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Efficiency and durability of the linings channels of geosynthetics

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Abstract. The investigation is concerned with seepage-control canal lining made of geosynthetic materials (GSM): polymer geomembranes and bentonitic mats (bentomats) with protective coatings. Efficiency and longevity criteria of lining made of geomembranes, bentomats and protective coatings (concrete, stone, gabion, and soil) have been stated. New lining designs with GSM of high reliability are proposed, including two or three layers of seepage-control lining made of bentomats and geomembranes, as well as protective layers made of geotextiles, rock filling, gabions. We have considered the effectiveness of already constructed sections of Bentofix bentomat linings at Donskoy principal canal (Rostov region, Russia) according to the following three criteria:

– - Filtration costs of the bentomat lining compared to the ground bed,
– - Efficiency degree due to the bentomat lining compared to the alternative options,
– - Filtering resistances of the bentomat lining compared to the alternative options.

We have developed a technique to assess the effectiveness of bentonite mats taking into account the regeneration (self-healing) of possible damage due to the regeneration of Ca-bentonite. It is based on the method of successive change of steady states, when the nonsteady process of filtering through damages of the bentomat is divided into a number of steady states. Studies of the aging coefficient of the geomembrane made of polyethylene (HDPE) by the modulus of elongation in the test basin during the period of 8–10 years have made it possible to extrapolate these data and determine the longevity (service life). There is also a calculation of the geomembrane longevity according to the Arrhenius equation. We have made a comparative analysis of the efficiency of various types of canal linings which showed that the most effective type is the bentomat liner, which also has the highest service life.

1. Introduction

Urgency of the research is caused by high losses of water during its transportation through canals in the Russian Federation [1], which amount is equal to 4.8 km^3/year (more than 30 % of use). The main reasons are the low technical level and a significant wear factor of land reclamation systems and hydraulic structures.

According to the FSBSI "RosNIIPM", the average value of the efficiency coefficient of the principal canals for today is 0.829, which is significantly less than the requirements of the standards [2]. In this case, the efficiency of the canals in the ground channel is 0.790, and the canals in the lining is 0.870.

Studies of the seepage-control efficiency of the canals were performed by A.G. Alimov [3], M.A. Bandurin [4], S.V. Solsky [5], Yu.M. Kosichenko and O.A. Baev [6–8].

Thus, the studies [3] made it possible to develop express methods for ultrasonic testing of water permeability of isolation joint and concrete of canal linings, which (with a sufficient density of ultrasonic sounding) provide acceptable accuracy (with an error of 5 %) for determining water losses through linings.

The issues of the evaluation of efficiency of drainage and concrete blankets of concrete dams on a rocky basis are considered in the work of S.V. Solsky et al. [5], where the authors used the method of numerical modeling and data of field observations.

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The study of M.A. Bandurin [9] contains an original software and hardware complex for diagnosing the technical condition of water supply structures of irrigation systems which ensures the detection of defects in linings and ground beds using acoustic and geo-radar location-based methods of non-destructive testing. However, there are no specific examples of their use on existing canals with lining.

During the last 10–20 years, geosynthetic materials [10] in small hydraulic engineering have been increasingly used. They can be successfully used for the facilities intended for nature protection purposes – storage of industrial and household waste, ash dumps, as well as on canals and reservoirs of clean water.

The use of waterproof geosynthetic materials (geomembranes and bentomats) on the canals of irrigation systems (with losses up to 30 %, where 80–90 % of these losses occur due to filtration), is especially promising [11]. In modern conditions, the efficiency of most irrigation canals is 0.75–0.80, and when using a new generation seepage-control lining made of geosynthetics, the efficiency will reach 0.97–0.98 [11]. Thus, the seepage-control effect due to the use of geosynthetic materials for canals can be about 20–30 %.

The articles [6, 7, 11] consider new multilayer constructions of seepage-control coatings using bentonite materials. They differ by the fact that they provide increased reliability due to healing of possible damage to the bentomat and duplication of protective and waterproofing layers.

Despite the fact that the linings using geosynthetic materials (geomembranes and bentomats) are highly reliable, nevertheless, various damages can happen during construction and operation. Therefore, a significant amount of scientific works has been devoted to studying the water permeability of polymer screens and linings.

We would like to highlight the article of the authors [12] where various methods for calculating the water permeability of polymer screens are considered: experimental, theoretical and experimental-theoretical. When analyzing the filtration flow through the hole in the polymer geomembrane according to a number of calculated dependences, including J.P. Giroud [13], the results are consistent with each other. However, according to the formula of R.K. Rowe [14], the discrepancy reaches 75 %.

Another article of the authors [15] investigates the problem of water permeability of a polymer screen made of geomembrane through a system of slots. The solution to this issue was obtained by the method of conformal mappings and the motion hodograph.

Here, comparison with the formula of J.P. Giroud gives more discrepancy in the range of 67–128 % depending on the width of the slot, which is fundamentally different from other formulas because it uses the law of nonlinear filtering and empirical coefficients according to field studies.

Foreign authors [16, 17] obtained an empirical equation for calculating the flow rate of the liquid through a composite coating due to defects in the geomembrane. Three types of defects (circular defects, defects of infinite length and damage in the form of cracks) and three types of contact (excellent, good and bad) were considered.

Hydrated bentonite has a low shear resistance, which can have a negative affect to the stability of structures including bentonite clay inserts (GCL) [16, 17]. The GCL bentonite layer is encapsulated between two geomembranes which reduce the possibility of bentonite hydration. These articles present an analytical method for evaluating the degree of hydrated area of a bentonite layer depending on time, initial and hydrated moisture of bentonite, the hydraulic conductivity of bentonite, the width of the floor, the distance between the floors.

The potential assessment of the longevity of exposed geotextiles and geomembranes is considered in [18]. In case of the unexposed (or coated) high density polyethylene (HDPE) geomembrane with a thickness of 1.5 mm with a value of 50 % of the remain firm and elongation, the half-life under these conditions was approximately 450 years. Laboratory incubation would take 12 years. The data was then extrapolated to a temperature of 20 °C for laboratory values of the half-lives. For open geosynthetics, the situation is completely different. They are directly exposed to ultraviolet radiation at elevated temperatures, that reduces the service life. The ratio of unexposed and exposed samples for the HDPE geomembrane is approximately seven. Research results for geomembranes range from 47 to 97 years, which took 12 years of laboratory incubation to reach. These results are considered to be the most interesting and were first obtained by the authors.

However, the data on the durability of closed geomembranes in [18] are significantly overestimated. So, according to our calculations [11] (according to the obtained formula from the Rice equation), the predicted (calculated) service life of geomembranes with a protective coating of rockfill is 130 years. As for the open geomembranes without protective coatings, their service life, according to our on-site surveys, can be maximum of 25 years. Similarly, Techpolymer company guarantees the service life of geomembranes made of HDPE and LDPE polyethylene to be minimum of 25 years. On-site and laboratory studies of Carpi company [19] also have showed that the service life of permanently open geomembranes is more than 50 years, and for geomembranes under water - 200 years. The Federal Institute for Materials Research in Berlin (BAM) has performed severe tests of the service life of bentonite mats [20] during the period of 365 days. Then the test results were extrapolated by the Arrhenius method, according to which the period of the possibility of using bentomats for 200 years was established, which confirms the previously considered data.

Considerable attention is also paid abroad to the use and research of geosynthetic materials (geomembranes) and bentonite mats (bentomats). The article [21] discusses laboratory studies of the flow efficiency of conventional and multicomponent geocomposites for five different bentonite clay inserts (GCL) and a number of different geomembranes (GM).

The canal lining is used to reduce the loss of water pressure during irrigation [22]. The use of geosynthetic materials that have been widely used in construction areas, in combination with concrete or as a separate material by replacing concrete with PVC, geosynthetic material is the most economical material for canal lining.

