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GENERALIZED STATEMENT OF THE PROBLEM OF REDUCING THE RISK OF MINER EVACUATION DURING AN EMERGENCY SITUATION USING TRANSPORT LOGISTICS

Abstract. The main task of the emergency protection system in the event of an emergency in a coal mine (we consider emergencies with aerological consequences, that is, those whose occurrence causes a violation of the ventilation regime in the emergency area) is to organize emergency evacuation of miners from the emergency and hazardous areas to the surface in the shortest possible time. Many domestic and foreign studies have been devoted to solving this problem, taking into account various aspects of the course of accidents and approaches to emergency evacuation, starting from the 60s and 70s of the twentieth century. The task is very complex, since it involves the preliminary solution of a number of related tasks , from prompt notification of people in hazardous areas about the need for emergency evacuation to bringing information about its features to people being evacuated. However, the following problems have not been solved: organizing collective self-rescue of people (using life support systems), periodic use of workings contaminated with gaseous products of the emergency on the evacuation route (people are still included in self-rescuers), provided that this will significantly reduce the safe evacuation time; using vehicles for evacuation, provided that at that time the mine has electricity; uninterrupted cyclic operation of lifting equipment is involved. The issues of accumulating people being evacuated at switching points into reserve self-rescuers, keeping them in storage chambers until the arrival of the State Paramilitary Mining Rescue Service, accumulating people in the shaft yards of shafts intended for emergency evacuation, etc. have not been solved. Therefore, in general terms, the problem of emergency evacuation is formulated taking into account all these factors.

Research has shown that to solve the problems of moving groups of people, taking into account their accumulation in the initial and intermediate evacuation points and the use of combined means of transport, the mathematical methods used to date are not enough. Methods based on the use of graph theory do not take into account the suspension of movement along routes to perform related tasks. Taking into account these related tasks requires imposing additional restrictions on transport flows.

As a result of the research, the problem of organizing emergency evacuation of miners from emergency and hazardous areas of the mine in the event of an exogenous fire using transport logistics has been formulated in a generalized manner.

Keywords: emergency evacuation routes of miners, hazardous areas of the mine, transport logistics.

1. Introduction

The main task of the emergency protection system (EPS) in the event of an emergency in a coal mine (we consider emergency with aerological consequences, i.e. those whose occurrence causes a violation of the ventilation regime in the emergency area) is to organize the emergency evacuation of miners from the emergency and hazardous areas to the surface in the shortest possible time [1]. The task is very complex, since it involves the preliminary solution of a number of related tasks, from prompt notification of people in hazardous areas about the need for emergency evacuation to providing people being evacuated with information about its features. Therefore, in domestic and foreign practice, considerable attention has been paid to solving the problems of reducing the risk of emergency evacuation of miners.

What is the risk of emergency evacuation? The fact is that within the framework of solving the plan of emergency liquidation (PEL) problems, the classical definition of risk as the product of the probability of an event and the severity of the consequences is unacceptable. The probability of an event, in the presence of an emergen-

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cy, is equal to one, and the severity of the consequences, at least in the first period of its occurrence, that is, until the end of emergency evacuation, cannot be estimated in monetary terms. Therefore, risk must be assessed as a measure of uncertainty; the criterion in this case is the full time of emergency evacuation. In all existing optimization methods based on solving route problems on strongly connected graphs, this time did not sufficiently correspond to reality, since it was determined for continuous movement along the route at a stable speed. However, forced delays were not taken into account, as mentioned above, and there was a risk of uncertainty in the PEL operational time and its violation, and therefore - the impossibility of timely starting to take measures to eliminate the emergency.

General issues of emergency evacuation organization were covered in works [2-8]. Works [9-11] are devoted to the creation and use of storage chambers on evacuation routes. Studies [16-18] are devoted to the study and optimization of people's movement speeds during evacuation, and works [15 and others] are devoted to their protection. The introduction of personal computers into mining practice has allowed to set and successfully solve the problems of automating the compilation and implementation of emergency evacuation plans, an integral part of which is emergency evacuation [12-14, 20-22 and others]. This list can be continued, not taking into account the studies carried out earlier.

At the same time, general approaches to solving emergency evacuation problems in a complex, not counting individual attempts to adapt route problems on graphs, are currently absent in both domestic and foreign practice.

