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S.I. Skipochka, D.Sc. (Tech.), Professor
V.V. Krukovskaya, D.Sc. (Tech.), Senior Researcher
(IGTM NAS of Ukraine),
S.D. Grebenyuk, Ph.D. (Tech.), Engineer
(JSC «Donetskstal»)

SIMULATION OF THE SOIL WASHING-OUT AND CAVITATION OUTSIDE THE CONCRETE CASING IN THE PROCESS OF SPILLWAY OPERATION

С.І. Скіпочка., д-р техн. наук, проф.
В.В. Круковська, д-р техн. наук, ст. наук. співроб.
(ІГТМ НАН України)
С.Д. Гребенюк, канд. техн. наук, інженер
(ЗАТ «Донецьксталь»)

МОДЕЛЮВАННЯ ВИМИВАННЯ ПОРОЖНИН В ҐРУНТІ ПОЗА БЕТОННОЮ ОБОЛОНКОЮ В ПРОЦЕСІ ЕКСПЛУАТАЦІЇ ШАХТНОГО ВОДОСКИДУ

С.И. Скипочка, д-р техн. наук, проф.
В.В. Круковская, д-р техн. наук, ст. науч. сотр.
(ИГТМ НАН Украины)
С.Д. Гребенюк, канд. техн. наук, инженер
(ЗАО «Донецксталь»)

МОДЕЛИРОВАНИЕ ВЫМЫВАНИЯ ПОЛОСТЕЙ В ГРУНТЕ ЗА БЕТОННОЙ ОБОЛОЧКОЙ В ПРОЦЕССЕ ЭКСПЛУАТАЦИИ ШАХТНОГО ВОДОСБРОСА

Abstract. Chemical and mechanical processes of the buried concrete elements breakage, water filtration through the damaged concrete into enclosing soil, and cave formation due to the soil washing-out were studied with the help of computer simulation. The authors created several mathematical models which describe: moisture diffusive transfer in the porous structure of concrete with taking into account water participation in the chemical reactions; changes in the stress state of the buried concrete constructions and strength retrogression caused by high humidity and corrosive medium; and water filtration through the damaged concrete into enclosing soil. The models adequacy was verified by a set of full-scale experiments. The data obtained by the calculations were successfully applied during reconstruction of hydraulic objects in the mine Colliery Group «Pokrovskoye».

Keywords: simulation, finite elements method, water transfer inside the concrete construction, concrete permeability, stress state, water filtration, soil washing-out and cavity formation.

State of reinforced-concrete constructions is of great importance for providing a long safety operation of hydrotechnical objects as the state deterioration could cause a number of emergency consequences including those of ecological nature.

The Colliery Group «Pokrovskoe»» has a branched infrastructure including a culvert complex. The culvert consists mainly of the spillways with two buried pipes of round section with 2.0 m diameter that are rated for long-term exploitation. Because .

of natural aging of concrete, negative effect of aggressive medium and static loads caused by soil, reliability of load and filling elements in the culvert is essentially degraded. Active processes of water filtration through the concrete casing happen in the soil thickness around the constructions. The seepage gradually washes out the enclosing soils forming cavities filled with water.

For mathematical description of the processes, the authors has worked out a scheme which truly reflects the following processes:

1) moisture diffusive transfer in the porous structure of concrete with taking into account water participation in the chemical reactions;

2) changes in the stress state of the buried concrete constructions and strength retrogression caused by high humidity and aggressive medium;

3) water filtration through the damaged concrete into the enclosing soil.

These problems are closely interdependent having common arrays of basic data. Any of the problems is solved basing on the result of previous problem solving. Thanks to the thorough verification every stage of the model, the authors created a set of computer programs practical application of which benefited a lot during reconstruction of the above mentioned mine.

Mathematical description of water transfer inside the concrete constructions takes into account the following processes: water diffusion in the concrete casing and participation of water in chemical reactions occurred due to the corrosion of concrete and metal fittings.

From the first and second Fick's laws for a plane problem, it follows that:

$$J_x = -D\frac{\partial w}{\partial x};\; J_y = -D\frac{\partial w}{\partial y};$$

$$\frac{\partial w}{\partial t} = D\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right);$$

where J_x, J_y is density of the diffusive flow along the x and y axes; D is a coefficient of diffusion; w is water amount in the pore space, %; and t is time duration.

Taking into account possible chemical interaction between transported by the spillway solution and components of the reinforced-concrete casing [1, 2], it is possible to write down the following:

$$\frac{\partial w}{\partial t} = D\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) + g(t); \tag{1}$$

where $g(t)$ is a function of moisture absorption (weep) in result of chemical interaction.

Concrete resistance to action of chemical reagents is lower than to any other actions among which cement leaching and actions of sulfates and natural weak-acid waters most frequently occur.

As for example, let's consider how sulfates effect on the concrete. Some clays contain alkalis and sulfates of magnesium and calcium, and subsoil waters in such clays present solutions of sulfates. Sulfates, being in the solution, enter into reaction with hydrate of lime and hydrocalcium aluminate of cement stone. Products of the reaction are gypsum of $CaSO_4 \cdot 2H_2O$ and sulfocalcium aluminate $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$. They are presented in greater volume than initial components, therefore, interaction with the sulfates causes the concrete expansion and disintegration. The reactions of $Ca(OH)_2$, hydrocalcium aluminate and sodium sulfate can be written as follows [3]:

$$Ca(OH)_2 + Na_2SO_4 \cdot 10H_2O \cdot\!\rightarrow CaSO_4 \cdot 2H_2O + 2NaOH + 8H_2O;$$
$$2(3CaO \cdot Al_2O_3 \cdot 12H_2O) + 3(Na_2SO_4 \cdot 10H_2O) \cdot\!\rightarrow$$
$$\cdot\!\rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O + 2Al(OH)_3 + 6NaOH + 17H_2O.$$

These reactions induce a crystallized water seepage from the original crystal hydrates. As speed of the reactions decays with time, it is possible to present the function in equation (1) in the following way: $g(t) = g_0 x^{-\alpha t}$, where g_0 is initial amount of the seeped water; α is a coefficient, which takes into account properties of the concrete and its porosity and penetrability in particular; and t is time passing from the moment when the reaction begins.

