people and lead to large-scale hazards for natural environment. The tragic examples of this are the Deepwater Horizon and Sayano-Shyshenskaya HPP disasters.

The peculiarity of critical systems lies in their complicated structure and in self-organization quality they possess. These systems have an ability to convert the structure, to create new configurations and hazards during their life cycle. The recent investigations have shown that self-organization is moving to self-organizing criticality, under which the systems turn out to be extra sensitive to breakdowns and external influence. Another feature lies in fast evolution of critical systems, which takes the lead over the hazards exploration. As a result, disaster risks of critical systems are rapidly increased. The Deepwater Horizon and Sayano-Shyshenskaya HPP disasters have shown that we must investigate the critical risks.

The second problem is that the new risks are unique and their evaluation should be based on a new probabilistic paradigm. The statistical paradigm uses hazards and risk as the basic definitions. The probabilistic paradigm introduces the new basic definitions of risk theory, such as vulnerability, survivability and security (protection). These definitions are determined by the securing resources base and reflect the analyzed peculiarities of systems. Therefore, a new approach in risk theory should be considered. This approach must include assessment of vulnerability, survivability and security within the disaster risk evaluation.

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The third problem consists in the need to develop new risk models of disasters. The new basic definitions must be included in models of risk assessment. Usually, risk assessment is based on the analysis of the disaster probability and loss probability. Along with the basic definitions, the new risk models must include vulnerability, survivability and security assessment. It is vital to develop a new methodology of risk assessment. The disasters are complicated events with hierarchical evolving structure. The level of risk depends on the object and the level of its structure being exposed to hazards. That is why methodology of hierarchical multiobjective risk analysis must be developed. Added to everything else, disasters have different mechanisms of occurrence. Type of disaster determines the law of risk function. Therefore, we need to investigate the link between the disaster mechanism and type of risk function.

In this paper, we propose new probabilistic models of disaster risk, which are outside the framework of traditional models [1, 2].

2 BASIC RISK MODEL (RISK FUNCTION)

Disaster risk of engineering system is commonly associated with the appearance of an initial event. Initial events are usually results of human error, external influence or violation of technological processes. If a system is vulnerable to such factors, the initial event forms the core damages in the structure. Development of damages leads to changes in structure and system state at random time points. Reaching the critical level of damages results in the system disaster. Thus, risk function can be defined as a function of initial event and core damage event sequence

$$\text{Risk} = \text{function}(\text{initial event frequency} \times \text{core damage event sequences}) \tag{1}$$

Damage development depends not only on system vulnerability but also on structure survivability and availability of systems of active and passive safety. This is why a risk function for evolving critical systems should be defined in the following form [3]:

$$\text{Risk} = \text{function (initial event frequency} \times \text{vulnerability} \times \text{core damage event sequences} \times \text{survivability} \times \text{safety)} \tag{2}$$

As already discussed, the distinctive feature of evolving systems is that there can take place random jumps of conditions with breakdown of previous and creation of new structures. Structural breakdowns in Large Scale, Super-Large Scale, Global Scale systems lead to cascaded events and nonlinear effects. In this case, risk assessment of disasters can be done according to the model (2). Hereinafter, formula (2) will be used as the basic. We will consider its structure, the probability assessment of initial events and sequence of damages.

3 EXPONENTIAL RISK FUNCTION

Mathematical model of dynamic stochastic system with accidental structure can be presented in the following form:

$$D(t) = A^S(D, t) + B^S(D, t)\,\xi(t) \tag{3}$$

where $D(t)$ is the n-dimensional vector of damages, $S(t)$ is the structure number, A, B are the prescribed matrix arrays of states, ξ is the Gaussian noise with zero mean, and t is the time.

The vector of damages includes multiple material element damages and multiple elements damages of structure.

Due to the existence of cross impact and interrelationship of disaster processes, risk models may be considered both in the space of damages D and in the state space S. The choice is determined by dimensionality and complexity of problem formulation.

Risk models in the space of damages are considered for systems, in which disasters occur due to damages of one or two components of the structure. In this case, the disaster probability is determined by the following form:

$$P_f(D, t) = P\{D(t) \geq D_c(t)\} \tag{4}$$

where D_c is the critical level of damages.

According to the nature of process, the answer for (4) can be obtained on the basis of cumulative model or stochastic processes of crosses model. The peculiarities of such models have been discussed in details in the works [3, 4].

