IOP Conference Series: Materials Science and Engineering

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IOP Conf. Series: Materials Science and Engineering **492** (2019) 012005 doi:10.1088/1757-899X/492/1/012005

The application of dynamic risk analysis methods for safety improvement on highways located near or on the territory of hydraulic engineering dams

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Abstract. A theoretical basis for the analysis of the hazards of industrial systems such as "Man-Machine-Environment system", including methods for qualitative and quantitative analysis, physical criteria and characteristics of hazard assessment, is proposed on the basis of fuzzy sets. A mathematical model for improving safety on highways located near or on the territory of hydraulic structures dams using the methods of dynamic risk analysis has been proposed. A mathematical model of a fuzzy system, taken as the basis of the method of dynamic risk analysis, is proposed.
An approach to the analysis of hazards is proposed, which consists in the fact that risk research and hazard ranking have to be carried out on the basis of the theory of fuzzy sets and fuzzy logic under conditions of strong uncertainty and the presence of a human factor.
A methodology for classifying the systems of the "machine" component by hazard classes and the ranking method for the "Man-Machine-Environment system" by degree of danger are proposed on the basis of fuzzy sets. The proposed fuzzy criteria for assessing the risk allow to select the following types of the "Man-Machine-Environment system" ranking: in the presence of a single spectrum of requirements; in the presence of "m" spectra requirements; by the criterion of the total hazard assessment; by the degree of compliance with regulatory requirements; in terms of proximity to various regulatory requirements; by degree of satisfaction with all regulatory requirements.

1. Introduction
The percentage of emergency situations (ES) occurring at the Russian Federation territory, is more than 60% of the total number of emergencies. In the regions of possible impact of damaging factors in the emergency situations a large population lives on motorways, there are fire and explosive objects, bridges and tunnels, hydraulic structures. Dangerous natural phenomena in intensity and duration can have a negative impact, exceeding in scale technogenic emergencies. The proportion of damage caused by natural phenomena is more than 80% of the total damage in an emergency on the territory of the Russian Federation for the year [1-5]. All this predetermines the necessity of long-term forecasting of emergency situations, monitoring the main sources of technogenic and natural hazards, conducting risk analysis at sites and territories, and developing measures to reduce risk [6].

The risks are integral indicators that determine the degree of technogenic and natural hazards within the territory [7, 8, 9]. A consistent scientific and methodological approach to risk analysis will increase the level of safety of the population and territories from anthropogenic and natural emergency situations based on optimizing population protection measures in response to large-scale accidents and disasters [10].

The science of risks in the technogenic and natural spheres has been formed in the last quarter of the XX century due to the practical needs of ensuring safety in the technosphere, particularly, in nuclear power engineering, as well as the development of space technologies [11, 12].

For the most accurate predictions of hazards on highways located near or on the territory of hydraulic engineering dams, it is recommended to apply the method of dynamic risk analysis [13]. The methodology is based on a statistical analysis of the risk of natural and technogenic hazards. The development of the methodology is based on the integration of statistical data, emergency information and meteorological information.

The method of meteorological forecasting of the hazard level is conducted taking into account seasonal changes in climatic conditions, as well as predicted meteorological data [14, 15]. Dynamic risk analysis involves the prediction of risk indicators based on the statistical information processing. The basis for calculating risk indicators is the trend identification, which determines the increase or decrease in risk indicators for previous years or decades, then the seasonality factor is calculated, which is analyzed by months, taking into account changes in indicators [16]. The emergencies can be predicted and prevented, based on meteorological information. Meteorological conditions include air temperature, rainfall, wind speed, taking into account the specific territorial belonging and a certain period of time. The coefficient of anomalies is calculated with their help.

For the most accurate prediction, taking into account the lack of information, it is possible to use a mathematical model [17], based on the application of the method of fuzzy sets [18, 19].

