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Transport of Dangerous Goods by Rail, and Threats to the Subsoil of the Railway Surface in the Event of a Disaster

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Abstract. In Poland, in 2020, the mass of dangerous goods (loads) transported by rail was 26 151.06 thousand tone. This translated into the performance of 8 899 691.89 thousand tone - km of transport performance. In 2020, these figures accounted for 11.72% of the weight of goods transported by rail. The situation is similar in other countries around the world. With such a large volume of transport of dangerous goods by rail, there is a high risk of a railway disaster involving hazardous materials. The effects of such a catastrophe affect the ground surface of the railway track and groundwater. For modeling, generalized dynamical systems are used. These are mathematical models of real systems describing the relationships between the so-called input $\vec{u}$ and output $\vec{x}$ (response) of a dynamical system. In the case of the railway disasters discussed here, they determine the functions showing the way the effects of the disaster spread in the subsoil of the railway track and show the properties of these functions. For this modeling, a non-classical calculus of operators is used that generates generalized dynamical systems, as the phenomenon of spreading the effects of a catastrophe in the ground is a complex dynamic process. It can be either slow or abrupt. This has been taken into account in the process analysis. It has been shown that the occurrence of a disaster, including the one involving hazardous materials, is influenced by the reliability of the railway line and its components, as well as the reliability of the subsoil. It was indicated that the effects of a disaster involving hazardous materials affect the discussed reliability. Determining the function of unreliability, reliability and intensity of damage to the subsoil is helpful in determining the methods of restoring the subsoil to its original (initial) operating parameters.

INTRODUCTION

Dangerous goods transported by rail are divided into classes according to the RID classification (Règlement concernant le transport international ferroviaire des marchandises dangereuses - Regulations for the international carriage of dangerous goods by rail). The following classes are distinguished in this classification: Class 1 - explosives and articles with explosives, Class 2 - gases, Class 3 - flammable liquids, Class 4.1 - flammable solids, self-reactive substances, polymerizing substances and solid desensitized explosives, Class 4.2 - substances susceptible to spontaneous combustion, Class 4.3 - substances which emit flammable gases upon contact with water, Class 5.1 - oxidizing substances, Class 5.2 - organic peroxides, Class 6.1 - toxic substances, Class 6.2 - infectious substances, Class 7 - radioactive substances, Class 8 - corrosive substances, Class 9 - miscellaneous hazardous materials and articles.

For example, in Poland in 2020 the mass of dangerous goods (loads) transported by rail was 26 151.06 thousand tone [1]. This translated into the performance of 8 899 691.89 thousand tone - km of transport performance. In 2020, these figures accounted for 11.72% of the weight of goods transported by rail and, respectively, 17.05% of the transport performance. The share of transported loads in 2020 in individual classes by weight and transport performance is shown in figure 1.