It is possible to judge about the sulfates impact by the concrete surface appearance. Usually, disintegration begins from the corners and edges; later the whole concrete massif cracks and crumbles and, further, transits into the loose state.

A boundary (2) and initial (3) condition for this problem is as follows:

$$w\big|_{\Omega_1} = 100\,\%; \tag{2}$$

$$w\big|_{\Omega_2} = 0; \quad w\big|_{\Omega_3} = 0; \tag{3}$$

where Ω_1 is an area filled with water; Ω_2 is a concrete casing of the construction, Ω_3 is soil enclosing the concrete casing.

The equation (1) with the boundary and initial conditions (2), (3) were solved by method of finite elements. In the matrix form, the differential equation (1) can be presented in the following way [4]:

$$[C]\frac{\partial\{W\}}{\partial t} + [K]\{W\} + \{G\} = 0\,; \tag{4}$$

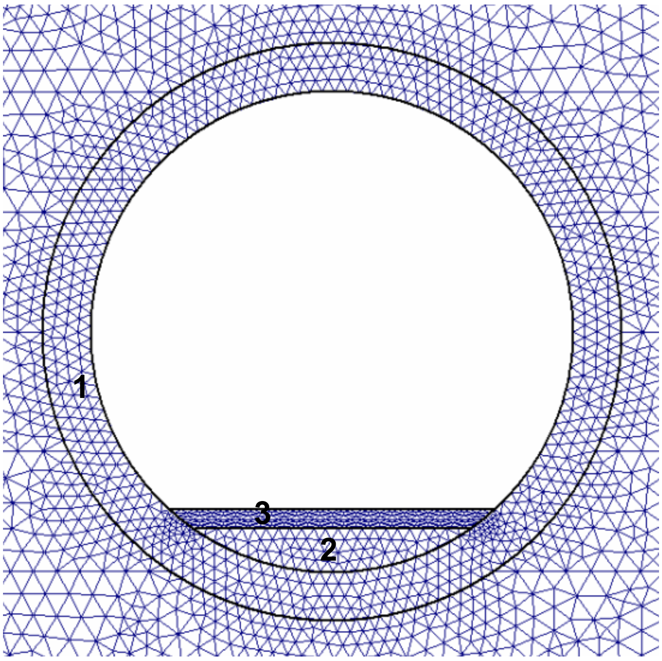
where $[K]$ is a matrix of diffusive permeability of the element; $[C]$ is a matrix of damping; $\{G\}$ is a vector of water inflow into the units, $\{W\}$ is a vector of humidity values.

In order to solve the system of equations (4) at a certain time interval, a finitedifference method is used.

$$\left([K]+\frac{2}{\Delta t}[C]\right)\{W\}_{t+\Delta t}=\left(\frac{2}{\Delta t}[C]-[K]\right)\{W\}_t-\left(\{G\}_t+\{G\}_{t+\Delta t}\right).$$

By assuming that distribution of humidity values is given for the moment of time t we get distribution of the humidity values at the moment of time $t+\Delta t$ by solving the system of equations. This process continues from the initial condition till any current moment of time.

A central fragment of the finite-element scheme in the area under the study is shown in the Fig. 1.



1 – concrete casing; 2 – silt; 3 – water
Figure 1 – Central fragment of the finite-element scheme

For the calculations, it is assumed that diameter of the reinforced-concrete pipes is 2.0 m, thickness of concrete layer is 0.2 m, maximal thickness of the silt layer in the pipe bottom is 0.18 m, and water level is 0.25 m. The calculations give distributions of values and directions of the diffusing flow speeds [5], humidity level inside the concrete casing (see Fig. 2), and rates of fluid consumption in each point of the area under the study at different moments of time of the hydrotechnical construction exploitation at the water level $U = 0.25$; 0.5 and 1.0 m in the pipes.