The influence of the defect in the geomembrane on the water filtration in soil dams and methods for filtration monitoring were considered in [23]. Defects in the geomembrane can lead to the potential danger of a dam with a geomembrane on its surface. Therefore, three-dimensional saturated and unsaturated seepage fields with various sizes of defects in the geomembrane were modeled by FEM method. The process of filtering through geomembrane defects was modeled using methods for removing defective elements and enhancing permeability. The results show that leakage, caused by defects, has a significant effect on the local seepage field near the defects and slightly affects other parts of the dam.

The overall scheme for calculating the flow rate of a liquid through a composite coating (geomembrane + ground base) with holes is presented in [14]. The solutions obtained for a circle hole and damaged riffles can be used to interpret field conditions and analyze leakage data under on-site conditions. Moreover, a number of existing solutions are obtained as special cases from the general solution.

The longevity of the open geomembrane coatings is considered in [24, 25]. It is noted that factors such as ultraviolet radiation, elevated temperature and exposure to oxygen reduce the geomembrane service life. For incubation purposes, ultraviolet fluorescent lamps were used, where five different geomembranes were evaluated. Each material was incubated at temperatures from 60 to 80 °C, up to 50 % of reduction in strength and elongation. The results received by the authors are similar [18].

M.P. Sainov and A. O. Zverev [26] have performed research of the stress-strain behavior of rockfill dam with a screen with the main waterproof element of a polymer geomembrane. Thin geomembrane modeling was carried out on the example of the Bovilla dam (Albania) built in 1996. The results of numerical calculations showed that the most vulnerable part of the dam is the interface node between the screen and the concrete structure.

Other authors consider the results of experimental studies of tensile polymer geomembranes (made of polyvinyl chloride and polyethylene). The test procedure differs from the standard and is similar to that adopted abroad. A geomembrane (fixed at the edges) experiences a normal state and is in a state of biaxial tension. As experiments have shown, the tensile strength of geomembranes made of polyethylene is about 2.5 times higher than that of geomembranes made of polyvinyl chloride.

Interesting studies on self-healing clay-cement diaphragm of ground dams are given in the article [27]. Using the dam of the Gotsatlinskaya HPP (Republic of Dagestan, Russian Federation) as an example, we can consider the process of colmation of slot-like damages of such a diaphragm. Mathematical models in two-dimensional and three-dimensional formulation were developed. By numerical simulation, a quantitative assessment of the dynamics of the pressure gradients for the following cases is obtained: fully operational seepage-control element with a through and washed crack.

Based on the review of both domestic and foreign publications, we can conclude the domestic literature has only few publications on the research issue that concern the efficiency and reliability of linings, but at the same time in the last 5–10 years a whole series of works appeared regarding the use of new geosynthetic materials for canals to create linings of increased efficiency and reliability, some of which are protected by patents of the Russian Federation. In foreign publications, many of the works are devoted to researchers of geosynthetic materials, in particular to polymer geomembranes and especially bentonite mats. Therefore, the main research questions relate to the water permeability of the geomembrane, there are only few works regarding the models of water permeability of bentomats taking into account self-healing of damages in view of their complexity, and a significant number of publications still raise the issues of longevity (service life) of geosynthetic materials. Meanwhile, there are no works regarding the screen constructions, coatings and linings in foreign publications. Studies of longevity give overestimated results because they are based on a very short test period. The calculation formulas for determining the water permeability of screens take into account many heterogeneous facts that have fractional degrees that violate the principles of dimensional theory, and, in the end, they are not confirmed by on-site data and laboratory tests with samples. No studies have been found in foreign publications on the comparative effectiveness of various canal linings, including the use of geosynthetics.

Taking into account the above conclusion on the review of publications, we the necessary study of the effectiveness and durability of concrete blankets made of geosynthetic materials (GM) in relation to the channels quite reasonable and appropriate. Moreover, the open irrigation network of channels in Russia (only in state ownership) is more than 50 thousand km, 43 % of which require reconstruction, and the total demand for fuel and lubricants for seepage-control lining is by 2030 will be 1.8 billion m^2. At the same time, the antifiltration effect of the use of GM on channels will be 20–30 %, which will save from losses up to 2 km^3/year.

Thus, the purpose of the present study is to examine the efficiency and longevity of seepage-control linings made of geosynthetics materials.

The purposes of the study include as follows:

- analysis of domestic and foreign publications regarding the methods for assessing the efficiency and longevity of seepage-control linings;
- justification of criteria for the efficiency and longevity of seepage-control linings of canals made of geosynthetics materials;
- development of new and improved constructions of seepage-control linings made of geosynthetics materials;
- study of the efficiency and longevity of seepage-control linings made of geosynthetics materials;
- development of a technique for efficiency and longevity of linings made of bentomats taking into account their self-healing;
- a comparative analysis of the efficiency of various types of seepage-control linings of canals.

2. Methods

Consider the methodology for determining the effectiveness of anti-filtration lining of bentonite mats in the presence of possible damage, taking into account their healing.

Methodology for calculation of the efficiency (permeability) of a bentomat lining (taking into account self-healing of damages) was carried out by the method of successive replacement of stationary states, when the time-varying contour of healing of a circular shape damage is replaced by a number of its stationary states with an interval of time $\Delta\tau_i$. Such a replacement of the healing circuit makes it possible to consider the filtering process through damage in the bentomat as established over a time interval $\Delta\tau_1$. This is justified by the fact that the healing process is very slow, and therefore, filtering through screen damage is quite acceptable to consider stationary for a time interval $\Delta\tau_i$ – with the healing speed in the sample $v_s = 0.67$ mm/hour.

As a result, the filtering process through damage to the screen will differ from other types of cladding in that it is unsteady, since when hydrated, the damage is partially healed.

With complete hydration of the damage for the considered example, the healing time is [10]: $\tau =$ 37.5 hour. With a diameter of damage of mm, the healing efficiency is 80–100 %.

The healing rate in the initial period for Ca-bentonite is determined by the formula:

$$v = \frac{r_0}{\tau}.$$

Healing of Na-bentonite lesions will be faster, and the healing rate will be greater. For this, it is necessary to conduct special studies in laboratory conditions.

To calculate the effectiveness (water permeability) of the anti-filtration cladding from bentates, the dependences of the flow rate through the hole in the bentonite mat with a protective layer of soil into the soil base were used.

To solve this problem, p-analytic functions of a complex variable and the conformal mapping method were used. An approximate solution to this problem consists first in considering a plane problem by the method of conformal mappings, followed by establishing a connection with the axisymmetric problem using p-analytic functions. As a result of the solution, the authors of [12] obtained approximate calculation formulas for the following particular cases:

when $k_2 / k_1 \geq 10$:

$$q_0 = \frac{2\pi^2 k_1 r_0 (h_0 + \delta_o)}{\ln(8\delta_0 / \pi r_0)}, \quad (1)$$

when $k_2 / k_1 < 10$:

$$q_0 = \frac{2\pi^2 k_1 r_0 (h_0 + \delta_o - h_1)}{\ln(8\delta_0 / \pi r_0)}, \quad (2)$$

h_1 is piezometric pressure in the bentate screen hole, m:

$$q_0 = \frac{2\pi^2 k_1 r_0 (h_0 + \delta_o - h_1)}{\ln(8\delta_0 / \pi r_0)}, \quad (3)$$

where σ is the ratio of the filtration coefficients of the protective and underlying layers of the screen, $\sigma = k_1 / k_2$;

k_1 is filtering coefficient of the protective coating, m³/day;

k_2 is coefficient of filtration of the underlying base, m³/day;

r_0 is hole radius in the bentomate screen, m;

h_0 is water depth in the channel, m;

δ_o is the thickness of the protective layer of soil, m;

H_c is capillary vacuum of the base soil H_c =(0.5–0.6);

h_c is the height of the capillary rise of water in the ground, m.

