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DOI: 10.35117/A_ENG_18_10_02

Hazardous material-related propagation of the effects of train accidents in the subgrade

Abstract: A large part of the transport of hazardous materials is carried out by rail. Therefore, the security of these transports is becoming increasingly important. Every catastrophe involving dangerous materials has a negative impact on the participants of the incident and the surrounding environment, because its range is generally not local. It follows that in the event of a catastrophe, its effects should be minimized and remediation should be considered in further actions. This whole process of minimization is possible only when we know the mechanism of spreading the effects of a catastrophe involving hazardous materials in the track, subgrade and ground. It should be remembered that in an extreme case, a catastrophe involving hazardous materials may even lead to an ecological disaster. Dynamic systems, especially those with distributed parameters, can be used to describe the mechanism of the disaster's spread. Properties of phenomena accompanying the analyzed catastrophes are well reflected in their linear or non-linear mathematical models analyzed using various operator methods.

Keywords: Railway disasters; Dangerous materials; The effects of disasters

Railway disasters and their impact on the track

The purpose of the article is not to deal with the conditions that dangerous goods should be transported, because it is regulated by relevant regulations. Such transports must meet very strict safety requirements. However, it often occurs for various reasons to the risks associated with the carriage of dangerous goods. This is not only about the transport of dangerous chemicals, but also explosives, technical gases, materials that generate flammable gases in contact with water, etc. These dangerous substances pose a threat to human, animal and environmental life. Transporting large quantities of these materials is a problem, for example, large quantities of H2SO4 sulfuric acid are transported, as well as legally or illegally, particularly from abroad, of various types of garbage. As a result of the uncontrolled release of significant quantities of dangerous substances with oxidizing, flammable, toxic, etc. properties to the environment (leakage during a collision - collision, derailment, unsealing of the tanker during transport, etc.) there may be a risk of ecological disaster.

The situations mentioned above are most often encountered in the case of derailment or collision (Figure 1).

All these events have a negative impact on the railway bedrock (Figure 2).

1. Railway disasters: a) in the Canadian province of Saskatchewan on 7/10/2014; b) in Wydminy on 2 January 2016. Sources: YouTube

2. The negative impact of the railway disaster on the track. The catastrophe in Szczygłowice 05/23/2002 [10]

Collisions and derailments should also be looked at as follows: What if there were dangerous goods on the train?

Railway disaster usually accompanies [5]:

- Leakage of petroleum materials from tanks - no fire (negative impact of petroleum compounds on the bedrack)
- leakage of petroleum-derived materials from tanks connected with a fire (additionally a negative influence of temperature on the bedrack)
- leaking other hazardous materials (e.g. chlorine, sulfuric acid H_2SO_4 - negative effect of chemical compounds on the bedrack)
- the spread of dangerous volatile compounds, etc.

All these materials have a negative impact on the track bed and its elements, e.g. under their influence the basic properties of geosynthetics used in the substructure construction (e.g. embankments, excavations) change in terms of their permeability, strength, and deformation. The widespread use of geosynthetics for the ground reinforcement in the subgrade and related retaining constructions or the strengthening of local caverns by geosynthetics causes their mobilization to stretch. Under these new conditions, the nature of the geosynthetic cooperation changes. Material characteristics caused by high temperatures and chemical agents change, and the characteristics and parameters describing the behavior of the contact zone change. They are different from those accepted in the design or theoretical studies of the dependence of cooperation (primer - geosynthetic or soil - geosynthetic - soil, etc.) and this fact should be taken into account when remediating [4].

Cooperation between the geosynthetics and the elements of the railway subgrade can be described using the d'Alembert operator marked with the symbol. This leads to a partial differential equation $\square u = f(x,y,z,t)$. In this equation $f(x,y,z,t)$ it is characterized by a continuous replacement load, *x, y, z* are coordinates of a point $P \in \Omega$ AT the moment *t*, a *u* is a function of the appropriate class in the set $\Omega \times < 0,\infty)$ and denotes the deflection (displacement, change of the position of the P points of the geosynthetic and its surroundings).

Using the non-classical operators' methods, we can save

$$u(x,y,z,t) = u(\boldsymbol{P},t) =$$

$$= \left\{ \frac{1}{4\pi} \iint_{\sigma} \left[\frac{1}{d(P,P_0)} A\left(\frac{\partial u}{\partial n}\right) - Au \frac{\partial}{\partial n}\left(\frac{1}{d(P,P_0)}\right) + \frac{1}{ad(P,P_0)} A\left(\frac{\partial u}{\partial t}\right) \frac{\partial d(P,P_0)}{\partial n} \right] d\sigma \right\} + \left\{ -\frac{1}{4\pi} \iiint_{\Omega} \frac{Af(P_0,t)}{d(P,P_0)} d\Omega \right\}$$

In the last formula, the symbols as in [4] were adopted. This model describes cooperation in typical conditions (without taking into account the influence of hazardous materials). Their influence in this formula can be taken into account by identifying the model due to the parameter *a* existing in the formula using multidimensional model laboratory research - ground-geosynthetic cooperation.

