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PRACTICE-ORIENTED PAPER

Geosynthetic barrier systems used in dams, ponds, and reservoirs of Turkey

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Abstract

Geosynthetic barriers are synthetic materials used to ensure the long-term sealing of hydraulic structures such as dams, ponds, and reservoirs. The number of applications of geosynthetic barrier systems that have become an integral part of dams and reservoir areas is increasing rapidly in Turkey. It is estimated that there are over 100 dams, ponds, and reservoirs sealed with geosynthetic barriers in Turkey. In this article, it is aimed (1) to show the statistical data of geosynthetics, i.e., the amount, types, thickness, etc., used or planned to be used in dams, ponds, and reservoirs and (2) to discuss many important uses of geosynthetic barrier systems including early applications in various dams. Although polyvinyl-chloride geomembranes are the most widely used geomembranes in the world, high-density polyethylene and ethylene propylene diene monomer geomembranes are the first choices in the case of the dam, pond, and reservoir lining in Turkey according to State Hydraulic Works (DSI) database. It is important to note that there are many successful DSI dam projects (generally less than 50 m high) that geosynthetic barriers have been installed (on the upstream face or in the core) and performing well.

Keywords Geosynthetics · Geosynthetic barrier systems · Geomembranes · Dam lining · Embankment dams · Turkish dams

List of symbols

f_k	Sand filter
$f_ç$	Gravel filter
f_t	All in aggregate filter
k_u	Rock stone filter
R	Riprap
K	Protective layer
Z	Random fill
D_{max}	Maximum particle size
M m^2	Millions of square meters

Abbreviations

DSI	State Hydraulic Works
GBS	Geosynthetic barrier systems

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Introduction

Geosynthetics are natural or manufactured polymers used with geotechnical materials in civil engineering applications such as roads, landfills, dams, embankments, retaining structures, etc. In the past 60 years, various geosynthetics such as geomembranes, geotextiles, geosynthetic clay liners, geocells, and geogrids have been used in nearly all types of dams. Geosynthetic materials have different functions: barrier, drainage, filtration, surface erosion control, protection, and reinforcement. They are widely used in new dams (especially embankment dams) and the rehabilitation of dams (embankment, concrete, or roller-compacted concrete). According to Scuero and Vaschetti [1], it is estimated that more than 400 large dams are associated with geomembrane systems all over the world. On the other hand, geomembranes (mostly polyvinyl-chloride), as reported by the international commission on large dams (ICOLD), are used on the upstream face or within the 280 dams in the world (188 embankment dams and 82 concrete + roller-compacted concrete + unknowns).

Geosynthetic barrier systems (GBS) are now considered long-term sealing techniques in dams if properly designed and installed. Such systems have been used as an alternative method to traditional materials (e.g., clays and silts) in

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seepage control of embankment dams [2]. There are many application types of geosynthetic barriers in such dams: impervious facing, impervious embankment elements, reservoir lining, cutoff walls, and so on [3]. Also, geomembranes, covered or exposed, have been used to cover the upstream face of RCC dams to provide imperviousness of joints and cracks [4]. For detailed information on geosynthetic barrier systems for dams, see Cazzuffi et al. [5]. Also, refer to Demirdogen [6] for details of internal geomembrane systems in dams.

The first application of geomembranes in dams was at the Contrada Sabetta Dam built-in [7]. Also, the first dam where geotextile was used is Valcros Dam built-in [8]. On the other hand, a geosynthetic sealing system was first used in 2014 on the upstream face of a dam in the projects of State Hydraulic Works (DSI), responsible for managing, developing, and protecting water and other related resources in Turkey. It is estimated that there are more than 100 dams, ponds, and reservoirs associated with GBSs in Turkey. In this article, statistical data of geosynthetics (total quantity, thickness, mass per unit area, etc.) used or planned to be used in Turkish dams, ponds and reservoirs are shown. The development process of the GBS from the early applications to the present is shown with some commonly accepted criteria in the design phase and practice. Also, successful and innovative examples of GBS in embankment dams are illustrated.

Advantages and disadvantages of various kinds of polymeric geosynthetic barriers

As shown in Table 1, 63% of geomembranes used in dams are polyvinyl-chloride (PVC), which means more flexible geomembranes than rigid ones have generally been selected in dams [4]. To better understand the reasons behind that, each of the geomembrane types is discussed below in detail:

- *PVC geomembranes.* PVC geomembrane is the most adopted type and has been successfully used in many hydraulic structures (especially in dams) due to their superior performance characteristics. The reasons for such successful performances can be: (1) their low elastic modulus; therefore, high flexibility; and better performance against puncture and burst by uneven rough subsurface, (2) easy to install, and (3) decades of field experience of properly formulated exposed applications [5]. On the other hand, a careful selection of a plasticizer type is significant for PVC geomembranes. According to the study carried out by Colmanetti et al. [9], PVC geomembranes are more suitable for particularly high dams.
- *HDPE geomembranes.* As well-known, HDPE geomembranes are commonly used in landfills due to their durability and chemical resistance. These geomembranes are also preferred in reservoir lining. This is because they are generally more economical than other geomembrane types, are easy to supply, and have very stable polyolefin material (i.e., chemically inert and long-lasting) [10]. However, using HDPE geomembranes in dams is limited due to geomembrane rigidity. They restrict the adaptation of geomembrane to large deformations in the supporting layer due to high hydrostatic pressures [5].
- *EPDM geomembranes.* Ethylene propylene diene monomer (EPDM) geomembranes, having somewhat fewer application areas in dams, are resistant to abrasion and tear, and have good resistance to UV exposure. However, EPDM geomembranes require the use of special adhesives and careful application to achieve the desired field weld quality as they are thermoset polymers [8]. In addition, the resistance of EPDM geomembranes against dynamic impact is lower than thermoplastic materials such as HDPE and PVC-P [10].