To determine the predicted service life of the linings, the on-site experiments of samples of polymer materials were used, which were carried out in a test basin with an area of 5×1.9 m along the bottom with slopes 1:2.5 with a water depth of 3.0 m under various conditions; under water at $t =$–20+30 °C, direct atmospheric exposure at $t =$–20+30 °C; with a protective coating of ground with a thickness of 0.5 m at $t =$ –15+20 °C. The tests were performed on a polymer geomembrane of high density polyethylene (HDPE) 1.0 mm thick with tensile strength of $\sigma_{p_0} = 27$ kN/m and elongation of $\varepsilon_0 = 700$ %. On-site tests of the samples have been carried out for 8–10 years, and later, the extrapolation method was used to evaluate the longevity. In addition, the longevity (service life) was determined by calculation using the Rice and Arrhenius equations. After sampling the geomembrane directly from the test basin, the tensile test (σ_p) and elongation tests (ε_p) were carried out at the tensile testing machine.

A comparative analysis of the efficiency of various types of seepage-control linings was carried out to compare the main technical indicators and reliability indicators, the longevity of traditional concrete linings, ground-film and concrete-film linings (from 0.2–0.4 mm thick polyethylene film) with new types of linings - concrete-film and ground-film linings from polymer geomembrane (thickness from 1.0 to 1.5 mm). As indicators, the averaged and admissible filtration coefficients of the lining were taken into account, reliability indicators - the probability of operation without failure and the probability of failure and longevity.

3. Results and Discussion

3.1. Criteria for the efficiency and longevity of linings made of geosynthetics materials

Modern seepage-control canal linings should have a sufficiently high efficiency and longevity. In accordance with these requirements, they should minimize filtering losses and exclude flooding of the canal territories with groundwater. In addition, they should exclude failures and damages, first of all, of the seepage-control element during operation and have a long service life corresponding to the canal class as a hydraulic structure in accordance with Russian Building Norms SP 58.13330.2012 [28].

Using the experience of designing, building and operating canals in Russia and abroad [11], the following criteria for the efficiency and longevity of seepage-control linings using geosynthetic and geocomposite materials are proposed:

– considering the permeability of the seepage-control element from the geomembrana (GM) or bentonite mats (GCL):

$$k'_{\text{GM}} \le k'_{\text{GM.PER.}}; \; k'_{\text{GCL}} \le k'_{\text{GCL.PER.}};$$

– considering the strength when breaking geomembrane or bentomats:

$$\sigma_{GM} \geq \sigma_{GM.PER.};\ \sigma_{GCL} \geq \sigma_{GCL.PER.};$$

– considering the relative elongation of the geomembrane or bentomats at break:

$$\varepsilon_{GM} \leq \varepsilon_{GM.PER.};\ \varepsilon_{бм} \leq \varepsilon_{GCL.PER.};$$

– considering the longevity (service life) of the geomembrane or bentonite mats:

$$\tau_{GM} \geq \tau_{GM.PER} = \tau_{NOR.};\ \tau_{GCL} \geq \tau_{GCL.PER.} = \tau_{NOR.}$$

For protective coatings (concrete, stone, gabion and ground), the criteria for efficiency and longevity are as follows:

– considering the efficiency of the protection of the seepage-control filter element ($k_{ef.}$) together with the geotextile gasket from through damage and punctures of the geomembrane or bentomat:

$$k_{ef.} = F_{dam.} / F_{total} \leq 0.01\ \%;$$

– considering the hydraulic protective covering:

$$n_{prot.} \leq n_{per.} = 0.0175 \div 0.0225;$$

– considering to the degree of destruction of the protective coating ($\varPi_{pr.}$):

$$\varPi_{pr.} \leq \varPi_{pr.per.} = F_{pr.cov.} / F_{pr.total} \leq (1 \div 2)\ \%;$$

– considering the longevity (service life) of protective coatings:

$$t_{pr.} \geq t_{pr.per.} = t_{nor.}$$

The following designations are accepted here:

– k'_{GM}, k'_{GCL} are averaged (according to the study) coefficient of filtration of the lining made of geomembrane or bentomat, m/s;

– $k'_{GM.PER.}$, $k'_{GCL.PER.}$ are permissible coefficient of filtration of the lining made of geomembrane or bentomat, m/s;

– σ_{GM}, σ_{GCL} are tensile strength of the geomembrane or bentomat according to tests, MPa, kN/m;

– $\sigma_{GM.PER.}$, $\sigma_{GCL.PER.}$ are permissible values of the strength of the geomembrane or bentonite, MPa, kN/m;

– ε_{GM}, ε_{GCL} are elongation at break of the geomembrane or bentomat according to test results, %;

– $\varepsilon_{GM.PER.}$, $\varepsilon_{GCL.PER.}$ are permissible values of elongation according to tests of geomembrane or bentomat, %;

– τ_{GM}, τ_{GCL} are longevity (service life) according to geomembrane or bentomat research, years;

– $\tau_{GM.PER.}$, $\tau_{GCL.PER.}$, $\tau_{nor.}$ are permissible values of geomembrane or bentomat service life, as well as the rated value of the hydraulic structure according to SP 58.13330.2012 [28], years;

– $k_{ef.}$ is efficiency factor of the protection of the seepage-control element together with the geotextile gasket;

– $n_{prot.}$, $n_{per.}$ are coefficient of hydraulic roughness of the protective coating according to observations and allowed according to the reference data;

– $\varPi_{prot.}$, $\varPi_{prot.per.}$ are the degree of destruction of the protective coating according to study or the permissible value according to the reference data, %;

– $\tau_{prot.}$, $\tau_{prot.per.}$ are the longevity (service life) of the protective coating according to the study and the permissible value according to the standard.

3.2. New constructions of seepage-control linings made of geosynthetics materials

In order to ensure increased water impermeability, reliability, and longevity, it is recommended to use multilayer coating structures on the canals of irrigation and drainage systems and reservoirs, including waterproof, protective, and filtering elements made of geosynthetic materials (Figure 1) [6].

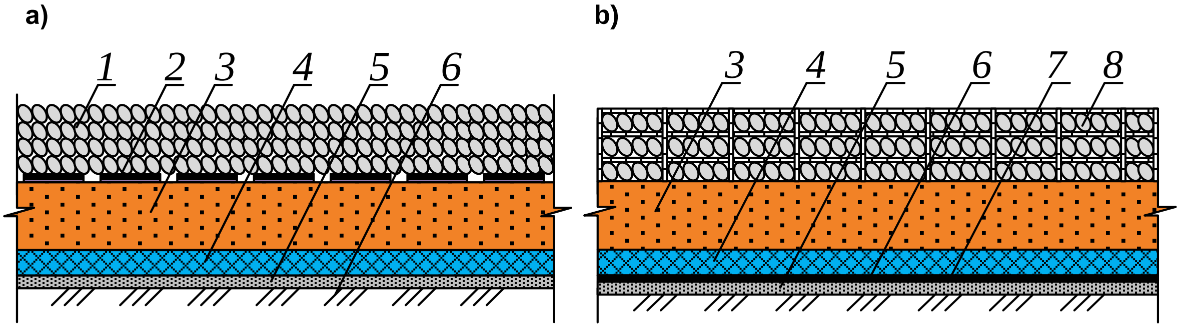


Figure 1. Multilayer constructions of seepage-control coatings with geosynthetics for canals and ponds: a, b – with a seepage-control element made of bentonite mats and a protective layer; 1 – a protective coating of rockfill; 2 – non-woven geotextile; 3 – a protective layer of ground; 4 – bentonite mat; 5 – the underlying layer of sand; 6 – compacted base; 7 – polymer geomembrane thermally bonded with a lower layer of bentonite mat; 8 – gabions filled with rocks.