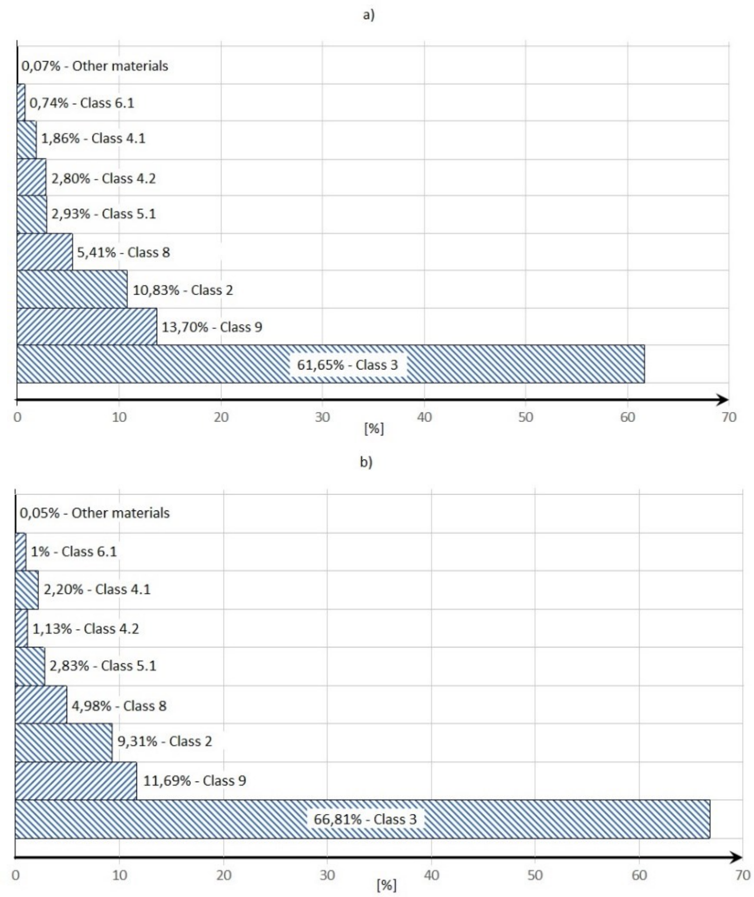

FIGURE 1. Share of transported dangerous goods in individual classes: by weight, b) by transport performance.

The situation is similar in other countries around the world. It is related to large volume of freight transport. For example, the total weight of cargo transported by rail according to Eurostat in Germany in 2020 was 320.1 million tone, and in Poland 223.2 million tone. Large masses of goods transported by rail generate large masses of transported dangerous goods.

Therefore, with such a large transport of dangerous goods by rail, there is a high risk [2] of a railway disaster involving hazardous materials. Each such disaster involving hazardous materials has a negative impact on the participants of rail transport and the surrounding environment. The elements of the environment that are affected by the consequences of a railway accident involving hazardous materials include: the track, subgrade and, further, subsoil and groundwater. Similar situations may also occur in places where dangerous goods are reloaded, despite the use of air-tight sealing systems.

With a large scale of the disaster, it can even lead to an ecological disaster in the ground, groundwater and more. In addition, these disasters are often accompanied by fires, because the share in the transport of class 3 and class 4.1 materials is about 65% - figure 1.

The probability of a catastrophe involving hazardous materials is related to the weight of this type of cargo and the related transport performance. Likewise, the likelihood of a fire breaking out is not small.

Even if these probabilities were close to zero, one should prepare for such a difficult situation.

If a disaster does occur, then its consequences should be minimized. It is possible only if we know the properties and course of the phenomena accompanying these railway accidents, mainly from the point of view of the railway surface, track bed and subsoil. It should be added that each such disaster has a negative impact on the capacity of a given railway line, and may even lead to its temporary closure.

On the one hand, it is necessary to prevent disasters in general, and especially those involving dangerous goods (materials), and on the other hand, one should prepare for the fact that such a dangerous catastrophe may occur. Mathematical modelling is helpful in solving all these issues.

MODELING WITH THE USE OF GENERALIZED DYNAMICAL SYSTEMS

The course of the phenomena accompanying disasters involving hazardous materials can be followed with the use of generalized dynamical systems. Generalized dynamical systems are mathematical models of real systems described by the following equation

$$\boldsymbol{S\vec{x} = A\vec{x} + B\vec{u}} \ , \tag{1}$$

where $\vec{x} \in (L^1)^n$, $\vec{u} \in (L^0)^m$ and u is a given element (see [3]).

In formula (1), the letters *A* and *B* denote given matrices composed of endomorphisms of the L^0 and L^1 spaces. They are matrices

$$\boldsymbol{A = [a_{ij}]_{\substack{1\le i\le n\\1\le j\le n}}} \ , \quad \boldsymbol{B = [b_{ij}]_{\substack{1\le i\le n\\1\le j\le m}}} \ . \tag{2}$$

The introduction of the last definition is possible thanks to the use of the notions of the non-classical calculus of operators $CO(L^0,\ L^1,\ S,\ T_q\ ,\ s_q,, Q$ - [3, 4, 5, 6].

The dynamical system (1) can be assigned block diagrams: general and detailed [3].

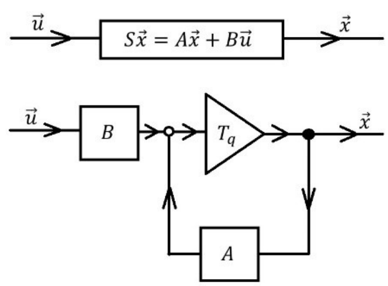

FIGURE 2. Block diagrams of the generalized dynamical system (1) - general and detailed.