Since the 1980s, the Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine has developed basic approaches to solving the problem of organizing emergency evacuation of miners from hazardous and dangerous areas of the mine. In a simplified form, with significant limitations, they are set out in the monograph [23]. Later, after conducting a number of calculation experiments in the mines of Donbas, additional risk factors for emergency evacuation were taken into account, namely:

- the possibility of periodic use on the evacuation route of workings gassed with gaseous products of the emergency (people are still included in the self-rescuers) provided that this significantly reduces the safe evacuation time;
- the use of vehicles for evacuation, provided that at the time of their use there is power supply to the mine;
- uninterrupted cyclic operation of lifting equipment is involved.

Under these conditions, methods for solving emergency evacuation problems are set out in [24].

However, these additions do not limit the list of emergency evacuation tasks. The issues of accumulating evacuees at transfer points to reserve self-rescuers (PRSR) keeping them in storage chambers until the arrival of the State Paramilitary Mining Rescue Service (SPMRS), accumulating people in the shaft yards of shafts intended for emergency evacuation, etc. have not been resolved. Therefore, in general, the purpose of the article is to generalize the formulation of the problem of emergency evacuation of miners, and the purpose of further research will be to develop a comprehensive method for solving.

2. Methods

Such a complex method will include:

- for individual simple sections of evacuation routes contaminated with gaseous products of the emergency - classical route methods of graph theory and analog methods of dynamic programming;
- for complex sections of routes (including vertical and inclined workings, as well as collective self-rescue means) - original methods [23];
- for individual sections that include the transition from clean workings to contaminated ones and, after a certain period of time, vice versa - original methods [24];
- to remove other restrictions on the problem statement, which will be given below - transport logistics and fuzzy logic.

3. Theoretical part

When solving the problem, we agree to consider the workings *(i,j)* not oriented along the course of the gas-air jet, that is, not to determine their movement from *i* to j. We define the workings with a given orientation as $\overline{(i,\,j)}$.

The chain connecting the nodes i_k and j_l is denoted as

$$\wedge\left(i_k, j_l\right) = \sum_{m=1}^{n}\left(i_m, j_m\right), i_1 = i_k, i_n = j_l, i_{m+1} = j_m.$$

Let us denote: I_H^i - the set of initial nodes (initial route set) of routes of type *I* (*i=1*), *II* (*i*=2) or *IV (i=4)*; I_c^i - the final route set of *II (i=2)* or initial *III (i=3)* or *IV (i=4)*; I_k^i - the final route set of type *I (i= 1), III (i=3)* or *IV (i= 4).* Obviously, $I_k^i = M_2$.

Since a type III route exists only if there is a type II route, then $I_c^i = i_k$, i=3, $i_k \in I_c^2$, $i_k \in I_c^2$ is the node at which the corresponding type II route ends.

The weight of node *i* is the number P_i (their set is MP_i), assigned to this node according to the rule

$$\tau_\mu = \sum_{(i',\,j')\in\mu(i,j)} \frac{P(i',\,j')}{\nu(i',\,j')}.$$

In accepted notation

$$\mu\left(i_k,\ \underset{i_k\in I_t}{I_s}\right) = \min_{\tau_\mu} \Lambda\left(i_k, j_l\right); \qquad I_s = \bigcup_l j_l = \left\{\begin{matrix} I_c^2, if\ I_T = I_H^2 \\ I_k^1, if\ I_T = I_H^1 \\ I_k^3, if\ I_T = I_c^3 \\ I_k^4, if\ I_T = I_c^4 \end{matrix}\right\}$$

Then the problem of finding emergency evacuation routes for people from a mine in the event of an exogenous fire can be mathematiclly formulated as follows:

$$\overline{M} = \sum_{i=1}^{n_1} \tau_{\mu(\underset{k_i \in I_c^1}{k_i}, I_k^1)} + \sum_{i=1}^{n_2} \left[\tau_{\mu(\underset{k_i \in I_H^2}{k_i}, I_c^2)} + \tau_{\mu(\underset{k_i \in I_c^3}{k_l}, I_k^3)} \right] + \sum_{i=1}^{n_3} \tau_{\mu(\underset{k_i \in I_c^4}{k_i}, I_k^4)} \to \min \qquad (1)$$

under restrictions:

a) the calculation of nodal weights is carried out according to the formula

$$P_{j_l} = \min_{\tau_\mu} \left\{ P_{i_k} + P(i_k, j_l), i_k \in \mu_{j_l} \right\}$$

b) depending on the conditions of formation, emergency evacuation routes for miners can be presented in the form

