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ANALYSIS OF MAIN CAUSES OF STRUCTURAL FAILURES IN IMPERMEABLE GEOMEMBRANE LINERS OF HYDRAULIC STRUCTURES

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The article considers problems associated with the application of geomembranes in hydrotechnical construction on the real-world example of technical and technological failures associated with the installation of impermeable structural elements. The most commonly occurring defects when using geomembranes as part of impermeable structural elements are analyzed.

Keywords: geomembrane; rolled geosynthetics; waterproofing; impermeable element.

According to the definition provided in SP 39.13330.2012 Embankment Dams (Revised Edition of SNiP 2.06.05–84*), geosynthetic materials (GMs) comprise "a class of construction materials from polymers (synthetic or natural) or inorganic substances coming in contact with soil and (or) other materials, designed to perform various geotechnical functions" [1].

Waterproofing geomembranes, whose use is permitted and regulated by the provisions of SP 39.13330.2012, comprise one of the GM types employed in impermeable elements (IEs) of hydraulic structures (HS). In this case, waterproofing means preventing or limiting the movement of liquids through the IEs of embankment dams, as well as other water-retaining HS and their structural elements. The term geomembrane refers to impermeable polymeric materials designed to reduce or prevent the flow of water or another liquid through the structure [2]. Geomembranes can be used in such structural HS elements as sloped or horizontal impermeable barriers, cores, aprons, cut-off trenches, etc.

In order to ensure the waterproofing of an IE structure using geomembranes, it is necessary to strictly observe specific requirements involving the use of bedding and protective layers. These requirements are specified in the Guidelines for the Design and Installation of Impermeable Systems using Rolled Polymeric Materials [3], SN 551–82 Guidelines for the Design and Installation of Impermeable Systems using Polyethylene Film for Artificial Reservoirs [4], Typical Pavement and Roadbed Designs Using Geosynthetics [5], in the monograph Impermeable Liners from Geosynthetic Materials [6], and elsewhere.

The design of geomembrane-based IEs should take into account the location of the facility and its operation in terms of engineering-geological, hydrogeological, engineering-environmental, and hydrometeorological conditions. Documentation for the construction project should include relevant diagrams showing the arrangement of geomembrane panels and seams, the sequence and direction of panel placement, identifiers denoting geomembrane panels and seams, the location of special structures, and the technology used for connecting them [2 – 8].

In addition to issues addressed in corresponding regulatory technical documents, the project must specify:

— the method of delivering polymeric materials to the site;

— the placement (including welding, interlocking, etc.) of GMs, as well as bedding and protective layers, taking the specific conditions of installation into account;

— methods and equipment for welding rolled polymeric materials; justification of the complex of general approach and specialized equipment / mechanisms used in polymeric IE construction;

— organization and methods for ensuring quality control of GM material;

— organization of construction work and methods for its quality control;

— specific safety and environmental instructions [1].

A number of publications on the practical application of geomembranes are extant: O. A. Baev and A. E. Larionova [9], O. A. Baev and A. M. Baeva [10], O. Yu. Lupachev and