Table 1 Geomembrane application in dams by type and systems (From ICOLD, International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

Geomembrane type	Total dam			%
	Exposed	Covered	Total	
PVC	92	77	169	63.5
LLDPE	0	29	29	10.9
HDPE	3	12	15	5.6
EPDM, PIB, IIR	5	5	10	3.8
Others	16	27	43	16.1
Total known	116	150	266	100

Additionally, underwater geomembrane installation evaluation is important to understand the suitability of geomembranes for dam applications. Puncture and burst experiments were conducted to assess the widely used geomembrane performance by the USACE [11]. Characteristics of geomembranes (imperviousness, tear resistance, dimensional stability, weldability, etc.) and other parameters (constructability, previous applications, durability, availability, repairability, and cost) were investigated. The study's results show that PVC geomembranes have the highest score among other geomembrane types (Fig. 1).

According to the USACE study, prominent features of geomembrane types can be summarized:

- PVC geomembranes: summability, overall constructability, previous applications, and repairability.
- HDPE geomembranes: easy to supply and cost.
- EPDM geomembranes: tear resistance.

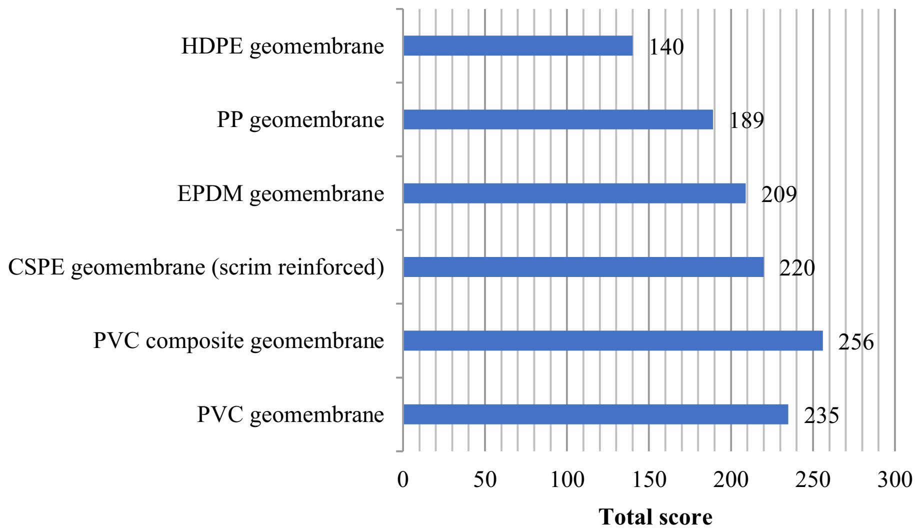


Fig. 1 The general assessment of geomembrane types evaluated over 260 points [11]

It is important to note that flexibility, puncture resistance, and tensile behavior are common features where both PVC and EPDM geomembranes stand out.

Blanco et al. [10] compared three different geomembrane types (PVC-P, HDPE, and EPDM) used to waterproof reservoirs in their study. They stated that "The geomembrane nature is not a decisive factor, it can be thermoplastic or thermostable but with a correct formulation." However, in the case of the geomembranes exposed to a significant amount of water pressure, especially in dams and reservoirs, the more it adapts to the ground, the more load exerted by the water is distributed. The risk of geomembrane puncture is reduced due to concentrated loads on the protrusions in the supporting layer [5]. For such reasons, it can be concluded that geomembranes that behave relatively smoothly are the first choice in reservoir and dam lining systems.

Geosynthetic materials used in DSI projects

The world's first examples of geomembrane applications in dams date back to the late 1950s, while the use of a geomembrane in a dam for the first time in Turkey is the Yedikapı Dam completed in 2014. As mentioned initially, it is estimated that there are at least 100 dams, ponds, and reservoirs – that are currently completed or will be completed by 2022 – associated with geosynthetic lining systems in Turkey. On the other hand, 89 dams, ponds, and reservoirs lined with geosynthetic barriers according to the DSI database 2020 (based on the data provided by the Regional Directorates of State Hydraulic Works). Out of 89 hydraulic structures, 31 are completed; 41 are in construction; and 17 are in the final design stage.

Almost all the geomembrane-faced dams in Turkey are below 50 m high (max 53 m high). Also, 86 of the 89 dams with GBSs are rockfill, while three are earthfill dams. Many of these dams are used for irrigation purposes. In nearly every region in Turkey (ranging from 260 to 2300 m), there are applications of GBSs in dams.

Based on the DSI (2020) database, over 20 million m^2 of geosynthetic materials have been used in dams, ponds, and reservoirs of Turkey. Approximately 44% (or 9 M m^2) of the used geosynthetic materials are geotextiles. They are commonly used as a cushioning barrier between a geosynthetic lining system. Also, 35% (or 7 M m^2) of such materials are geomembranes; 9% (or 1.8 M m^2) are geosynthetic clay liners (GCLs); 8% (or 1.6 M m^2) are geocells, and 4% are other geosynthetic materials (Fig. 2).