$$\mu(i_k, I_T) = \left\{ \begin{array}{l} \mu(i_k, I_c^1) + \mu(I_c^1, I_k^1), i_k \in I_H^1, \quad if \quad \sum\limits_{(i',j') \in \mu(i_k, I_T)} \dfrac{L(i',j')}{\nu(i',j')} \prec \tau_{c.c.} \\ \mu(\underset{i_k \in I_H^2}{i_k}, I_c^2) + \mu(\underset{j_k \in I_c^3}{j_k}, I_c^3) + \mu(I_c^3, I_k^3), if \text{ the route passes through switching PRSR} \\ \mu(i_k, I_k^4), i_k \in I_c^4, \quad if \text{ people are heading to the support chamber} \end{array} \right\}$$

c)

$$P(i_k, j_l) = \left\{ \begin{array}{ll} \infty, & S(i_k, j_l) \prec S_{\min} \; or \; t(i_k, j_l) \succ t_{ul} \; or \; C(i_k, j_l) \succ C_{ul} \\ L(i_k, j_l), & (i_k, j_l) \in (\theta \setminus \theta_{gas}) \bigcap (\theta \setminus \theta_T) \\ L(i_k, j_l)(1 + k_1), & (i_k, j_l) \in \theta_{gas}, C_c \le C(i_k, j_l) \le C_{ul} \\ L(i_k, j_l)(1 + k_2), & (i_k, j_l) \in \theta_T, t_c \le t(i_k, j_l) \le t_{ul} \\ L(i_k, j_l)(1 + k_1 + k_2), & (i_k, j_l) \in \theta_{gas} \bigcap \theta_T, C_c \le C(i_k, j_l) \le C_{ul}, t_c \le t(i_k, j_l) \le t_{ul} \\ \dfrac{L(i_k, j_l)\nu_p(i_k, j_l)}{\nu_K, (i_k, j_l)} \cdot k_3, & (i_k, j_l) \in \theta_c \end{array} \right\}$$

d) taking into account the orientation of the route's workings that are included in the gas-contaminated zone

$$\begin{array}{l} (i_k, j_l) \in \mu(i_p, I_s), (i_k, j_l) \in \theta_{gas}, C_c \le C(i_k, j_l) \le C_{ul}, \\ if \quad a) \; (i_k, j_k) = \overline{(i_k, j_k)}; \qquad\qquad ; \\ \qquad b) \; \mu(i_p, I_s) = \mu\overline{(i_p, I_T)} + \mu(I_t, I_s), I_t = \{j_k\} \end{array}$$

e) taking into account the movement of people through the shafts.

The time for lifting people in the number $\lambda_c(i,j)$ to the surface should be calculated in the following variants:

1) $\lambda_c(i,j)$ is equal to the capacity of the cage, $\Rightarrow$ the evacuation time is determined by the time of twice the movement of the cage from the initial node of the shaft of he surface;

2) $\lambda_c(i,j)$ is equal to the capacity of the cage, but there is no cage

$$\tau_{sh} = \tau(i_k, j_k) + \tau_{mov}, i_k = i_c, j_k \in M_2$$

3) $\lambda_c(i,j)$ is greater than the capacity of the cage;

$$n_\partial \le t_\partial / t_y \cdot n_y;$$

4) $(i_k, j_k) = \bigcup (i'_k, j'_k), i_k \in i_c, i'_k \in i_c, j_k \in M_2, j'_k \in M_2$ that is, this fragment of the route is a set of parallel sections from the i_c to the surface; the number of such sections is determined by the time of the cage rotation cycle for one cycle of removing a group of people and their number n_y. $\forall \tau(i'_k, j'_k) = \tau(i_k, j_k)$;

f) emergency evacuation starting points (EESP) (points k_i in (1)) are determined as follows:

1) $(i,j)=(i^*,j^*)$;

$$(j, j) \in \{(i^*, j_1), (i^*, j_2), \ldots, (i^*, j_{n_1}), (l_1, j^*), (l_2, j^*), \ldots, (l_n, j^*)\};$$

2) $$P(i, j) + \sum_{(i_k, j_k) \in \mu(j, i_p)} P(i_k, j_k) = \min\{ \sum_{(i_k, j_k) \in \mu(j, i_p)} P(i_k, j_k)\}, \quad i_p \in M_2.$$

The EESP includes a minings that are incident to the initial node (i^*,j^*), i.e. either not gassed at all or is part of a temporarily gassed zone. The formation of a route from it determines the direction of evacuation of people from the emergency mining located in it to the fire center.