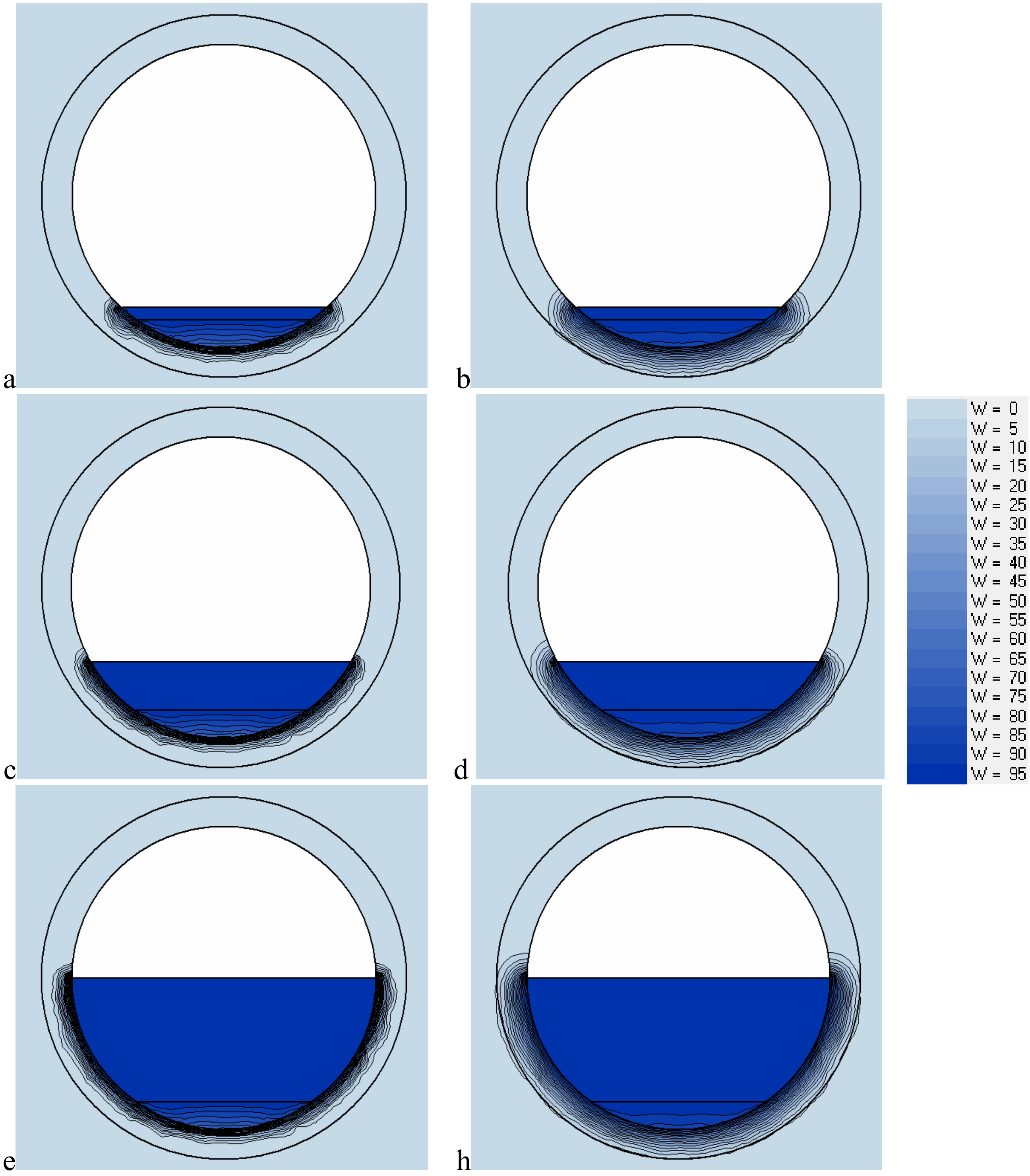


Figure 2 – Humidity of concrete casing at different water levels in the pipes: "a" , “c”, and “e” after 10 years of and “b”, “d”, and “h” after 30 years of the construction exploitation

Assuming that corrosive damages occurred in the concrete at the humidity more than 10 % , corrosion depth and volume of the damaged concrete were calculated. An interdependence between increase of the corrosive damage depth and time duration was formulated for the similar conditions.

Results of the geophysical examining of the spillway technical state in the upper and lower ponds at the Colliery Group «Pokrovskoe» showed that the calculated values of the depth of the aggressive medium penetration into concrete complied with the experimental values. Comparatively short life of the culvert reinforced-concrete sectors is explained by the impact of aggressive substances dissolved in water and the impact of moisture itself. These processes occur when volume of the reinforced-concrete components increases and induces the concrete cracking and disintegration.

The medium permeability is a key characteristic for specifying parameters for the filtration process. It is known that permeability of solids depends on their stress-strain state. In order to predict possible disintegration of the concrete casing, and to specify coefficients of the concrete permeability, the stress fields were calculated for the area under the study with plasto-elastic sectors by method of finite elements.

The calculation was performed with taking into account weight of the: enclose soil (spillway was located at the depth of 4.0 m), the concrete construction itself and fluid flowing in the pipes. The calculation also took into account deterioration-in-time of the concrete strength due to the high humidity, corrosion and aggressive medium (the deterioration was defined by previous calculations at specific time interval iteration). The calculated areas with inelastic deformations at different moments of the concrete construction exploitation and with water level $U = 0.5$ m in the pipes of the spillway are shown in Fig. 3.

It is evident from the figures that inelastic deformations are more developed in those sector of the concrete casing which directly contacts with water. It means that the construction is disintegrated from lateral sides of the spillway pipes under the impact of chemical aggressive medium, high humidity of the concrete and static load from the weight of the construction and overlying soil. Similar disintegration is observed in real conditions in the culvert facilities of coal mines.

The following issues were taken into account while analyzing interdependencies between stress parameters of the concrete casing and the casing water permeability:

1) In sector of concrete ring not damaged by corrosion, a permeability coefficient is very small, practically close to zero, in area of elastic deformation and uniform compression .

2) At nonuniform load in area of initial microcracking increase of the permeability coefficient is insignificant, because accumulation of single, uninteractive defects is typical for this stage of loading.

3) Beyond the limit of elasticity, and upon reaching an ultimate strength, which are consistent with the area of intensive crack formation, the cracks grow uncontrollably. At this stage, deformations quickly increase due to the crack proliferation and concrete loosening [6]. In area of intensive cracking, the permeability coefficient increases by 2-3 orders depending on different rocks and materials.

4) When cracking velocity becomes maximal, and stress reaches ultimate strength of the concrete, a process of macroscopic fracture begins. A brittle failure of the concrete intensifies the permeability. The permeability coefficient takes its maximal values in the area of the brittle failure.