The construction made of the bentonite mat coating (Figure 1, a) consists of three protective layers (rockfill, geotextiles, and a protective ground layer) and a seepage-control layer of bentonite mats. Moreover, in case of damage to the bentonite mat during the construction or operation of the structure, the damage will be regenerated (healed) during the hydration period of the material.

The coating structure (Figure 1, b) consists of two protective layers (gabions filled with rock material and a protective layer of ground), and the main working layer, including a bentonite mat, additionally thermally bonded with a polymer waterproof geomembrane. In case of damage to one of the seepage-control elements (bentonite mat or geomembrane), the structure will be watertight due to the second (duplicate) element.

Based on the analysis of the functions of each structural element of multilayer seepage-control coatings (Figure 1), the authors concluded that, in general, the first structure acquires an increased level of protection (from erosion and damage) - a triple level of reliability, and to provide a seepage-control function – a single level. For the second structure, the protective and seepage-control function correspond to a double level of reliability.

3.3. Study of the efficiency and longevity of canal linings made of geosynthetics materials

The calculations of the efficiency (water permeability) of linings with a geomembrane and protective coatings of ground and concrete were previously considered in the works of the authors [11, 15, 29].

Considering the fact that there are no methods for calculating of efficiency of bentonite mats linings (water permeability) taking into account self-healing of their damages, let us consider these features and, accordingly, the calculation method.

The main advantage of bentonite mats is the ability to regenerate (“heal”) damage due to swelling of the bentonite mat when it is moistened [20]. Bentonite mats withstand a large number of cycles of “freezing – defrosting” and “hydration – dehydration” with high waterproofing properties.

When using Na-bentonite due to its hydration, a 12–16 times increase in volume occurs, and when hydrating Ca-bentonite – only 2–4 times. For a tight fit of the bentomat to the base, loading with a protective coating is necessary with a pressure on the bentomat of at least 250 kg/m^2, for example, with a concrete thickness of at least 0.10 m and a rock material thickness of at least 0.20 m.

Currently, bentonite mats in Russia are manufactured by “Techpolymer”, “Bentisol”, “Isobent” (Russian Federation) and some other manufacturers, that usually use activated calcium bentonite. This results in a high filtration rate at the first contact with water. Another disadvantage of domestic production of bentonite mats is the uneven distribution of bentonite clay granules between geotextile layers. The use of calcium bentonite clay significantly affects the deterioration of the properties of bentomats, the producibility of their use and the longevity of the seepage-control screen.

The bentomats have been used abroad for several decades already. “NAUE” (Germany) developed and patented bentonite mats of the “Bentofix” brand back in 1937. “Bentofix” brand bentonite mats are made from natural sodium bentonite in the form of a powder, mainly with a fraction of ≤ 0.063 mm (85 %). Due to the use of bentonite powder, the best (uniform) seepage-control characteristics of bentomats (over the entire surface) are achieved, resulted in the instant hydration upon contact with water. Due to the absence of air cavities in the mats, a higher internal pressure is created inside, which provides higher seepage-control properties of the material [6].

Bearing and covering geotextile materials in such bentomats are needle-punched together with subsequent heat treatment, resulting in the formation of a so-called “thermal lock”, which contributes to higher shear strength of the lower and covering geotextiles, and due to high internal pressure, the period of the bentomat hydration and self-healing of possible damage is reduced [6].

Starting from 2012 the Donskoy Principal Canal (DPC) (Rostov region, Russian Federation) has been under reconstruction that provides for the expansion of the canal from 45th to 112th km, an increase in its flow efficiency from 80 m^3/s to 110 m^3/s and a lining with a seepage-control screen made of “Bentofix” bentomats in the most dangerous areas with a length of more than 2500 m with a protective coating of rockfill (thick at the bottom – 0.7 m, on the slopes – 0.3 m [6].

On-site investigation and calculations of the efficiency of DPC sections with bentomat linings carried out at the end of 2018 by the authors of [6] showed high efficiency, reliability, and working capacity of the lining.

Table 1 shows the results of comparing the efficiency of the canal lining made of bentomats with alternative options.

Table 1. Estimated efficiency of seepage-control lining made of bentomats at DPC and alternative option in the 1st section (PK 108 + 62 – PK 112 + 94).

Type of lining or screen	Lining (screen) filtration coefficient, k, m/s	Filtration resistance of the lining (screen), F, m	Specific filtration losses from the canal with the lining (screen) $Q_{\text{f.scr.}}$ or $Q_{\text{f.alt.}}$, m²/day	The efficiency of lining (screen) use $Э_{\text{scr.}}$ or $Э_{\text{alt.}}$	Efficiency criterion		
					$N_1=\frac{Q_{\text{f.land}}}{Q_{\text{f.scr.}}}$ or $N_1=\frac{Q_{\text{f.land}}}{Q_{\text{f.alt.}}}$	$N_2=\frac{Э_{\text{scr.}}}{Э_{\text{alt.}}}$	$N_3=\frac{\Phi_{\text{scr.}}}{\Phi_{\text{alt.}}}$
Bentofix lining	10^{-14}	$5.2 \cdot 10^8$	$1.3 \cdot 10^{-7}$	$5 \cdot 10^6$	$5 \cdot 10^6$	–	–
Alternative options							
Film screen	10^{-8}	520	0.109	6.0	6.0	$8.3 \cdot 10^5$	$1 \cdot 10^6$
Geomembrane screen	10^{-10}	51800	0.0013	506.0	$5 \cdot 10^2$	$1 \cdot 10^4$	$1 \cdot 10^4$
Clay compacted screen	$1.2 \cdot 10^{-9}$	4290	0.0015	427.0	$4.3 \cdot 10^2$	$1.2 \cdot 10^4$	$1.2 \cdot 10^4$

Note: Specific losses for filtering from a canal in the ground channel $Q_{\text{f.land}} = 0.658$ m²/day.

The criteria given in Table 1 correspond to the following: N_1 is efficiency criterion for filtration costs of lining made of bentomats in comparison with the ground bed; N_2 is efficiency criterion according to the effect degree of the lining from bentomats in comparison with alternative options (film screen, screen made of geomembrane, clay compacted screen); N_3 is efficiency criterion for filtration resistance of a bentomat lining compared to alternative options.

Analysis of the results of the calculated assessment of the criteria in Table 1 indicates that, according to the efficiency criterion, N_1 the lining made of bentomats far exceeds the ground channel by $5 \cdot 10^6$ times, and alternative options exceed the ground channel by 6 to 500 times. According to the criterion N_2, the lining made of bentomats exceeds all alternatives from $1 \cdot 10^4$ to $8.3 \cdot 10^5$ times, and by the criterion N_3 is respectively, from $1 \cdot 10^4$ to $1 \cdot 10^6$ times. Thus, according to all the criteria, a very high assessment of the efficiency of bentomat lining was obtained, and this characterizes its high seepage-control properties.

Figures 2, 3 show the results of studies of the longevity (service life) of a lining with a polymeric geomembrane made of HDPE polyethylene with a thickness of 1.0 mm in a test basin where samples of materials were in different conditions.