A variety of geomembrane types have been installed in dams, ponds, and reservoirs of Turkey. According to the database, HDPE geomembranes are by far the most used geomembranes in such applications. On the other hand, EPDM geomembranes follow this at a rate of 35%. LLDPE geomembranes also account for approximately 3% of the total. In Turkish dams, ponds, reservoirs, it is essential to note that there are no applications of PVC geomembranes, which are the most frequently used types in dams in the world (Fig. 3).

When the geomembranes used in DSI projects are evaluated in thickness, HDPE geomembranes, the most commonly used type, have generally been selected as 2 mm thick. On the other hand, 1.5 mm or 2.0 mm thick EPDM geomembranes have widely been used in projects. There are also relatively thin and thick EPDM geomembrane applications available (Fig. 4). It should be noted that the minimum geomembrane thickness that is currently required in DSI projects is 1.5 mm based on the technical specification of GBS.

In the DSI project, a mass per unit area of 500 gr/m^2 polypropylene (PP) or polyester (PET) non-woven geotextiles

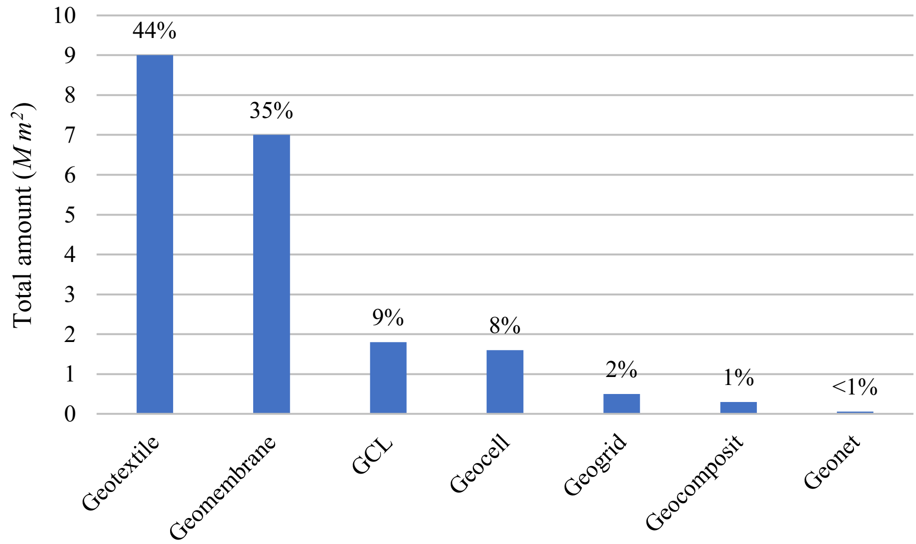


Fig. 2 Proportional representation of geosynthetic materials used in DSI projects

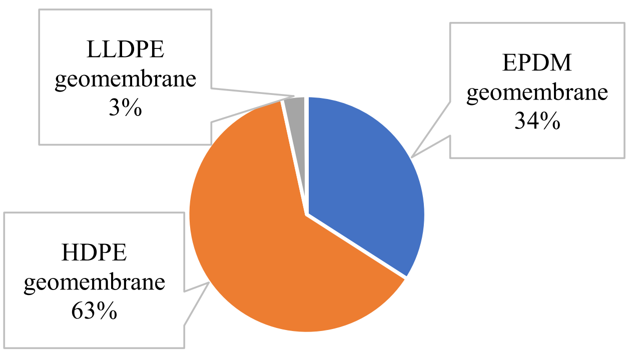


Fig. 3 Distribution of geomembrane types used in DSI projects

have generally been used as anti-puncture protection to the geomembranes. Depending on the project requirements, a mass per unit area from 250 gr/m^2 (%5) to 1000 gr/m^2 (%18) geotextiles have been installed (Fig. 5).

The data presented herein revealed the trends (tendencies towards the selection of geosynthetics in terms of types, thickness, etc.) in the use of geosynthetics for dams, and also provides the compatibility of such trends with the global practice. It is clearly shown that PVC geomembranes are the most widely adopted type of geomembrane in dams, although HDPE and EPDM geomembranes varying a wide range of thicknesses have generally been selected as sealing elements in Turkey's dams, ponds, and reservoirs. The reasons can be the following:

- Especially HDPE geomembranes are more economical and easier to supply than other geomembrane types.
- Since the first reservoir lining applications with HDPE geomembranes were followed by installing geomembranes on the upstream faces of dams, the use of HDPE geomembranes in dams has been greatly affected by reservoir lining applications carried out as part of the routine.
- Considerable experience has been acquired from previous successful applications of HDPE and EPDM geomembranes in dams, ponds, and reservoir lining systems in Turkey.