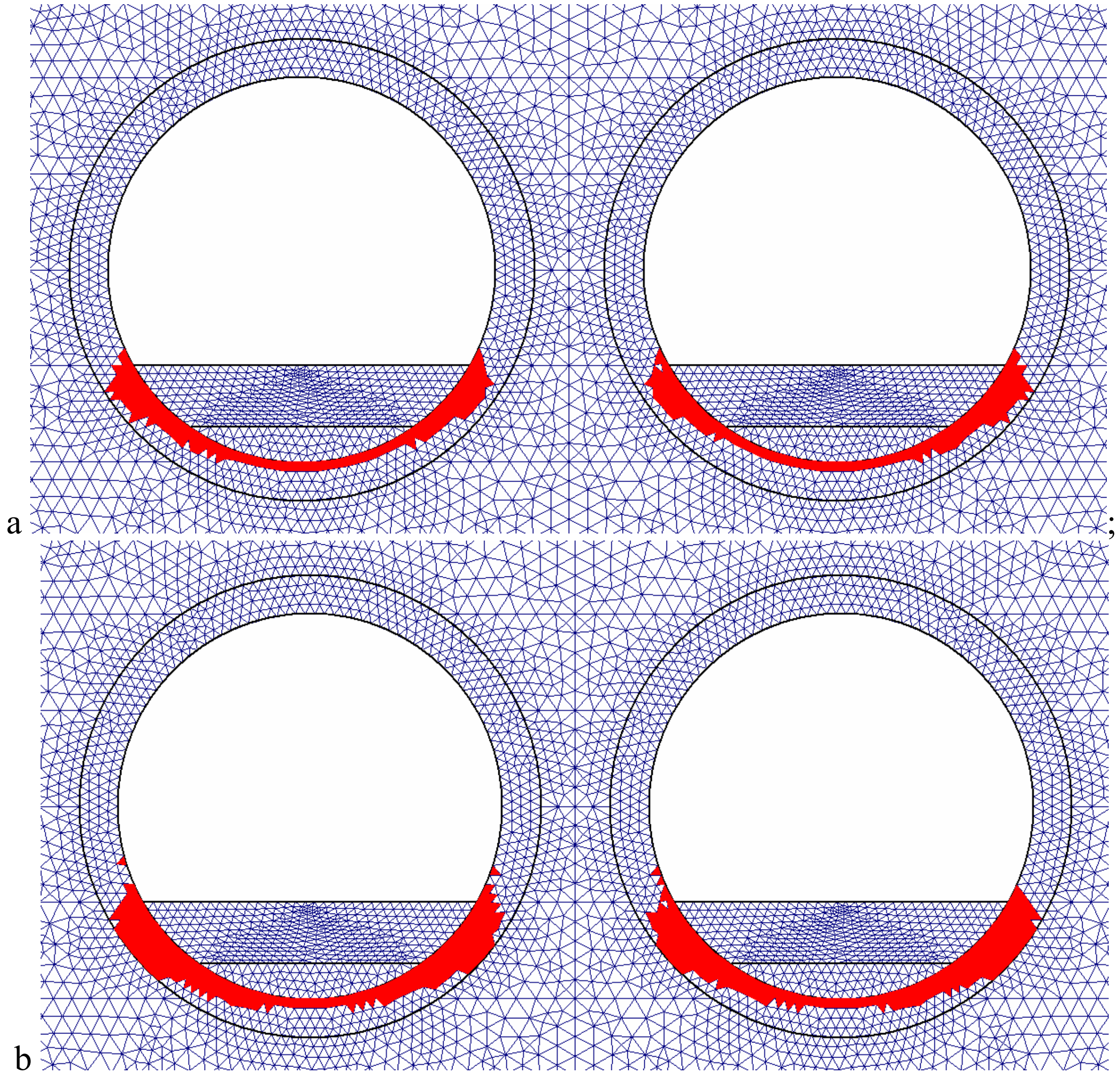


Figure 3 – Zone of inelastic deformations, U = 0.5 :
“a” – after 20 years and “b” – after 40 years of the construction exploitation

With the help of finite elements method, humidity of soil was calculated which was changed due to the water filtration through the damaged concrete pipes after 20 years of hydrotechnical construction exploitation at the Colliery Group «Pokrovskoe». In the calculations, the permeability coefficient k_n was determined by the above mentioned issues. Results of the calculations (humidity of the concrete casing and enclosing soil) at different water levels U in the spillway pipes after 20 years of the construction exploitation are shown in the Fig. 4.