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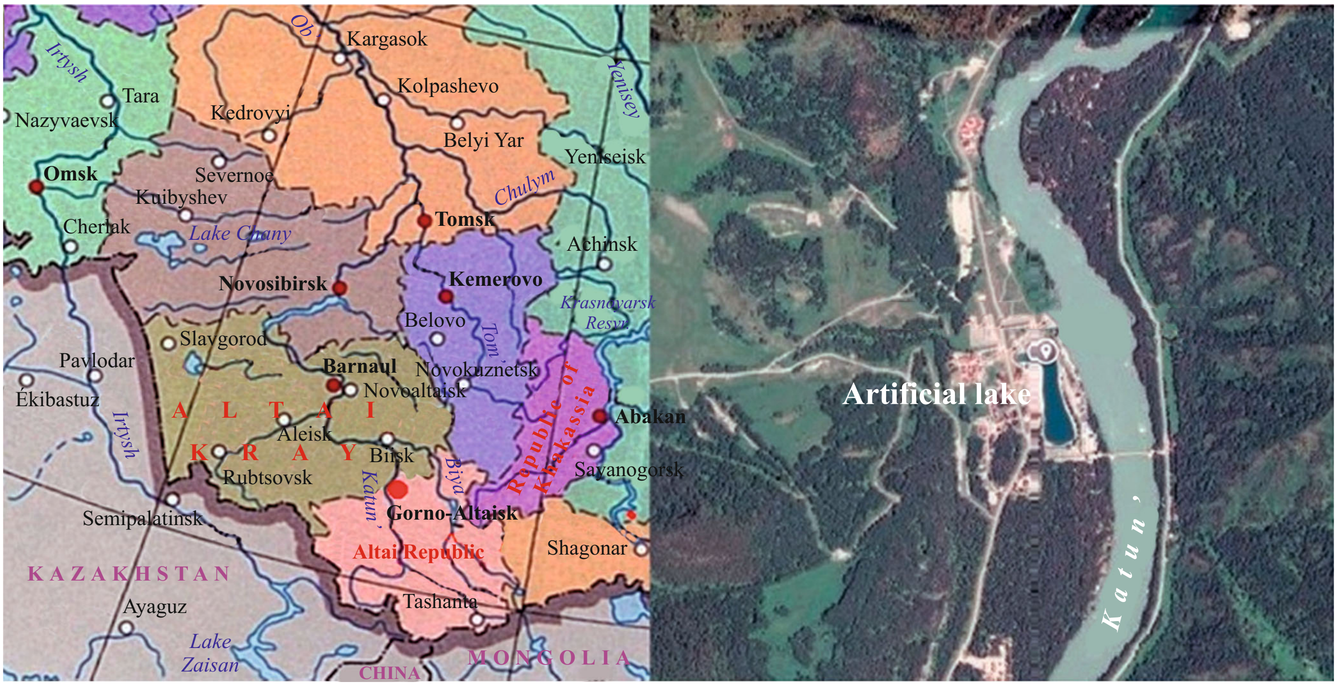

Fig. 1. Location map of the artificial lake in the Altai Republic.

V. I. Teleshev [11], M. E. Minchukova [12], Yu. M. Kosichenko [13], V. G. Radchenko and V. M. Semenkov [14], A. Yu. Garbuz [15], et al. [16 – 21]. However, while these sources consider particular cases of the design, construction, and operation of HS that use geomembranes, they do not provide a general idea of the structure, types, and significance of failures arising at various stages of the IE life cycle or a full discussion of the impact thereof. In the present work, by analyzing failures occuring in geomembranes used in IEs, and, relying on this analysis, systematizing the main factors affecting the final state of IEs, their types, as well as possible control actions for avoiding them, we have attempted to address this gap. The analysis focuses on the data obtained from studying the consequences of emergency situations arising at large HS facilities, illustrating the main practical problems arising in connection with the installation of IEs using geomembranes.

For this purpose, we consider the case of an artificial lake located in a special economic zone (Mayma raion, the Altai Republic), which was designed and constructed in 2008 – 2012 to provide tourism and recreational amenities (Fig. 1). The lake extends to an area of 52 ha, with an average depth of 6.1 m, and a water volume at the normal water level (NWL) of 2574.13 thousand m^3 (Fig. 1).

Geomorphologically, the Altai Valley, formed by the western slopes of the Iolgo mountain range, belongs to the Cherginskiy physiographic region located in the low basin of the Katun' River between the villages of Souzga and Ust'-Sema. The climatic conditions at the construction site are described as harsh, while the relief in the special economic zone of the Altai Valley exhibits sharply contrasting forms. In terms of geological-geomorphological and geotechnical conditions, the artificial lake is primarily located within an alluvial plain, rising to foothills in the western part. The alluvial plain is confined to the surface of the second terrace above the Katun' River floodplain, having an absolute elevation of 275 – 281 m. The erosional-accumulative relief of the area is attributable to the activity of the Katun' River. The site is elevated above the Katun' river bed by about 10 m.

The geological structure of the area can be described in terms of two distinct levels. While the lower structural level is represented by Vendian, Cambrian, and Devonian bedrock (overlain by diluvium, proluvium, and alluvial deposits in the foothill area and on the alluvial plain) at a depth of 12.8 – 35 m, the upper structural level comprises Quaternary deposits of various origins, whose thickness varies from 35 m in the alluvial plain area to 0.8 – 5.5 m in the foothill part. Under average soil conditions, the estimated seismic intensity of the area amounts to 8 points on the MSK-64 scale.

The hydrogeological conditions of the territory are characterized by the presence of subsoil water and groundwater. Subsoil water is distributed sporadically and confined to recent proluvial-diluvial deposits comprising sandy loams with an admixture of gravel, large rocks, and fine earth. The subsoil water level was determined at a depth of 0.7 – 2.10 m during the period of investigations. Groundwater associated with the Upper Quaternary deposits is confined to cobble, fine filtering deposits, encountered primarily at a depth of 9.0 – 10.5 m (absolute elevation of 266.68 – 270.31 m). It has been established that the groundwater is hydraulically connected to the surface water of the Katun' River. The level of the river reaches a maximum elevation of 274.9 m.