They show the relationship between the quantities $\vec{x}$ and $\vec{u}$ in connection with the operations $S\,,T_q$ and matrices A, B (Figure 2). Adopting appropriate representations of operations $S\,,T_q$ and matrices A, B and L^0 i L^1spaces allow us to model and analyze specific engineering problems in the continuous or discrete domain. It allows to establish the relationship between cause (causes) and effect (effects) with the use of ordinary or partial differential equations or difference equations.

For example, in the case of a railway accident involving tanks with hazardous substances and in the event of their unsealing, contamination (pollution) spreads, among others, in the ground - in its groundwater, and in the event of a disaster near a water reservoir - also in water and surface waters.

Rainfall has a negative impact on the spread of the effects of a railway disaster.

The precipitation runoff [7] is characterized by high concentrations of total suspended solids, which is a carrier of pollutants absorbed on its particles and changes during the rainfall, thus accelerating the spread of the effects of the catastrophe and increasing the area of its negative impact.

This runoff is influenced by the terrain (slopes) and vegetation. For example, in the case of an embankment, the intensity Q of the rainwater runoff can be estimated from the formula

$$\boldsymbol{Q = rCA}\ \left[\boldsymbol{\frac{dm^3}{s}}\right] \tag{3}$$

where:

r - precipitation intensity $[{dm^3}/{s \cdot m^2}]$,
C - runoff coefficient [-],
A - effective area of the embankment section $[m^2]$.

Particles of any medium (solid, liquid, gaseous) are in continuous random motion, the intensity of which is determined by the temperature of the medium. As a result of this movement, the exchange of molecules between adjacent layers of the medium takes place, causing a transfer phenomenon called diffusion transfer or, for short, diffusion. If the layers are of different temperature, the exchange causes a heat transfer (e.g. a fire accompanying a disaster). If, on the other hand, we are dealing with a liquid medium (water in the ground) with admixtures (e.g. impurities), then the difference in the admixture concentration in the adjacent layers of water causes mass transfer. The values of individual quantities are directly proportional to the respective spatial gradients of temperature or concentration. The flow coefficients depend on the properties of the medium, and their dependence on temperature, pressure and concentration is generally determined experimentally.

Assuming one-dimensional flow, it takes a form analogous to the diffusion equation, i.e. in mathematical modeling they are described with analogous formulas using parabolic differential equations. In general, the mathematical form of the contamination dispersion model is a combination (parallel or chain) of descriptions of individual component processes, among which the diffusion process is important.

The one-dimensional homogeneous diffusion equation is a dynamic system

$$\frac{\partial}{\partial \mathrm{x}}(\mathrm{D}\frac{\partial \mathrm{u}}{\partial \mathrm{x}})=\frac{\partial \mathrm{u}}{\partial \mathrm{t}}, \tag{4}$$

where D is the diffusion coefficient, u is the concentration of the component subject to diffusion at point x at time t, corresponds to the homogeneous equation of thermal conductivity

$$\frac{\partial}{\partial \mathrm{x}}(\mathrm{k}\frac{\partial \mathrm{u}}{\partial \mathrm{x}})=\mathrm{c}\rho\ \frac{\partial \mathrm{u}}{\partial \mathrm{t}}, \tag{5}$$

where k is the coefficient of thermal conductivity, c is the specific heat of the body, ρ is the density, and u is the body temperature at point x at time t. Thus, in the case of a fire accompanying a railway disaster, the function u (x, t) can be treated as a representation of the temperature propagation in rails or other elements of the railway infrastructure. This temperature is then transferred to the subgrade and subsoil and has a negative effect on the geosynthetics used.

It follows that the processes of diffusion and thermal conductivity analyzed here are analogous. One of them can be modeled with the other and it is enough to focus on one of them when analyzing the spread of negative phenomena accompanying railway accidents. It is important that these are always special cases of generalized dynamical systems (1) in which $n = 1$, $\mathrm{S} = \frac{\partial}{\partial \mathrm{t}}$, while the endomorphism of A is correspondingly of the form

$$\frac{\partial}{\partial x}(D\frac{\partial}{\partial x})\ \ or\ \ \frac{1}{c\rho}\frac{\partial}{\partial x}\left(k\frac{\partial}{\partial x}\right),\ \ (\vec{y} = u). \tag{6}$$

