Methods and principles of forecasting risks of accidents on hazardous hydrotechnical objects

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Abstract. Risk analysis of accidents and emergencies on hazardous objects such as hydrotechnical objects is becoming increasingly important against the backdrop of annually increasing number of technological emergencies and significant increase of the damage they cause to the population and the environment. Methods of risk forecasting that take into consideration the object condition are highly important in this matter, but these methods have not been studied. Moreover, current forecasting methods do not take into consideration the change of object condition and its operating conditions over time. Hence creating modern approaches and methods of accident and emergency risk forecasting is an actual task aimed at increasing the level of safety for hazardous industrial objects. This paper deals with a method of forecasting accident situations and emergencies on hazardous industrial objects; the method takes into account the operating condition as well as the change of object condition, i.e. wear and tear. The presented method is a linear midterm forecast with the forecasting horizon of 1 to 5 years. The proposed method is based on the object condition statistical data. This methods can not only be used as a tool for forecasting and preventing accidents and emergencies at hazardous industrial objects, but also as a tool for optimizing expenses on developing industrial objects and ensuring its required level of safety for the population and environment.

1. Introduction

The potential of Russian technosphere for meeting the society’s demands has drastically reduced over the last decade. There has been a decrease in investment on developing technosphere or even maintaining its current condition.

The percentage distribution of causes that contributed the most to the growth of the number of emergencies on hazardous industrial objects, including hydrotechnical installations, from 2009 to 2017 is shown in Figure 1 [1]:

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[1] Data reference
There is a problem of sustaining living conditions and ensuring safety of the people living for the people and operation of the power system infrastructure (grid lines, roads, pipelines, technological fleet in nearly all industries, utilities sector) which poses a threat to people’s health and safety. Lastly, many of the hydrotechnical installations are high risk objects as they have been operated without maintenance for more than 50 years. Increase of their size and numbers makes vital the problems of preventing large-scale environmental disasters and ensuring safety of the people living below waterfronts and dams.

Hydrodynamic accidents are unexpected events tightly linked to significant damage to the hydraulic works (lock, dam) and uncontrollable displacement of the large masses of water leading to large area flooding and damage. The accident scale is completely determined by the conditions and parameters of the waterworks installation, the reservoir water volume, dam failure level and pattern. There is a problem of sustaining living conditions for the people and operation of the power system objects in Russia in the autumn-winter season. The main causes of such accidents are the following:

- unsatisfactory preparation of the power system objects for operation in winter conditions;

![Figure 1. Percentage ratio of the accidents on hazardous industrial objects in the Russian Federation from 2009 to 2017.](image)
− equipment wear and accident state of the heat distribution networks of the residential and public sector;
− lack of energy supplies.

Sometimes “human factor” took place – local authorities could not perform their duties and the matter “got out of control”.

This is just one of the ways the growing technosphere vulnerability manifests itself in, when even minor accidents require taking measures on the national level.

Having no strategy of technological development leads to a paradoxical situation. While the developed countries are focusing efforts on developing areas that determine the post-industrial paradigm, Russia is focusing on maintaining the industrial paradigm, keeping the “underdog” technological niches. IT, telecommunications, biotechnology, micromechanics and other areas of “the new economy” are developing very slowly in Russia [3]. The same goes for the new generations of energy- and resource-saving technologies. This can cause a crisis and the risk growth over the medium term and a disaster over the long term.

The growing interdependence of the technological and social spheres, mass consciousness value scales, degradation of science and education are adding further technological risks.

2. Principles of accident risk forecasting for hazardous industrial objects

From the physics point of view an accident is the situation when one or more parameters of a system changes beyond the permissible limit because of external or internal factors. The permissible levels are determined a priori, as a rule, by expert evaluation.

The violation of permissible parameter limits are determined by both subjective and objective reasons.

Objective reasons include: ignorance of the processes (natural, technical, social, etc.) by the society in general or by the individual making a decision in particular. As the society evolves this factor is going to diminish until it eventually becomes zero. This is a lengthy process and requires large expenses, mainly, by the state, on science and education [5–7].

Our present level of knowledge is not allowing us to fully evaluate the impact these factors have on the accident probability and to obtain a reliable forecast on implementing them. Therefore from the point of view of these forecasts the society will long be operating in the range of marginal estimates of the system parameters going beyond the permissible limits.

Subjective reasons include: orderliness and discipline levels of the society in general and individuals in particular, design and operation errors (“human factor”). Here the success in eliminating these reasons is achieved much faster and at lower cost.