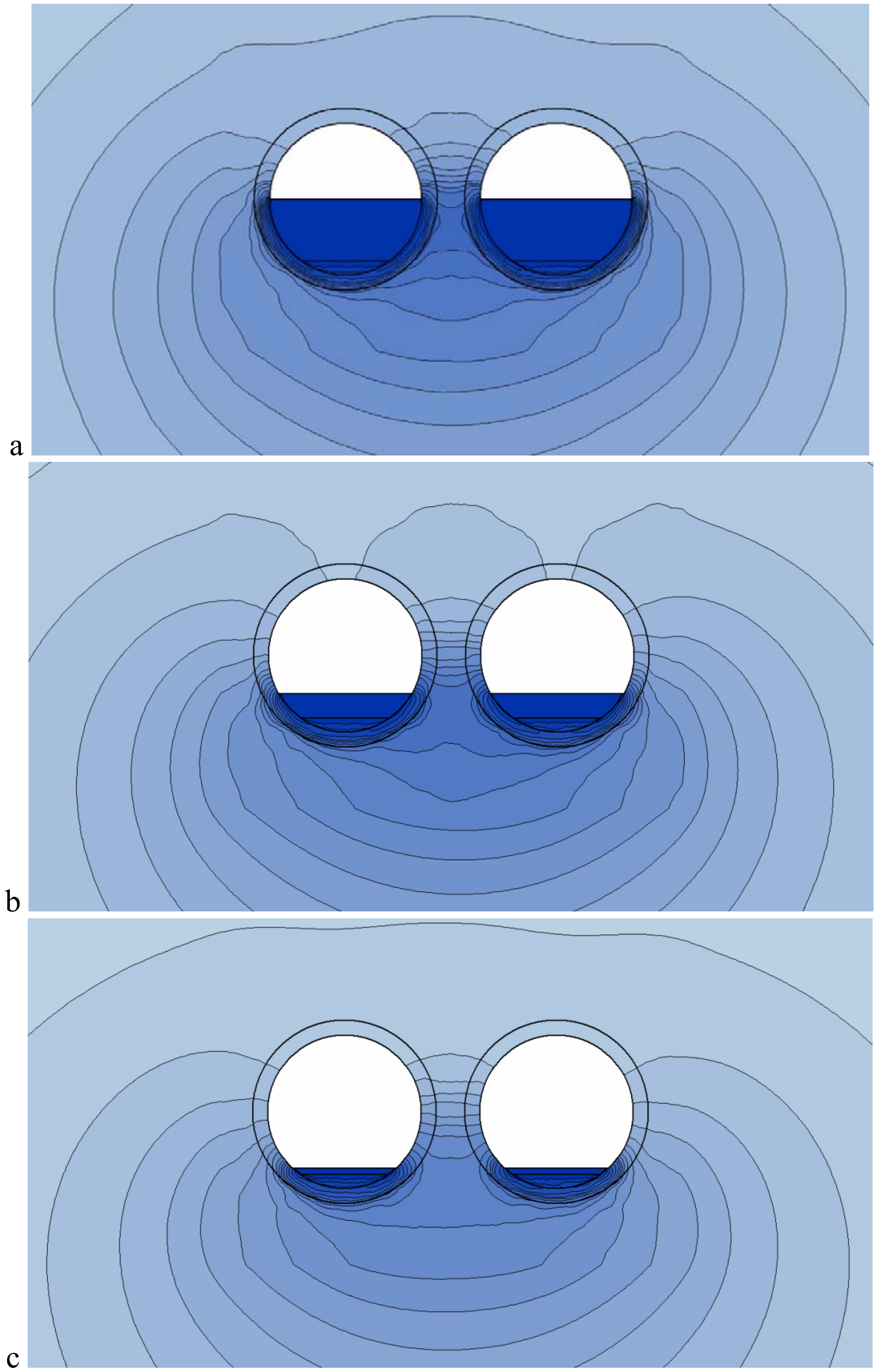


Figure 4 – Humidity in the area under the study at different water levels:
“a”– 1.0 m; “b”– 0.5 m; “c”– 0.25 m

As it is seen in the figures, soil humidity, while reaching 100% at U = 1.0 m in the edge area, increases with the greater filling of pipes. Presence of water in the free state outside the concrete casing is confirmed by the results of the visual observation of the process of borehole drilling in the sides of pipes. Maximal humidity is in the areas outside the pipe walls which directly contact with water.

From the array of the calculated data, let's choose humidity values shown in a horizontal line running through the center of the side wall of the concrete pipe (at different water levels in pipes), see Fig. 5.

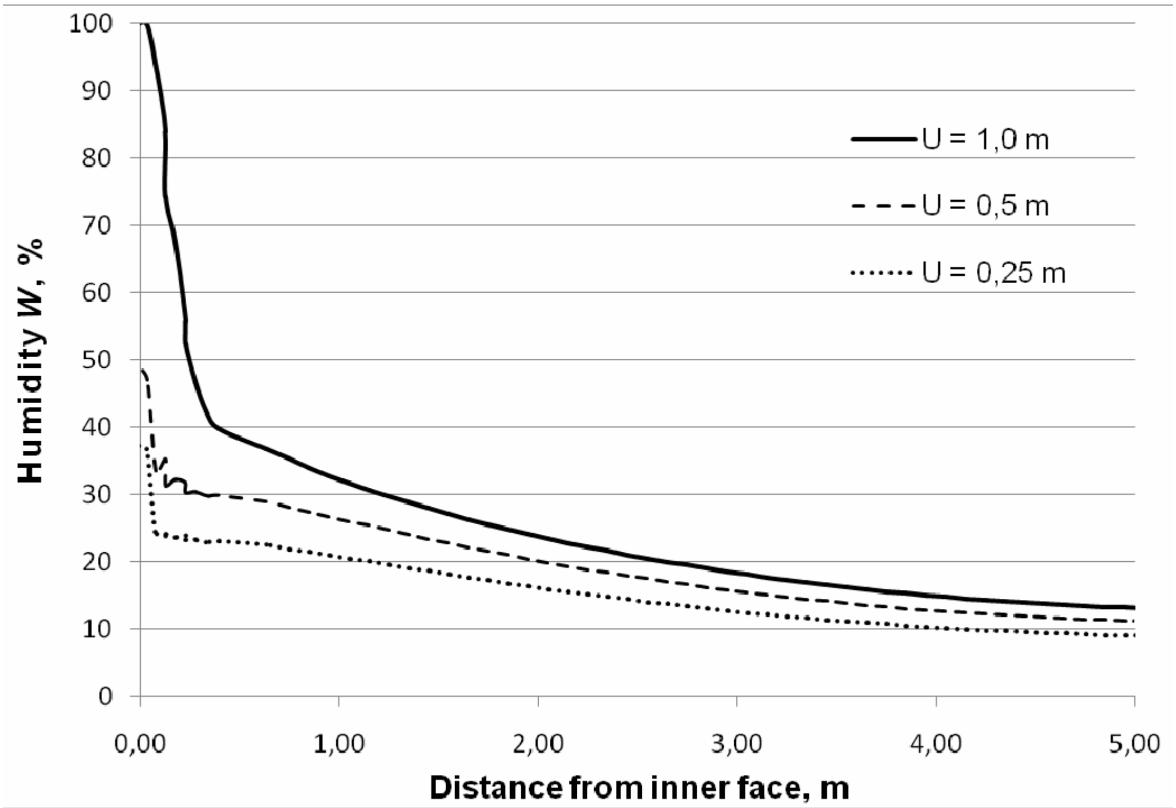


Figure 5 – Humidity of concrete and enclosing soil at different distance from the inner surface of the spillway pipe

Let's compare the calculated data with the results of full-scale experiments on studying the state of the soil mass around the culvert in the spillways. The calculated and experimental curves of the changed soil humidity are shown in the Fig. 6 with distance intervals from 0.2 m to 3.2 m from the free surface. It is obvious that the calculated values of humidity closely correlate with the experimental ones; and the created model of water filtration through the damaged concrete casing adequately reflects a real state of the buried reinforce-concrete construction and soil.