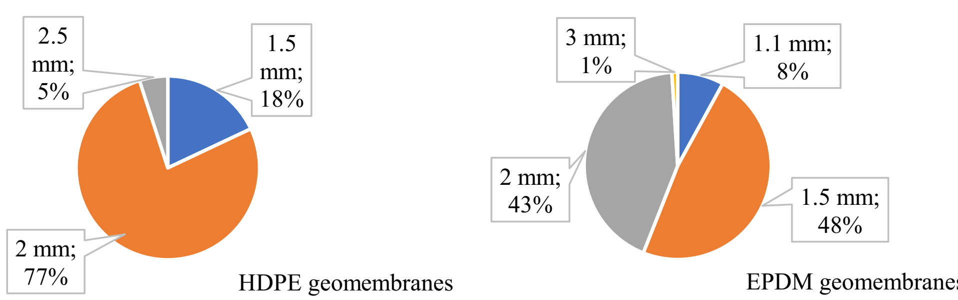


Fig. 4 Distribution of HDPE and EPDM geomembranes used in DSI projects in terms of thickness

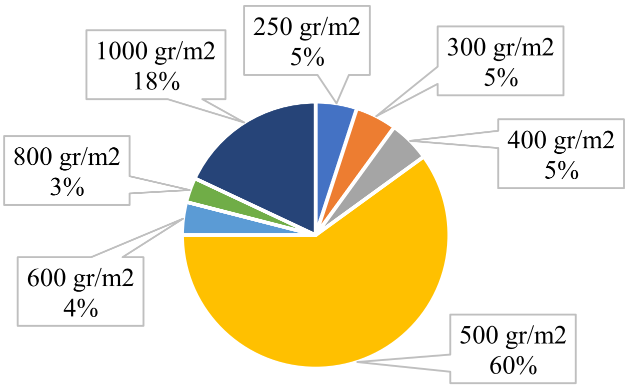


Fig. 5 Distribution of geotextiles used in DSI projects in terms of mass per unit area

Geosynthetic barrier application in Turkish dams, ponds, and reservoirs

Almost all geosynthetic barriers have been placed in embankment dams, mostly rockfill, in Turkey. This is evident among 100 Turkish dams where geomembranes or GCLs have provided water tightness. In this section, the design and construction aspects of geosynthetic barriers in these embankment dams are considered. Also, several examples of relatively new dams, including the early dams constructed using geosynthetic barriers, are shown.

Design aspects and typical applications of geosynthetic barriers

Design aspects of GBSs in hydraulic structures depend on laboratory testing, interface strength, slope geometry, welding design, anchor ditch, and connections, leaks, uplift pressure, settlement, exposed vs. covered systems, protective cover design, etc. [3]. The details of the design of geomembrane sealing systems are based on the above-mentioned factors. A typical section of the GBS can be shown depending on dam types. For example, a typical cross-section of a new rockfill dam with a waterproofing system consisting of a geomembrane sealing system and an optional cover layer is shown in Fig. 6 [4].

Also, Fig. 7 shows a typical example of a geomembrane sealing used in a 35 m high rockfill dam in Turkey. In this dam, 2 mm thick elastomeric (EPDM) geomembranes were used in an area of 79,323 m^2, which were placed both on the upstream face and reservoir.

In such a classical application, a GBS consists of the rock stone used as a transition zone, filter sand, or all in aggregate filter used as a supporting layer (D_{max} 30 cm). It is a protective geotextile and a geomembrane. On the other hand, the cover layer (stated optional by ICOLD) consists of a protective geotextile and a concrete lining. A detailed cross-section of this dam is shown in Fig. 8.

The use of non-woven geotextiles under and/or above geomembranes significantly increases the puncture resistance. Protective geotextile layers are generally included together in the design of geomembrane sealing systems in Turkey. Such layers can be below or above the geomembrane, as seen in Fig. 9. According to the US Bureau of

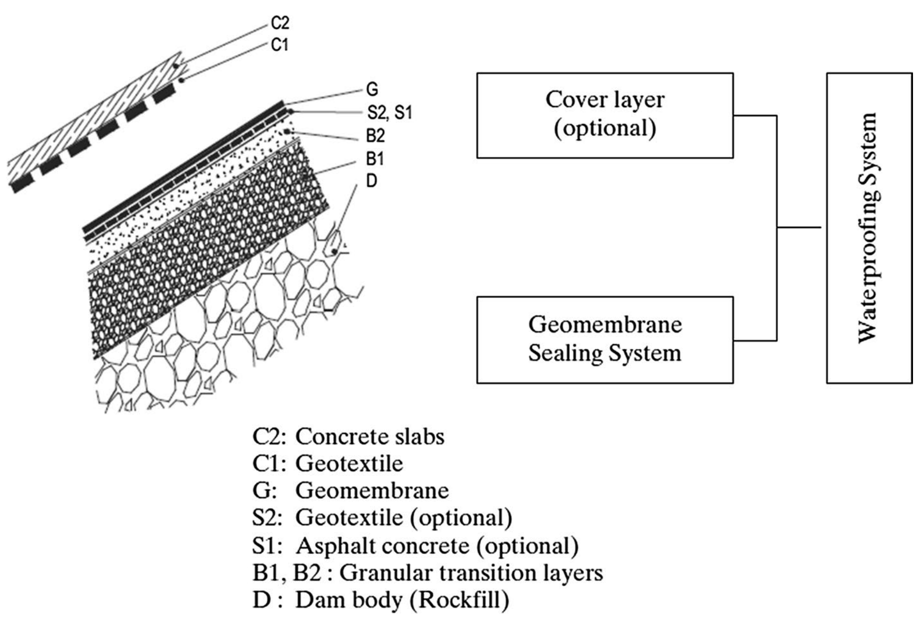


Fig. 6 Typical cross-section of a waterproofing system for new rockfill dams (From ICOLD, International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