Using these models, the vulnerability, survivability and security of systems can be considered only toward processes $D(t)$ and $D_c(t)$.

The greater interest is paid to disaster models of complicated hierarchical systems. In this case, the hierarchy of structural damages plays the main role. Thus, to formulate the risk model we need to turn to analysis of the state probability dynamics and disaster trajectory.

Let us observe the structural multistep disaster model (Fig. 1). Let us suppose that at the moment t_0 the system was in the state S_0 (normal operating state). As a result of influence with magnitude λ from initial event at the moment t_λ the system turns to the state S_1 (initial faulty state). Further, the propagation of structural damages with consistent state, transition and formation of the disaster trajectory ψ:$\{S_1, S_2, \ldots S_f\}$ takes place.

Probability $P(S_f)$ of disaster (reaching the final state S_f) can be defined by

$$P\left(S_f\right) = \lambda P\left(S_0\right) \sum\nolimits_i t_{Si} \tag{5}$$

where $P(S_0)$ is the probability of the normal operation state.

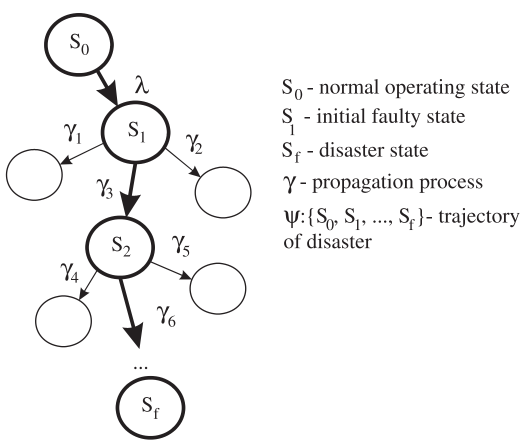

Figure 1: Notion of disaster trajectory.

Magnitude of initial event is determined by methods of mathematical statistics or can be evaluated through the density function of probability distribution $f_\lambda(t)$ of waiting period for this event:

$$\lambda = \left[\int_0^\infty t f_\lambda(t)\,dt\right]^{-1} \tag{6}$$

It is commonly supposed that $f_\lambda(t)$ is of exponential type $f_\lambda(t) = \lambda e^{-\lambda t}$.

The sum in eqn (5) is defined by survivability and security of system structure. It can be calculated from the following equation:

$$t_\Sigma = \sum_i t_{Si} = \int_0^\infty \Pi_i P_i(t)\,dt = \int_0^\infty f_\lambda(t) \int_{t_1}^\infty f_{01}(t) \int_{t_2}^\infty f_{12}(t_2) \ldots \int_{t_n}^\infty f_{n-1,n}(t_n)\,dt_n \ldots dt_1\,dt \tag{7}$$

Similar to (5) we can obtain the equation for magnitude of state achievement:

$$\Lambda(S_f) = \lambda P(S_0) \sum_i \lambda_{Si} \tag{8}$$

Taking into account eqn (8), the probability of disaster $P(S_f)$ can be expressed as:

$$P(S_f, t) = 1\text{-}exp\{-\Lambda(S_f)t\} \tag{9}$$

It is possible to show that in the examined scheme the processes of structural damages are precritical or critical, for which the extinction probability equals 1. Assuming that the losses from damages are of additive form $u_i = u_{i-1} + \Delta u$, the accumulated total losses will concentrate near the average value. Due to the fact that function $f(t)$ in formula (7) and function (9) are of exponential type, the risk function will also have exponential peculiarity. Such risk functions are typical for disasters of Large-Scale Systems.

4 POWER MODE RISK FUNCTION

Let us observe another scheme of damage propagation in a hierarchical structure. Let us take into account that a large number of elements in the system leads to a large number of interactions and nonlinear effects. We suppose that damaging processes simultaneously impact several subsystems (Fig. 2). In this case due to feedback coupling, a self-organizing cluster of faulty states is generated. This cluster determines a destruction front, which consists of all the damage trajectories. Every damage in the cluster causes new failure processes. In this case, the expected value of a number of new failure processes exceeds 1, $M[D(t)] > 1$.