Process of the soil washing-out and cavity formation can be divided into three basic periods [7] with different time lengths (see Fig. 7).

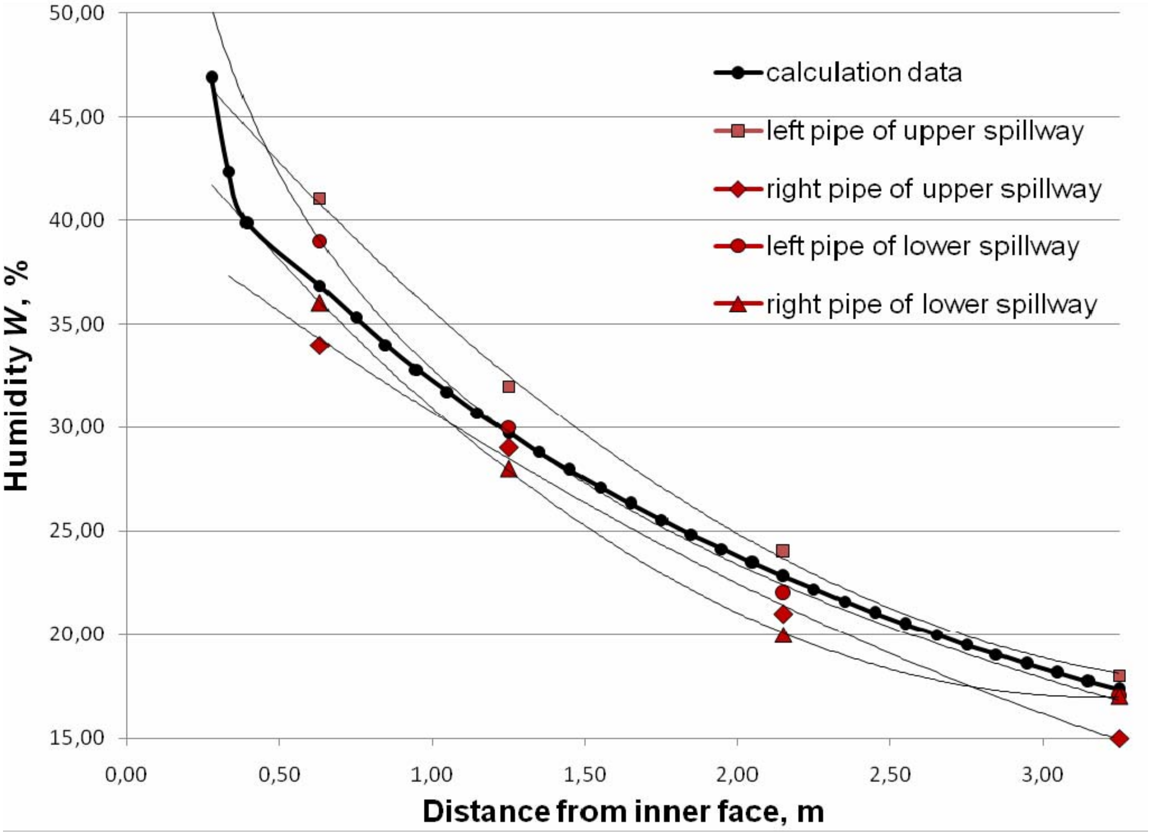
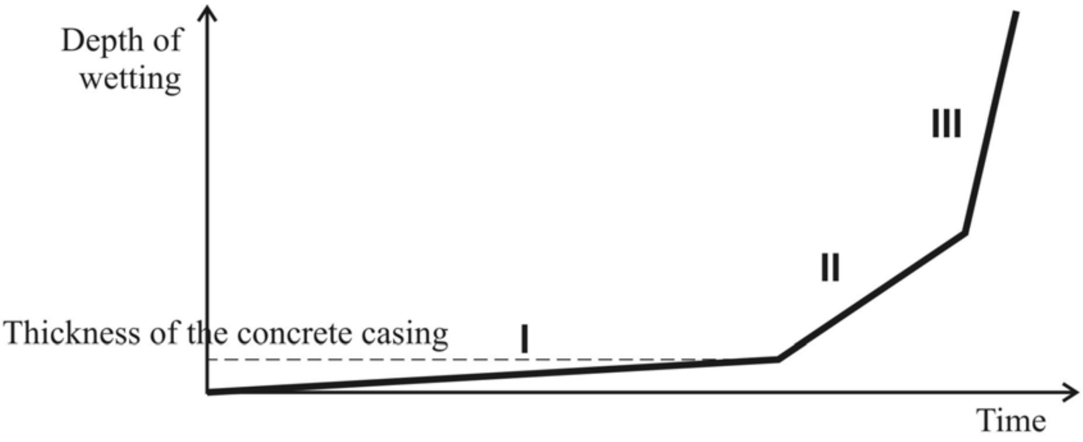


Figure 6 – Calculation and experimental curves of changes of containing soil humidity



I period – corrosion development (diffusion processes in the concrete casing);
II period – intense wetting of the enclosing soil (water filtration in the system «spillway concrete pipes – soil mass»);
III period – formation of cavities filled with water (free water flow)
Figure 7 – Periods of the soil washing-out and cavitation

Velocity of the water filtration reaches its maximum when water flows freely in the formed cavities. Let’s define areas where formation of the cavities is most probable. To this end, let’s choose from the scope of calculated velocities of the water filtration those areas where the velocities reach their maximum values.

Probable cavity locations defined by velocities of the water filtration at U = 0,25 m; 0,5 m and 1,0 m are shown in the Fig. 8.