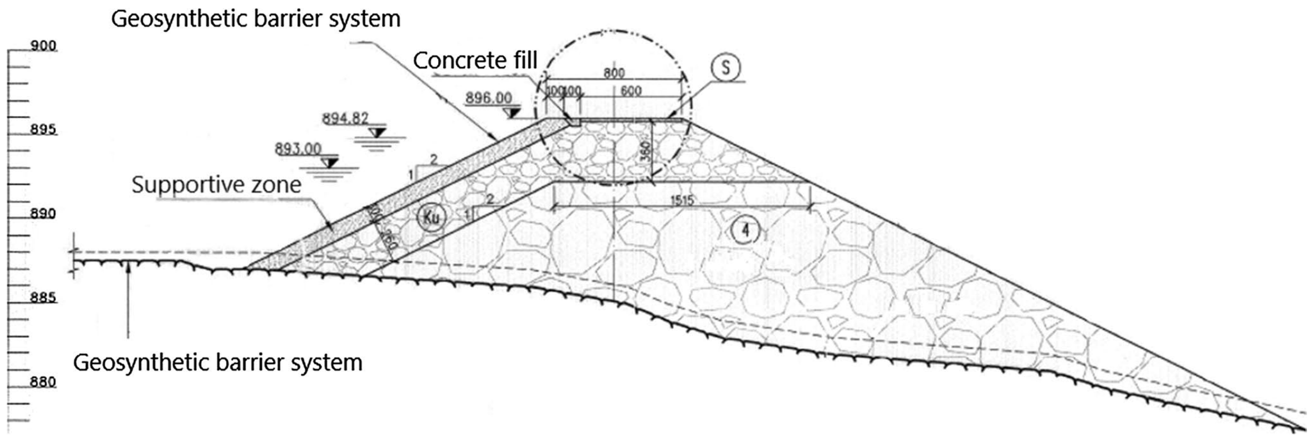


Fig. 7 A Typical section of geomembrane-faced rockfill dam in Turkey (DSI 2014)

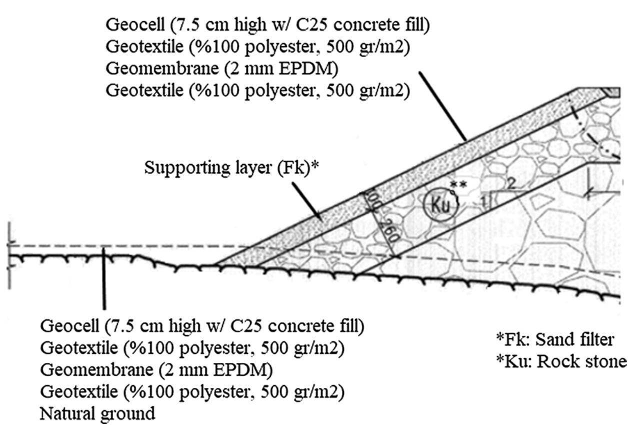
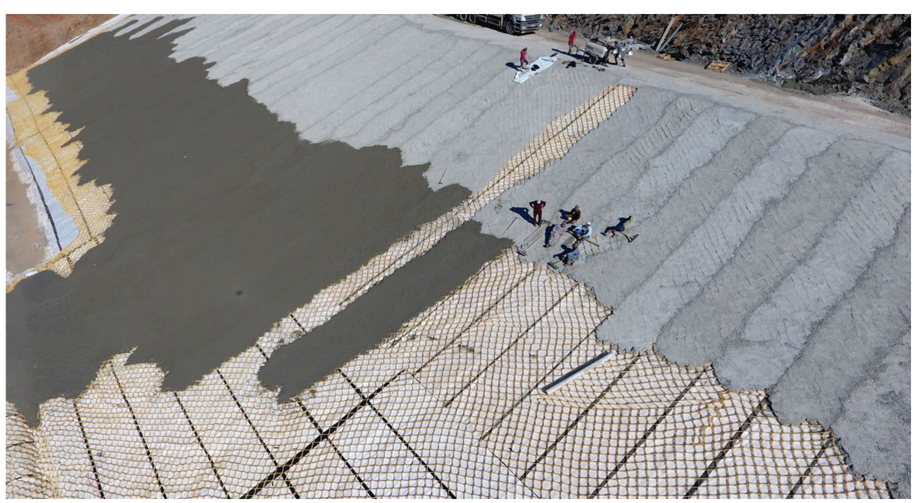


Fig. 8 The elements of geosynthetic barrier systems including geocell, geotextile, geomembrane, geotextile, sand filter, rock stone, and rockfill used in a rockfill dam (DSI 2014)

Reclamation (USBR) [3], the protective geotextile layers of a minimum mass per unit area of 340 g/m^2 (10 oz/yd^2) are recommended, but 406–610 g/m^2 (12–18 oz/yd^2) are desirable. Parallel to the recommendation, mass per unit area of 500 gr/m^2 geotextiles have generally been placed in dams, ponds, and reservoirs of Turkey (see Fig. 5). It is important to note that geotextiles' mass per unit area is a crude indicator of geomembrane protection. The tensile properties of geosynthetic materials are essential rather than the mass per unit area [12].