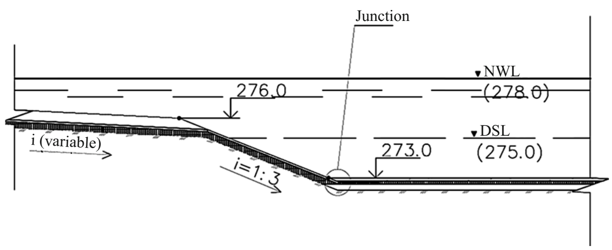

Fig. 2. Shoreline section of the artificial lake.

According to its design, the artificial lake comprises an open basin equipped with a filling/emptying system, as well as a recirculation system for maintaining water quality. In order to prevent seepage and maintain the design water volume, an impermeable barrier was installed in the bed and flanks of the entire area of the lake. The project comprises a single-layer impermeable barrier design employing protective geotextiles to enclose the geomembranes along with bedding and protective layers of cohesionless soil (Figs. 2 and 3).

Upon completing construction and filling the artificial lake in 2013, an off-design lowering of the water level was observed to occur as a result of leakage through the impermeable barrier. In order to determine the causes of the leaks, identify the areas exhibiting increased seepage, and develop recommendations on eliminating seepage in the reservoir, specialists from the Department of Foundations, Earth, and Underground Structures at the B. E. Vedeneev All-Russia Research Institute of Hydraulic Engineering conducted comprehensive studies including an analysis of design and execution documentation, field engineering inspection via destructive and nondestructive methods, verification calculations, and the development of measures to restore the surface integrity of the IE. A visual and instrument-aided structural inspection (including via indicator dye and geoelectrical methods) of the bed and flanks of the artificial lake revealed local failures (Fig. 4) in the impermeable barrier scattered across the site area. The analysis suggested that the leakage

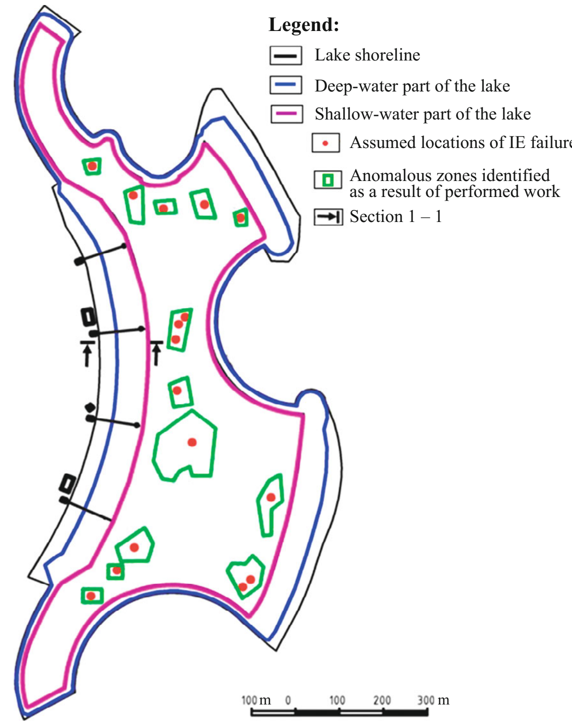

Fig. 4. Schematic of the artificial lake drawn up on the basis of the performed work: locations of section, junction, and failures in the IE.

areas, confined to breaches in geomembrane liners, accounted for about 30% of the total lake area.

The analysis of the design documentation and design solutions revealed the following violations:

— unexpected underflooding of the lake subgrade during the Katun' River freshet, which led to installed IE sections floating to the surface due to a sharp rise in subsoil water levels of the non-flooded artificial lake;

— lack of seepage strength solutions for the bedding layer, which resulted in the suffosion of its material in the gravel-cobble subgrade of the bed;