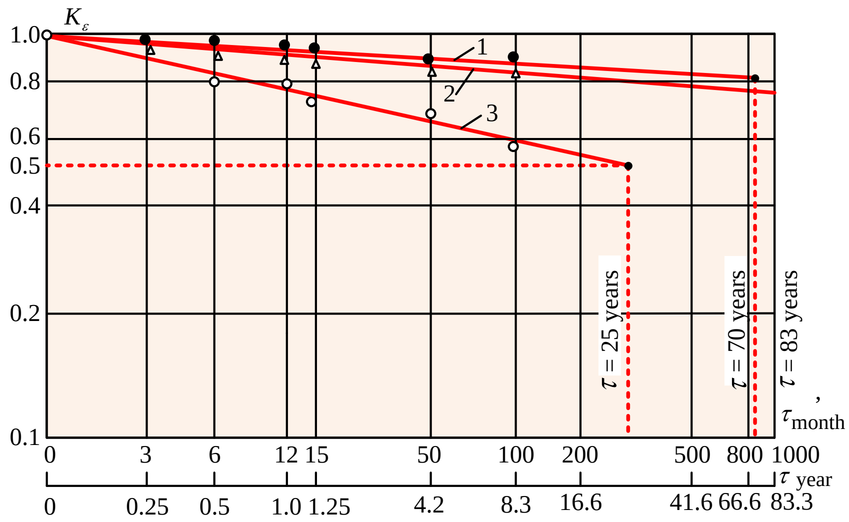


Figure 2. Change in the coefficient of aging of polymer membranes by breaking elongation in various conditions: 1 – under water at t = –20+30 °C; 2 – direct atmospheric exposure at t = –20+30 °C; 3 – a protective coating of ground with a thickness of 0.5 m at t = –15+20 °C.

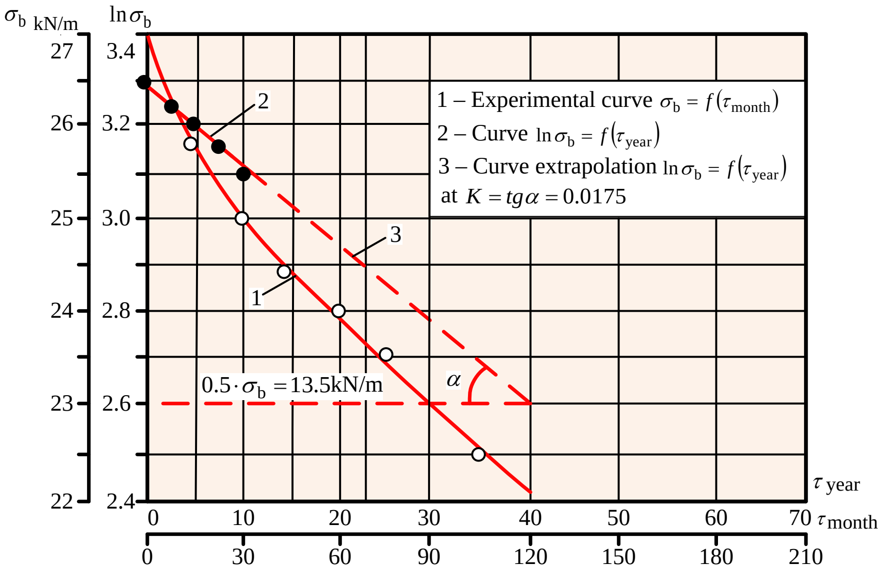


Figure 3. Diagram of changes of geomembrane strength at break depending on the time of observation.

Studies have shown the aging coefficient of the polymer geomembrane $K_\varepsilon = \varepsilon_\tau / \varepsilon_0$ (where ε_0 is the initial value of the relative elongation of the geomembrane at break (σ_b); ε_τ is the relative elongation after exposure over time τ). On the diagram, in the logarithmic coordinates (Figure 3.2) during the exposure of the samples (10 years) and their further extrapolation, the service life of the geomembrane under water was equal to 70 years, and under the protective coating from the ground – 83 years. Under direct atmospheric exposure (ultraviolet radiation), curve 3 is characterized by a significant drop in values K_ε with the intersection of the limit line with $K_\varepsilon = 0.5$ at $\tau =$ 25 years.

Figure 3 shows the experimental curve 1 of the change in the geomembrane strength at break $\sigma_b = f(t\text{month})$, which intersects the abscissa axis with $t = 120$ months or 10 years, curve 2 $\ln \sigma_b = f(t\text{month})$ is built on a different time scale for clarity, which is built on the upper section based on the results of testing the geomembrane under a protective coating of ground, and on the bottom one, it is extrapolated as a straight line on a semi-logarithmic scale. We will use these data to calculate the longevity (service life) according to the Arrhenius equation, which has the following form:

$$\ln\delta_p = \ln\delta_{p_0} - K''\cdot\tau\cdot e^{-\frac{Q}{E}},\qquad (4)$$

where δ_p is minimum strength, kN/m;

δ_0 is initial strength, kN/m;

Q is activation energy;

E is reaction energy;

K'' is the coefficient including the constants K and K' is a function of the concentration of substances, as well as their nature.

After transforming equation (4) we obtain an expression for determining the longevity (service life):

$$\tau = \frac{\ln\sigma_0 - \ln\sigma_p}{K''\cdot e^{-\frac{Q}{E}}},\qquad (5)$$

where K'' is the coefficient determined by the slope of line 3, as $tg\alpha$:

$$K'' = tg\alpha = \frac{3.3-2.6}{40} = 0.0175.$$

Substituting the found value in equation (5), we obtain the value of the service life of the geomembrane according to the Arrhenius equation:

$$\tau = \frac{3.3-2.6}{0.0175\cdot e^{-0.65}} = \frac{0.7}{0.0175\cdot(1/1.912)} = 76.5 \text{ years},$$

where the ratio $\frac{Q}{E} = 0.65$ is taken.

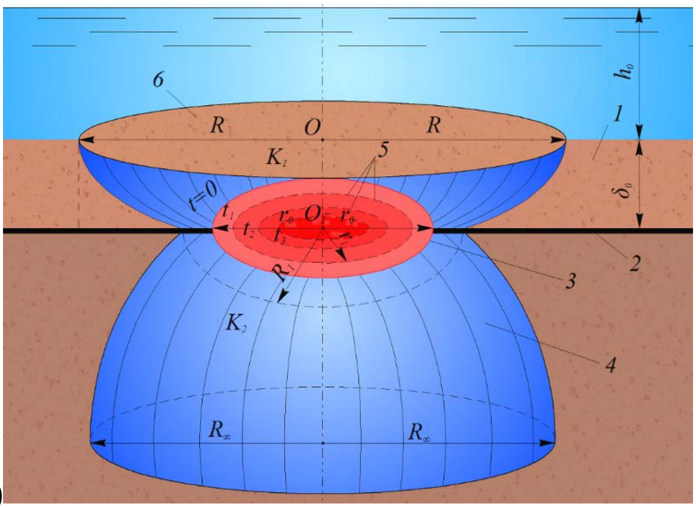
The obtained value of $\tau = 76.5$ years according to the Arrhenius equation closely matches the data in Figure 3.2 in the presence of water or a protective coating from the ground.

3.4. Technique for calculating the efficiency and longevity of the bentomat lining taking into account their self-healing

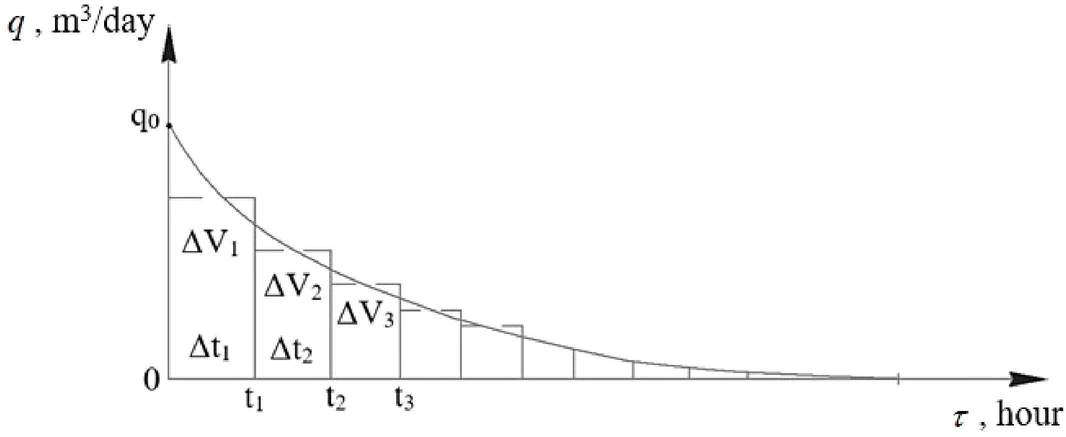
This technique for calculating efficiency (water permeability) is based on the assumption that during the operation of such lining the damage can happen, so they will be healed as a result of the regeneration of bentonite granules.