The fact that the geomembrane is exposed or covered is a critical assessment in dam design [13]. While covered geomembrane systems were the most advanced technique according to the ICOLD Bulletin in 1991, the number of exposed systems has substantially increased due to some

Fig. 9 Application of concrete pouring into geocells to protect the geomembranes on the face of a rockfill dam



factors such as improvements in resin and additives and increased UV resistance [4].

In Turkey, covered geomembrane systems have been preferred in geomembrane used dams. This is due to its durability requirements and vandalism. The covered systems can consist of protective gravel (typically 50 cm) or a concrete layer (typically 15 cm). On the other hand, there are many difficulties, including cost, durability, stiffness, etc., in protective concrete layers. Therefore, protecting the geomembrane by laying the geocells on geomembranes and filling them with concrete was first used in the Mud Luke Dam to solve such problems. Heap et al. [14] noted that this method (1) is cheaper than the traditional concrete cover, (2) has a longer lifetime and (3) is easier to be applied.

Such a geocell/concrete protection method was first used in the rehabilitation project of the Hisarardı Dam in Turkey. After this application, geocell slope-protection systems have become common in practice. In the application shown in Fig. 9, concrete was poured into 75 mm high, 1.5 mm thick holeless geocells with a range of 60 cm welding intervals to protect the underlying geomembranes.

There are few geomembrane applications in homogenous dams in Turkey. The elements of waterproofing systems of homogenous dams can differ from rockfill dams. The example of a dam rehabilitated with geomembranes is shown in Fig. 10. In this application, the imperviousness of the upstream face of the dam was provided by a waterproofing system. The system consists of a 25 cm thick sand filter, 800 gr/m^2 protective geotextile, 2 mm thick HDPE geomembrane, 800 gr/m^2 protective geotextile, 40 cm thick sand filter, and 90 cm thick riprap.

Examples of geosynthetic sealing systems in Turkey

Yedikapı Dam

The first geomembrane-faced embankment dam in Turkey is the Emirdağ Yedikapı Dam that was completed in 2014. The volume of Yedikapı Dam is 699878 m^3. 40 m high Yedikapı Dam has a crest length of 327.83 m. It irrigates 5,350,000 m^2 of land.

In this dam, HDPE geomembranes with a thickness of 2 mm were used as an impervious element on the 24,000 m^2 upstream face. Geotextiles with mass per unit area of 600 gr/m^2 were used above and below the geomembrane layer. Figure 11 shows the placement of protective geotextiles and geomembranes on the upstream face of the Yedikapı Dam.

Yıprak Dam

Another example of the use of geomembranes as an upstream and reservoir lining in Turkey is Yıprak Dam. 32 m high such rockfill dam was completed in 2015. This rockfill dam used for irrigational purposes has upstream and downstream slopes of 1 V: 2H (vertical-horizontal), a crest width of 10 m, and a crest length of 87 m. The volume of the dam is 240000 m^3, and the reservoir volume is 875000 m^3 [15].

As stated by Çavuş [15], geological formations along the longitudinal axis of the dam and the reservoir area consist of highly permeable limestone and consolidated clay-shaped marl units. Therefore, a clay blanket was evaluated to ensure the impermeability of the reservoir area of Yıprak Dam; however, impervious clay materials were far from the dam site and not in the distance for the economic haul. As a result, geomembranes were installed from the bottom reservoir area up to the crest to ensure water tightness (Fig. 12). In addition, the second geomembrane layer has been placed within the dam core. This responded to the risk of any

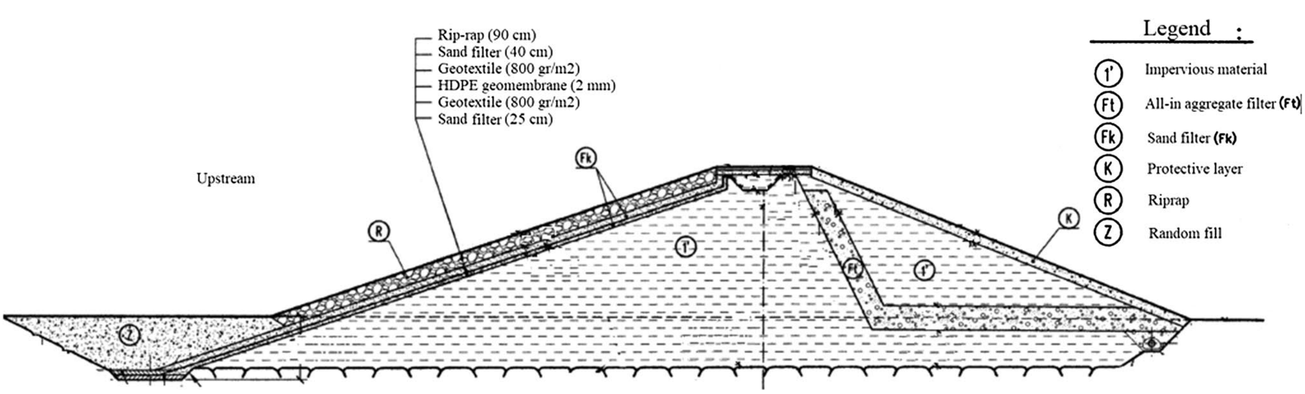


Fig. 10 Homogenous dam section supported with a geomembrane barrier system (DSI 2015)