The problem of accident prevention and control, i.e. the task of returning system parameters within permissible limits, is tightly linked to the abovementioned reasons that caused the accident. Thus understanding the nature of reasons potentially causing accidents in a given system is enabling development of adequate prevention measures aimed at preventing an accident and minimize time spent on eliminating its consequences.

The approach based on synergetics, theories of nonlinear dynamics and time series is very interesting. Often times the approach called technology transfer is used. The approach comes down to using developed and tested methods from one area (for instance, strength and fracture mechanics, automatic control theory, etc.) to describe phenomena in another area [5, 8, 9]. However all existing and emerging methods are based on computer simulation of the processes and phenomena being studied.

The possibilities of setting up a computer experiment and conducting a detailed simulation modeling have significantly expanded capabilities of researchers. It is now possible to explore scores and hundreds of simulated disasters in order to find ways of preventing the real ones. Besides, there are two interrelated factors. Firstly, computer models help create teaching programs, simulators, employee training complexes that help acting effectively in crisis situations. Secondly, they often show what the kind and volume of information is ought to be collected.
These models are closer to fundamental sciences than to engineering; however, without such models the risk of the decisions being taken would be greater because the real threats would be aggravated by ignorance. However the existing model toolbox is not adequate.

Fundamental changes in safety engineering that have taken place over the last decades are making the problem of creating new generations of models for modeling and forecasting crises and disasters very relevant. Solving any practical tasks using probability theory requires formulating it in probabilistic terms. But formulating a problem in probabilistic terms comes down to building a mathematical model of the problem. There are many ways of building mathematical models of such problems, but in each case it is required to construct a simplified object model and preserving the adequacy to the real object. Very often the model itself is so complex that even obtaining a solution causes problems of purely mathematical nature.

Sometimes the model adequacy can be verified empirically, but as a rule this kind of verification is practically unfeasible and requires involving a wide range of specialists so that the mechanism postulated in the model is in congruence with the studied phenomenon. The level of consistency between the mathematical solution and the phenomenon character depends on the model adequacy, but it may be inconsistent with the phenomenon itself, which will require further corrections of the mathematical model of the phenomenon.

Accidents can be classified by the cause \( j \) in the following way:

- Accidents of freight and passenger trains; accidents of freight and passenger ships; air accidents;
- Large car accidents; accidents on main and in-field oil pipelines; accidents on main gas pipelines; fires (explosions) in buildings, utilities, technological equipment of industrial objects; fires (explosions) on agricultural objects; fires (explosions) on ship industry transport and ships, on main oil and gas products main pipelines; fires (explosions) in mines and metro system; fires (explosions) in residential and public buildings; detection (loss) of unexploded ordnance and explosives; accidents with emission (possibility of emission) of chemical hazardous substances; accidents with radioactive release or possibility thereof; accidents with release of biologically hazardous substances or possibility thereof; sudden collapse of factory buildings, installations, rock fall; collapse of residential and public buildings; accidents on power electric systems; accidents on public utilities; accidents on heat supply networks in the cold time of the year; hydrodynamic accidents.

The presented list of accident causes is comprehensive enough and encompasses all spheres of technical activity; however each of the causes can include a range of accidents for different areas of the economy. A more diverse database of accidents, their causes and cause-and-effect relations is required in order to analyze accident causes, forecast them and formulate prevention measures.

The work on accident causes and accident forecasting has been conducted since the appearance of the technosphere; they are presented in depth in \[1, 10 - 14\].

The event of an occurring emergency (event \( E \)) is only possible if its cause is substantiated (event \( E_i \)). Probability of event superposition \( E \cap E_i \) is given by (1):

\[
P\{E \cap E_i\} = P\{E_i\} \cdot P\{E / E_i\} \tag{1}
\]

where

- \( P\{E_i\} \) – probability of accident cause substantiation (hazard, fire, explosion, etc.);
- \( P\{E / E_i\} \) – accident situation probability if the accident cause is substantiated.

In order to simplify notation, accident situation probability for \( i \)-th hazardous industrial object within one year \( P_{i\text{,year}}(E \cap E_i)/\text{one year} \) will be denoted as \( P_{i\text{,E}} \).

Accident substantiation is only possible in the following circumstances:

1. Accident cause is violation of permissible limits by one or several system parameters [15] caused by initial states not accounted in design basis accidents followed by additional safety system failure compared to design basis accidents and erroneous decisions by the personnel leading to dire consequences.
2. Accident can be caused by violation of different requirements (construction, emergency prevention, environmental, safety engineering, etc.) that ensure safety of the object territory, of the population living near a hazardous technical object and the personnel or there are ignorance areas because of which the necessary requirement have not been formulated.