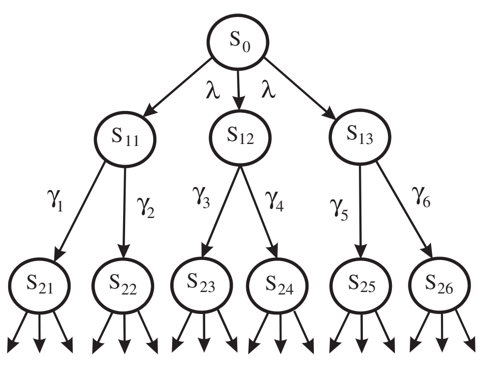

Figure 2: Multi-failure disaster trajectory.

The process turned out to be above-critical, for which the extinction probability is <1. As a result, cascaded damages with a typical multiplicative form of loss $u_i = (1+k)u_{i-1}$, $k > 1$ are generated. The final value of losses can be very large as the average loss value tends to infinity. Consequently, the risk function has 'heavy tail' instead of exponential form (Fig. 3).

In literature for the description of such 'tails', the Pareto distribution is usually used [5].

$$F(x) = 1-(x_0/x)^a \tag{10}$$

where x_0 and a are the parameters of distribution.

For a certain range of parameters, the exponential distribution and Pareto distribution closely approach or pass into each other at the point x_0. If $x < x_0$, the risk function is exponential, while at $x \geq x_0$, the function is of power mode (Pareto) type. If the expected values of the distributions are equal, parameter a is related to parameter λ as $a = \lambda + 1$.

The Pareto distribution in the disaster risk function appears as a result of nonlinear transformation of physical processes of structural damages to the processes of loss formation. These transformations can be presented by the formula relating the parameters λ and a. One form of such transformations is as follows [6]:

$$a = \frac{z(\lambda+1)}{z(\lambda+1)-1}, \; z > 1 \tag{11}$$

The parameter z reflects the transformation of the heaviness of system damage. As an example in Fig. 4, the nonlinear transformation (11) of the exponential risk function into Pareto

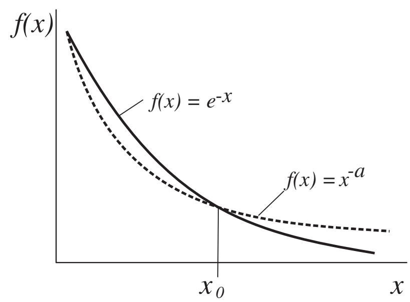

Figure 3: Probability risk function for exponential and power mode law.

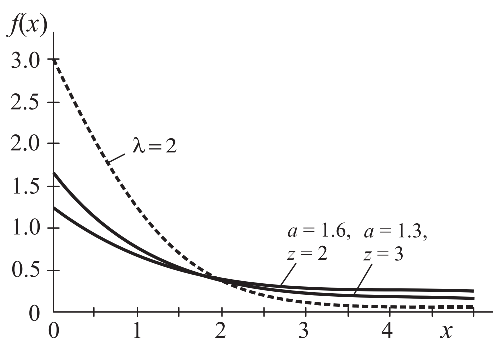

Figure 4: Nonlinear transformation of risk function.

distribution is presented. As we can see, the probability of large losses increases with the growth of damage severity.

There are several critical values of parameter a in the Pareto distribution. The most interesting processes take place when $a \leq 2$. In other words, when the distribution variance tends to infinity. If $a \leq 1$, the expected value of the distribution approaches infinity. When $a \approx 1$, the processes of self-organizing criticality occur in complex systems.

The considered peculiarities are typical for disaster risk functions of Super-Large Scale and Global Scale systems.

5 CONCLUSION

Modern society can be considered as society of risk. This risk is determined not only by natural hazards but also by growing hazards of engineering disasters. Nowadays, the greatest danger goes from evolving critical systems that are the basis of life-supporting infrastructure. Developing the probabilistic paradigm and probabilistic risk models is required to analyze disasters of such systems. Probabilistic risk models should take into account vulnerability, survivability and safety of complex systems in relation to disastrous external influences and internal damage processes.

In most cases, disaster risk models are based on the use of probability distribution laws of exponential type. These laws adequately describe a damage distribution in complex systems. However, they become unsatisfactory when we analyze not only the damage processes but also the results of their impact on systems. In this case, the use of power mode law of probability distribution (Pareto's law) is more relevant in modeling the risk of disasters. Further study on application of the Pareto distribution for evolving critical systems will allow predicting the possible critical states. This in turn will help in developing measures to avoid such critical states. Our results show the need for excluding initial events and avalanche of damages to provide the safety of evolving critical systems. The great attention should be paid to research on self-organizing criticality.

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