3) $$(i, j) \in M_N \bigcap \theta_{gas} \ne \varnothing, M_N : \{(i_1, j_1), \ldots, (i_n, j_n)\}, \lambda(i, j) = \max_{(i_k, j_k) \in M_N \bigcap \theta_{gas}} \lambda(i_k, j_k) \quad .$$

The following basic notations are used in the formulation of the problem: N - the number of the PEL position. Otherwise, one working from each gassed PEL position is included in the list of EESP; moreover, it has the maximum $\lambda(i,j)$ among them; n_1, n_2 - the measure of the set I_k^1 and I_c^2, respectively, which is equal to the number of nodes that make it up; S_{min} - the minimum value of $S(i,j)$, at which the working (i,j) becomes impassable for people; $P(i_k,j_k)$ - the criterion for the permeability of the working; k_1, k_2 - numerical coefficients chosen from practical considerations and characterizing the degree of permeability of the working (i,j), if $(i,j)\in\theta_{gas}$ or $(i,j)\in\theta_T$ respectively; μj_k - the set of nodes adjacent to j_k; C_c, t_c - critical values of $C(i,j)$ and $t(i,j)$, starting from which they begin to affect the permeability of (i,j); C_{ul}, t_{ul} - values of $C(i,j)$ and $t(i,j)$, at which (i,j) becomes impassable for people; I_c^i - set of initial, in the direction of movement along the route, nodes of trunks intended for emergency evacuation; $V_p(ik,jl)$ - speed of movement of people along the trunk, if the movement along it took place on foot; $V_к(i_k,j_l)$ - speed of movement of the cage; $к_3$ - coefficient, taking into account the time spent on organizing the cycle of cage movement; τ_{mov} - time of cage movement along the trunk from M_2 to i_c; $n_д$ - number of people who can be transported during the time period $t_д$; t_y - time of one cycle of cage operation; n_y - number of people transported during one cycle.

The record $\mu(\overline{i_p, I_T})$ means that .

$$\forall(i_k, j_k) \in \mu(\overline{i_p, I_T}) \Rightarrow (i_k, j_k) = \overline{(i_k, j_k)}.$$

4. Results and discussion

The problem statement should be commented on as follows:

a) the form of the functional (1) does not mean minimizing only the total value of the criterion. The minimum of the sum implies the sum of the minimums of the components;

b) only those components that are present at a specific mine are included in (1). The same applies to constraint 2;

c) if $\theta_T = \varnothing$ - in constraint 3, $P(i_k,j_l)$ associated with the introduction of k_2 are not considered.

Thus, based on the list of persons (their groups within the position of the PEL) subject to evacuation, starting from the places of their accumulation, the evacuation direction is formed, taking into account the limitations of the task. Further consideration should be directed to identifying the risks of emergency evacuation and methods for their reduction.

The result obtained indicates maximum consideration of all factors that characterize the emergency evacuation of miners. The approach is original, different from those proposed in previous studies (we emphasize that such generalized approaches do not exist at all to this day).

Studies have shown that to solve the problems of moving groups of people, taking into account their accumulation in the initial and intermediate places of evacuation and the use of combined means of transport, mathematical methods that have been used to this day are not enough. Taking into account the implementation of related tasks requires imposing additional restrictions on transport flows. Therefore, it seems more appropriate to use, in addition to classical, methods of transport logistics. It is only necessary to find out what its main provisions correspond to the principles of emergency evacuation of miners in the event of an aerological emergency in a coal mine.

In accordance with the requirements of transport logistics, the main task of the PEL is formulated in an expanded form as follows: *it is necessary to determine the optimal routes for emergency evacuation of people from their locations in the mine to the surface, taking into account the passability of mining workings according to geometric, emergency, ergonomic and time characteristics, the possibility of using un-*

derground transport, the cyclicity of lifting equipment and the possibility of violating the requirements of the Safety Rules (using expert assessments) to increase their efficiency.

Mathematically, this task was exhausted set above.

The task of transport logistics, according to a well-known definition, is the organization of delivery, namely the movement of material objects, substances, **etc**. (we have highlighted - namely people!) from one point to another along optimal routes. All components are present in our task:

a) *selection of the type of vehicle* – movement on foot is assumed due to the mine power outage in the event of an emergency; in some cases, underground transport may be used;

b) *joint planning of transport processes with warehouse and production operations* – organization of gathering people at the initial evacuation points, interruption of the route (analogous to refueling and rest) to switch to reserve self-rescuers or waiting for SPMRS departments;

c) *joint planning of transport processes by different types of transport* – the route consists of sections that are overcome on foot (partially, if possible, using underground transport) and mine shafts (pendulum route);

d) *ensuring technological unity of the transport and warehouse process* – organization of evacuation in such a way as to synchronize the approach of groups of people to the initial evacuation points and movement along the route with their accumulation/removal from the near-shaft yard by lifting means;

e) *determination of rational delivery routes*. In determining transport logistics, this is taking into account the factors of labor intensity of overcoming routes. When determining evacuation routes, the following are taken into account:

- geometric factors - the mine is too "tight";
- emergency factors - thermal and gas;
- ergonomic factors - how much the average person is able to overcome workings of various slopes and clutter;
- time - taking into account the time of the self-rescuer's protective action;
- the possibility of violating the requirements of the Safety Rules - an attempt to clearly shorten the route without violating the above requirements (except for the emergency factor; a substantiated expert assessment is necessary to assess the possibility of its violation)

5. Conclusions

1. Summarizing the above, we can conclude that the formulated task of organizing emergency evacuation of miners from emergency and threatening sections of the mine in the event of an exogenous fire is relevant, different from previously proposed ones.

2. A new approach to emergency evacuation has been obtained, which includes a differentiated approach to assessing various elements of the route, including suspending movement along it depending on the peculiarities of the evacuation conditions.

This is impossible using classical methods and requires the use of transport logistics and methods of minimization not insignificance by fuzzy logic.

3. The method for solving the problem of reducing the risk of evacuation of miners during an emergency is under development, since it requires adapting transport logistics methods to the goal of the task. In addition, it is necessary to substantiate some aspects of the use of fuzzy set theory.

4. Among the transport logistics tasks for the EPS one can name the organization of inspection of emergency and hazardous areas of the mine by the SPMRS forces, delivery of materials and equipment for liquidation of the accident, etc. They are waiting for their solution.

Conflict of interest

Authors state no conflict of interest.

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УЗАГАЛЬНЕНА ПОСТАНОВКА ЗАДАЧІ ЗНИЖЕННЯ РИЗИКУ ЕВАКУАЦІЇ ШІХТАРІВ ПІД ЧАС ВИНИКНЕННЯ АВАРІЙНОЇ СИТУАЦІЇ З ВИКОРИСТАННЯМ ТРАНСПОРТНОЇ ЛОГІСТИКИ

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Анотація. Основним завданням системи протиаварійного захисту при виникненні аварії у вугільній шахті (нами розглядатимуться аварії з аерологічними наслідками, тобто такі, виникнення яких викликає порушення вентиляційного режиму у аварійній ділянці) є організація аварійної евакуації гірників з аварійної і загрозливих ділянок на поверхню у найкоротший термін. Вирішенню цієї задачі з урахуванням різних аспектів протікання аварій і підходів до аварійної евакуації, починаючи ще з 60-х – 70-х років XX століття було присвячено багато вітчизняних і іноземних досліджень. Задача є вельми складною, оскільки передбачає попереднє вирішення цілого ряду супутніх задач, від оперативного оповіщення людей у загрозливих ділянках щодо необхідності аварійної евакуації до доведення до людей, що евакуюються, відомостей про її особливості. Однак при цьому не вирішені все одно проблеми: організації колективного саморятування людей (використання систем життєзабезпечення), періодичного використання на маршруті евакуації виробок, загазованих газоподібними продуктами аварії (люди все одно включені у саморятівники) за умови, що це значно скоротить безпечний час евакуації; використання для евакуації транспортних засобів за умови, що на момент цього електропостачання шахти існує; задіяна безперебійна циклічна дія засобів підйому. Не вирішені питання накопичення у пунктах переключення людей, що евакуюються, у резервні саморятівники, знаходження їх у камерах-сховищах до прибуття відділення Державної воєнізованої гірничорятувальної служби, накопичення людей у навколоствольних дворах стовбурів, призначених для аварійної евакуації, тощо. Тому у загальному вигляді сформульовано задачу аварійної евакуації з урахуванням усіх цих чинників

Дослідження показали, що для вирішення задач переміщення груп людей з урахуванням їх накопичення у початкових і проміжних місцях евакуації і використання комбінованих засобів руху недостатньо математичних методів, які використовувались донині. Методи, засновані на використанні теорії графів, не враховують призупинення руху маршрутами для виконання супутніх завдань. Врахування цих супутніх завдань потребує накладення додаткових обмежень на транспортні потоки.

В результаті досліджень узагальнено сформульовано задачу організації аварійної евакуації гірників з аварійних і загрозливих ділянок шахти при виникненні екзогенної пожежі з використанням транспортної логістики.

Ключові слова: маршрути аварійної евакуації гірників, загрозливі ділянки шахти, транспортна логістика.