However numerical values of accident probability do not fully characterize the event, the most important characteristic of any accident situation is the damage (human lives, human health, economic, moral, material damage) caused by it. Therefore the term of risk is used to characterize accident situations.

2.1 The concept of risk and its cause-and-effect relationships

Right now there is no rigorous definition of such terms as: risk, risk of accident situation, forecasting risk of accident situations. As a rule, the authors use this terminology in the context that fits best this or that problem. In the papers [1, 11, 16, 17] there are several varying definitions of risk and risk of accident situation; however, the most rigorous definition from the mathematics standpoint is given in [1]. According to the definition, risk is the measure of danger that combines the probability of harmful event and the impact this event has (losses and casualties). One can evaluate the measure of danger and make decisions whether this or that measure should be taken by making combinations of these elementary events and choosing a decision rule.

We are going to adopt this definition of risk. Going further, the risk of accident situation is going to be defined as a measure of danger including the probability of the accident situation and the expected value of damage if the accident situation takes place. It is going to be denoted as follows (2):

\[ R_{IE} = \{P_{IE}, S_{iY}\} \] (2)

where

- \( P_{IE} \) – accident situation probability within one year;
- \( S_{iY} \) – expected value of damage if the accident situation takes place.

The way these events are combined for risk analysis depends on the accident situation type, its conditions and other factors.

This definition of risk of accident situation \( R_{IE} \) is formulated for a single technical object; according to [14] it is defined as a differential risk of an accident situation. As a rule, generalized indicators or integral risks of accident situations are used in statistical records and government reports.

Thus if the integral risk of accident situation is going to be used, the probability of an accident situation has to be replaced by another indicator – expected value of the number of the \( j \)-th type accident situations within one year. Hence the integral risk of the \( j \)-th type accident situations \( (RI_{IE}) \) is going to be equal to the sum as \( i \) runs from \( 1 \) to \( N \) of the \( i \)-th differential risk:

\[ RI_{IE} = \sum \{P_{jIE}, S_{jY}\} = \{MP_{jIE}, MS_{jY}\} \] (3)

where

\( i \in [1, N] \), \( N \) – number of the technical objects of the \( j \)-th type.

2.2 Methods of accident situation risk forecasting

It is necessary to be capable of forecasting accident situation risks in order to create an efficient accident situation prevention system. Moreover, forecasts have to be as accurate as possible and have the longest possible horizons. This is where a very common contradiction appears: the longer the forecasting horizon is, the less accurate the forecast is. A forecast has to be optimized, i.e. it is necessary to find the optimal combination of parameters (forecasting horizon and accuracy) depending on a specific problem.
The analysis of the problem of accident situation risk forecasting shows that there are three forecasting horizons and the three respective forecast types. Each type has to be approached individually:

1. Forecasting horizon within which the state change of system elements is constant, i.e. quasi-stable state.

   The state of system parameter is described by the following equation:

   \[ \mathbf{B} = \text{const} \]  \hspace{1cm} (4)

   where \( \mathbf{B} \) – column vector of parameters characterizing the state of the system elements. Quasi-stable system state and the stability of the parameters characterizing its state depends on the given system, its particularities, external environment and other factors.

   Accident situation risk forecast is done by numerical simulation of the way the processes causing the accident situation are evolving and further simulation of how the accident situation itself and its consequences are going to evolve. There are many papers [14, 15, 18–20] that outline the principles of technical system accident situation simulation, including beyond design basis accidents. This allows one to construct a system of differential characteristics of the accident situation risk forecast.

   Let us denote the risk forecast for the accident situation in a technical system in the quasi-stable state being the cause of emergency as an operational forecast. Time horizon of an operational forecast can vary from several seconds to several tens of days.

2. Forecasting horizon within which the state change of system elements is almost linear. This is the case when the technical object does not undergo technological shift or the production does not expand within the forecasting horizon.

   The equation governing the state \( \mathbf{Y} \) of technical system parameters is the following (5):

   \[ \mathbf{Y} = \mathbf{K} \cdot T + \mathbf{B} \]  \hspace{1cm} (5)

   where

   \( \mathbf{Y} \) – column vector of the parameters characterizing the technical system elements state for the forecasting time \( T \);

   \( \mathbf{B} \) – column vector of the parameters characterizing the technical system elements state at the current time instant;

   \( \mathbf{K} \) – column vector of the coefficients characterizing the change of the technical system elements state;

   \( T \) – time.