To calculate the water permeability of a screen made of bentomats (Ca-bentonite) with a protective ground layer (ground-film lining), we will use the method of successive change of steady states proposed by. It lies in the fact that the entire process of non-steady filtration is divided into a number of steady states, when damage is partially healed, where we will consider the filtration costs through the damage over a time interval $\Delta\tau$ to be constant, and the leakage volumes vary along a concave curve.

Figure 4 shows a diagram of the water permeability of the bentomat screen under conditions of healing.



a)



b)

Figure 4. Scheme of water permeability of a bentomat screen with a protective layer of ground under conditions of damage self-healing:
a) design diagram of screen permeability; b) a graph of changes in costs and volumes of leakage through the screen;
1 – a protective layer of ground; 2 – seepage-control screen from bentomats;
3 – contour of the initial damage; 4 – domed filtering area at the base of the screen;
5 – contours of changes in the position of damage at time instants τ_1, , τ_2 ... τ_3;
6 – filtration area in the protective layer of ground.

To calculate the water permeability in the conditions of healing of bentomat we will accept the following assumptions:

1. damage to the screen is formed during prolonged use of the canal due to significant deformation of the ground base under the screen;
2. the pressure on the screen will be assumed constant and appropriate to the normal operation of the canal;
3. healing of screen damage occurs due to repeated regeneration;
4. the boundaries of the damage healing contours are conditionally accepted around the circumference.

For the following screen healing contours:

$$q_i = \frac{2\pi^2 k_1 r_i (h_0 + \delta_0)}{\ln(8\delta_0 / \pi r_i)}, \tag{6}$$

where r_i is the radius of damage during healing.

The time interval (t) is determined by the formula:

$$\Delta\tau = \frac{\tau}{n_{\text{int}}}. \tag{7}$$

Taking the number of intervals $(n_{\text{int}} = 10)$, $\Delta\tau$ will be as follows:

$$\Delta\tau = \frac{37.5}{10} = 3.75 \text{ hours.}$$

Then the radius of the hole in the screen during healing will be the following:

$$r_i = r_0 - n_{\text{int}} \cdot r_0, \tag{8}$$

where n_{int} is the number of intervals when healing damage.

The amount of water leakage during the time interval $\Delta\tau_i$ will be:

$$\Delta V_i = q_{\text{av}.i} \cdot \Delta\tau_i, \tag{9}$$

where $q_{av.i}$ is the average consumption for the healing time interval $\Delta\tau_i$,

$$q_{\text{av}.i} = \frac{q_i + q_{i-1}}{2}. \quad (10)$$

The total volume of leakage during filtration for the entire healing period (τ) is found as:

$$V_{\text{fil}} = \sum_{i=1}^{n_{\text{int}}} \Delta V_i = \sum_{i=1}^{n_{\text{int}}} q_{\text{av}.i} \cdot \Delta\tau_i. \quad (11)$$

With $k_2 / k_1 < 10$ the calculated formula of the filtration flow will take into account the pressure in the hole (3) [12]. For the initial screen damage contour.

For the following healing contours:

$$q_i = \frac{2\pi^2 k_1 r_i (h_0 + \delta_0 - h_1)}{\ln(8\delta_0 / \pi r_i)}, \quad (12)$$

where $h_1 = \dfrac{\pi^2\sigma(h_0 + \delta_0) - 4H_\kappa \ln(8\delta_0 / \pi r_i)}{\pi^2\sigma + 4\ln(8\delta_0 / \pi z_i)}$;

$\sigma = k_1 / k_2$.

Let us consider an example of calculating the water permeability of a bentomat lining film based on self-healing of bentonite granules.

Initial data: $L_c = 10$ km $= 10000$ m, $\chi_c = 15$ m, $k_1 = 1.0$ m/day, $k_2 = 0.3$ m/day, $\delta_0 = 0.5$ m, $h_0 = 3.0$ m, $d_0 = 50$ mm $= 0.05$ m $= 5.0$ sm, $r_0 = d_0 / 2 = 0.05/2 = 0.025$ m, $H_c = 0.5$ m, $\tau = 37.5$ hour, $n = 10$.

1. Let us determine the speed of healing of circle damage in the bentomat screen according to the formula:

$$v = \frac{r_0}{\tau}, \quad (13)$$

at $r_0 = 0.025$ m:

$$v = \frac{0.025}{37.5} = 0.00067 \text{ m/hour} = 0.67 \text{ mm/hour}.$$

2. Let us determine the time interval $\Delta\tau_i$ by the formula (7):

$$\Delta\tau_i = \frac{\tau}{n_{\text{int}}} = \frac{37.5}{10} = 3.75 \text{ hours}.$$

3. The radius of change of the hole in the screen for the i-th interval is:

$$r_i = r_0 - n_{\text{int}} \cdot \Delta r,$$

where Δr is the change in the radius of damage in one time interval ($\Delta r = r_0 / n_{\text{int}} = 0.025/10 = 0.0025$ m =2.5 mm).

4. Let us calculate the filtration leakage rate for the entire healing period, according to the formula (12):

at $r_0 = 0.025$ m:

$$q_0 = \frac{2\pi^2 k_1 r_0 (h_0 + \delta_0 - h_1)}{\ln(8\delta_0 / \pi r_0)} = \frac{2 \cdot 3.14^2 \cdot 1.0 \cdot 0.025(3.0 + 0.5 - 2.21)}{\ln(8 \cdot 0.5 / 3.14 \cdot 0.025)} =$$

$$= \frac{0.636}{3.93} = 0.162 \text{ m}^3\text{/day},$$

where:

$$h_1 = \frac{\pi^2\sigma(h_0+\delta_0) - 4H_к \ln(8\delta_0/\pi r_0)}{\pi^2\sigma + 4\ln(8\delta_0/\pi r_0)} =$$

$$\frac{3.14^2 \cdot 3.33(3.0+0.5) - 4\cdot 0.5\cdot \ln(8\cdot 0.5/3.14\cdot 0.025)}{3.14^2\cdot 3.33 + 4\cdot \ln(8\cdot 0.5/3.14\cdot 0.025)} =$$

$$= \frac{114.91-7.86}{32.83+15.72} = \frac{107.05}{48.56} = 2.21 \text{ m};$$

$$\sigma = k_1/k_2 = 1.0/0.3 = 3.33.$$

The summary results of the calculation of the permeability of the bentomat through a single damage are presented in table 3.2 (at $h_0 = 3.0$ m, $\delta_0 = 0.5$ m, $d_0 = 0.05$ m, $k_1 = 1.0$ m/day, $k_2 = 0.3$ m/day, $\tau =$ 37.5 hour).

5. The amount of leakage through a single damage to the ground-film lining made of bentomats according to the formula (12):

at $\tau_1 = 3.75$ hour, $q_{\text{av.1}} = \dfrac{0.162+0.195}{2} = 0.154$ m³/day,

$$\Delta V_1 = q_{\text{av.1}} \cdot \Delta\tau = 0.154 \cdot 0.156 = 0.0244 \text{ m}^3.$$

In accordance with the performed calculations and total leakage for the healing period $\tau = 37.5$, presented in Table 2, the total leakage (V) through possible single damage to the bentomat after its complete healing will be $V = 0.1223$ m³.