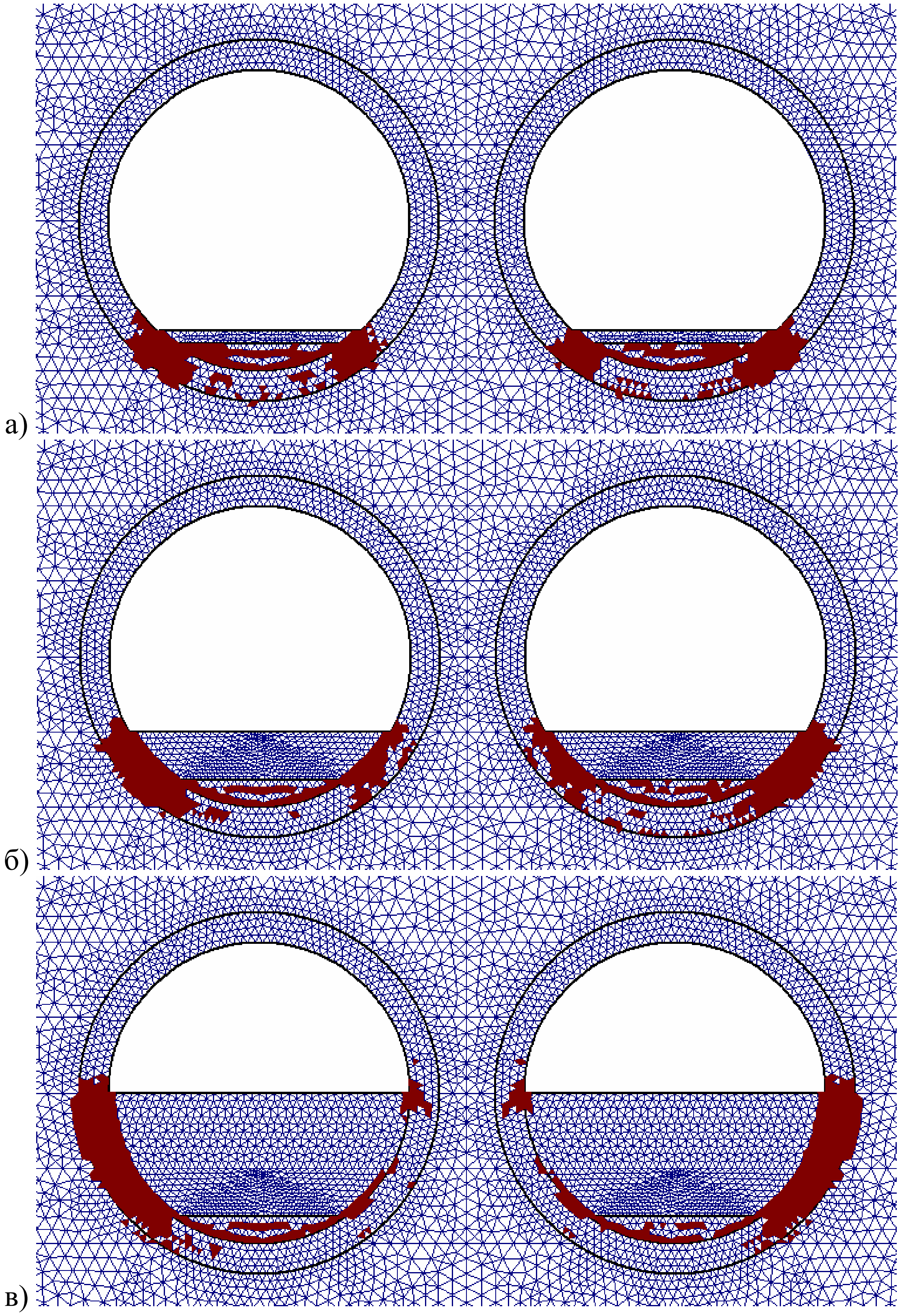


Figure 8 – Areas with maximum filtration velocities, period of exploitation is 40 years:
а) $U = 0{,}25$ m; б) $U = 0{,}5$ m; в) $U = 1{,}0$ m

Conclusions.

This research has defined the following:

- breakage of the construction under the chemical action of aggressive medium, high concrete humidity and static load of weight of the construction itself and overlying soil starts from the sides of the spillway pipes, i.e. in that concrete casing sector which directly contacts with water;
- at $U = 1.0$ m, humidity of the enclosing soil reaches 100 % in the edge area and that is an evident of free-state water presence outside the concrete casing.

The created model of water filtration through the damaged concrete casing correctly reflects a real state and allows to calculate parameters for the process of water flow in the soil enclosing culvert facilities, and to study concrete and soil state with the purpose of realization of quality reconstruction.

In result of these calculations the authors received data which were successfully applied for repairing the hydraulic objects of the Colliery Group «Pokrovskoye».

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About the authors

Skipochka Sergey Ivanovich, Doctor of Technical Sciences (D. Sc), Professor, Head of Department of Rock Mechanics, M.S. Polyakov Institute of Geotechnical Mechanics under the National Academy of Science of Ukraine (IGTM, NASU), Dnepropetrovsk, Ukraine, skipochka@ukr.net

Krukovskaya Victoriya Victorovna, Doctor of Technical Sciences (D. Sc), Senior Researcher, Senior Researcher in Department of Control of Dynamic Demonstrations of Rock Pressure, M.S. Polyakov Institute of Geotechnical Mechanics under the National Academy of Sciences of Ukraine (IGTM, NASU), Dnepropetrovsk, Ukraine, igtm@ua.fm

Grebenyuk Sergey Dmitrievich, Candidate of Technical Sciences (Ph. D), Engineer, Deputy Director on manufacture, JSC «Donetskstal», Donetsk, Ukraine, grebenuk.sd@donetsksteel.com