   Let us denote the accident situation risk forecast for the forecasting time of linear change of technical system state parameters being the cause of accident situation as the mid-term (linear) forecast. The time horizon for such forecast can vary from one month to several (3-5) years.

   It is the mid-term forecast that is of the most interest to us, because it preserves the accuracy while having a long forecasting horizon. Furthermore, there is a large database of integral and differential risk indicators that can be used to calibrate forecasting methods. Accident situation risk forecast for the time horizon of 1 to 5 years can be very useful in forming socio-economic forecast, planning resource allocation, forming financial and material reserves for emergency prevention and recovery, for developing system of accident situation insurance on hazardous industrial objects.

3. Forecasting horizon within which the state change of system elements is nonlinear. This is the case when the technical object starts running by new technologies, the production expansion takes place, when the personnel qualification is low or the fixed capital has not been renewed which led to irreversible degradation processes.

   The equation governing the state \( \mathbf{Y} \) of the technical system is the following (6):

   \[ \mathbf{Y} = \mathbf{B} + \Psi(\mathbf{B},T) \]  \hspace{1cm} (6)

   where
\( \Psi (B, T) \) – column vector characterizing the nonlinear change of parameters characterizing the elements state of technical system for the time \( T \).

Let us denote the accident situation risk forecast for the period of nonlinear technical system parameter change a long-term (nonlinear) forecast. The time horizon for this kind of forecast can vary from five years to twenty years.

Accident situation risk forecast for this horizon is rather uncertain. It can be used for national strategic planning or for planning within an individual industry. The accident situation risk forecast for the time horizon of more than five years is very uncertain and can only be useful from the standpoint of integral characteristics.

There are only a few studies in that area \([1, 16, 21]\).

3. Methods of calculating integral and differential parameters of the accident situation risk forecast for hazardous industrial objects and analysis of their structure

3.1 Methods of calculating emergency probability and its expected value

One has to know the “history” of a problem and have full systematic information in order to make a forecast.

Right now there is a large pool of data on the accident situation causes and the factors affecting accident situation probability. This data has been collected for more than ten years and it is being published in annual government statistical reports.

Unfortunately this data is very hard to process for the forecasting purposes because it was collected according to different classifiers and the collection criteria often do not correlate, the data is often collected from different standpoints.

For each complex technical system there is a chain of cause-and-effect relationships between the state indicators \( X_i(t) \) of the technical system \( Y = \{X_1(t), X_2(t), \ldots X_n(t)\} \) parameters, the probability \( P_{E1} \) of accident situation cause substantiation and the probability of accident situation \( P_E \) (7):

\[
Y = \{X_1(t), X_2(t), \ldots X_n(t)\} \rightarrow P_{E1} \rightarrow P_E \tag{7}
\]

where

\[
P_E = P_{E1} P_{E/E1};
\]

\( P_{E/E1} \) – probability of accident situation caused by the given cause factor.

The same can be written for the parameters characterizing the integral risk values.

For each industry there is also a chain of cause-and-effect relationship between the averaged indicator values \( X_i(t) \) of the system state \( Z = \{X_1(t), X_2(t), \ldots X_n(t)\} \), the expected value of the number of accident situation causes \( MP_{E1} \) and their expected value \( MP_E \) (8):

\[
Z = \{X_1(t), X_2(t), \ldots X_n(t)\} \rightarrow MP_{E1} \rightarrow MP_E \tag{8}
\]

where

\[
MP_{E1} = \Psi \{X_1(t), X_2(t), \ldots X_n(t)\};
\]

\[
MP_E = \Theta (MP_{E1}, KP_{E/E1});
\]

\( KP_{E/E1} \) – efficiency of accident prevention measures for a given industry.

3.2 Method and algorithm for a mid-term forecast of the probabilistic characteristics of the accident situation integral risks

Let us assume that an industry has statistical information on the number of accidents \( (MP_{E1}(t)) \), emergencies \( (MP_E(t)) \), emergency damage \( (MSjY(t)) \) and the generalized parameters
$Z = \{X_1(t), X_2(t), \ldots, X_n(t)\}$ characterizing the change of the industry (fixed capital renewal, production levels, personnel number, etc.) for several years ($m$) [22].

As we have mentioned earlier, $MP_{EI} = \Psi\{X_1(t), X_2(t), \ldots, X_n(t)\}$ is a linear function, thus it is possible to determine the forecasted number of emergencies in the time moment $t_{m+1}$ by knowing the functional relationship between the number of emergencies and time and the initial conditions at the time $t_m$ (see figure 2).