A distinctive feature of this article is the application of a consistent scientific and methodological approach to the implementation of dynamic risk analysis methods to improve safety on highways located near or on the territory of hydraulic engineering dams [20].

2. The proposed methodology

The use of fuzzy sets is the basic for classifying hazards and ranking the “Man-Machine-Environment system”.

The analysis of the “Man-Machine-Environment system” allows to select the main individual indicators and characteristics for the state of the “Man-Machine-Environment system”. Analysis of the system also allows to reflect emerging hazards.

The classification of the hazards of the “Man-Machine-Environment system” is also be carried out for certain types of harmful and dangerous factors.

These factors affect directly the highway workers, including drivers who organize and carry out road works, loading and unloading of cargo, as well as the carriage of dangerous goods.

Four classes of hazards are listed according to the degree of health effect of harmful substances, depending on the concentration of this substance. They are introduced in table 1.

Table 1.

Classofhazard	**Title**
1-stclass	Extra-hazardous
2-ndclass	Highly-hazardous
3-rdclass	Moderatelyhazardous
4-thclass	Lowhazardous

The established hygienic criteria for assessing the working conditions of workers of the highway and hydraulic structures are determined by the hygienic assessment of the existing conditions and the sort of work, respectively, in terms of the hazards of the working environment factors, the severity and intensity of the working process. The severity coefficients of work and the injury frequency rate are used to account injuries and allow a comparison of the work performed between them.

The variety and multiplicity of hazard factors create a problem of complex danger in the "Man-Machine-Environment system". A hazard assessment system can become the solution of this problem. With its help one can rank the "Man-Machine-Environment system" by hazards, and, if it is necessary, by other significant parameters that can characterize this system and are relevant to the assessment problem under consideration. Such characteristics may be the population in the areas adjacent to the highway, the number of engineering workers on hydraulic engineering structures that are close to the roadway, the amount of consumed energy, the number of road workers, the novelty and complexity of the system. The solution of the multicriteria problem under consideration with deterministic fuzzy data can be obtained on the basis of the fuzzy sets theory.

Hazard identification begins with the definition of a certain contour as a set or vector:

$$E = \{e_1, e_2, \ldots, e_n\}, (1)$$

where
e_n – the contour element, which is one of the hazard or dangerous factors of many other factors - chemical, physical, biological, economic, ergonomic, organizational, social, environmental, anthropometric, aesthetic.

Ensuring safety on a highway located near or on the territory of hydraulic structures dams is also determined by the combination of many presented factors, particularly physical and organizational. These factors are assessed quantitatively and qualitatively by expert judgment and measurements.

It is necessary to consider systems relating specifically to this particular element, during evaluating each of the contour elements. Evaluation of system elements can be made on the basis of expert opinion and to represent any evaluation system that is convenient for use. Table 2, developed by the authors, shows an example of assessing system elements by systems and categories on a five-point scale for highways located on the territory of hydraulic structures or near the it, taking into account the preparedness of evacuation services to eliminate emergencies, and also taking into account the work of highway services.

Table 2. The evaluation table for highway systems.

System	Mark
EmergencyResponseSystem	**4.25**
EmergencyAlertSystem	5
EvacuationSystem	3
Medical Assistance in Emergency Situations	4
Rescue System in case of Emergency Situations	5
System for providing training and prevention of emergency situations	**4**
HazardAnalysisSystem	4
ProfessionalSelection	3
StaffTraining	4
Deployment of services responsible for events in Emergency Situations	4
Development of an action plan in case of Emergency Situations	5
DisasterRecoveryFramework	**3.8**
Post-accidentDamageAssessment	5
WorkRecovery	3
Restitution	3
Determining the causes of Emergency Situation	4
Evaluation of the state of the "Man-Machine-Environment system"	4

Each element of the circuit has a quantitative characteristic, which allows to obtain one of the three main estimation spectra.

1) Regulatory spectrum – the assessment of elements is performed using regulatory documentation, in some cases the assessment is based on common sense.