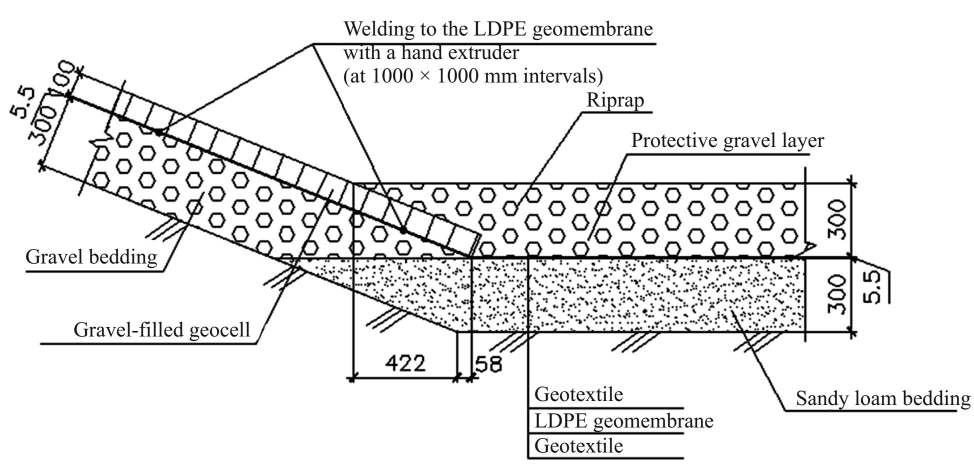

Fig. 3. Structure of the junction between the shore and bed of the artificial lake.

Rupture of the geomembrane along the edges of a boulder embedded in the barrier base

Damage to the geomembrane liner due to its placement on inadequately prepared subgrade

Rupture of the geomembrane along the edges of a sinkhole formed in the sandy-loam bedding at the geomembrane base

Violation of the subgrade surface by machinery during construction

Rupture of the geomembrane on the slope in the area of a pit/track due to poor subgrade preparation

Further expansion of geomembrane rupture in the transverse direction

Washed-out cobbles under the breached geomembrane seam

Sinkholes formed in loam

Fig. 5. Some observed failures in the impermeable geomembrane barrier installed at the artificial lake in the Altai Republic.

— the lack of a location plan for the temporary road along the artificial lake bed along with an indication of equipment unloading points.

The study of identified defective IE sections of the artificial lake and laboratory tests of geomembrane samples revealed multiple deformations and failures of the geomembrane: abrasions, indentations, and perforations. In addition, local areas of bedding layer degradation were noted and confirmed by laboratory soil tests. Figure 5 shows some of the observed defects.

Several significant violations were committed during the construction work. The deformations and failures of geomembranes detected at the site are primarily attributable to poor subgrade preparation and improper formation of the bedding and protective soil layers, specifically involving a failure to take appropriate measures taking into account their granulometric composition. The geomembrane surface was used for loading and unloading operations during the delivery and transfer of inert materials, as well as to permit the passage and turning of wheeled and tracked machines over the geomembrane (as evidenced by numerous tears and scuffs from the impact of buckets, wheels, and tracks). In addition, the specified 1.5 mm thick geomembrane was replaced with 1.0 mm thick geomembrane during the project implementation.

The conducted research revealed a total of about 200 distinct failures and discrepancies occurring during geotechnical investigations, design, and construction of this IE, which had a corresponding impact on its quality.

In general, the dynamics of IE degradation in the artificial lake can be characterized as follows. Numerous breaches in the geomembrane were caused during IE installation; the adequate seepage strength of the bedding and protective layers required for the operating loads was not ensured. Under the influence of seepage gradients formed during the filling process, fine sediments contained in the bedding and protective layers were washed away into the highly permeable gravel and cobble alluvial deposits of the subgrade. With a reduction in the bedding layer volume due to the suffusion of its fine sediments into the large pores of the subgrade, the layer underwent reshaping accompanied by the formation of sinkholes. Under the weight of the protective layer and water pressure, these sinkholes became filled with geomembrane material thus expanding the perforations and subsequently tearing the geomembrane in weakened spots. This factor resulted in increased seepage from the artificial lake.

According to the study results, two sets of recommendations were developed for addressing IE seepage issues along with the corresponding quality control measures for the works performed during the artificial lake filling process:

— the first set of recommendations proposes a local spot repair solution that involves the clearing of identified leak points, the subsequent removal of the damaged geomembrane section to access the seepage-related sinkhole, its filling with clay soil, as well as the restoration of the bedding layer and surface integrity of the damaged geomembrane section;

— the second set of recommendations proposes a complete IE reinstallation involving the use of appropriately pro-