Note:
Generally for $\mathrm{S} = S_0\frac{\partial}{\partial \mathrm{t}}$ it is an equation in the form [8]

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial \emptyset}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial \emptyset}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial \emptyset}{\partial z}\right)=S_0\frac{\partial \emptyset}{\partial t}. \tag{7}$$

In order to use the source influence in the model, a function f (x, t) characterizing (describing) the source of the diffusing substance or the heat source should be added to the given partial differential equation. This then leads to a non-homogeneous partial differential equation [9], [10]. The properties of solutions to the aforementioned equations decided about their use in modeling the phenomenon of propagation of the effects of railway accidents. The resulting (generated) effect of the catastrophe at the initial moment $t = 0$ spreads in the environment (in the ground, in water) similar to the heat in the material (heated rails, heated ground) in accordance with the adopted models (4), (5), or actually - due to a certain equivalence between them - according to one of them. Note that the aforementioned equation (4)

$$\frac{\partial}{\partial x}(D\frac{\partial u}{\partial x})=\frac{\partial u}{\partial t}, \qquad D=const \tag{8}$$

with an initial condition

$$u(x,0) = \varphi(x), \tag{9}$$

can be adapted to our purposes, because it is enough to assume that now D denotes a constant diffusion coefficient or $D = \frac{k}{c\rho} = const$, moreover, $\varphi(x)$ is a quantity characterizing the initial phase of the catastrophe, generated at time $t = 0$, and $u(x,t)$ denotes the spread of the selected phenomenon accompanying the catastrophe (at the moment t in point x), when we treat the problem as one-dimensional. It follows that the response of the dynamical system (4) with the condition (9) or of the system (5) with the condition (9) must be sought. The answer is given by a formula

$$u(x,t) = \int_{-\infty}^{\infty} \varphi(\xi) K(x-\xi,t) d\xi, \tag{10}$$

where

$$K(z,t) = \frac{1}{\sqrt{4\pi Dt}} \exp\left(-\frac{z^2}{4Dt}\right). \tag{11}$$

The response $u(x, t)$ of the system is non-zero at each point of the $R \times R_+$ region immediately after the process begins, because the function $K(x, t)$ - figure 3 - appearing in the formula for $u(x, t)$ - is positive and $\varphi(x) > 0$. This proves the rapid spread of the effects of the disaster and shows possible directions of counteracting their spread.

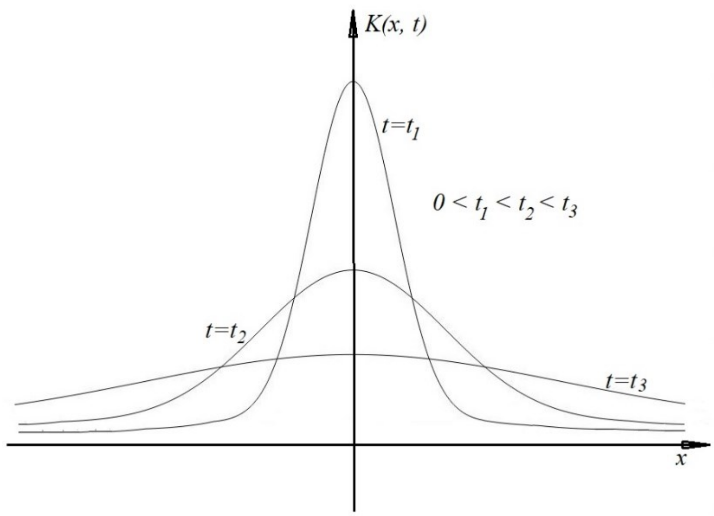

FIGURE 3. The spread of the phenomenon in time with its rapid appearance in the initial moment in the form δ(x).

The function $K(x, t)$ is also a solution to equation (4). It describes the development of the phenomenon depending on x and t for a very "sudden" appearance of the phenomenon accompanying the catastrophe at time $t = 0$, that is, for $\varphi(x) = \delta(x)$ - Dirac distribution (figure 3).

The phenomena accompanying catastrophes described by functions (10) are in practice smooth functions in time t. The function K(x, t) is also an infinitely smooth function for $t > 0$, symmetrical with respect to zero, tending to zero as time increases to infinity, i.e. the phenomenon accompanying the catastrophe disappears with time, until it finally disappears after a sufficiently long time - figure 3.