Then the total volume of filtration leaks through the total number of possible damages at $n = 10$ will be:

$$V_{\text{total}\, n=10} = V \cdot n = 0.1223 \cdot 10 = 1.223 \text{ m}^3.$$

Figure 5 shows diagrams of changes in filtration flow depending on the time of healing of a single damage, as well as the volume of water leakage through circular damage, which decreases due to the regeneration of bentonite and healing damage.

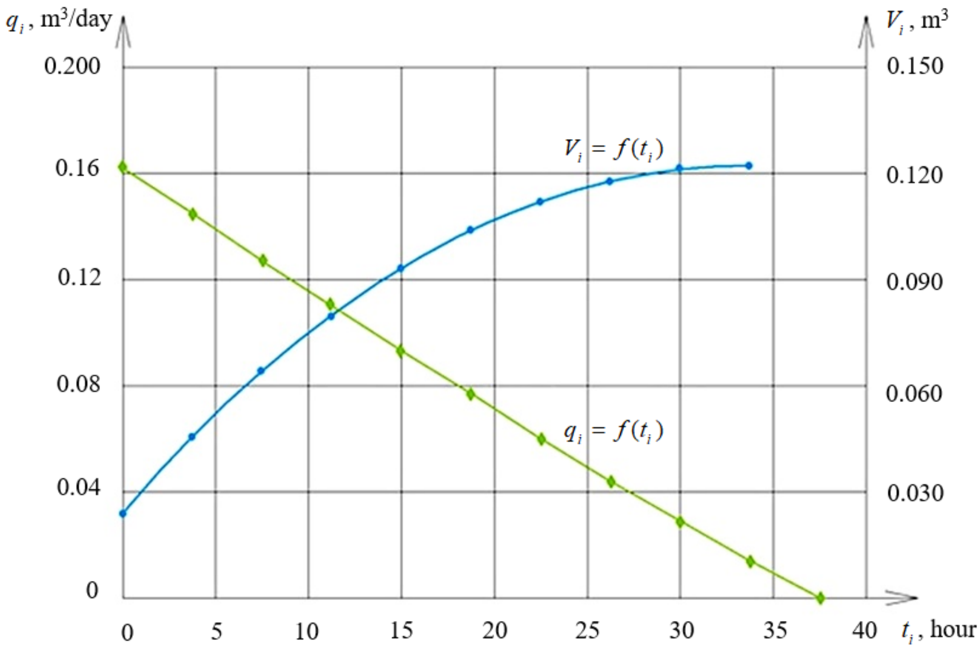


Figure 5. Diagrams of dependencies $q_i = f(\tau_i)$ and $V_i = f(\tau_i)$.

According to this diagram, the filtration flow curve $q_i = f(\tau_i)$ varies from the healing time period along a certain curve close to a straight-line dependence, and the curve $V_i = f(\tau_i)$ of the volume of water leakage through possible single damage to the bentomat is of the type related to the parabolic curve.

Table 2. Summary results of the calculation of water permeability through a single damage to the ground-film lining from bentomats.

Number of intervals $n_{\text{int}.i}$	Time interval $\Delta\tau_i$, hour	The time period for healing damage, τ_i, hour	The radius of the hole when healing damage, r_i, m	Piezometric pressure in the hole, h_{1i}, m	Filtration flow rate for the time interval q_i, m³/day	The average filtration rate for the time interval $q_{sr.i}$, m³/day	Amount of leakage per time interval ΔV_i, m³	Total leakage over a period of time V_i, m³
0	0	0	0.0250	2.21	0.162			
1	3.75	3.75	0.0225	2.18	0.145	0.154	0.0244	0.0244
2	3.75	7.50	0.020	2.16	0.127	0.136	0.0213	0.0457
3	3.75	11.25	0.0175	2.13	0.110	0.118	0.0185	0.0642
4	3.75	15.00	0.0150	2.10	0.093	0.102	0.0158	0.0800
5	3.75	18.75	0.0125	2.06	0.077	0.085	0.0133	0.0933
6	3.75	22.50	0.0100	2.02	0.060	0.068	0.0107	0.1040
7	3.75	26.25	0.0075	1.96	0.044	0.052	0.0081	0.1121
8	3.75	30.00	0.0050	1.89	0.029	0.036	0.0057	0.1178
9	3.75	33.75	0.0025	1.77	0.014	0.022	0.0034	0.1212
10	3.75	37.50	0.0	–	0.0	0.007	0.0011	0.1223

6. The predicted service life (longevity) of the bentomat lining. The calculation is carried out according to the Rice equation [11]. The source data is taken according to analogues.

Initial data: $\Pi_{per.} = 5.1 \cdot 10^{-12}$, $\Pi_{\tau 0} = 2.2 \cdot 10^{-11}$, $k_\sigma = \dfrac{\sigma}{\sigma_0} = \dfrac{10}{12} = 0.83$, $\bar{\nu} = 0.04$, $m^2_{\Pi_{\tau 0}} = 0.10 \cdot \Pi\tau_0^2 = 0.10(2.2 \cdot 10^{-12})^2 = 0.484 \cdot (10^{-12})^2$.

The service life of the bentomat lining is determined by the formula [11]:

$$\tau\{P\} = \frac{(-\ln P_{\text{GCL}})}{\bar{\nu}} \exp\left[\frac{[\Pi_{\text{per.}} - (\Pi_\tau / k_\sigma)]^2}{2m^2_{\Pi_{\tau 0}}}\right], \tag{14}$$

$$\tau\{P\} = \frac{(-\ln P_{\text{GCL}})}{\bar{\nu}_{\text{П}}} \exp\left[\frac{[\Pi_{\text{per.}} - (\Pi_\tau / k_\sigma)]^2}{2m^2_{\Pi_{\tau 0}}}\right] =$$

$$\tau\{P\} = \frac{(-\ln 0.99)}{0.04} \exp\left[\frac{[5.1 \cdot 10^{-12} - (2.2 \cdot 10^{-12} / 0.833)]^2}{2 \cdot 0.484 \cdot (10^{-12})^2}\right] = 129.5 \text{ years.}$$

Thus, the predicted service life of the bentomats with the adopted initial data will be about 130 years. According to research [20], the service life of a bentomat screen is 200 years.

3.5. Comparative analysis of the efficiency and longevity of various types of seepage-control canal linings

Using the data of calculations of the efficiency and reliability of seepage-control linings given above in paragraphs. 3.2 and 3.3, we will conduct a comparative analysis of various types of seepage-control linings. The summary results of the lining calculation are presented in Table 3.

As a criterion for the lining efficiency during comparison, we will use the averaged filtration coefficient of the lining calculated according to the theoretical formulas obtained by the methods of filtration theories (by the method of conformal mappings and the motion hodograph).

Comparing the value of the averaged filtration coefficient of concrete lining with the permissible value, we can see that the calculated value is more than the allowed value ($k'_{scr.} = 2.13 \cdot 10^{-5}$ m/s> $k'_{scr.nor.} = 0.55 \cdot 10^{-6}$ m/s), i. e. the necessary efficiency condition is not fulfilled here. This is due to the relatively high permeability of the concrete lining, which exceeds the permissible filtration coefficient by 2.6 times. We can obtain similar data on other traditional lining such as: ground film and concrete film with a plastic film.

Table 3. Results of the calculation of the efficiency and reliability of different types of seepage-control canal linings.