The leakage of hazardous materials also affects the stabilization of mixtures such as ash and slag mixtures used, inter alia, for the construction of embankments. Hydraulic binders such as lime, cement, Terramix, Solitex etc. can be used here.

In the event of a catastrophe involving tanks with dangerous substances and in the event of their unsealing, contamination (pollution) spreads in the air and soil of the subgrade. In the case of lands, it is known that the change of environmental factors (thermal, chemical, biological) affects the mechanical - strength behavior of the subgrade.

The flow of liquid hazardous materials through drainage ditches means that they also penetrate deep into the ground, penetrate into groundwater and, in some unfavorable cases, they can reach rivers or water reservoirs. In each of these cases, they are a source of dangerous pollution.

Contamination of groundwater from the unsaturated zone (soil waters, membranous waters, capillary waters) and groundwater from the saturated zone and waters with an open flow (with a free surface) is dangerous from the point of view of threats to the natural environment [8].

All these phenomena are dynamic processes [7], which are especially uncontrollable in the initial phase and we should strive to allow the transition to controlling these processes in the shortest possible time because then the impact of the disaster can be reduced, especially in relation to the subgrade and will be facilitated and less expensive remediation [5, 6].

About modeling the effects of a catastrophe

In general, it can be assumed that the effects of a railway disaster are spreading according to the principle that is well described by the solutions of the partial differential equation

$$\frac{\partial}{\partial x}\left(D\frac{\partial u}{\partial x}\right)=\frac{\partial u}{\partial t} \tag{1}$$

with a constant D characterizing the analyzed process under a given condition

$u(x,0)=\varphi(x)$

Each solution to this differential problem is non-zero immediately after the beginning of the process and demonstrates the rapid spread of the effects of the disaster. The solution to the problem is also a function describing the development of the phenomenon depending on x (location) and t (time) for a very non-smooth initial condition, i.e. for φ(x) determined by the Dirac distribution. This reflects the case of a very "sudden" appearance of a negative phenomenon accompanying disasters involving dangerous materials at the moment t=0 (rys. **3**).

This function also shows that the phenomenon accompanying the disaster disappears with time, until it finally disappears.

Emission of the effects of a catastrophe in the ground [6]

Pollution from disasters can dissolve in water or move with it as a slurry. In the case of a disaster involving hazardous materials, it is important to model the propagation of groundwater pollution. Petroleum compounds get into the ground not only in the event of a collision or derailment but also as a result of accidental floods during transport, filling, transfer, etc. They contain toxic compounds such as benzene, toluene or xylenes. In unfavorable conditions, they can migrate over long distances, and the cleaning of groundwater is associated with high costs. The assessment of the impact of these and other pollutants on groundwater quality, and especially the design of measures to minimize the negative effects of contamination requires the creation of models that will allow for qualitative and quantitative prediction of migration of pollutants in the ground of the subgrade, including geosynthetics. These migrations depend on the hydrogeological properties of the soil. Pollutants that get into the ground flow down under the influence of gravity and thanks to the permeability of the medium they reach the underground water. This flow through the porous medium describes Darcy's law [1]

$$q=-K\Delta\varnothing/L$$

where q is the flow of water through a section of the medium with a unit cross-sectional area and volume L in a unit of time at a hydraulic slope $\Delta\varnothing$. K is the hydraulic conductivity coefficient, and the minus sign means that the flow direction is opposite to the direction of potential growth.

If $\vec{q}$ is a vector unit flow, then for an isotropic medium, i.e. a medium in which the permeability is not dependent on the direction, Darcy's law has the formć

$$\vec{q}(\vec{x},t) = -K(\vec{x})grad\varnothing(\vec{x},t)$$

For the anisotropic medium in which the permeability depends on the direction, the hydraulic conductivity is the tensor represented by the symmetrical matrix of the form

$$K=\begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

which after entering the appropriate coordinate system can be reduced to a diagonal form

$$K = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix}$$

The equation of mass behavior at constant water density is a form [2]

$$-div\vec{q} = \frac{1}{V_0}\frac{\partial V_w}{\partial t} \ .$$

If

$$\frac{1}{V_0}\frac{\partial V_w}{\partial t} = \frac{1}{V_0}\frac{\partial V_w}{\partial \phi}\frac{\partial \phi}{\partial t} \ ,$$

so using the elastic filtrationS_0, which is defined by the formula

$$S_0 = \frac{1}{V_0}\frac{\partial V_w}{\partial \phi} \ ,$$

Where V_0 and V_w mean respectively the volume of the medium and the volume of water can be saved using the Darcy equation

$$div\left(K(\vec{x})grad\emptyset\right) = S_0\frac{\partial \emptyset}{\partial t} \qquad (2)$$