The initial data (initial conditions) are smoothed out even in a very irregular case, when condition (9) is responsible for the violent ("explosive") start of the adverse phenomenon process. It is for example a rectangular signal with length 2ε and height $\frac{1}{2\varepsilon}$ or a triangular signal. It is a signal given by the formula

$$\varphi(x) = \frac{h(x+\varepsilon) - h(x-\varepsilon)}{2\varepsilon}, \quad \varepsilon > 0, \tag{12}$$

or

$$\varphi(x) = \frac{1}{\varepsilon}\left(1 - \frac{|x|}{\varepsilon}\right)\left(h(x+\varepsilon) - h(x-\varepsilon)\right) \; , \varepsilon > 0 \, , \tag{13}$$

where $h(x)$- denotes the Heaviside function or the unit jump signal.

The process under study always strives to be as smooth as possible, i.e. its violence disappears with time, disappears after a very short time - figure 4.

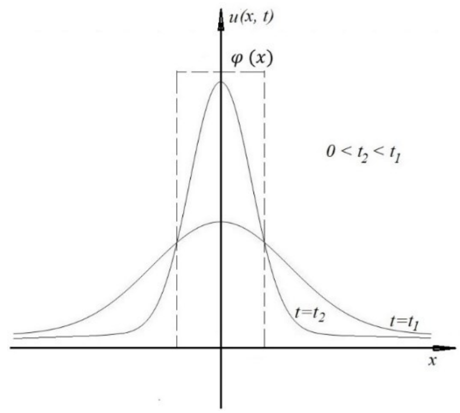

FIGURE 4. The idea of smoothing the phenomenon over time with its rapid appearance in the initial moment in the form of a rectangular pulse.

Here, too, the phenomena accompanying disasters spread from points (places) where their effect is large to points (places) where it is smaller. They show the negative direction of the spread of the effects of railway accidents involving hazardous materials.

The gradual phasing down of the changes caused by the catastrophe, and more precisely its effects, according to the last equation, takes place in time - as in figure 4, and also with increasing depth in the ground - figure 5.

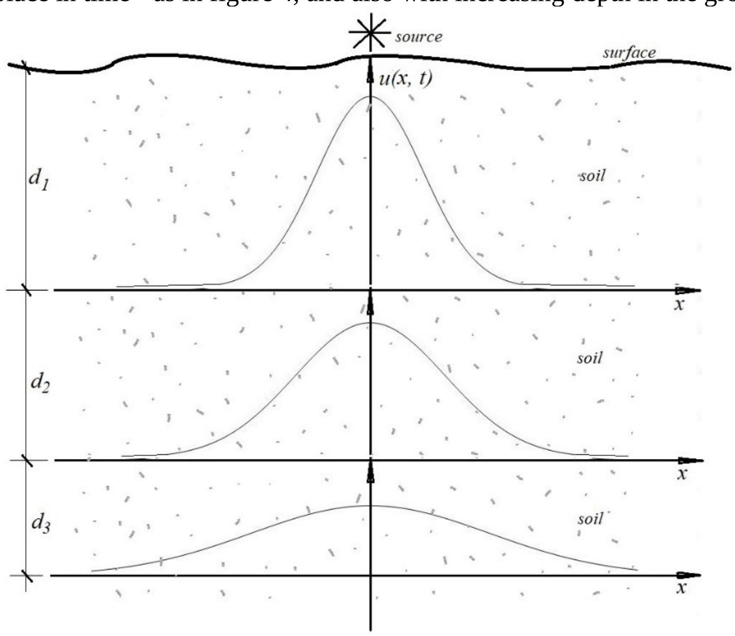

FIGURE 5. Change of the effects of the catastrophe with the change of depth.

It follows that the negative effects of the catastrophe, from the point of view of their course, behave like the results presented in figure 4 and figure 5, as long as we eliminate the source of the catastrophe or limit (reduce) its operation. If so, in order to limit the negative effects of a railway disaster, its source (leakage, explosion, fire) should be eliminated in a short time or at least its range should be reduced. By doing so, it is also possible to reduce its negative impact, among others, on the railroad track and subsoil.