The name of the efficiency and reliability indicators	Types of seepage-control linings					
	Concrete	Ground-film (with a film)	Concrete -film (with a film)	Concrete-film (with geomembrane)	Ground-film (with geomembrane)	From bentomats (according to the company "NAUE" [2])
1. The average coefficient of lining filtration, $k'_{\text{scr.}}$, m/s	2.13·10^{-5}	0.5·10^{-9}	1.4·10^{-9}	0.215·10^{-10}	0.1·10^{-10}	0.5·10^{-11}
2. Allowed filter coefficient, $k'_{\text{scr.per.}}$	0.55·10^{-6}	1·10^{-8}	2·10^{-8}	0.372·10^{-6}	1.65·10^{-6}	5·10^{-11}
3. The probability of fail safe performance, $P(t)$	0.95	0.90	0.90	0.99	0.990	0.999
4. The probability of lining failure, $Q(t)$	0.05	0.10	0.10	0.01	0.010	0.001
5. Longevity (service life) of lining, $\tau_{\text{scr.}}$, years	35.5	25.0	40.0	61.3	75.6	130.0

When comparing the data of the efficiency of concrete lining with concrete-film lining, including a geomembrane, we are convinced that the latter one has less permeability by $1\cdot 10^4$ time, and, consequently, the efficiency of concrete-lining is 10,000 times higher than concrete. Such a high efficiency of concrete-film lining with a geomembrane is explained by an increase in its waterproofing properties due to the use of a geomembrane, which is characterized by high resistance to puncturing and other damages.

Even greater efficiency was obtained for a ground-film lining with a geomembrane, and compared to concrete lining it is 4.26·10^{6} times.

The analysis of the calculation results in Table 3 shows that the greatest efficiency and reliability are for Bentofix linings from "NAUE" (Germany): by filtration coefficient – 0.5·10^{-11} m/s. According to the calculation, the predicted service life of such a lining is about 130 years, which is 3.6 times higher than for concrete lining, 2.1 times higher than for concrete-film lining with a geomembrane and 1.7 times higher than for a ground-film lining with a geomembrane.

Table 4. Comparison of the obtained results with other authors on the leakage rate during the filtration through the damage of the bentonite covering.

Source data	Leakage rate due to initial screen damage, q_0 = m^3/day, according to the formulas				
	Authors (2)/(1)	V.N. Zhilenkova	J.P. Giroud at *n*		
			10	15	20
h_0 = 3.0 m, δ_0 = 0.5 m, d_0 = 0.05 m, k_1 = 1.0 m/day, k_2 = 3.0 m/day.	at $k_2 / k_1 < 10$				
	0.162	0.150 / 7.4 %	0.082 / 45.3 %	0.122 / 24.7 %	0.164 / –1.2 %
	at $k_2 / k_1 \geq 10$				
	0.439	0.427 / 2.7 %	0.0334 / 92.4 %	0.0501 / 88.6 %	0.0668 / 84.7 %

Note:

1. The numerator is values q_0, m^3/day, in the denominator there is a discrepancy with the authors' formulas, %.

2. In the formula of J. P. Giroud takes into account the number of damages *n* and the screen area on which they are located A = 1 acre = 4000 m^2.

Table 5. The comparison of the obtained results with other authors (companies) regarding the durability (service life) of the screen of bentonite coverings.

Source data	Screen life (lifetime), τ, years			
	Calculation by Rice equation (14)	According to BAM [20] using the Arrhenius equation		According to “Bentizole”
$\Pi_{dop} = 5.1 \cdot 10^{-12}$ $\Pi_{\tau 0} = 2.2 \cdot 10^{-11}$ $k_{\sigma} = 0.83$ $\bar{v}_p = 0.04$	129.5	at t = 15°C 200.0	> 400.0	Not limited

Table 6. The comparison of the obtained results with other authors (companies) regarding the durability (service life) of the screen of the geomembrane.

Source data	Screen life (lifetime), τ ,years				
	Calculation using the Arrhenius equation (5)	According to Carpi	According to the German Institute of Technology (DIBT)	According to Polypine	According to [18]
$\sigma_{p_0} = 26.5$ kN/m $\sigma_p = 22.0$ kN/m $K_{\varepsilon} = 0.5$	76.5	$\frac{200}{50}$	500	80	47–97
Note: The numerator shows data for closed geomembranes, the denominator – for open geomembranes.					

The comparison of the obtained results with other authors on the consumption of leaks for filtration through the initial damage in the bentonite covering (Table 4) shows a satisfactory convergence with the formula of V.N. Zhilenkov, as well as the empirical formula of J.P. Giroud at $k_2 / k_1 < 10$. However, $k_2 / k_1 > 10$ in the case of J.P. Giroud's formula the results are erroneously low.

The results of the calculations of the screen durability (service life) of bentonite covering (Table 5) show similar results according to the Rice equation and the data of the Institute of BAM (Germany) at t = 15°C. However, the second result of BAM – 400 years – is very much overestimated, and the last one according to “Bentizol” is not real.

The comparison of the obtained results on the durability of the screen from the geomembrane (Table 6) shows that the calculations made by the authors according to the Arrhenius equation (5) give close values of service life with the data [18] and “Polypine”. At the same time, according to Carpi company, they are significantly overestimated, and the values τ according to DIBT (the German Institute for Technical Construction) - overstated many times (more than 5 times).

4. Conclusions

1. According to the results of the conducted researches the authors received new scientific results, which consist for the first time in estimation of efficiency (water permeability) of seepage-control lining from bentonite coverings taking into account their autogenous healing, as well as in the calculation method of the determination of durability of geosynthetic materials: bentonite coverings, geomembranes, which are confirmed by other studies.

2. The criteria for the efficiency and longevity of the seepage-control canals linings with anti-filter elements made of geomembranes and bentomats for water resistance, tensile strength, elongation and longevity (service life) have been formulated. The criteria for the efficiency of protection against end-to-end damage to the geomembrane and bentomats, hydraulic efficiency, the degree of destruction and the longevity have been proposed for protective coatings.

3. A technique to evaluate the efficiency and longevity of bentonite mats has been developed taking into account self-healing of possible damage due to the regeneration of Ca-bentonite. For the calculation, the method of successive change of steady states is used, when the unsteady filtering process through a single damage is divided into a number of steady states for a time interval $\Delta\tau$. Application of the technique is

illustrated by an example of calculation and graphical dependencies of changes in filtration flow $q_i = f(\tau_i)$ rate and leakage amount $V_i = f(\tau_i)$.

4. The Rice equation is used to calculate the predicted life of the bentomat lining which helped to obtain calculate dependence to determine the service life. The considered calculation example with given initial data allowed us to obtain a bentomat service life of about 130 years.

5. Based on the surveys of the Donskoy Principal Canal with Bentofix Na-bentonite linings, we have obtained a calculated assessment of the efficiency of such a lining for three criteria, which confirms the high efficiency of the bentomat compared to the ground channel of the canal, which is equal by the criterion $N_1 = 5{\cdot}10^6$ times, and also by efficiency with alternative options according to the criterion $N_2 = 1{\cdot}10^4 \div 8.3{\cdot}10^5$, the lining of bentomats exceeds all alternatives from $1{\cdot}10^4$ to $8.3{\cdot}10^5$ times and according to the criterion $N_3 = 1{\cdot}10^4 \div 1{\cdot}10^6$ times compared to filtration resistances.

6. The studies of changes in the coefficient of aging of the geomembrane made of HDPE polyethylene by relative elongation in the test basin for 8–10 years allowed to extrapolate them in a diagram in logarithmic coefficients and to obtain the service life of the geomembrane under a protective coating of ground of 0.5 m thick equal to $t = 83$ year; at the same time, the calculation by the Arrhenius equation gave a result close to extrapolation and is equal to $\tau = 76.5$ years.

7. A comparative analysis of the efficiency of various types of seepage-control linings showed that the bentomat linings with a filtration coefficient (that is respectively in 50–25 times less than the ground-film and concrete-film lining with a geomembrane and more than $4{\cdot}10^6$ time less than the most ineffective concrete lining) are the most effective. In addition, the bentomat lining has the highest service life of about 130 years, which is 3.66 times greater than for concrete lining.

5. Acknowledgement

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