TABLE 1. Main Failures Occurring in Geomembranes during IE Installation

Defects	Manifestations	Causes of failures	Recommendations on how to avoid failures
Deformations	Dents and punctures	Impact of the soil particles of the protective or bedding layers on the geomembrane surface as a result of external loads in the event of these layers containing soils not meeting the appropriate granulometric composition requirements	Performance of work in accordance with SP 39.13330.2012 [1] and SN 551–82 [4]. Justifying calculations for the IE structure: bedding and protective soil layers, protection geotextiles, and geomembrane
Breach in the panel	Tears in the transverse and longitudinal directions	Uneven load on the panel due to subgrade irregularities, i.e., presence of a pit/track created by construction equipment, geometric disturbances of the slope, and the presence of boulders	Compliance with the requirements of the design engineering firm and the recommendations formulated by the geomembrane manufacturer regarding the preparation of an even, homogeneous IE subgrade having no protruding elements, foreign objects, and inclusions
Mechanical damage	Perforations	Vehicle traffic on exposed geomembranes, passage of construction equipment, unloading operations, no temporary road in the construction project	Development of a layout plan for the temporary road, including a traffic pattern for the duration of construction work
Geomembrane wrinkles	Formation of through cracks in the bend	Failure to meet the technical requirements for the geomembrane liner placement, mechanical action on the placed panel in the bent area exceeding its strength characteristics	Compliance with the requirements of the design engineering firm, recommendations of the geomembrane manufacturer, and regulatory documents on the rules of IE installation
Geomembrane seam failure	Incomplete fusion of the seam at the junction between geomembrane panels, an overlap between panels at the seam failing to reach the minimum permissible value	Poorly performed welding	Compliance with the requirement for the minimum overlap between polymeric panels during welding and the avoidance of wrinkles and folds during repair work

tected bentonite mats or clay as the main IE over the existing gravel-cobble protective layer of the subgrade.

The analysis of examples similar to the one described above along with literature data on failures in impermeable geomembrane elements demonstrates the complexity of this problem. While the geomembrane is an excellent waterproofing material, it is not possible to ensure an adequately functioning impermeable system in the absence of a number of associated rules and conditions, including:

— geomembrane handling (transport, loading and unloading, storage, cutting, layout, welding, etc.);

— preparation of bedding and protective layers (granulometric composition; thickness; compliance with the principle of filter layering from fine to coarse fractions; the use of other GM types — reinforcing, filtering, and anti-erosion);

— the complex operation of the impermeable geomembrane element coupled with the general configuration of the impermeable HS contour and the HS itself (fixation of edges; junctions; abutment points; damping points, etc.);

— consideration of specific natural and climatic conditions (engineering-geological, hydrogeological, hydrometeorological, etc.).

With that being said, the geomembrane comprises the main waterproofing element in the described IE structure, whose failure analysis allowed us to make some generalizations (see Table 1). Table 1 presents the typical defects of geomembranes, along with their main causes and manifestations, as well as recommendations on how to avoid them. As follows from this data, the most commonly occurring defects in geomembranes include deformations (dents, punctures, etc.), breaches taking the form of tears in transverse and longitudinal directions, mechanical damage (perforations), through cracks in the geomembrane bends, and seam failures. The main causes for these defects are as follows: poor subgrade preparation; improper installation of the GM liner; the use of soil materials for protective layers in the absence of justifying calculations of their granulometric composition and physical properties; uneven mechanical loads; panel bending; the passage of wheeled and tracked machinery over geomembranes; poorly performed welding; non-compliance with the minimum overlap of two geomembrane panels, etc.

The above-described typical geomembrane failures are associated with violations of proper working procedures. Generally, the installation of a reliable IE in an HS constitutes a complex, multistage, and long-term process, which depends on a large number of participants making their appropriate contribution to it.

Here, particular mention should be made of the need to identify appropriate geomembrane suppliers and their responsibility for material quality. The current lack of a unified regulatory document in the Russian Federation governing the quality of geomembranes and determination of their properties hinders an objective quality assessment of geomembrane materials supplied for construction purposes. The only regulatory document that provides a Table listing the properties of all GMs in accordance with the currently known (often not hydrotechnical or otherwise unsuitable for geomembrane materials) standards is SP 23.13330.2018 (Annex S) with amendments and additions, which came into force on January 19, 2020 [22].

CONCLUSIONS

The present article discusses problems associated with applying geomembranes in hydrotechnical construction, which can be divided into three main groups:

— firstly, the incompleteness of standards and requirements used to justify technical solutions for geomembrane IE design, which affects the result of work;

— secondly, the apparent impact of insufficiently established norms and requirements on the IE installation process;

— thirdly, an underestimation of the need for standards and requirements governing the operating conditions of geomembrane IEs.

The data obtained from the study of emergency situations at large HS occurring in practice illustrate the consequences of poor construction work standards and improper quality control when handling geosynthetic materials.

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