Note:
Equations (4), (5) can also be analyzed in the discrete domain using operations

$$S\{x_{k,l}\} = \{x_{k,l+1}\} \tag{14}$$

or

$$S\{x_{k,l}\} = \{x_{k,l+1} - x_{k,l}\}. \tag{15}$$

These operations, of course, correspond to the operations T_q - [6]. In such a case, equations (4), (5) will correspond to classical discrete dynamical systems.

INFLUENCE OF THE RELIABILITY OF A RAILWAY LINE ON THE OCCURRENCE OF A RAILWAY DISASTER

Railway disasters and accidents are often connected with the derailment of a train or its parts. Whether or not such a situation occurs depends on the reliability of the railway structure. The reliability of the railway line as a whole or its individual elements has an impact on the occurrence of a railway disaster, including a disaster involving hazardous materials. The above mentioned reliability is influenced by: vertical and horizontal unevenness of the track, changes in track width (track gauge), sudden changes in cant, track twist, etc. Reliability of individual elements of the railway superstructure is also important. This applies to the reliability of the rails themselves (cracking, buckling), ballast, sleepers, rail connections, their fastening to sleepers, etc.

The reliability of a railway line is also influenced by the reliability of railway traffic control devices and the reliability of railway traffic protection devices.

The entire railway line, its surface and its listed elements are working properly until the time of the disaster. They work properly until they are damaged by a disaster. This time of correct operation of the railway line, railway track and its elements is a random variable *T* with a probability distribution depending on the properties of the entire facility, operating conditions and a fixed set of safe operation characteristics. Of course, a random variable *T* can be assigned its distribution function

$$F(t) = P(T \leq t)\ , \tag{16}$$

which, as it results from the last formula, means the probability of correct work time or, in other terms, it is a function of failure. With its use, it is possible to determine the *R(t)* function, also called the reliability function. It is defined by the formula

$$R(t) = 1 - F(t). \tag{17}$$

The failure intensity function *λ(t)* is defined by the formula

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{P(t < T \leq t + \Delta t | T > t)}{\Delta t}\ , \tag{18}$$

in which the probability is a conditional probability and relates to failure in the time interval (t, $t + \Delta t$), provided that until moment *t*, e.g. until the catastrophe, the object was working properly. Importantly, the failure intensity function is related to the *R(t)* function and vice versa, as follows

$$\lambda(t) = -\frac{d}{dt} lnR(t) \tag{19}$$

$$R(t) = e^{-\int_0^t \lambda(\tau) d\tau}\ . \tag{20}$$

Using the R (t) function, the expected condition of fitness can be determined by the formula

$$\int_0^\infty R(t) dt\ . \tag{21}$$

On the other hand (vice versa), all these disasters, especially those involving hazardous materials, have an additional impact on the reliability of the railway line, its surface, its elements, its subsoil. For example, high temperature results in deformation of rails, damage to sleepers and geosynthetics, has a negative effect on the subsoil of the railway track. It affects the reliability of the entire railway line.

A disaster involving hazardous materials also affects the operational reliability of the railway line and its capacity.

In each case, the performed observations should be used to test the reliability, and on their basis, using e.g. the two-parameter Weibull distribution, the functions $R(t)$, $\lambda(t)$ should be determined and used for the testing and analysis of reliability.

CONCLUSIONS

The creation of appropriate mathematical models concerning the spread of the effects of the disaster in the ground allows to limit its negative effects. It also allows to prevent the spreading of its effects in the ground over "great" distances and depths.

Disasters involving hazardous materials have a negative impact on the elements of the railway track, subgrade, subsoil and the geosynthetics used.

The properties and course of the phenomena accompanying railway accidents are helpful in limiting their effects on the subsoil of the railway track.

The properties of the phenomena accompanying the analyzed disasters are well reflected in their mathematical models using non-classical operator calculus and generalized dynamical systems.

The tools used simplify the transcription of the presented models and facilitate their analysis. They simplify and limit the assumptions required in modeling.

The phenomena accompanying the analyzed disasters can be studied with the use of analog models and applied in practice to reduce the effects of disasters.

The condition of the railway line, including its ground, has an impact on the occurrence of a catastrophe. Testing the reliability of a railway line and its components, taking into account the subsoil, is of key importance for the safety of transport of hazardous materials by rail.

A disaster involving hazardous materials also affects the operational reliability of the railway line and its capacity.

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