Об авторах

Скипочка Сергей Иванович, доктор технических наук, профессор, заведующий отделом механики горных пород, Институт геотехнической механики им. Н.С. Полякова Национальной академии наук Украины (ИГТМ НАН Украины), Днепропетровск, Украина, skipochka@ukr.net

Круковская Виктория Викторовна, доктор технических наук, старший научный сотрудник, старший научный сотрудник отдела управления динамическими проявлениями горного давления, Институт геотехнической механики им. Н.С. Полякова Национальной академии наук Украины (ИГТМ НАНУ), Днепропетровск, Украина, igtm@ua.fm

Гребенюк Сергей Дмитриевич, кандидат технических наук, инженер, заместитель директора по производству, ЗАО «Донецксталь», Донецк, Украина, grebenuk.sd@donetsksteel.com

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Анотація. Для дослідження процесів хімічного та механічного руйнування заглиблених бетонних споруд, фільтрації рідини крізь бетон до ґрунту, що вміщує споруду, вимивання порожнин було застосовано метод математичного моделювання. Авторами розроблено математичні моделі, що описують дифузійний перенос вологи в пористій структурі бетону з урахуванням участі води в хімічних реакціях, зміну напруженого стану заглиблених бетонних конструкцій з урахуванням зниження міцності бетону внаслідок підвищеної вологості та під дією агресивного середовища, фільтрацію рідини крізь порушений бетон до ґрунту. Для верифікації було проведено серію натурних експериментів, які показали адекватність розроблених моделей. В результаті розрахунків отримано дані, що успішно застосовані при реставрації водовідних споруд ШУ «Покровське».

Ключові слова: моделювання, метод скінчених елементів, перенос вологи в бетонних конструкціях, проникність бетону, напружений стан, фільтрація води, вимивання ґрунту і утворення порожнин.

Аннотация. Для исследования процессов химического и механического разрушения заглубленных бетонных сооружений, фильтрации жидкости через бетон во вмещающий грунт, вымывания полостей использовался метод математического моделирования. Авторами разработаны математические модели, описывающие диффузионный влагоперенос в пористой структуре бетона с учетом участия воды в химических реакциях, изменение напряженного состояния заглубленных бетонных конструкций с учетом снижения прочности бетона вследствие повышенной влажности и под действием агрессивной среды, фильтрацию жидкости через нарушенный бетон во вмещающий грунт. Для верификации были проведены серии натурных экспериментов, показавшие адекватность разработанных моделей. В результате расчетов были получены данные, успешно использованные при реставрации водопроводящих сооружений ШУ «Покровское».

Ключевые слова: моделирование, метод конечных элементов, влагоперенос в бетонных конструкциях, проницаемость бетона, напряженное состояние, фильтрация воды, вымывание грунта и образование полостей.

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А.И. Волошин, чл.-корр. НАН Украины,
С.Н. Пономаренко, канд. техн. наук, ст. научн. сотр.,
Ю.Н. Игнатович, канд. техн. наук, ст. научн. сотр.
(ИГТМ НАН Украины)

ОСОБЕННОСТИ ДВИЖЕНИЯ АЭРОСМЕСИ НА ЗАГРУЗОЧНОМ УЧАСТКЕ ВИБРОПНЕВМОТРАНСПОРТНЫХ СИСТЕМ С КОЛЬЦЕВЫМ ЭЖЕКТОРОМ

О.І. Волошин, чл.-кор. НАН України,
С.М. Пономаренко , канд. техн. наук, ст. наук. співр.,
Ю.М. Ігнатович, канд. техн. наук, ст. наук. співр.
(ІГТМ НАН України)

ОСОБЛИВОСТІ РУХУ АЕРОСУМІШІ НА ЗАВАНТАЖУВАЛЬНІЙ ДІЛЬНИЦІ ВІБРОПНЕВМОТРАНСПОРТНИХ СИСТЕМ З КІЛЬЦЕВИМ ЕЖЕКТОРОМ

A.I. Voloshyn, Cor. member NASU,
S.N. Ponomarenko, Ph. D. (Tech), Senior Researcher,
Y. N. Ignatovich, Ph. D., Senior Researcher
(IGTM NAS of Ukraine)

SPECIFICITY OF THE AIR MIXTURE FLOWING IN THE FEED SECTOR OF THE VIBRO-PNEUMATIC TRANSPORT SYSTEMS WITH ANNULAR EJECTORS

Аннотация. Статья направлена на исследование параметров и режимов движения аэросмеси на загрузочном участке трубопроводных систем пневмотранспорта с кольцевым эжектором. Приведены характерные особенности взаимодействия потоков воздуха на смесительном участке кольцевого эжектора. Выполнен анализ синхронных и асинхронных режимов движения аэросмеси на загрузочном участке вибропневмотранспортных систем с кольцевым эжектором. Получена зависимость для определения коэффициента рассеивания кинетической энергии аэросмеси с учетом технологических и режимных параметров работы оборудования данного типа. В статье предложен новый подход к рассмотрению потерь энергии на различных участках загрузочной зоны вибропневмотранспортных систем с кольцевым эжектором. Показано влияние на энергетические потери воздушного потока различных режимов движения аэросмеси в загрузочной зоне вибропневмотранспортых систем эжекторного типа. Полученные результаты могут быть применены при расчете и проектировании загрузочных устройств пневматических трубопроводных систем, в том числе оборудования для пневматической закладки выработанного пространства шахт.

Ключевые слова: аэросмесь, сыпучий материал, кольцевой эжектор, пневмотранспорт, коэффициент рассеивания энергии.

Среди трубопроводных систем пневмотранспорта, применяемых, в частности, для пневматической закладки выработанного пространства, особое место занимают установки эжекторного типа. Это обстоятельство объясняется простотой их конструкции, надежностью в эксплуатации и относительно низкими удельными энергозатратами на транспортирование различного рода сыпучих материалов, включая липкие и влажные горные породы.