Fig. 11 Geomembrane sealing systems on the upstream face of Yedikapı Dam

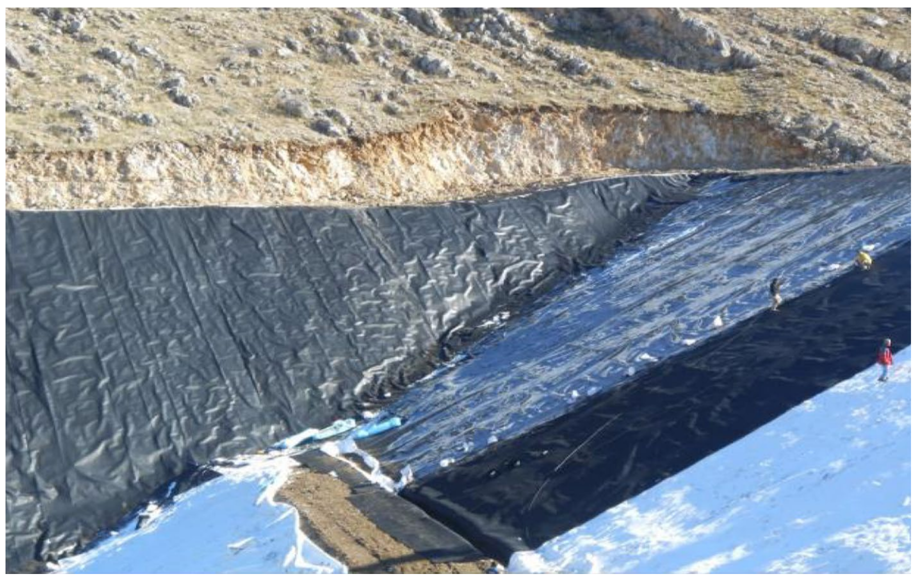


Fig. 12 Geomembrane sealing systems both on the reservoir area and the upstream face of the Yıprak Dam (Courtesy Dr. Uğur Şafak Çavuş)

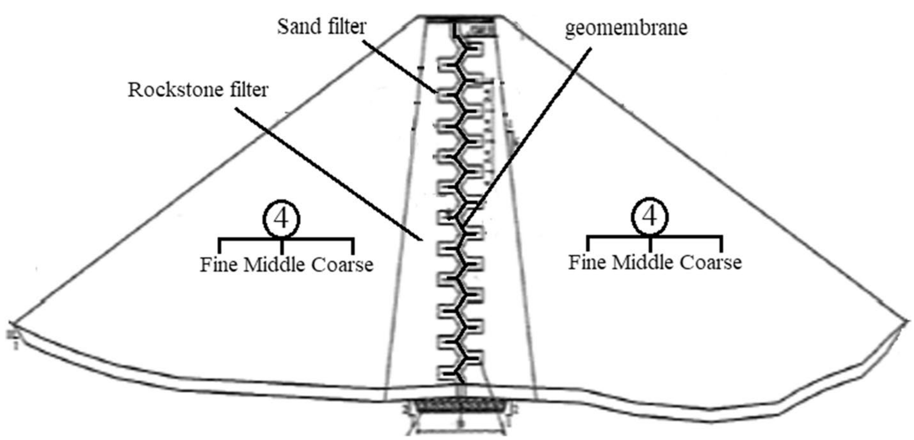


Fig. 13 A zig-zag geomembrane within the core of Yıprak Dam (DSI 2015)

damage to the geomembrane barrier on the upstream face because the region is a highly active seismic area (Fig. 13).

Morgedik and Avgadı Dams

Morgedik Dam, the first dam in Turkey where the clay core was supported with GCL, was planned for a central clay core rockfill dam. The dam is 60 m high, a volume of 780,000 m^3, and a reservoir volume of 100,000,000 m^3 [16]. In the early phase of the construction, it was predicted that the clay materials of 232,038 m^3 would be required for the core of the Morgedik Dam. When the Morgedik Dam reached an elevation of 2215.00 m, the amount of clay material needed to complete the impervious filling was 55,000 m^3. At that stage, the reserve of the clay pits specified as A, B, C, and D were out of impervious material. On the other hand, the unit weight of the remaining material in the clay pit of C was low, and the material was in poor quality. Therefore, the Technical Committee of the Morgedik Dam stated, "The material in the clay pit of C should be used above the normal water level (2227.50 m), where the water pressure is low."

The Morgedik Dam has a very short construction period because of its location. Therefore, it was predicted that the procurement, expropriation, and acquisition of licenses for new quarries during this limited period would cause a serious waste of time. Additionally, the construction of pit transportation routes would cause a high cost. As a result, it was considered that the remaining clay fill should be supported with geosynthetic clay liners (GCLs) to use this low-quality material. It was also stated that this would be a cost-effective solution.

After modifying Morgedik Dam's projects, GCLs consisting of a layer of sodium bentonite supported by a mass per unit area of 200 gr/m^2 non-woven and woven geotextiles (below and above, respectively) were used with the low-quality clays starting at an elevation of 2215 m on the slope of 5 V/1H (Fig. 14). It is important to note that Morgedik Dam has been in operation since 2015 and is performing well.

In Fig. 15, the raising of the clay fills on the downstream side after GCL placement is shown. For more application details of Morgedik Dam, see Aydın and Gelberi [16].