In the last equation, there is a quantity whose determination allows to determine the unit flow and this is the basic equation describing the movement of water, which is the medium responsible for the spread of contamination, pollution in the trackbed.

If we accept the coordinate system so that the tensor K will be a diagonal tensor, then the last equation will simplify and take the form

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

In the case of a homogeneous, isotropic medium, the last differential equation will take the form

$$K\left(\frac{\partial^2\emptyset}{\partial x^2} + \frac{\partial^2\emptyset}{\partial y^2} + \frac{\partial^2\emptyset}{\partial z^2}\right) = S_0\frac{\partial\emptyset}{\partial t}, \ K = K_x = K_y = K_z.$$

If the flow is stationary, then for$\emptyset$ we get the Laplace equation of the form

$$\frac{\partial^2\emptyset}{\partial x^2} + \frac{\partial^2\emptyset}{\partial y^2} + \frac{\partial^2\emptyset}{\partial z^2} = 0 \ .$$

This equation can be solved using a non-classical account of operators with many derivatives or by approximation of laplacian using the flow in a tube of diameter δ [7].

If the pollution changes the density of water, i.e. $\rho = \rho(c)$, where c is the concentration of contamination then the mass behavior equation will take the form [9]

$$-div\rho\vec{q} = \frac{1}{V_0}\frac{\partial(\rho V_w)}{\partial t}$$

We calculate $\frac{\partial(\rho V_w)}{\partial t}$ and use the formula $div\ \rho\vec{q} = \vec{q}grad\rho + \rho div\vec{q}$ from field theory.

We obtain

$$\frac{\partial(\rho V_w)}{\partial t} = V_w\frac{\partial\rho}{\partial t} + \rho\frac{\partial V_w}{\partial t}$$

so

$$\frac{1}{V_0}\frac{\partial(\rho V_w)}{\partial t} = \frac{V_w}{V_0}\frac{\partial\rho}{\partial t} + \frac{\rho}{V_0}\frac{\partial V_w}{\partial t} = -\vec{q}grad\rho - \rho div\vec{q}$$

so

$$-\vec{q}grad\rho - \rho div\vec{q} = \frac{V_w}{V_0}\frac{\partial\rho}{\partial t} + \rho S_0\frac{\partial\emptyset}{\partial t}$$

Assuming that $P = \frac{V_w}{V_0}$ is the porosity of the center, the last dependence can be written in the form

$$-\vec{q}grad\rho - \rho div\vec{q} = P\frac{\partial \rho}{\partial t} + \rho S_0\frac{\partial \emptyset}{\partial t}.$$