2) Objective spectrum – the assessment of elements is in the form of target values, which are the goal at the present moment, the assessment is made on the basis of the available possibilities.

3) The real spectrum – the real state of the elements in the present moment is displayed with the spectrum.

Evaluation spectra are converted to the following formulas.

Regulatory fuzzy set $T = \int_E \mu_T(e)/e$;(2)

Objective fuzzy set $C = \int_E \mu_C(e)/e$;(3)

Real fuzzy set $R = \int_E \mu_R(e)/e$,(4)

where

$\mu_i(e)$ – the membership function of the element *e* to the *i*-th set, *i* = *T*, *C*, *R*.

When considering possible dangers appearing on motorways, the most applicable is to consider the estimated spectra of the normative and real fuzzy sets. However, their incompatibility with each other may indicate the presence or possibility of the occurrence of hazards. In this way, it is possible to obtain appropriate hazard assessment criteria.

For convenience of the hazard assessment it is proposed to consider the following cases:

- Assigning a no-hazard condition in the form $Q \le [Q]$; $[Q]$ is a valid value of Q, for which the inequality μ_*R* (*e*) ≤ μ_*T* (*e*) is satisfied, which can also be expressed as: $1 + \mu_T(e) - \mu_R(e) \ge 1$. Under this condition, the hazard criterion is characterized by the presence of danger

$$K_e(T,R) = 1 - \{1 \wedge [1 + \mu_T(e) - \mu_R(e)]\}. (5)$$

- Setting the no-hazard condition in the form of $Q \ge [Q]$; Under this condition, the hazard criterion is characterized by the presence of hazard

$$K_e(T,R) = 1 - \{1 \wedge [1 + \mu_R(e) - \mu_T(e)]\}. (6)$$

- Setting a no-hazard condition in the form of an interval $[Q^-, Q^+]$, the following inequality is necessary

$$\mu_T^-(e) \le \mu_R(e) \le \mu_T^+(e). (7)$$

In this inequality, the indices are specified and characterized by the minimum and maximum values of the membership function, respectively. Based on this inequality, the hazard criterion can be expressed as follows:

$$K_e(T,R) = 1 - min\{1 \wedge [1 + \mu_T^+(e) - \mu_R^+(e)]; 1 \wedge [1 + \mu_R^-(e) - \mu_T^-(e)]\}. (8)$$

Using all three cases of hazard assessment it is possible to form a criterion for the overall hazard assessment in the "Man-Machine-Environment system" in the following form

$$K_S(T,R) = \frac{1}{n}\sum_{i=1}^{n} K_{e_i}(T,R). (9)$$

Thus, the hazard assessment criteria proposed in this paper, calculated using the fuzzy sets $K_S(T,R)$ and $K_E(T,R)$, allow defining hazard indicators and classifying by the identified contour of elements.

The ranking of the identified contour elements can be carried out as follows:

• ranking due to the presence of a single range of requirements;
• ranking due to the presence of a certain range of requirements - m;
• ranking is based on the total hazard rating criterion;
• ranking is made according to the degree of compliance with regulatory requirements;
• ranking is made according to the degree of proximity to various regulatory requirements;
• ranking is made according to the degree of satisfaction with all regulatory requirements.

3. Conclusion

Thus, the paper proposed an idealized mathematical model based on fuzzy sets and risk analysis technique using fuzzy sets.

A model that can be used for ranking the systems of the "machine" component by hazard classes based on fuzzy sets has been proposed in this paper. Criteria for ranking the "Man-Machine-Environment system" by types of hazardous factors based on fuzzy sets have been also proposed.

The proposed hazard analysis model will allow:

– to predict the dangers of simple and complex technical systems, using established and systematic methods;

– to carry out the ranking of the component "machine" systems by hazard classes in the conditions of strong uncertainty;

– to rank all types of the "Man-Machine-Environment system" according to hazard criteria and compliance with regulatory documentation.

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