After the experience gained in Morgedik Dam, a similar approach was followed at the Avgadı Dam project, where it was again encountered low-quality impervious materials at the project site. In contrast to the Morgedik Dam, GCL materials with a zig-zag pattern that performs flexibly

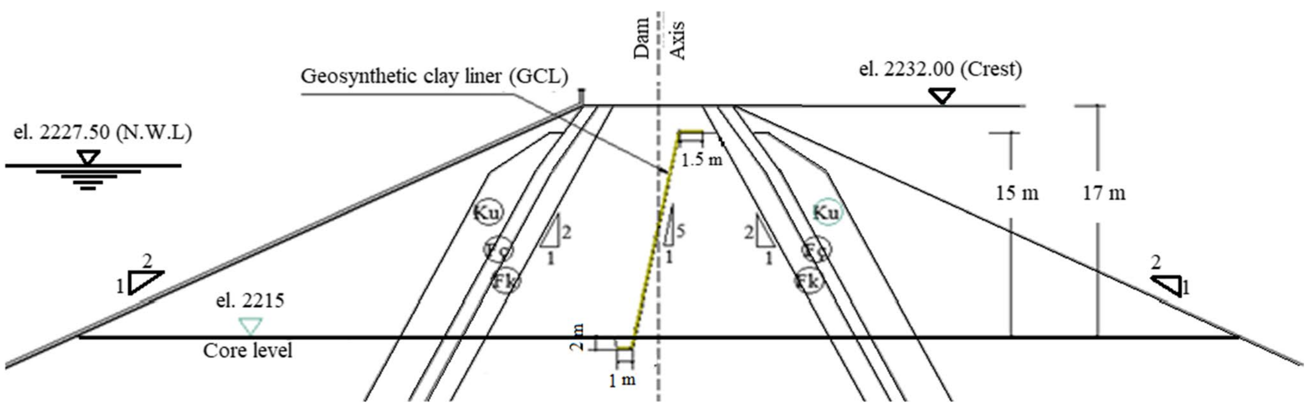


Fig. 14 Impervious clay supported by GCLs at Morgedik Dam (DSI 2015)

Fig. 15 Slope cutting on 2.71 m raised downstream clay fill after GCL placement

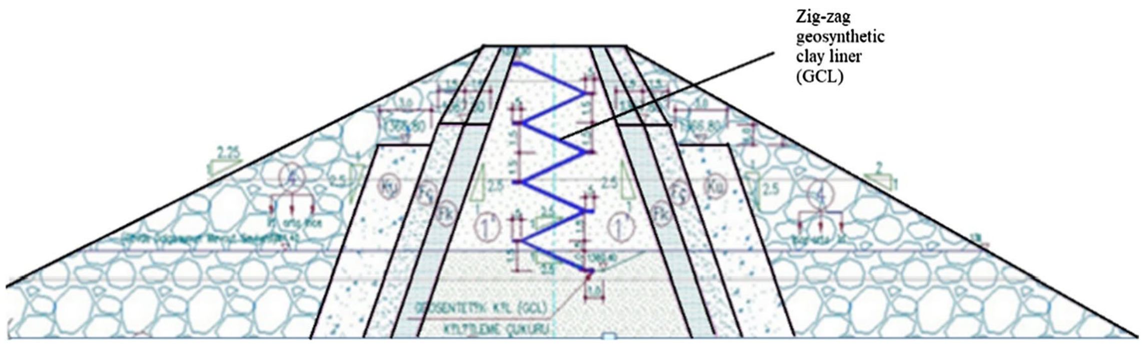


Fig. 16 The section of the zig-zag pattern GCL in Avgadı Dam (DSI 2016)

Fig. 17 At left, second stage installation of GLC. At right, placement of the low-quality clay over GCL in Avgadı Dam

Fig. 18 A general view of the Avgadı Dam

against settlement were installed in the Avgadı Dam, as shown in Fig. 16.

Also, Fig. 17 and Fig. 18 show the transition stage of GCL placement after the completion of the first stage and a general view of the Avgadı Dam, respectively.

Conclusions

Comprehensive data on the geosynthetic barriers of Turkey for the first time has been presented in this article. It has also been shown that geosynthetic barrier systems have been successfully used in many Turkish dams.

In detail, this article shows that:

More than 20 million m^2 of geosynthetic materials have been used in dams, ponds, and reservoirs in Turkey.

Although PVC geomembranes are generally preferred in dams worldwide, HDPE geomembranes have become the most preferred type in Turkey due to cost, market volume, and experience gained in practice. EPDM geomembranes also have an important area of application.

Exposed geomembrane systems, a rapidly developing field, are not common practice in Turkey. The covered systems have been preferred due to environmental impact and vandalism.

Although it varies depending on the design requirements, geomembrane protection systems with concrete-filled geocells in rockfill dams are one the most frequently adopted solution in Turkey.

There are many successful applications of geosynthetic sealing systems in Turkey, from geomembrane face sealing to GCL in the core (on a flat or zig-zag pattern).

Geosynthetic sealing systems as an alternative to traditional materials are becoming more common in dams, ponds, and reservoirs of Turkey. Such systems are likely to be used in embankment dams and the rehabilitation projects of Turkey's conventional concrete and RCC dams.

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Author contributions The first author collected and contributed the data of this study, while the second author wrote and organized the paper.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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