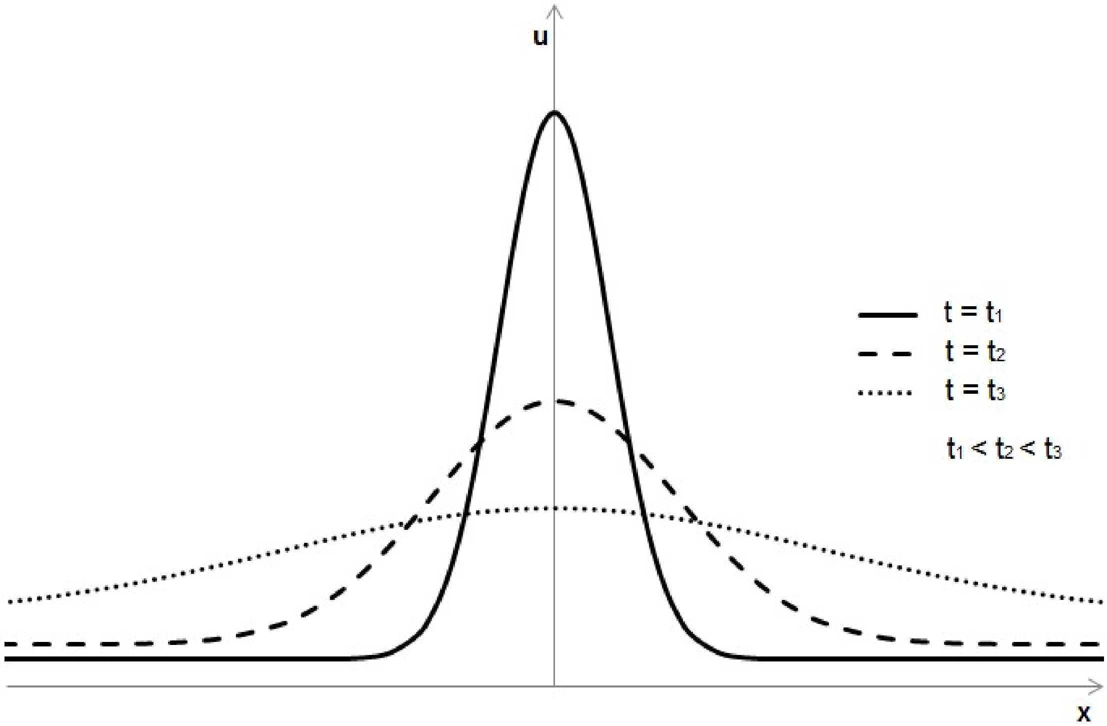
With small changes in density, it can be assumed that the first components on both sides of the last equality are small enough and can be omitted. After taking this fact into account, in this case, we will also get the equation of the form (2). This means that in the next model we get the same equation describing a given problem. It follows that the spread of dangerous compounds in the ground caused by the railway disaster can generally be described by the equation (2) and used in practice to limit its negative effects, including in relation to the subgrade.

As mentioned, a railway disaster involving hazardous materials may be accompanied by fire. It is additionally dangerous if, for example, a gas pipeline runs nearby. Then such an uncontrolled increase in the temperature of the track bed may additionally lead to a gas explosion and cause further losses. This change in temperature also has a negative impact on the mixes used to build the track bed, as well as the applied reinforcement with geosynthetics. In this case, it is important to describe the vertical changes in temperature in the ground. They can be determined from the equation

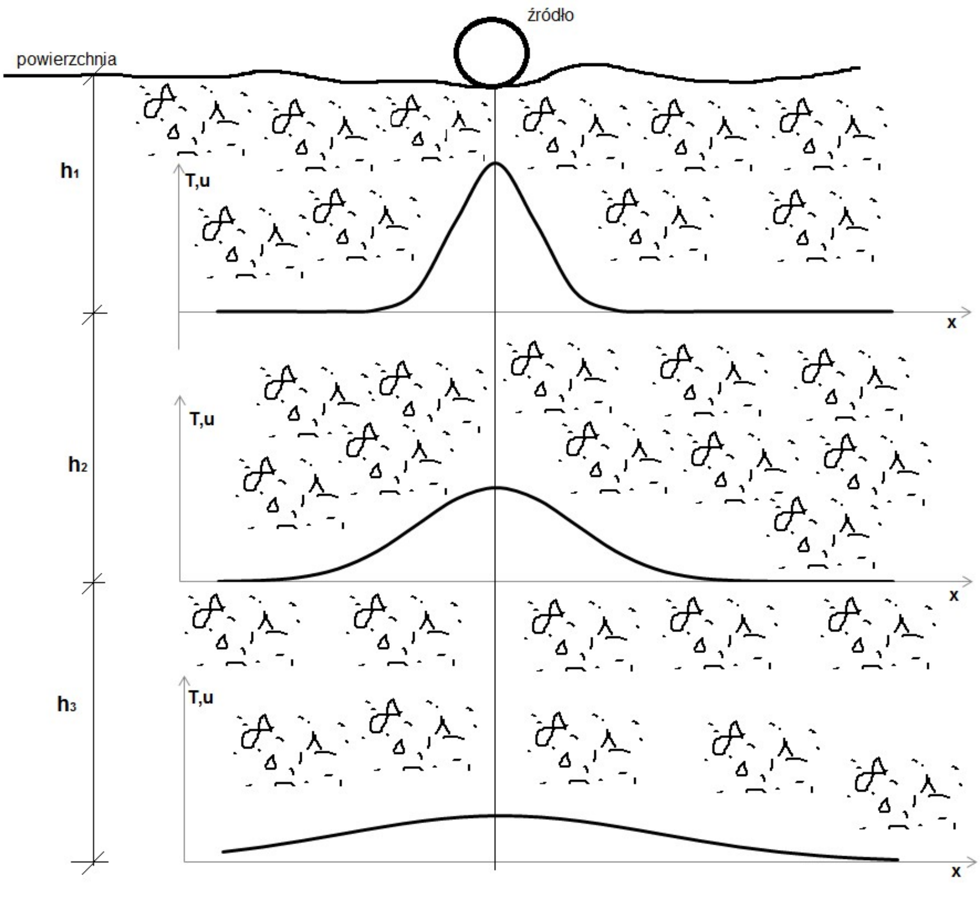
$$\frac{\partial(cT)}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right),$$