**Figure 2.** Schematic relationship the forecast for the number of emergencies and time history of the number of emergencies

Our task is to construct the image of function $\Psi$ and determine its value $\Psi_{m+1}$ at the time moment $t_{m+1}$ by using the collected information, the function value $\Psi_m$ at the time moment $t_m$ and the forecasted values of its parameters $X_1(t), X_2(t), \ldots, X_n(t)$

For any time interval (9), (10):

$$\frac{\Delta \Psi}{\Delta t} = \frac{\Psi_{m+1} - \Psi_m}{t_{m+1} - t_m} = \frac{d \Psi}{dt} \to \Psi_{m+1} = \Psi_m + \frac{d \Psi}{dt} \Delta t \quad (9)$$

$$\frac{d \Psi}{dt} = \frac{d \Psi}{dt} \left[X_1(t), X_2(t), \ldots, X_n(t)\right] = \frac{\partial \Psi}{\partial X_1} \frac{dX_1}{dt} + \frac{\partial \Psi}{\partial X_2} \frac{dX_2}{dt} + \cdots + \frac{\partial \Psi}{\partial X_n} \frac{dX_n}{dt} \quad (10)$$

As the function $\Psi$ is linear

$$\frac{\partial \Psi}{\partial X_1} = K_1; \frac{\partial \Psi}{\partial X_2} = K_2; \ldots; \frac{\partial \Psi}{\partial X_n} = K_m \to (11)$$

$$\Psi_{m+1} = \Psi_m + \left(K_1 \frac{dX_1}{dt} + K_2 \frac{dX_2}{dt} + \cdots + K_m \frac{dX_m}{dt}\right) \Delta t \quad (12)$$

where $\frac{dX_1}{dt}, \frac{dX_2}{dt}, \ldots, \frac{dX_m}{dt}$ are the rates of change of the generalized parameters characterizing the condition of an economic sector. They are calculated using (13) from statistical development data:

$$\frac{dX_i}{dt} = \frac{X_m(t_m) - X_m(t_{m-1})}{t} \quad (13)$$
After that values of $K_1, K_2, \ldots, K_m$ have to be determined. In order to do that one has to construct a system (14) of $m$ linear equation for $m+1$ years using statistical information for the given economic sector. The equations are written for $m$ time intervals

$$
\Delta_1 = t_2 - t_1; \Delta_2 = t_3 - t_2; \ldots \Delta_m = t_{m+1} - t_m
$$

$$
\Psi_2 = \Psi_1 + K_1 \frac{X_1(t_2) - X_1(t_1)}{\Delta_1} + K_2 \frac{X_2(t_2) - X_2(t_1)}{\Delta_1} + \ldots + K_m \frac{X_m(t_2) - X_m(t_1)}{\Delta_1};
$$

$$
\Psi_3 = \Psi_2 + K_1 \frac{X_1(t_3) - X_1(t_2)}{\Delta_2} + K_2 \frac{X_2(t_3) - X_2(t_2)}{\Delta_2} + \ldots + K_m \frac{X_m(t_3) - X_m(t_2)}{\Delta_2};
$$

$$
\Psi_m = \Psi_{m-1} + K_1 \frac{X_1(t_m) - X_1(t_{m-1})}{\Delta_m} + K_2 \frac{X_2(t_m) - X_2(t_{m-1})}{\Delta_m} + \ldots + K_m \frac{X_m(t_m) - X_m(t_{m-1})}{\Delta_m} \quad (14)
$$

By solving this system of linear equation for $K_1, K_2, \ldots, K_m$ we obtain the values characterizing the influence the generalized parameters of a given economic sector have on the number of emergencies in this sector. The number of emergencies is a component of the integral risk indicator. By plugging the values of $K_1, K_2, \ldots, K_m$ in (12) we obtain the number of emergencies in the given economic sector. It is one of the components of the integral indicator of emergency risks for the forecasting horizon $\Delta t$.

4. Conclusion

This paper deals with methods and principles of forming mid-term accident situation forecasts based on linear function of change of the parameters characterizing the industrial objects, such as hydrotechnical installations or individual economic sectors.

The proposed method can be useful for analytical and forecasting studies of the socio-economic development of the Russian Federation or its entities and also for individual economic sectors and different industrial objects taking into account the “accident factor”. It can also be used in optimizing damage recovery expenses, for creating economic policies and national development strategies, in formulating requirements for the budget of the Russian Federation.

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