where T is the temperature, c is the thermal capacity of the unit of ground volume, and K is the thermal conductivity of the ground. Using this equation, you can determine the temperature distribution depending on time and depth (Figure 4), and by attaching the component to it $f(z,t)$ characterizing the temperature source, you can additionally take into account the influence of the heat emission source. The last differential equation is analogous to the equation (1), although it describes another phenomenon occurring in the track bed, however, from a mathematical point of view, it has the same properties as (1) [3]. The extinction of changes caused by a catastrophe, and more precisely its effects according to the last equation, takes place in time (Figure 3), as well as the depth increase (Figure 4). This also applies to propagation of vibrations, e.g. from an explosion.

From this, it follows that the negative effects of a catastrophe from the point of view of their course behave, as shown in Figures 3 and 4, as long as we liquidate the source or limit (reduce) its operation. Therefore, in order to limit the negative consequences of a railway disaster, their source (leak, explosion, fire) should be eliminated in a short time or at least its range should be reduced. By doing this, you can also limit its negative impact, among others, on the railway track.



3. The spreading of the phenomenon in time with its sudden appearance in the initial moment in the form of distribution



4. Change in temperature and other effects of a catastrophe in the track, along with a change in depth.

Summary

The number of transports of dangerous goods is constantly growing, among them transport of these materials by railways.

As a result of railway disasters involving hazardous materials, there may be eg fires, air contamination, subgrade and further ground, water.

Disasters involving hazardous materials cause many disasters, fatal poisoning, burns, etc. They have a negative impact on the environment.

In the event of a disaster, its negative effects should be minimized and remediation carried out.Knowledge of the properties and course of phenomena accompanying rail disasters involving hazardous materials reduces their effects and facilitates remediation.

The properties of phenomena accompanying the analyzed disasters are well reflected in their mathematical models relating to air, water and ground flow, including the flow of heat.

The phenomena accompanying the analyzed catastrophes can be studied using the operator methods, and the results obtained in practice.

The negative impact of a railway disaster on the track bed is also connected with its construction in which geosynthetics, mixtures, etc. sensitive to the effects of various chemical compounds or temperatures can be used.

Source materials

[1] Eagleson P. S., Hydrologia dynamiczna, Państwowe Wydaw. Naukowe, Warszawa, 1978.
[2] Holnicki P., Nahorski Z., Żochowski A., Modelowanie procesów środowiska naturalnego, Wyższa Szkoła Informatyki Stosowanej i Zarządzania, Warszawa, 2000
[3] Lawrence C. Evans, Partial Differential Equations, American Mathematical Society, 2002
[4] Mieloszyk E., Grulkowski S., Generalized Taylor formula and shell structures for the analysis of the interaction between geosythetics and engineering structures of transportation lines, Shell Structures: Theory and Applications, vol. 4/ ed. Wojciech Pietraszkiewicz & Wojciech Witkowski Londyn: Taylor & Francis, 2018, s.561-564.
[5] Mieloszyk E., Milewska A., Grulkowski S., Rozprzestrzenianie się skutków dużych katastrof kolejowych, Archiwum Instytutu Inżynierii Lądowej, Poznań, iss. 25 (2017), s.301-310.
[6] Mieloszyk E., Milewska A., Risks associated with the transportation of hazardous materials on public roads, XII Międzynarodowa Konferencja Bezpieczeństwa Ruchu Drogowego Gambit 2018, Politechnika Gdańska, 12-13 kwietnia 2018
[7] Mieloszyk E., Nieklasyczny rachunek operatorów w zastosowaniu do uogólnionych układów dynamicznych. Gdańsk: IMP PAN, 2008.
[8] Świdziński W., Mierczyński J., Badania laboratoryjne zjawiska podatności cyklicznej w nawodnionym, Inżynieria Morska i Geotechnika, nr 4/2009, 271-280
[9] Tihonow A. N., Samarski A. A., Równania fizyki matematycznej, PWN, 1963
[10] Węsierski T., Nagrodzka M., Wypadek kolejowy w Szczygłowicach. Przebieg zdarzenia oraz analiza zagrożeń rzeczywistych oraz potencjalnych, Bezpieczeństwo i Technika Pożarnicza, 2012, nr 1, 113-120